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Safety Effectiveness of
Highway Design Features

VOLUME VI

PEDESTRIANS AND BICYCLISTS

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PREFACE

This is the sixth volume in a series of six publications providing research results on the safety effectiveness of highway design features. This series provides designers and traffic engineers with useful information on the relationship between accidents and design features and facilities for pedestrians and bicyclists.

The Scientex Corporation, the Highway Safety Research Center at the University of North Carolina, Chapel Hill, and Michael Baker Jr., Inc., have compiled this Compendium under contract with the Federal Highway Administration. The six volumes include:

Volume I:	Access Control
Volume II:	Alignment
Volume III:	Cross Sections
Volume IV:	Interchanges
Volume V:	Intersections
Volume VI:	Pedestrians & Bicyclists

Authors with extensive experience in each subject area have reviewed past research, and significant findings are summarized here, along with an additional bibliography for reference.

PEDESTRIANS AND BICYCLISTS

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INTRODUCTION

Collisions between pedestrians and motor vehicles and between bicyclists and motor vehicles continue to be serious safety problems in the U.S. In 1989, for example, 6,552 pedestrians were killed, which represents 14.4 percent of the Nation's 45,555 motor vehicle fatalities.[1] An estimated 119,000 pedestrians were injured or killed during that same year.[2] Moreover, each year approximately 900 bicyclists are killed in collisions with motor vehicles, and thousands more are seriously injured. The Consumer Product Safety Commission estimates that over half a million persons are treated each year in hospital emergency rooms for bicycle-related injuries.[3]

Although the number of pedestrian and bicyclist fatalities is currently less than the roughly 9,100 reported nationwide in 1979, and the proportion of total motor vehicle deaths accounted for by pedestrians and bicyclists has declined in recent years, the problem remains serious.[1] There has been renewed interest in walking as a form of transportation and exercise in recent years. Additionally, over the past 2 decades the United States has experienced a tremendous growth in the popularity of bicycling, particularly among its adult population. An estimated 23 million adults cycle regularly, along with 42 million children.[4]

This increase in pedestrian and bicyclist activity combined with an aging population and ever-increasing traffic volumes on public streets has resulted in a situation where creative and immediate countermeasures are needed to minimize future crashes between pedestrians, bicyclists, and motor vehicles.

The first section of this chapter is intended to provide a brief overview of what we currently know about pedestrian accident characteristics and types. Also included is a discussion of potential geometric improvements which may enhance pedestrian safety. Unfortunately, little information exists about the specific relationships between pedestrian accidents and geometric conditions. Therefore, some information in this chapter is based on subjective opinions and judgements of researchers and practitioners, although some objective accident relationships are also described.

The second section of this chapter reviews the results of research efforts undertaken by the National Highway Traffic Safety Administration (NHTSA) and the Federal Highway Administration (FHWA) focusing on the safety of bicyclists. It also looks at activity related to bicycle facility design and evaluation. The review incorporates a variety of studies, including accident data analyses, facility design guidelines and safety standards, route designation criteria, and evaluations of facilities based on observational studies and, where available, accident data analyses.

Finally, any successful safety program for pedestrian and bicyclist crashes must certainly include effective efforts toward pedestrian and driver education, as well as police enforcement of traffic laws and regulations. At the national level, these areas are the primary responsibility of NHTSA. This chapter, however, deals only with geometric and roadway features and treatments as they relate to pedestrian and bicyclist safety.

SUMMARY OF PEDESTRIAN RESEARCH

Pedestrian Accident Characteristics

Numerous studies have been conducted in recent years related to the causes and characteristics of pedestrian crashes and resulting crash severity. Such characteristics of interest include pedestrian age and sex, alcohol impairment, time-related factors, roadway environment, and others. The understanding of such characteristics is useful for selecting roadway or geometric improvements for pedestrians. A discussion of some of these characteristics is given below.

Pedestrian age and sex

Robertson and Carter analyzed 2,397 intersection pedestrian crashes and calculated the accident risk by dividing pedestrian crashes by percent of population. Pedestrian risk at intersections was greatest for the young (between 5 and 15) and older adults (65 years and older), as shown in figure 1.[5]

A 1988 study for TRB found that the fatality rate increases sharply for pedestrians 70 years or older (see figure 2). While young children were over-involved in the number of pedestrian accidents, their fatality rate (deaths per 10 million population) was no more than other age groups.[6] This could be the result of the greater ability of younger pedestrians to survive a crash, compared to older pedestrians. Also, accidents involving young pedestrians occur on residential streets where vehicle speeds are lower.[7]

Rates of pedestrian injuries and deaths by age and sex from NHTSA's General Estimates System (GES) show the highest pedestrian accident rate of 149 (pedestrian crashes per 100,000 population) for pedestrian males aged 5 to 9. There is a steady drop to a rate of 40 for males 65 and older (see figure 3).[2] This trend for older pedestrians differs from the study by Robertson and Carter, perhaps because that study involved intersection pedestrian accidents only, where older pedestrians may have particular problems crossing.

It should also be remembered that pedestrian exposure (i.e., miles of walking along streets or numbers of times crossing wide or dangerous streets) is not accounted for in any of these statistics. Little data on pedestrian exposure exists, since it is difficult and costly to collect by pedestrian age for a large sample of sites. The amount of walking is relatively unknown, and may vary widely by age groups.[2,7]

Alcohol involvement

Alcohol impairment has also been found to be a serious problem for pedestrians, as well as drivers of motor vehicles. One recent study reported that during the period of 1980 through 1989, between 37 and 44 percent of fatally-injured pedestrians had blood alcohol concentrations (BAC's) of .10 or greater. These percentages were only slightly lower than those involving drivers of passenger vehicles and motorcycles, as shown in table 1. Of all adult pedestrians killed in nighttime collisions with motor vehicles in 1989, 59 percent had BAC's of .10 or greater, while only 31 percent had no alcohol in their blood.[7,8]

It is also interesting to note from table 1 that while the percentage of fatally-injured pedestrians with high BAC's (.10 or more) stayed relatively constant in the 1980's, a steady decrease occurred for drivers of motor vehicles. These results, based on data reported from 29 States,[8,9] suggest that the increase in driver information campaigns and enforcement of laws related to drunk driving may be having an effect. However, efforts are also needed to reduce the incidence of drunk walking.

Times of occurrence

The times of pedestrian crash occurrence have also been well documented. In urban areas, peak pedestrian accident experience occurs between 3:00 and 6:00 p.m., which

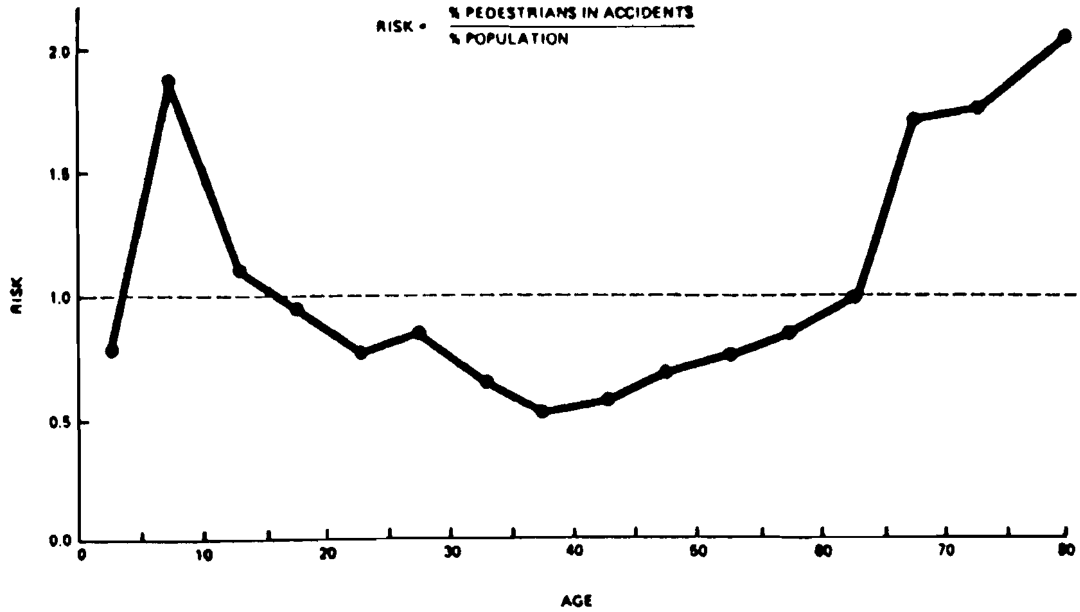

Figure 1. Pedestrian intersection accident risk by age based on exposure.[5]

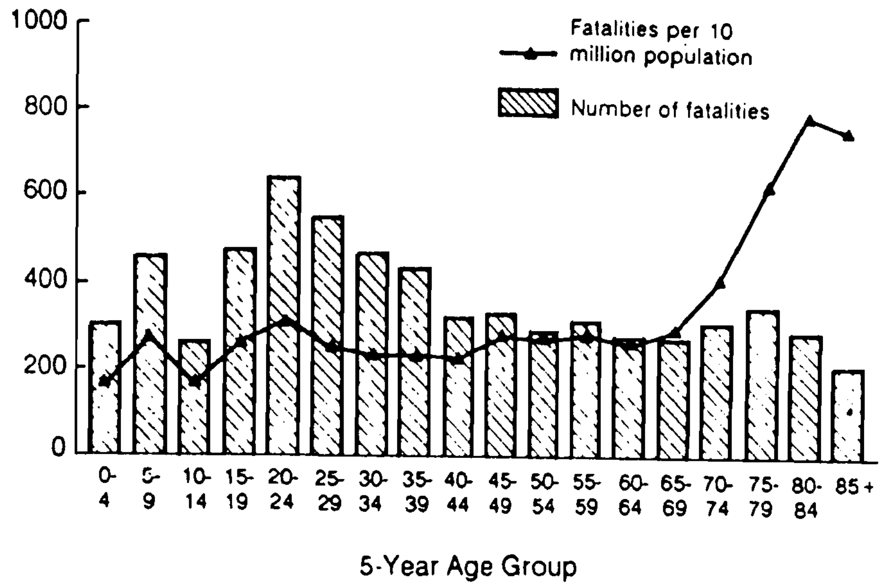

Figure 2. Pedestrian facilities and fatality rates by age in 1986 (based on NHTSA data).[6]

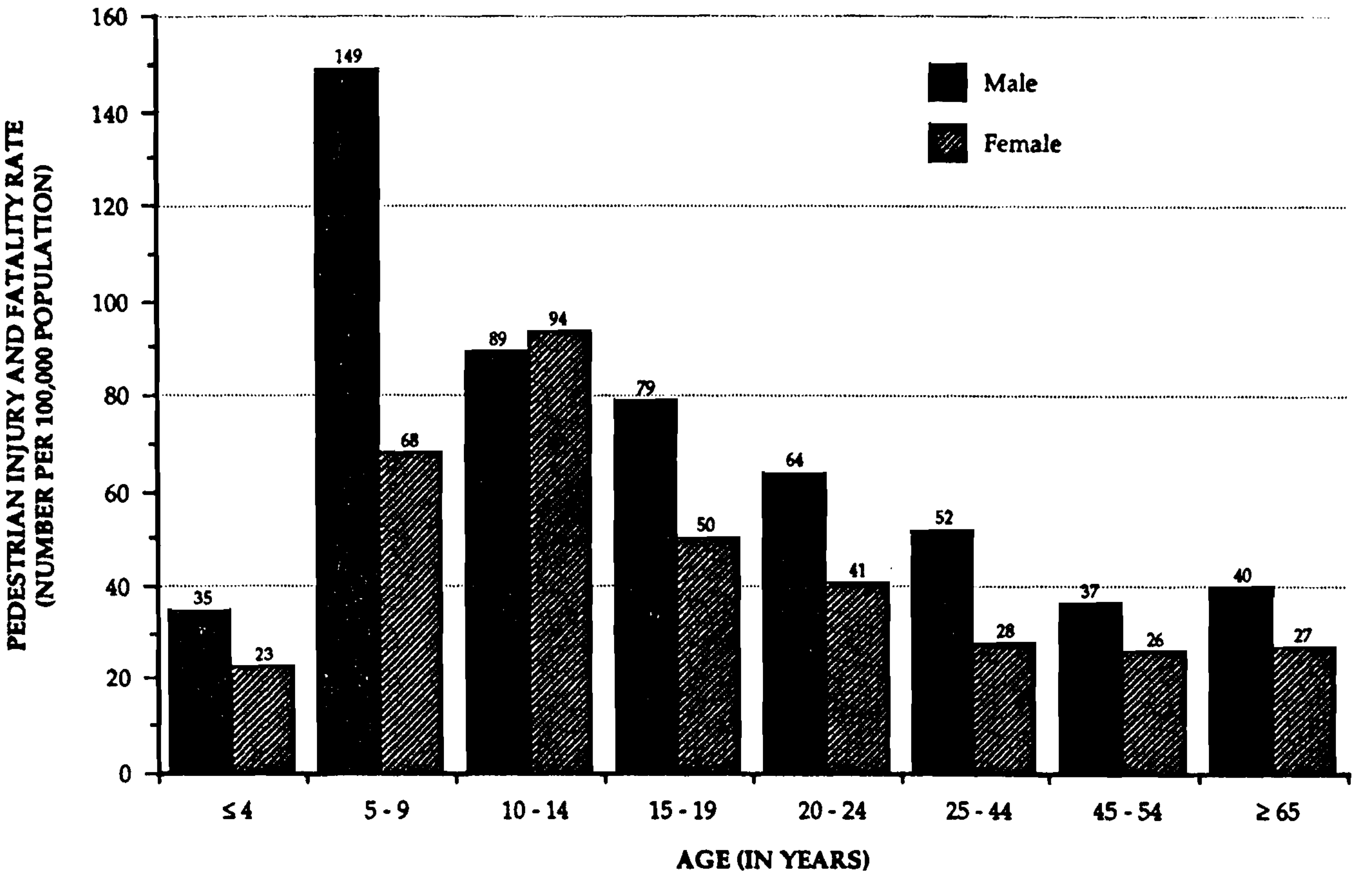

Figure 3. Rate of pedestrian injuries and deaths by pedestrian age.[2,7]

Table 1. Alcohol involvement for driver and pedestrian fatalities, 1980-1989.[8,9]

Percent of Fatally Injured Drivers and Pedestrians with BACs $\geq$ 0.10					
Year	Passenger Vehicles	Tractor Trailers	Pedestrians (Age 16+)	Motor-cycles	All Drivers
1980	53	16	41	43	50
1981	51	15	43	47	49
1982	50	15	44	44	48
1983	48	13	42	46	46
1984	44	11	41	44	43
1985	42	7	39	42	41
1986	42	4	38	42	41
1987	41	4	37	38	40
1988	41	5	38	38	40
1989	40	8	40	41	39

is typically the afternoon rush period. Smaller peaks occur from 7:00 to 9:00 a.m. and noon to 1:00 p.m.[1,2,10,11]

Fatal pedestrian accidents typically peak later in the day, between 5:00 and 11:00 p.m. This could be partly the result of pedestrians being struck along high-speed rural roads which often occurs at night, or in some cases lying unconscious in the road before being struck (where alcohol involvement is often a factor).[1] In fact, 15 percent of all pedestrian fatalities in North Carolina involve a pedestrian lying in the road.[10,12]

The days of the week that are overrepresented with respect to pedestrian accidents include Fridays and Saturdays, with Sundays being underrepresented.[2] Pedestrian fatalities also are more frequent on Fridays and Saturdays, with nearly constant frequencies on other days.[1,11]

The months of September through January have the highest number of pedestrian fatalities nationwide, based on 1989 data. These are months with typically fewer daylight hours and more inclement weather. Child pedestrian fatalities are highest in May, June, and July, due perhaps to an increase in outside activity after the winter months.[1,12]

Area type

Estimates from the National Safety Council reveal that of all non-fatal pedestrian crashes in the U.S., 85.7 percent occur in urban areas with 14.3 percent in rural areas. This is due to the greater amount of pedestrian activity and generally heavier traffic volumes in urban areas as compared to rural areas. However, 25 percent of pedestrian fatalities occur in rural areas, due partly to higher vehicle speeds in rural areas than in urban areas.[13]

Intersection vs. non-intersection

Estimates from NHTSA's GES database reveal that approximately 65 percent of crashes involving pedestrians occur at non-intersections. This is particularly true for pedestrians 9 years old or younger, with 79 percent involving midblocks, and where dartouts into the street are a major accident cause. For ages 45 to 65, pedestrian crashes are nearly equal for intersections and non-intersections. Pedestrians aged 65 and older are more likely to be struck at intersections (60 percent) than non-intersections (40 percent), since older pedestrians tend to cross at intersections more often than younger ones.[2] Moreover, some older pedestrians may become overwhelmed or confused at intersections.

Pedestrian Accident Types

Pedestrian crashes have been classified by specific types based on studies conducted in the 1970's.[14,15,16] As defined in table 2, some of the most common crash types include dart-out-first-half (i.e., pedestrian is struck in the first half of the street being crossed) (24 percent), intersection dash (13 percent), dart-out-second half (10 percent), midblock dart (8 percent), and turning vehicle accidents (5 percent). An illustration of several of these accidents is given in figure 4.[20]

Pedestrian Accident Countermeasures

Several studies in the 1970's were conducted to suggest possible countermeasures for the predominant pedestrian accident types listed above.[14,15,16] Based on these studies, a matrix of roadway-related countermeasures was developed for various pedestrian accident types, as shown in figure 5.[16] For example, candidate countermeasures to reduce "Walking on Roadway" pedestrian accidents include roadway/sidewalk barriers, street lighting and retroreflective materials (for nighttime accident problems), the addition of a sidewalk or pathway, and signs and markings.

Several points concerning figure 5 deserve mention. First, information in figure 5 is intended only as a general "shopping list" of countermeasures that was based on the subjective judgements of researchers and is not based on formal accident evaluations of countermeasures. Further, as stated in a 1988 TRB report by Zegeer and Zegeer, the effect of any roadway treatments for pedestrians is very much dependent on traffic conditions, pedestrian mix and volume, street width, existing traffic controls, sight distance, accident patterns, level of enforcement, and other factors.[19] Therefore, highway agencies should avoid blanket installation of any roadway treatment, but should "tailor fit" the most appropriate safety measure(s) to suit the site conditions.[19]

It should also be mentioned that figure 5 contains a variety of engineering improvements, both geometric and non-geometric. This report, of course, will focus only on the geometric improvements. Also, as stated earlier, education and enforcement improvements are covered elsewhere, such as in the WALK ALERT Program Guide.[20]

Pedestrian Accident Relationships

The primary geometric features related to pedestrian safety include the following:

1) Sidewalks and pedestrian paths.

2) Grade-separated crossings.

3) Pedestrian refuge islands.

4) Street closures and pedestrian malls.

5) Neighborhood traffic control measures (e.g., cul-de-sacs, traffic circles, curb extensions, street diverters).

6) Curb cuts (e.g., to assist wheelchair users).

7) Widened and/or paved shoulders.

Numerous other traffic control measures that are not considered geometric features in this study have also been used in an attempt to affect pedestrian safety and/or operations. These include signs, crosswalks (and stop bars), traffic and pedestrian signals, parking regulations, roadway lighting, handicapped facilities (e.g., audible pedestrian signals),

DART-OUT (FIRST HALF) (24%)
Midblock (not at intersection).
Pedestrian sudden appearance and short time exposure (driver does not have time to react)
Pedestrian crossed less than halfway.

DART-OUT (SECOND HALF) (10%)
Same as above except pedestrian gets at least halfway across before being struck.

MIDBLOCK DASH (8%)
Midblock (not at intersection).
Pedestrian running but *not* sudden appearance or short time exposure as above.

INTERSECTION DASH (13%)
Intersection.
Same as dart-out (short time exposure or running) except it occurs at an intersection.

VEHICLE TURN-MERGE WITH ATTENTION CONFLICT (4%)
Vehicle turning or merging into traffic.
Driver is attending to traffic in one direction and hits pedestrian from a different direction.

TURNING VEHICLE (5%)
Vehicle turning or merging into traffic.
Driver attention *not* documented.
Pedestrian *not* running.

MULTIPLE THREAT (3%)
Pedestrian is hit as he steps into the next traffic lane by a vehicle moving in the same direction as vehicle(s) that stopped for the pedestrian.
Collision vehicle driver's vision of pedestrian obstructed by the stopped vehicle.

BUS STOP RELATED (2%)
Pedestrian steps out from in front of bus at a bus stop and is struck by vehicle moving in same direction as bus while passing bus.

VENDOR-ICE CREAM TRUCK (2%)
Pedestrian struck while going to or from a vendor in a vehicle on the street.

DISABLED VEHICLE RELATED (1%)
Pedestrian struck while working on or next to a disabled vehicle.

RESULT OF VEHICLE-VEHICLE CRASH (3%)
Pedestrian hit by vehicle(s) as a result of a vehicle-vehicle collision.

TRAPPED (1%)
Pedestrian hit when traffic light turned red (for pedestrian) and vehicles started moving.

WALKING ALONG ROADWAY (1%)
Pedestrian struck while walking along the edge of the highway or on the shoulder.

OTHER (23%)
Unusual circumstances, not countermeasure corrective.

Table 2. Pedestrian accident types and critical behavioral descriptors.[18]

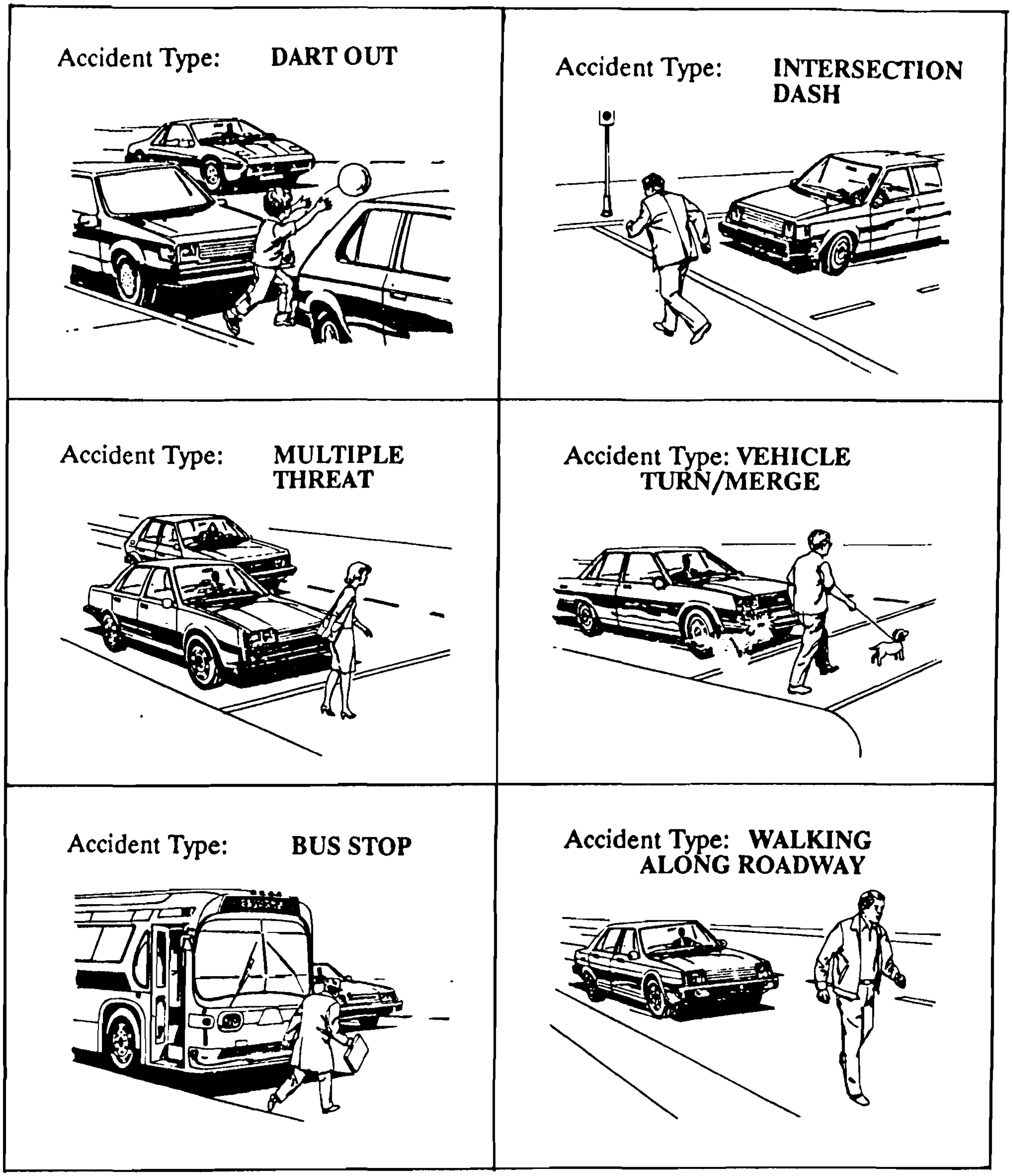

Figure 4. Illustration of common types of pedestrian accidents.[17]

Countermeasures / Accident Type	Engineering and Physical																					
	Barrier: Median	Barrier: Roadway/Sidewalk	Barrier: Street Closure	Bus Stop Relocation	Crosswalk: Intersection	Crosswalk: Midblock	Diagonal Parking-1 Way Street	Grade Separation	Facilities for Handicapped	Lighting: Crosswalk	Lighting: Street	One-Way Streets	Retroreflective Materials	Safety Islands	Sidwalk/Pathway	Signal: Ped. (Shared)	Signal: Ped. (Delayed)	Signal: Ped. (Separated)	Signal: Traffic	Signs and Markings	Urban Ped. Environment	Vehicular Traffic Diversion
Dart-out (First Half)	●	●				●	●														●	●
Dart-out (Second half)	●	●				●	●					●		●							●	●
Midblock Dash	●	●				●								●							●	●
Intersection Dash					●			●		●	●			●			●	●		●		
Turn-Merge Conflict								●									●	●				
Turning Vehicle								●									●	●				
Multiple Threat								●		●	●					●	●	●	●		●	
Bus Stop Related				●																	●	
School Bus Stop Related				●																		
Ice Cream Vendor																				●		
Trapped					●			●						●		●	●	●				
Backup																						
Walking on Roadway		●									●		●		●					●		
Result Vehicle-Vehicle Crash																				●		
Hitchhiking											●		●									
Working in Roadway																				●		
Disabled Vehicle Related																				●		
Nighttime Situation										●	●		●									
Handicapped Pedestrians									●													

Figure 5. Matrix of pedestrian accident countermeasures.[18]

reduced speed limits, right-turn-on-red prohibitions, left turn regulations and phasing, pedestrian barriers, use of far-side bus stops, one-way streets, and others. Thus, the seven geometric features listed above are the ones addressed in this chapter.

Sidewalks and pedestrian paths

Sidewalks and pedestrian pathways provide means for separating pedestrians from motor vehicle traffic. The term sidewalk generally refers to a paved (usually concrete) walkway that is separated from the street by at least a curb and gutter. Pedestrian paths (or pathways) are gravel or asphalt walkways that may or may not be located near a roadway.[18,19]

Sidewalks and paths should logically reduce accidents between pedestrian and motor vehicles when installed in residential and business areas. Sidewalks in residential areas are particularly beneficial to children, since they provide off-street areas for children to play. However, extensive use of sidewalks and paths by bicyclists in addition to pedestrians can result in serious injuries from pedestrian/bicycle collisions.[18,19]

The effects of sidewalks on pedestrian accidents was addressed in a 1987 study by Knoblauch for FHWA.[21] The number of pedestrian accidents was calculated and two measures of pedestrian exposure -- pedestrian volume (P) and pedestrian volume times vehicle volume (P x V) -- were computed for roads with no sidewalks, with sidewalks on one side, and with sidewalks on both sides. The percentages of accidents and exposure occurring at each site were also calculated. Hazard scores were derived from the ratio of the percent of accidents to the percent of exposure. If the percent of accidents was greater than the percent of exposure, then the hazard score was the percent of accidents divided by the percent of exposure, which was expressed as a positive ratio ($\geq +1.0$). When the percent of accidents was less than the percent of exposure, then the hazard score was the percent of exposure divided by the percent of accidents and was expressed as a negative ratio (≤ -1.0). Thus, higher positive hazard scores indicate greater hazard to pedestrians, while greater magnitudes of negative scores indicate safer conditions for pedestrians. For example, a hazard score of +2.6 indicates that the percent of pedestrian accidents is 2.6 times the percent of exposure for the given roadway situation. A hazard score of -2.6 corresponds to percent exposure being 2.6 times higher than the accident percentage.

The authors considered a factor to be hazardous if its hazard score was +1.4 or greater. A factor was considered to be neither hazardous nor safe if its hazard score was within the range -1.3 to +1.3. A factor was safe if its hazard score was less than -1.3. The data base included 35 variables pertaining to roadway, intersection, and vehicle/ pedestrian characteristics. Results are discussed in this chapter only as they relate to geometric features of interest, particularly sidewalks.

The study found that sites with no sidewalks were hazardous (P = +2.6, P x V = +2.2), sites with sidewalks on one side were less hazardous (P = +1.2, P x V = +1.1), and sites with sidewalks on both sides were the least hazardous (P = -1.2, P x V = -1.2). To translate these results into accident reductions, one might reasonably expect that, in general, pedestrian accidents will be reduced by the installation of sidewalks, the magnitude depending on specific site conditions. For example, the reduction in pedestrian crashes should be greatest in cases where most of the pedestrian accidents involve walking along the roadway, since sidewalks are intended to reduce the incidence of pedestrians walking in the road. On the other hand, adding sidewalks may do little to reduce "intersection dash" accidents. However, in areas with considerable pedestrian activity, sidewalks may reduce the potential for many types of pedestrian accidents.

Guidelines for sidewalk installation were developed for FHWA in 1988 based on functional roadway class and density of land development for new and existing streets, as shown in figure 6.[21] For example, on residential/local streets with more than four dwelling units per acre, sidewalks should be constructed on both sides of the road on new urban and suburban streets. On existing urban and suburban streets, sidewalks are preferred on both sides of the street but required on at least one side. These guidelines were not based on formal accident analyses, but were the results of inputs from practitioners in different parts of the U.S.[19]

Based on questionnaire responses from 48 State and local highway agencies in a 1988 TRB study, conditions were identified where sidewalks or pedestrian paths are considered to be most beneficial:[19]

- Suburban streets, particularly those with moderate or high pedestrian volumes or with high traffic volumes or speeds.
- Roads where no other place is available for pedestrians to walk except in or near the travel lane, particularly where nighttime pedestrian activity exists.
- Narrow streets having pedestrian traffic.
- Roads and streets with high pedestrian accident experience.
- Roads near schools, parks, or areas which are heavily travelled by pedestrians or with young children at play.
- Recreational areas with joggers, etc.

Grade-separated crossings

Pedestrian safety can be considerably enhanced with grade-separated crossing facilities, which allow for the free-flowing movements of pedestrians and motor vehicles at different levels. The basic types of grade-separated pedestrian facilities include overpasses and underpasses, where stairs or ramps are used to lead pedestrians over or under the roadway. In urban areas, enclosed walkways, termed skyways or skywalks, provide for pedestrian crossings one or more levels above ground level to connect buildings at midblock.[18,19]

Little information exists on the specific effects of grade-separated crossings on pedestrian accidents. This is due to the fact that pedestrian accidents generally do not occur in large numbers at a given location. Thus, even if an overpass is constructed over an existing roadway as a result of 2 or 3 pedestrian accidents, accident-based evaluations are not possible for a given overpass due to small sample sizes. Also, many grade-separated facilities are installed to provide access to pedestrians over a <u>new</u> high-speed roadway, so no reliable accident history exists for the before condition.

One of the few studies available on safety effects of grade-separated crossings was a 1969 study conducted in Tokyo, Japan, where pedestrian-motor vehicle accidents were reviewed for 6-month periods before and after overpasses were installed at 31 locations. Such an evaluation of a group of overpasses allowed for much larger sample sizes for purposes of accident evaluation. Pedestrian-related accidents per structure 200m (656 ft) on either side of the overpasses decreased from 2.16 to 0.32, an 85.1 percent reduction. Based on 31 sites, this translates to a total of 67 pedestrian accidents in the before period and 10 during the after period. For sections within 100 meters of the structures, pedestrian accidents decreased from 1.81 to 0.16 per structure, a 91.1 percent decrease. During that same period non-pedestrian accidents (used as a control group) increased.[7]

Although not from the U.S., these results indicate a high potential for reducing pedestrian accidents using grade-separated crossings. However, the installation of such facilities is quite expensive, and the effectiveness of any such facility depends largely

Proposed Minimum Sidewalk Widths

Central Business Districts - Conduct level of service analysis according to method in 1985 Highway Capacity Manual.

Commercial/industrial areas outside a central business district - Minimum 5 ft wide with 2 ft planting strip or 6 ft wide with no planting strip.

Residential areas outside a central business district:

Arterial and collector streets - Minimum 5 ft with minimum 2 ft planting strip.

Local Streets:

- Multi-family dwellings and single-family dwellings with densities greater than four dwelling units per acre - Minimum 5 ft with minimum 2 ft planting strip.

- Densities up to four dwelling units per acre - Minimum 4 ft with minimum 2 ft planting strip.

Land-Use/Roadway Functional Classification/Dwelling Unit	New Urban and Suburban Streets	Existing Urban and Suburban Streets
Commercial & Industrial (All Streets)	Both sides.	Both sides. Every effort should be made to add sidewalks where they do not exist and complete missing links.
Residential (Major Arterials)	Both sides.	
Residential (Collectors)	Both sides.	Multi-family - both sides. Single-family dwellings - prefer both sides required at least one side.
Residential (Local Streets) More than 4 Units Per Acre	Both sides.	Prefer both sides, required at least one side.
Residential (Local Streets) 1 to 4 Units Per Acre	Prefer both sides; required at least one side.	One side preferred, at least 4 ft shoulder on both sides required.
Residential (Local Streets) Less than 1 Unit Per Acre	One side preferred, shoulder both sides required.	At least 4 ft shoulder on both sides required.

Figure 6. Guidelines for sidewalk installation.[21]

on their use by pedestrians. Experience has shown that many pedestrians are unwilling to use overpasses or underpasses, depending on their convenience of use, walking distances and time to cross compared to crossing at street level.

The percentage of pedestrians who use grade-separated crossings was investigated by Moore and Older in 1965.[22] The authors defined a measure of convenience, R, as the ratio of time to cross a subway or bridge divided by the time needed to cross at street level. As shown in figure 7, 95 percent of pedestrians would use a subway (underpass) if the crossing time were equal to the time to cross at street level (i.e., R = 1). However, an R-value of approximately .75 was needed for 95 percent of pedestrians to use an overpass. Virtually nobody would use either type of grade-separated crossing if the R-value was 1.5 or greater (i.e., if using the facility would increase crossing time by 50 percent compared to crossing at street level).[22]

General guidelines on situations where grade-separated crossings are most beneficial include:[19]

- Locations where pedestrian demand is moderate to high to cross freeways or expressways.
- Roads with high traffic speeds or volumes where young children must cross regularly (e.g., near schools).
- Streets with high volumes of vehicles and crossing pedestrians where extreme hazards exist for pedestrians (e.g., poor sight distance, wide streets, high-speed traffic).
- Situations with one or more of the conditions stated above combined with well-defined pedestrian origins and destinations. These could include needed connectors between a residential neighborhood and a school, parking structure to a university or hospital, apartment complex to a shopping mall, etc.

Pedestrian refuge islands

Pedestrian refuge islands or safety islands are areas between traffic lanes or within an intersection where pedestrians may stand until traffic clears. Refuge islands may be raised above the street surface or delineated with roadway markings or both. They are sometimes installed on wide, multi-lane streets in which an adequate pedestrian crossing interval cannot be provided without having an adverse effect on traffic flow.[18,19]

The safety effects of refuge islands are relatively unknown. They are needed on wide streets having insufficient time for pedestrians to cross during a single crossing phase. However, pedestrians may not be willing to stop in the median or safety island to wait for the next WALK interval, particularly if the island is too narrow, not elevated, or otherwise makes the pedestrian feel at risk. On all elevated safety islands, curb ramps (or cut through areas) should be provided for use by wheelchair users.[18,19] An ongoing FHWA study is attempting to quantify the safety effects of medians and pedestrian refuge islands.[23]

Street conditions where refuge islands are considered most beneficial to pedestrians include:[17]

- Two-way streets that are wide with high vehicle speeds and volumes, and large pedestrian volumes.
- Wide streets with regular crossings by elderly, handicapped, or child pedestrians.
- Streets with signal timing that is not sufficient for pedestrians to cross safely.
- Wide intersections with heavy traffic volumes and crossing pedestrians.

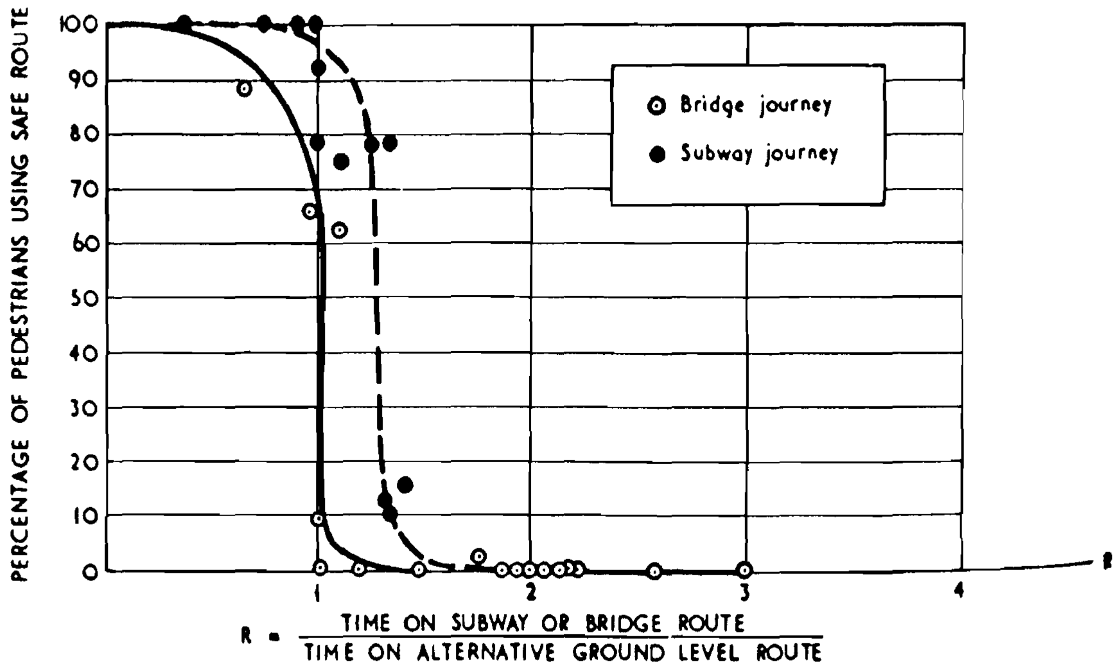

Figure 7. Use of pedestrian overpasses and underpasses.[22]

Street closures and malls

The partial or total closing of streets to motor vehicles to provide a "pedestrian environment" can be a desirable pedestrian safety enhancement, but may also create negative effects on motorists and deliveries to nearby business owners. The development of pedestrian malls and other auto-free zones are often the result of urban renewal or downtown revitalization efforts, and not necessarily the result of pedestrian safety planning.

Various alternatives have also been used partly to restrict motor vehicles from certain roadways. For example, "residential yards" are shared streets designed for driving, playing, cycling, walking, and parking. As used in The Netherlands, such areas are termed "Woonerfs." Other streets where motor vehicle traffic is limited include play streets (which are residential streets closed to vehicular traffic during certain hours to allow for supervised child activity), and transit-pedestrian malls (malls where pedestrians share spaces with buses and perhaps trucks and taxis).[7,19]

While many such facilities have been implemented in cities around the U.S. and abroad, little or no information currently exists to quantify their true effects on pedestrian safety. For example, opening up a new pedestrian mall may virtually eliminate pedestrian mishaps on the mall street, with a possible increase in pedestrian accidents on nearby and adjacent streets (i.e., pedestrian accident "migration"). Also, motor vehicle accidents can be affected by the changes in traffic patterns and routing as a result of such measures.

Serious questions also remain as to whether the shared-street concept (e.g., play streets) is beneficial to pedestrian safety, or whether they could increase pedestrian accidents and deaths, particularly if parents become complacent and allow their children to play on such streets without adequate supervision. In summary, various types of street closures and pedestrian malls have the potential for creating a safer pedestrian environment with some potential adverse effects. The true safety effects under various situations, however, are unknown.

Neighborhood traffic control measures

A variety of geometric designs or retrofits has been used in residential neighborhoods in the U.S. and abroad to improve pedestrian safety while reducing vehicle speeds and/or volumes. Some of these alternatives (as illustrated in figure 8) include:[24]

- Cul-de-sacs: Closing streets either at midblock or at an intersection, which blocks through traffic and reduces vehicle speeds and volumes on the street.

- Chokers or curb extensions: Narrowing the street by widening the sidewalk close to the intersection or providing an on-street parking area in the midblock area. Pedestrian crossings are often made easier as a result of the narrower street crossings at the intersections.

- Semi-diverters: Limiting access to a street in one direction only by blocking half the street. Although traffic volumes are often reduced on these streets, they allow greater access to emergency vehicles than full diverters.

- Diagonal diverters: Placing a diagonal diverter across the intersection that disconnects the intersection legs. Traffic volumes are reduced and traffic circulation patterns are changed, although they provide more overall freedom of circulation than cul-de-sacs.

- Traffic circles: This involves using raised circular islands in the middle of the intersection to create a one-way

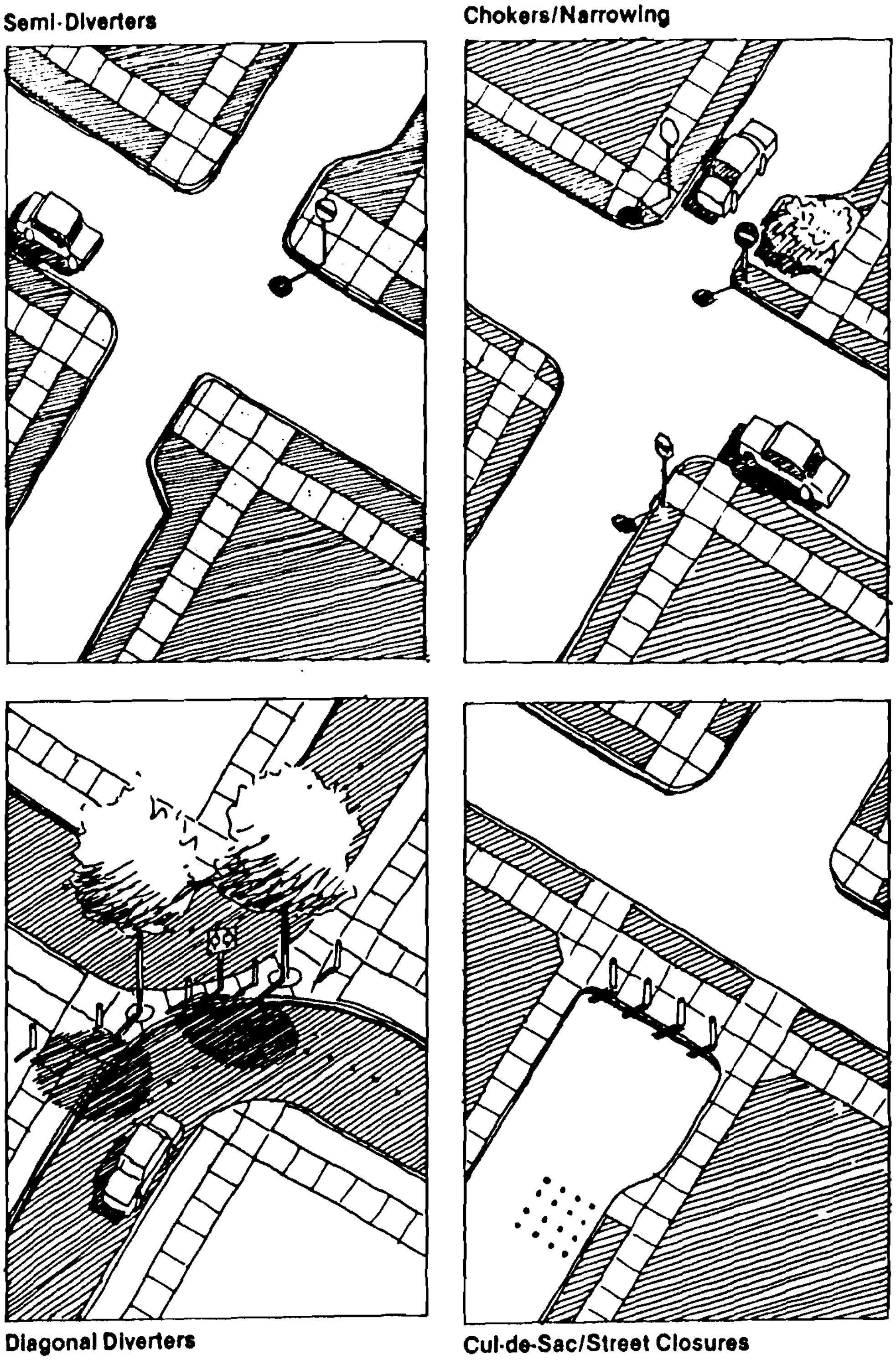

Figure 8. Illustration of various neighborhood traffic control measures.[24]

circular flow of traffic in the intersection. Traffic circles are intended to separate conflict points and slow vehicular traffic.

Some of the cities in the U.S. with the most experience in using these kinds of neighborhood traffic control measures include Portland, Oregon, and Seattle, Washington. Both of these cities have active programs in using one or more of these measures. Such neighborhood traffic control measures seem appealing to improve pedestrian safety, since traffic volumes and/or speeds are reduced in neighborhoods. However, there is no quantitative information on the actual safety effects of such measures or on resulting accidents on the surrounding streets.

Other geometric features

Various other roadway and geometric features could also affect pedestrian accidents. For example, curbs are used in urban areas for many reasons, such as for drainage purposes and to separate traffic flow from pedestrians on the sidewalk. Curb ramps are installed extensively in many cities in the U.S. and abroad to facilitate movement by wheelchair users. Also, many non-wheelchair users have difficulty traversing high curbs and therefore benefit from curb cuts. There is a danger, however, with some curb cuts, since visually impaired pedestrians may not notice the ramp and walk unknowingly into the street.[25]

Widened and/or paved shoulders have also been recommended strongly for use by pedestrians in rural areas.[17,18,19,26] Although the construction of sidewalks or walkways is preferred, they are not always feasible, and walking on shoulders is much safer than walking in the road. Although the specific effects of widened and/or paved shoulders on pedestrian accidents are not known, they have been found to significantly reduce run-off-road and other accident types, as discussed in more detail in Volume III - "Cross Sections." Thus, while shoulder improvements may be justified in many instances based on proven safety benefits to other types of motor vehicle crashes, improved pedestrian (and bicycle) safety may also result.

In summary, pedestrian crashes represent a serious safety problem in the U.S. and abroad, which must be addressed through a comprehensive program of engineering, education, and enforcement. While various engineering improvements have been implemented relative to geometric features, the specific safety effects of most of these features is not currently known. A limited number of studies, as well as judgement from practitioners and researchers does, however, indicate that some of these geometric improvements will likely reduce pedestrian accidents under certain situations. It is hoped that well-planned safety research in the future will increase knowledge about specific effects of such improvements on pedestrian safety.

SUMMARY OF BICYCLE RESEARCH

There are fewer studies pertaining to bicycle facility performance and safety than to pedestrian facilities, and fewer of the evaluations have been based on analyses of accident data. This summary is organized around three main categories of research: bicycle accident types, facility characteristics and design criteria, and facility performance evaluations. The summary begins with a review of the landmark research carried out by Kenneth Cross and Gary Fisher identifying bicycle/motor vehicle accident types and countermeasure approaches.[27] A second section reviews literature pertaining to a wide range of on-road and off-road facility treatments, including marked bike routes, bike lanes, wide outside curb lanes, sidewalk treatments, and off-road pathways. Evaluation literature is reviewed in a final section, and focuses primarily on bike lanes and wide curb lanes.

Bicycle Accident Types

Although not directed at bicycle facilities, per se, the 1977 study carried out by Cross and Fisher[27] has formed the basis for many of the decisions regarding bicycle accident countermeasure development, including facility design and construction. Prior to this study, very little was known about the kinds of collisions in which bicyclists were being injured and the factors precipitating these collisions. The purpose of the Cross and Fisher study was to compile national data on the causes of bicycle/motor vehicle accidents and to develop countermeasure approaches for reducing the number of accidents. The specific study objectives were to identify the types of bicycle/motor vehicle accidents occurring, determine their relative frequency, and examine how they vary across urban/rural location and across fatal/non-fatal accidents. The study also attempted to identify and, to the extent possible without additional testing, evaluate potential countermeasures for each accident type.

Data on bicycle/motor vehicle accidents were collected in four sampling areas that consisted of contingent counties containing metropolitan as well as rural areas and selected to be representative of the types of riders and kinds of bicycling occurring nationally. The four areas were Los Angeles, California; Tampa/Orlando, Florida; Denver/Boulder, Colorado; and Detroit/Flint, Michigan. Data was collected and compiled by trained field investigators at each of the sites following a structured data collection procedure. Sources of information included the official traffic accident report, observations and measurements taken at the scene of the accident, and detailed interviews with the bicyclist, motor vehicle operator, and in some cases witnesses.

Data was collected over a 1 year period (calendar year 1975), with equal numbers of urban and rural crashes. In order to have a sufficient number of fatal crashes for the analysis, all fatal bicycle/motor vehicle crashes occurring in the states of California and Florida during 1975 were also included. The final sample sizes were 166 fatal and 753 nonfatal bicycle/motor vehicle crashes, for a total of 919.

The descriptive analyses of the data yielded a wealth of information concerning the characteristics of bicyclists involved in crashes with motor vehicles and the nature of these crashes. For example, bicyclists age 12 to 15 were found to account for the greatest percentage of accidents (37 percent). Ten percent of nonfatal bicycle/motor vehicle crashes, but 30 percent of fatal crashes, occurred during darkness. And whereas 11 percent of nonfatal crashes occurred in rural areas, 32 percent of fatal crashes occurred in rural areas. Fatal crashes were also found to involve higher speeds, with over half occurring on roadways with posted speed limits over 35 mi/h.

Results from the analysis by accident type are summarized in table 3, taken from an abbreviated version of the report published by the AAA Foundation for Traffic Safety in 1978[28]. A total of 36 unique bicycle/motor vehicle accident types was identified. The 25 most frequently occurring problem types were found to account for 87 percent of the fatal and 93 percent of the nonfatal cases, and the ten most frequent for 67 percent of the fatal and 64 percent of the nonfatal cases. The most common nonfatal bicycle/motor vehicle problem types were bicyclist rideout at an intersection controlled by a sign (10.2 percent), motorist turn/merge or drive through at an intersection controlled by a sign (10.2 percent), and bicyclist making an unexpected left turn in front of a vehicle moving in the same direction (8.4 percent). By far the most common fatal collision type was a motorist overtaking an unobserved bicyclist (24.6 percent).

Although not specifically directed at an analysis of roadway design features, the Cross and Fisher study provides considerable insight into the kinds of

Table 3. Quick-reference table showing relative frequency of occurrence and bicyclist age distribution for each problem type. [24]

Class/Type Designator		Problem-Type Description	Relative Frequency of Occurrence		Bicyclist Age (Centiles)				
Class	Type		Fatal	Non-Fatal	5th	25th	50th	75th	95th
		Bicycle Rideout:							
A	1	Residential Driveway/Alley, Pre-Crash Path Perpendicular to Roadway	6.7%	5.7%	5.2	7.4	9.8	12.3	15.9
A	2	Commercial Driveway/Alley, Pre-Crash Path Perpendicular to Roadway	2.4%	3.2%	7.6	9.4	13.8	14.9	24.9
A	3	Driveway/Alley Apron, Pre-Path Crash Path Parallel to Roadway	2.4%	2.5%	5.9	9.6	11.5	13.1	16.0
A	4	Entry Over Shoulder/Curb	3.6%	2.5%	6.9	9.5	11.5	14.5	15.0
		Bicycle Rideout:							
B	5	Intersection Controlled by Sign	7.8%	10.2%	6.8	9.1	11.8	14.3	194
B	6	Intersection Controlled by Signal, Signal Phase Change	.6%	3.1%	10.1	13.3	16.1	17.8	32.8
B	7	Intersection Controlled by Signal, Multiple Threat	2.4%	2.0%	11.8	12.9	15.2	15.9	33.2
B	-	Intersection Controlled by Signal, Other	1.2%	1.7%	9.6	13.9	16.9	23.9	34.4
C	8	Motorist Turn-Merge: Commercial Driveway/Alley	—	5.3%	7.9	13.3	15.4	17.5	49.9
C	9	Motorist Turn-Merge/Drive Thru Intersection Controlled by Sign	1.2%	10.2%	10.4	13.8	16.3	20.5	35.6
C	10	Motorist Turn-Merge: Inter-Section Controlled by Signal	—	1.9%	10.6	12.1	13.3	24.4	72.4
C	11	Motorist Backing from Residential Driveway	—	.8%	-	-	-	-	-
C	12	Motorist Driveout: Controlled Intersection	1.2%	.5%	-	-	-	-	-
		Motorist Overtaking:							
D	13	Bicyclist Not Observed	24.6%	4.0%	11.2	15.4	18.1	23.2	59.6
D	14	Motor Vehicle Out of Control	4.2%	.7%	-	-	-	-	-
D	15	Counteractive Evasive Action	2.4%	1.7%	5.7	9.2	12.3	14.4	15.7

Table 3. Quick-reference table showing relative frequency of occurrence and bicyclist age distribution for each problem type (Con't).

Class/Type Designator		Problem Type Description	Relative Frequency of Occurrence		Bicyclist Age (Centiles)				
Class	Type		Fatal	None	5th	25th	50th	75th	95th
D	16	Motorist Overtaking: Motorist Misjudged Space Required to Pass	1.8%	2.0%	8.7	13.5	15.0	25.2	41.3
D	17	Bicyclist's Path Obstructed	.6%	2.0%	9.1	12.9	16.3	23.2	32.2
D	18	Type Unknown	4.2%	.1%	-	-	-	-	-
E	18	Bicyclist Unexpected Left Turn: Parallel Paths, Same Direction	8.4%	8.4%	7.2	10.6	12.7	14.5	20.9
E	19	Parallel Paths Facing Approach	3.0%	3.2%	6.2	11.7	13.8	18.5	35.8
E	20	Bicyclist Unexpected Swerve Left: Parallel Paths, Same Direction (Unobstructed Path)	3.6%	1.5%	8.5	10.2	11.5	15.1	16.4
E	21	Wrong-Way Bicyclist Turns Right: Parallel Paths	1.2%	1.1%	-	-	-	-	-
F	22	Motorist Unexpected Left Turn: Parallel Paths, Same Direction	.6%	1.3%	11.5	13.5	15.9	23.5	37.5
F	23	Parallel Paths, Facing Approach	—	7.6%	10.8	15.7	20.1	26.6	46.2
F	24	Motorist Unexpected Right Turn: Parallel Paths	1.8%	5.6%	12.1	14.6	16.8	22.9	33.9
G	25	Vehicles Collide at Uncontrolled Intersection: Orthogonal Paths	.6%	2.8%	6.0	9.3	12.4	13.9	19.9
G	26	Vehicles Collide Head-On, Wrong-Way Bicyclist	2.4%	3.6%	6.5	10.9	12.9	15.3	20.5
G	27	Bicyclist Overtaking	.6%	.9%	-	-	-	-	-
G	28	Head-On, Wrong-Way Motorist	1.8%	.8%	-	-	-	-	-
G	29	Parking Lot, Other Open Area: Orthogonal Paths	.6%	.8%	-	-	-	-	-
G	30	Head-On, Counteractive Evasive Action	—	.1%	-	-	-	-	-
G	31	Bicyclist Cuts Corner When Turning Left: Orthogonal Paths	.6%	—	-	-	-	-	-
G	32	Bicyclist Swings Wide When Turning Right: Orthogonal Paths	—	.3%	-	-	-	-	-
G	33	Motorist Cuts Corner When Turning Left: Orthogonal Paths	—	.4%	-	-	-	-	-
G	34	Motorist Swings Wide When Turning Right: Orthogonal Paths	—	.1%	-	-	-	-	-
G	35	Motorist Driveout From On-Street Parking	—	.3%	-	-	-	-	-
G	36	Weird	—	1.1%	-	-	-	-	-
G	37	Insufficient Information to Classify	7.2%	—	-	-	-	-	-

accident events occurring and the characteristics of the roadways on which they occur. Some of the accident locations examined include signed intersections, signalized intersections, commercial driveway/roadway junctions, residential driveway/roadway junctions, alley/ roadway junctions, uncontrolled intersections, and parking lots. Information on the directions of the vehicles' pre-crash paths (orthogonal, parallel, etc.) was also incorporated into the accident typography. The discussion accompanying each accident type description presents additional detail about the factors precipitating the accident (motorist failed to see bicyclist; nighttime accident, etc.). Number of traffic lanes, roadway alignment (lateral or vertical curvature) and roadway surface type and condition were also examined. Following the presentation of the accident types, countermeasure approaches are identified in the areas of environmental changes, bicycle modifications, education and training, and regulation and enforcement. Much of the later work on bicycle facility design, construction and evaluation draws from this initial bicycle accident investigation.

Bicycle Facility Characteristics and Design Criteria

The growth in the popularity of bicycling brought with it a demand for better facilities to accommodate this increase. Engineers and planners were largely unprepared for this surge, and aside from some European studies, there was little empirical data on which to base initial program standards and design criteria. Smith (1974) evaluated this early phase of regulation in his report, "Bikeways - State of the Art, 1974."[28] The discussion of available facilities includes: bike routes and lanes, protected lanes, sidewalk treatments, and independent pathways. Also addressed are the standardization of route signs, lane demarcation, pavement message markings, crossing signs, and sign placement. In discussing the issue of design specifications, the author noted that due to the lack of a standard, many facility design elements varied quite a bit between jurisdictions, especially bikeway widths, design speed and curvature, and grade profiles. Based upon various research, the author proposed several guidelines to be used as preliminary standards. He also discussed the pitfalls of these initial approaches to accommodate the cyclist with respect to transition areas, maintenance, location issues, etc. An appendix to the report considers the cyclists' perceptions of these attempts.

Kaplan (1976) also addressed the issue of standard in the document, "A Highway Safety Standard for Bicycle Facilities."[30] The author outlined the role of the Federal Highway Administration in developing a highway safety standard for bicycle facilities, as required by the Highway Safety Act of 1973. Some of the concerns that such a standard would address were discussed, and how some states and communities had already addressed these concerns was described.

By assessing the needs of the different types of cyclists -- children, recreational riders, and those who use bicycles as a mode of transportation -- the standard proposed by Kaplan would require that existing facilities be examined and refined to better suit these different needs. Such an assessment may reveal that only slight modifications need to be made, and possibly that no further physical construction is necessary. On the other hand, it may be found that travel lanes prepared specifically to accommodate the cyclist are warranted.

Following this brief discussion, Kaplan presented photographs illustrating the types of bicycle facilities in use at the time. These included channelized bikeways, on-street bikeways, exclusive bike lanes, and several types of bike trails. Traffic devices used to aid cyclists were also pictured, such as push button signals, bicycle signals that turn green for cycle only movement, and signs warning motorists of bicycle traffic.

More recently, Pfefer et al. (1982) reviewed the research that exists to support bicycle facility standards.[31] Chapter 15 in Synthesis of Safety Research Related to Traffic Control and Roadway Elements, Vol. 2, reviews available accident data with respect to the safety of bicycles and bicycle facilities. It begins with a listing of definitions, which are based upon the American Association of State Highway and Transportation Officials' (AASHTO) "Guide for Development of New Bicycle Facilities 1981." After presenting a general overview of the bicycle accident experience, drawing from nearly a dozen studies, the authors highlight results pertinent to each of the following: traffic control devices, shared versus separate bicycle facilities, shared roadways and legal issues, wide curb lanes shared by bicycles, drainage grate safety, roadway shoulders for bicycle use, bicycle routes, bicycle lanes, intersection safety hazards, barriers to safe bicycle travel, bicycle paths, and bicycle education and enforcement.

McHenry (1985) used observational data to examine the effects of bicycle use on roadways with three different outside curb lane widths (12 ft, 13 ft 8 in, and 17 ft). Results of the study are documented in the report, "Evaluation of Wide Curb Lanes as Shared Lane Bicycle Facilities."[32] The roadways that were studied were all high speed (40 to 45 mi/h) multilane urban highways with high traffic volumes (15,000 to 25,000 ADT). Using 35-mm cameras mounted alongside the roadway and experienced volunteer cyclists, data were collected on the distance of the bicyclist from the curb and the distance of cars from the curb before, during, and immediately after passing the bicyclist, as well as the distance between the bicycle and the car during overtaking. Note was also made as to whether there was another vehicle present in the adjacent (inside) travel lane, and the width of the motor vehicle. Results indicated that a standard 12-ft outside lane width was not sufficient to accommodate shared use by bicycles and motor vehicles, based on greater motor vehicle displacements and speed changes and the potential impact on the capacity of the roadway. Lanes in excess of 13 ft 8 in, but less than 17 ft, were viewed as optimal. As a comparison, 4-ft wide marked bicycle lanes contiguous to the roadway were found to offer some advantages relative to traffic flow and the comfort of the bicyclist. Additional study was recommended to quantify the impacts of bicycle/motor vehicle lane sharing, taking into account a wide range of parameters including number of travel lanes, shoulder presence, motor vehicle volumes, vehicle speeds, etc., to help establish national guidelines for shared roadway use.

A comprehensive review and synthesis of this literature and state of the art related to bicycle route selection and designation can be found in a two-volume 1986 report, "Highway Route Designation Criteria for Bicycle Routes," by Wilkinson and Moran.[33]

The authors recommended criteria for State and local transportation officials and other agencies and organizations to use in selecting and designating streets and highways for bike use. The final report includes some background discussion on bicycle routes (their evolution, trip types and user characteristics, types of facilities/ routes, and types of agencies and organizations designating bicycle routes); alignment factors (factors related to the desirability, functionality, and feasibility of bike routes); suitability factors (outside lane width, shoulders, traffic volume, speed, etc.); the process of selecting a route (types of routes, planning and analysis of route options, suitability assessment, etc.); and route designation options. Also included in the Volume I Final Report is a discussion of four special topics: bicycle use of controlled access freeway shoulders, research problem statements, liability aspects of bikeway designation, and bicycle mapping.

The Volume II Handbook is an abbreviated version of the full report "designed to simplify the task of selecting and designating streets and highways for bike routes." It covers the definition and purpose of bicycle routes; factors affecting route alignment; factors affecting the suitability of streets and highways for bicycling; approaches to planning, selecting and designating routes; and guidelines for various types of route selection and designation projects. Discussions of liability, bicycle use of controlled access freeways, and mapping are also included.

Facility Performance Evaluations

There is little information in the literature pertaining to the evaluation of bicycle facilities using accident data. Three studies will be discussed.

Smith (1976) developed a set of three reports concerned with bicycle facilities. The objective of the main report was to develop methods and guidelines for the planning and design of safe and effective bikeway facilities. The other two volumes in the set deal with the design details of facilities and the locational criteria and systematic planning necessary to integrate facilities into a community.[34,35,36]

Much of this study dealt with factors pertaining to bikeway facility design, such as speeds of vehicles and mixing, operating space, effects on driver and bicyclist behavior (e.g., separation), sight distance, shoulder usage, intersection treatments, etc. However, a portion of one chapter evaluated bicycle accident reports from the City of Davis, California, and compared the findings with earlier research performed by Cross using bicycle accident data from Santa Barbara, California.[36]

Lott and Lott (1976) examined the same basic data as Smith (1976) in a report whose objective was to demonstrate the effectiveness of bike lanes in reducing the incidence of various types of bicycle/motor vehicle accidents. The research addressed the following question: Is there a change in the absolute frequency of certain accidents occurring on bike-lane streets as compared to non-bike-lane streets?[37]

The authors compared the relative frequency of bike-auto accidents in each of 10 categories (based on the Cross typology) in Davis, California, a city with an extensive bike-lane system, to the relative frequency of bike-auto accidents in Santa Barbara, California, a comparable city without bike lanes. They used the same categories to compare streets with bike lanes to those without bike lanes within Davis. The authors judged three accident types to be uninfluenced by bike lanes (neutral accidents) and used these as a standard for determining the effect of bike lanes on the absolute frequency of other accident types. To avoid repetition, the results from Lott and Lott (1976) will be reported.

The authors analyzed 145 out of the 177 bike-auto accidents reported from 1970 to 1973. The remaining 32 accidents were either nonclassifiable according to the Cross scheme or involved low cyclist visibility. Ten categories of crashes based on the Cross typology were utilized in the analysis. These were:

1) Cyclist exited driveway into motorist path.
2) Motorist exited driveway into cyclist path.
3) Cyclist failed to stop/yield at controlled intersection.
4) Cyclist made improper left turn.
5) Cyclist rode on wrong side of street.
6) Motorist collided with rear of cyclist.
7) Motorist failed to stop/yield at controlled intersection.
8) Motorist made improper left turn.
9) Motorist made improper right turn.
10) Motorist opened car door into cyclist's path.

The authors categorized the Davis accident data according to Cross' scheme and subdivided the categories by the presence or absence of bike lanes and by the age class of the cyclist involved (table 4). They then compared the relative frequencies of each accident type in Davis with those of Santa Barbara. Within Davis, they compared the relative frequencies of each accident type on streets with bike lanes to those on streets without bike lanes (tables 5 and 6).

Lott and Lott defined an accident as neutral if:

1) The position and track on the street of both the cyclist and the motorist were not changed by the presence of a bike lane.

2) The amount of information each operator had about the probable next maneuver of the other - and hence the ability of each to predict the behavior of the other - was not changed.

Table 4. Davis bike-auto accidents (1970 to 1973) by cyclist age groups. [37]

Accident Type	Streets Without Bike Lanes					Streets with Bike Lanes				
	0-11	12-17	18-24	25+	Total	0-11	12-17	18-24	25+	Total
A. Cyclist exited driveway into motorist path	3	1	2		6	1				1
B. Motorist exited driveway into cyclist path		1	2		3		1	1		2
C. Cyclist failed to stop/yield at controlled intersection	1	2	3		6	2	3	2	1	8
D. Cyclist made improper left turn	2	1	1		4	4	1	1	4	10
E. Cyclist rode on wrong side of street	3	3	8		14	1	2	2		5
F. Motorist collided with rear of cyclist	1	2	3		6			1		1
G. Motorist failed to stop/yield at controlled intersection		2	8	3	13	1	2	5	7	15
H. Motorist made improper left turn		2	6	3	11	2	3	6	8	19
I. Motorist made improper right turn	1	1	8		10	1		5	2	8
J. Motorist opened car door into cyclist's path										
Total by Age Groups*	11	15	41	6	73	12	12	23	22	69

*In four accidents, two type G (off bike lanes) and two type H (one off and one on bike lanes), the cyclist's age was unknown so the accidents are not reported on this table. One type G accident associated with bike lanes involved a male and a female cyclist, both 18, and so is reported twice.

3) The probability of both the cyclist and the motorist conforming to traffic laws was not changed.

They identified three accident types as neutral:

1) C - cyclist failure to stop/yield at a controlled intersection
2) G - motorist failure to stop/yield at a controlled intersection
3) H - improper left turn by motorist

These neutral accident types were then used as a standard for comparing the relative frequency of other accident types on streets with and without bike lanes. In Davis, the neutral accidents were a lower percentage (41.10 percent) on streets without bike lanes than on streets with bike lanes (60.87 percent). In fact, the percentage of all accidents which were neutral accidents on streets <u>without</u> bike lanes was 69 percent of the percentage of all accidents which were neutral accidents on streets <u>with</u> bike lanes. By definition, the presence or absence of bike lanes does not affect the rate of neutral accidents. Therefore since neutral accidents constituted a higher percentage of all accidents on streets with bike lanes (60.87 percent) than on streets without bike lanes (41.1 percent), the streets with bike lanes have lower non-neutral accident rates.

The relative frequency of each non-neutral accident type occurring on streets with bike lanes was equated to the relative frequency of the same non-neutral accident type on streets without bike lanes by multiplying by 0.69 (because non-neutral accident rates on streets with bike lanes were 69 percent of the rates on streets without bike lanes). For example, table 7 shows that accident type A constituted 1.45% of the accidents occurring on streets with bike lanes. This percentage was multiplied by 0.69 to correct for the lower expectation of accidents on streets with bike lanes. This percentage was multiplied by 0.69 to correct for the lower expectation of accidents on streets with bike lanes. The result, 1.45 x 0.69 = 1.00, is the expected percentage of accident type A on streets with bike lanes.

In the Cross scheme, the cyclist is at fault (not necessarily in a legal sense, but in terms of a particular maneuver or action) for types A, C, D, and E. The motorist is at fault for the remaining types.

Lott and Lott cited an observation by Williams that as cyclist age increases, the proportion of accidents that are the cyclist's fault decreases.[14] In Davis, 74 percent of the accidents involving 0 to 11 year-old cyclists were the cyclist's fault. This declined to 48 percent in 12 to 17 year-olds, to 30 percent for 18 to 24 year-olds, and to 18 percent among those 25 and older (Table 8).

Overall, bike lanes reduced the non-neutral accident types (A, B, D, E, F, and I) by slightly more than one-half (53 percent). The magnitude and direction of change varied from one accident type to another. In fact, type D - cyclist made improper left turn - occurred more frequently on bike lanes than off bike lanes. All classes of accidents combined were reduced 31 percent by bike lanes.

Type A (cyclist exited driveway into motorist path) accidents accounted for 8.2 percent of bike-auto accidents on streets without bike lanes but had an equated relative frequency of 1.0 percent on streets with bike lanes. Lott and Lott suggest that the painted line keeps motorists off the bike lane and also indicates the area where a cyclist must turn in order to avoid entering the motor vehicle lanes.

Type B (motorist exited driveway into cyclist path) decreased from 4.1 percent off bike lanes to 2.0 percent on bike lanes. Cyclists usually ride near the left margin of the bike lane, placing them further to the left than they would be on the same street without a bike lane. This increases the distance at which a cyclist and a motorist exiting a driveway can see one another and allows for more time to avoid a collision.

Table 5. Accident distribution comparison: Santa Barbara vs. Davis.[37]

Accident Type[a]	Percent of Accidents	
	Santa Barbara	Davis
A. Cyclist exited driveway	8.6	3.9
B. Motorist exited driveway	5.7	2.8
C. Cyclist not stop/yield	8.3	7.9
D. Cyclist improper left	11.2	7.9
E. Cyclist wrong side	14.3	10.7
F. Motorist overtake cyclist	4.1	3.9
G. Motorist not stop/yield	7.8	15.8
H. Motorist improper left	12.7	17.0
I. Motorist improper right	11.2	10.2
J. Motorist opened car door	7.2	
K. Other	8.6	19.8
Total	99.7[b]	99.1[b]

[a]Accident type categories are given fully in table 2.
[b]Figures do not add to 100 percent due to rounding.

Table 6. Davis bike auto accidents: Bike-lane vs. non-bike-lane streets.[37]

Accident Type[a]	Percent of Accidents	
	With Bike Lanes	Without Bike Lanes
A. Cyclist exited driveway	1.45	8.22
B. Motorist exited driveway	2.90	4.11
C. Cyclist not stop/yield	11.59	8.22
D. Cyclist improper left	14.49	5.48
E. Cyclist wrong side	7.25	19.18
F. Motorist overtake cyclist	1.45	8.22
G. Motorist not stop/yield	21.74	17.81
H. Motorist improper left	27.54	15.07
I. Motorist improper right	11.59	13.70
J. Motorist opened car door		
K. Other		
Total	100.0	100.1[b]

[a]Accident type categories are given fully in table 2.
[b]Figures do not add to 100 percent due to rounding.

Table 7. Accident rate expectation among non-neutral accident types.[37]

Accident Type	Percent of Acc. With Bike Lanes	Expected Accident Rate	
		With Bike Lanes (Scaled by 0.69)	Without Bike Lanes
A. Cyclist exited driveway	1.45	1.0	8.2
B. Motorist exited driveway	2.90	2.0	4.1
D. Cyclist improper left	14.49	10.0	5.5
E. Cyclist on wrong side	7.25	5.0	19.2
F. Motorist overtake cyclist	1.45	1.0	8.2
I. Motorist improper right	11.59	8.0	13.7
Total	39.13	27.0	58.9

Table 8. Davis bike-auto accidents by cyclist age groups and fault.[37]

Fault	Age	TOTAL STREETS (STREETS WITH BIKE LANES AND STREETS WITHOUT BIKE LANES)							
		0-11		12-17		18-24		25+	
		No.	Percent	No.	Percent	No.	Percent	No.	Percent
Cyclist Types A,C,D,E		17	74	13	48	19	30	5	18
Motorist Types B,F,G-J		6	26	14	52	45	70	23	82
Total by Age Groups		23	100	27	100	64	100	28	100

The same cyclist behavior will reduce the number of accidents caused by drivers opening car doors into the paths of cyclists (Type J). This accident type accounted for 8 percent of the bicycle/motor vehicle accidents in Santa Barbara but did not occur in Davis. The authors believe that the streets where Type J accidents would most likely occur already have bike lanes and that the streets without bike lanes are streets where traffic and parking conditions are less likely to result in this type of accident.

Type E (cyclist rode on wrong side of the street) accidents decreased from 14.2 percent to 5.0 percent. Cyclists are much less likely to ride on the wrong side of the street where there are bike lanes than when there are none.

Lott and Lott do not explicitly explain the decrease in Type F (motorist collided with rear of cyclist), but it may be assumed that with bike lanes, cyclists and motorists are traveling in clearly marked zones.

Bike lanes reduced the rate of accidents caused by improper right turns (Type I) from 13.7 percent to 8.0 percent. The authors propose that a bike lane stripe causes motorists to check for traffic in that lane before proceeding with a right turn. Alternatively, the bike lane stripe may remind motorists that cyclists may legitimately share the roadway.

Type D - cyclist made improper left turn - accidents actually increased from 5.5 percent to 10.0 percent. A breakdown into subtypes (table 9) showed that with bike lanes, a higher percentage of cyclists are hit from behind while crossing in front of a motorist at an intersection in order to make a convenient but dangerous and illegal left-turn.

The main objective of a more recent study by Smith and Walsh (1988) was to evaluate the impact of two bicycle lanes in Madison, Wisconsin, particularly their impact on the safety of bicyclists.[39] Also, since the bicycle lanes were installed on different sides of different streets, a comparison of right-side and left-side bicycle lanes was made as a secondary point of interest.

Bicycle accident as well as traffic count data were supplied by the Madison Department of Transportation. The traffic count program was begun in 1974 and involves counting bicycles for a 2-hour period at each of two intersections in the a.m. and p.m., one weekday each month. Counts are then factored to produce a citywide daily bicycle trip estimate. The bicycle lanes in

Table 9. Percentage of left turn accidents with bicyclist at-fault: Santa Barbara and Davis. [37]

ACCIDENT SUBTYPE	SANTA BARBARA	DAVIS	
		Without Bike Lanes	With Bike Lanes
D1. Cyclist hit oncoming motorist	26	25	
D2. Cyclist hit from behind crossing in front of motorist at intersection	16	25	60
D3. Cyclist turned into path of motorist	58	50	40

question began servicing the city in 1977. To take advantage of the available count and accident data, 4-year periods before and after this date were used in the analysis. Thus, the period from 1973 to 1981 supplied the study data.

Since bicycle accidents had, in general, increased in Madison from the before to the after period, the statistical significance of this increase was tested after the data were adjusted to take into account the estimated increase in the number of trips. The significance of changes in the overall number of accidents and number of accidents by type was tested using chi-square tests for significant differences in the overall before/after totals. In addition, tests based on the cumulative Poisson distribution were used to compare average yearly accident counts before and after installation of the bicycle lanes. Time series analyses were also carried out both overall and within accident type categories.

The overall number of bicycle accidents in the Madison area increased by 20 percent from the before to the after period. The correlation between the total number of bicycle accidents and the amount of trips made by bicycle from the 1974 to 1981 time period was 0.518, suggesting that increased exposure was a factor in the observed accident increase. However, even when the before data were expanded by 7.7 percent to account for increased exposure, there was still an 18.6 percent increase in total accidents. These results were significant at the 0.001 level based on a chi-square test. Average yearly accident totals also increased significantly, based on the cumulative Poisson distribution.

In the study area corridor where the bike lanes were installed, accidents were observed to increase by 42 percent. After adjusting for the increased number of trips, the increase in total before/after accidents was found to be significant at the 0.03 level based on the cumulative Poisson distribution. For average yearly accidents before and after, the corresponding p-value was 0.18.

When accident types were examined it was found that this overall increase in accidents was due primarily to an increase in accidents where the automobile made a left turn in front of the bicyclist, occurring on the street with the bike lane installed on the left-hand side of the roadway. The time series analysis revealed that this increase was reduced over time, although it was still significant at the .05 level in 1980. The authors conclude that "introduction of a left-side bicycle lane ... will result in an initial increase in accidents, whereas the more conventional right-side bicycle lane... will not. After a reasonable period of time, neither bicycle lane location appears to cause additional accidents." The authors also note that, "except for the first year of bicycle lane implementation on [the street with the left-side bicycle lane], the bicycle lane corridor accidents did not increase significantly compared with significant increases in bicycle accidents citywide," and that "except for the first year of implementation of the left-side bicycle lane, there is no clear indication that left-side bicycle lanes are less safe than the conventional right-side bicycle lanes." A summary of results is given in Tables 10, 11, and 12.

A fairly standard set of publications exists to guide bicycle facility planning, design, and construction. However, additional research is needed to establish more specific guidelines for selecting particular treatments or facilities and to evaluate their safety.

One of the three reports in a series developed by Smith (1976) is primarily concerned with the bikeway design process and how it relates to facility location. Selected topics include:

1) Bikeway design and user characteristics.
2) Route and right-of-way design specifications.
3) Intersection treatments.
4) Signs and markings.[35]

A guide prepared by the Bicycle Transportation Committee of the American Society of Civil Engineers (1980) addresses facility planning, landscaping, geometrics, structures, pavements, drainage, traffic controls, amenities, lighting, parking, and maintenance and security.[40]

Two other valuable resources on bicycle facility planning and engineering are the Manual on Uniform Traffic Control Devices (MUTCD) and the Traffic Control Devices Handbook.[41,42] Part IX of the MUTCD discusses signs, pavement markings, and signals which may be used on roadways or on bikeways. Part IX of the Traffic Control Devices Handbook deals with traffic control devices for bicycle facilities. It also covers signage, pavement markings on bikeways, accommodating bicyclists at signalized intersections, and maintaining bicycle facilities.

AASHTO's "Guide for Development of Bicycle Facilities," published in 1981 and revised in 1991, offers detailed guidelines for the construction of both on-and off-road bicycle facilities.[43] Specific instructions are given for determining minimum curve radii, stopping sight distances, and other engineering considerations. Topics discussed in the 1991 revision include restriping to create wide curb lanes, curb cuts and ramps at intersections, and transition areas where bicycle paths merge into existing roads.

Wilkinson and Moran (1986) developed a handbook for the selection and designation of streets and highways as bike routes.[44] They considered alignment factors which make specific routes desirable and also discuss factors which make certain streets and highways suitable for bike routes. The handbook covers approaches to planning and selecting bike routes and offers project guidelines.

In summary, there is much to be learned about the way crashes are affected by various bicycle facilities. Studies of this type are candidates for future research.

Table 10. Bicycle accidents and trips in Madison, 1974 to 1981. [39]

Year	Total Accidents	Johnson and Gorham Accidents Number	Johnson and Gorham Accidents Percent of Total	Estimated Daily Trips	Total Accident Rate per 1,000 Daily Trips
Before					
1974	135	7	5.2	86,000	1.6
1975	163	8	4.9	68,100	2.4
1976	146	12	8.2	79,000	1.8
1977	175	9	5.1	75,100	2.3
After					
1978	173	20	11.6	59,100	2.9
1979	172	8	4.7	77,400	2.2
1980	247	14	5.7	97,600	2.5
1981	200	9	4.5	97,900	2.0
Summary					
Before					
Total	619	26	5.8	308,200	2.0
Average	155	9		77,050	
After					
Total	792	51	6.4	332,000	2.4
Average	198	12.8		83,000	
Increase (%)	+27.7	+41.7	+11.1	+7.7	20
Expanded Before Accidents[a]					
Total	665[.001][b]	38.8[0.03][c]			
Average	167[0.01][c]	9.7[0.18][c]			
Increase (%)	+18.6	+31.4			

[a]Before accidents expanded by 1.077 to account for increase in daily bicycle trips.
[b]Level of significance of increase based on chi square (2).
[c]Level of significance of increase based on cumulative Poisson distribution.

Table 11. Statistical significance of change in accidents. [39]

Accident Type	Johnson Street Before[a] (no.)	Johnson Street After (no.)	Johnson Street Change[b] (%)	Johnson Street Level of Significance	Gorham Street Before[a] (no.)	Gorham Street After (no.)	Gorham Street Change[b] (%)	Gorham Street Level of Significance	Total Before[b] (no.)	Total After (no.)	Total Change[b] (%)	Total Level of Significance
Total	29.1	39	34	.05	9.7	12	24	-	38.8	51	311	.03
Intersection	18.3	24	31	.11	7.5	7	-7	-	25.8	31	20	.18
Midblock	10.8	15	39	.15	2.2	5	127	.07	12.9	20	55	.05
Angle	8.6	9	5	-	4.3	5	14	-	12.9	14	9	-
Northbound automobile	4.3	8	86	.08	4.3	5	14	-	8.6	13	51	.09
Southbound automobile	4.3	1	-77	.07	0.0	0	0	-	4.3	1	-77	.07
Automobile turns in front of bicycle	8.6	17	98	.007	3.2	5	56	-	11.8	22	86	.006
Automobile left turn	3.2	16	400	.001	0	0	0	-	3.2	16	400	.001
Automobile right turn	5.4	1	-81	.03	3.2	5	56	-	8.6	6	-30	-
Bicycle going												
Contraflow	9.7	7	-28	-	0.0	2	-	.01	9.7	9	-7	-
On sidewalk or crosswalk	7.5	4	-47	.14	0.0	2	-	.01	7.5	6	-20	-
On street	2.2	3	36	-	0.0	0	0	-	2.2	3	36	-
Other	2.2	6	173	.02	2.2	0	-100	.11	4.3	6	40	-

[a]Before accidents multiplied by ratio of citywide estmate of bicycle trips for after versus before period, 332,000/308,200 = 1.077.
[b][(before-after)/before] x 100%.

Table 12. Distribution of bicycle accidents by year for Johnson and Gorham streets. [39]

Year	Johnson Total	Johnson Angle Northbound	Johnson Left Turns by Automobile	Gorham Total	Gorham Angle Northbound	Gorham Right Turns by Automobile
Before						
1974	5	1	1	2	1	0
1975	6	1	0	2	2	0
1976	8	0	1	4	1	3
1977	8	2	1	1	0	0
After						
1978	16[.004][b]	5[.005][b]	7[.001][b]	4	1	2
1979	7	1	4[.01][b]	1	0	1
1980	10	1	3[.05][b]	4	2	1
1981	6	1	2	3	2	1
Summary						
Before						
Average	6.75	1.0	0.75	2.25	1.0	0.75
Average x 1.077[a]	7.3	1.1	0.8	2.4	1.1	0.8
After average	9.8	2.0	4.0	3.0	1.2	1.2

[a]Expanded by 7.7 percent to account for greater bicycle use in after period.
[b]Indicates level of significance of accident rate for that year compared with expanded average accident rate/yr for before period.

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