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Contents

Foreword

The papers in this volume address three distinct topics: bicycling, pedestrians, and older drivers. Within each area a diversity of technical topics is covered. Accident data requirements for increasing the understanding of bicycling accidents are put forth, an environmental benefits analysis of bicycling and walking is given, and clearance intervals at signalized intersections for mixed traffic are analyzed. An intelligent bicycle routing system to supply cyclists with important travel information and a study of bicyclist characteristics in Phoenix round out the section on bicycles and bicycle facilities.

A similar variety of subjects is found among the papers on pedestrians: a method for determining service levels is described, models for estimating pedestrian volumes are tested, and characteristics of pedestrian accidents in Saudi Arabia are analyzed. The last paper in this set makes a transition between the pedestrian and older driver sections in that it discusses accidents among older pedestrians and appropriate countermeasures.

Concluding the Record are evaluations of suggestions for improving the driving of older persons and a study of the basis in selected states for referring older drivers for license reexamination.

Accident Data Requirements for Improving Cycling Safety

ROBERT G. THOM AND ALAN M. CLAYTON

Canadian cities have experienced a 50 to 60 percent increase in police-reported collisions between bicycles and motor vehicles over the past decade; along with this increase are growing problems in coping with bicycle traffic. In some locales, as many as 10 percent of police-reported injury-producing road accidents involve a cyclist. Even though cycling accidents are increasing, efforts to make urban areas more accommodating to cyclists are seldom based on accident experience. A thorough understanding of the nature and extent of cycling accidents is essential to develop meaningful countermeasures. The poor representation of cycling accidents in existing data sources inhibits the understanding of such accidents. Police data have traditionally been the primary information source on bicycle accidents and are generally limited to collisions involving motor vehicles. Emergency room surveys show that between 50 and 87 percent of these accidents do not involve motor vehicles. Thus police-reported data represent only a small fraction of cycling accidents. An analysis of police-reported data in Winnipeg, Canada, for 1990 reveals several problems: collision descriptions are inaccurate in 60 percent of the cases, inconsistencies in coding are common, and information on cyclist safety equipment and contributing factors is completely overlooked. Opportunities exist to improve data collection efforts and to extend data sources so that they cover all bicycling accidents. Hospital emergency room surveys can determine the nature and magnitude of cycling accidents and associated injuries. Travel surveys can be used to estimate distances cycled and to develop accident rates. Cyclist surveys can provide information on the nature of accidents, distances cycled, and accident rates.

To assist urban planning efforts in making cities safer and more accommodating to cyclists, a thorough understanding of the nature and extent of cycling accidents is essential. Police accident data have traditionally been the primary source of information on bicycle-related accidents. This information is generally limited to the study of collisions between bicycles and motor vehicles and represents only a small fraction of the bicycle accident problem. Furthermore, the subject of cycling accidents is poorly understood and is poorly represented in existing accident data sources.

This paper (a) discusses the need for bicycle accident data for developing countermeasures and assesses the adequacy of existing bicycle accident data sources in serving this need; (b) examines the quality of data in police accident reports, using Winnipeg's police-reported data for 1990 as an example; and (c) explores possible methods to extend bicycle accident data sources to satisfy requirements.

ACCIDENT DATA REQUIREMENTS AND THEIR USEFULNESS IN DEVELOPING COUNTERMEASURES

The purpose and application of bicycle accident data are described in this section. Key questions are posed to define the application of data collection efforts and to determine the limitation of existing bicycle accident data sources. This section also assesses the adequacy of current data sources in addressing the key questions.

Key Question 1: Trends in Number of Bicycle Accidents, Amount of Bicycle Travel, and Bicycle Accident Involvement Rates

What are the trends in number of bicycle accidents, amount of bicycle travel, and bicycle accident involvement rates per mile traveled?

Information about bicycle accident frequencies, travel, and accident rates is useful for determining and justifying the need for countermeasures. Trends in bicycle accident rates are needed to determine whether cycling safety is improving or getting worse. For example, an increase in the number of accidents in a particular region may be attributable to an increase in bicycle travel instead of an increase in the danger of cycling.

Currently, police-reported data in most jurisdictions are available to determine only trends in bicycle–motor vehicle collisions. Exposure data relating to bicycle travel are largely unavailable. Even with the police-reported data, there is an important potential problem with underreporting. Cross and Fisher estimated that only a third of all bicycle–motor vehicle collisions are reported to police (*1*).

Good data on bicycle accidents that do not involve a motor vehicle are also largely nonexistent. Cross demonstrated that 95 percent of all bicycle injuries do not result from collisions with motor vehicles (*2*). Hospital emergency room surveys examining bicycle accidents have been carried out in a number of locales. These studies show that between 50 and 87 percent of bicycle accidents reported by emergency rooms do not involve cars (*3,4*). Many of these accidents were the result of cyclist falls or collisions with fixed objects, other cyclists, pedestrians, or animals.

Key Question 2: Types of Accidents and Their Severity Levels

What are the types of accidents (e.g., car/bike, bike/bike, bike/pedestrian, bike/animal, falls, and collisions with fixed objects)

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in which cyclists are likely to be involved, and what are the corresponding severity levels?

Information on accident type is useful to determine the potential accident reduction benefits of countermeasures and to determine the type of countermeasures that may be required. Examples of countermeasures include roadway improvements, provision of separate bicycle facilities, increased roadway maintenance, increased enforcement of traffic laws, awareness campaigns, and cyclist training programs. Information on accident severity is useful to determine the relative safety of different types of facilities and operations. Information on accident types can be used to assess the content of cyclist training programs.

Police reports provide a readily available source of information on bicycle collisions involving motor vehicles. Generally, such data provide only limited information on the nature and severity of injuries sustained by cyclists. However, in many places, the number of accidents is statistically large enough that the nature of car-bike collisions and their contributing factors can be understood.

Key Question 3: Bicycle Accident Involvement Rate and Cyclist Age and Experience

What is the relationship between bicycle accident involvement rate and cyclist age, training, and experience?

This information is useful to identify the types of cyclists that are at greatest risk of having an accident and to identify target groups for cyclist training programs. It is also useful to determine how cycling experience and amount of training influences accident rates and whether training programs can be a partial substitute for experience.

Police-reported data usually record the cyclist's age but do not keep any record of an individual's previous accident experience or amount of bicycle travel or training.

Key Question 4: Bicycle Accident Involvement Rate and Roadway Type

What is the relationship between bicycle accident involvement rate and roadway type (e.g., arterial, collector, residential, bike path), rural or urban areas, and daytime or nighttime?

Information on cycling accident rates by roadway type is useful to determine whether certain types of roadways are more dangerous than others. For example, do efforts to encourage cyclists to use side streets in lieu of arterial roads actually increase safety or merely shift the accident problem from one part of the roadway system on to another? This information may be used to determine whether facilities such as separate paths or bike lanes improve safety or are counterproductive. Knowledge of accident locations and roadway types are necessary to determine high risk areas and to determine where countermeasure programs should be applied. Information on daytime versus nighttime and rural versus urban accident rates can be used to identify special nighttime or rural needs.

Police-reported data are useful for determining the time and location of bicycle–motor vehicle collisions. The roadway type, light conditions, and setting can be easily deduced. However, without data on bicycle travel volumes, accident rates cannot be determined. Police reports also exclude accidents occurring on separate paths, except for those involving motor vehicles where the path crosses a roadway.

POLICE-REPORTED BICYCLE ACCIDENT DATA: WINNIPEG EXPERIENCE

To identify problems and inconsistencies in police-reported data, a 100 percent sample of Winnipeg's traffic accident reports involving cyclists was examined for 1990. The purpose of the analysis was to determine how well data coded on the face sheets of traffic accident reports describe collisions and to identify inconsistencies in coding.

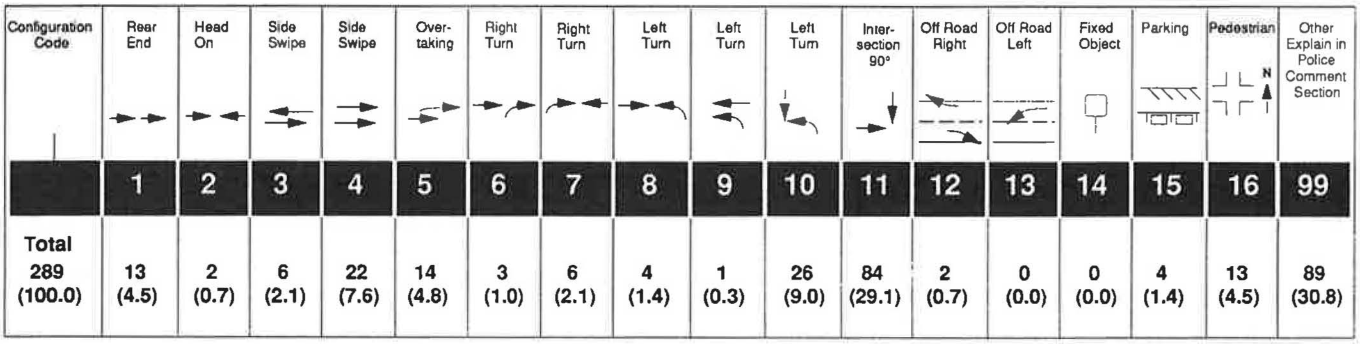
The analysis was carried out by comparing the data coded on the face sheet with the description of the collision as "reconstructed" from the police narratives in the reports. Of particular interest was the police description of the collision configuration, contributing factors on the part of the motorist and the cyclist, and the availability of safety equipment on the cyclist.

A total of 302 bicycle-related accidents were reported to Winnipeg police in 1990; of these, only 9 (or 3 percent) did not involve a motor vehicle. Four collisions involved persons walking bicycles, so only 289 of the accidents could be classed as car-bike collisions.

Collision Configuration

The distribution of accidents by police configuration code for the 289 collisions involving motor vehicles is shown in Figure 1. These collisions were also classified according to a system devised by the authors by reconstructing each collision from the narratives (*5*). This classification is shown in Figure 2. The following findings were made:

- Only 40 percent of the police configuration codes agreed with the configurations as determined from the narratives.
- More than 30 percent of the collisions were coded by police as "99-other." This indicates that to understand the nature of the collision, it is often necessary to refer to the collision narratives in the pages after the face sheet.
- Nearly 5 percent (or 14) of the collisions were coded as "16-pedestrian." In fact, only one of these collisions involved a person walking a bicycle and thus should not have been classified as a car-bike collision. The other 13 "pedestrian" collisions involved persons riding a bicycle. Three other accidents that were coded as car-bike collisions involved persons walking bicycles.
- Nearly 30 percent of the collisions were coded by police as "11–right angle." This is lower than the 48 percent as determined from the narratives. The police configuration codes do not accurately reflect all likely car-bike collision configurations. In particular, the "straight through cyclist struck by motorist turning right" (Configuration 7a) and "opening car door" (Configurations 2a and 2b) are not clearly represented by the police codes. The closest police codes would be "5-overtaking" and "15-parking," respectively.



Configuration Code	Rear End	Head On	Side Swipe	Side Swipe	Over-taking	Right Turn	Right Turn	Left Turn	Left Turn	Left Turn	Inter-section 90°	Off Road Right	Off Road Left	Fixed Object	Parking	Pedestrian	Other Explain in Police Comment Section
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	99
Total 289 (100.0)	13 (4.5)	2 (0.7)	6 (2.1)	22 (7.6)	14 (4.8)	3 (1.0)	6 (2.1)	4 (1.4)	1 (0.3)	26 (9.0)	84 (29.1)	2 (0.7)	0 (0.0)	0 (0.0)	4 (1.4)	13 (4.5)	89 (30.8)

FIGURE 1 Distribution of accidents by police configuration code, Winnipeg, 1990.

Contributing Factors

On the police face sheet there is provision for identifying as many as three contributing factors for both the motorist and the cyclist.

From the police-reported data, the most frequent contributing factor for the motorist was "failure to yield right of way," in 8 percent of the collisions. For the cyclist, the most frequently coded factor was "disobeyed traffic control device," in 6 percent of the collisions. In nearly half of the collisions, no codes were assigned whatsoever.

From the collision reconstruction based on the narratives, the most frequent contributing factors for the motorist were as follows:

	Percentage
Failure to yield right of way	14
Improper right turns	3
Improper overtaking	5

For cyclists, the following contributing factors were most frequent:

	Percentage
Failure to yield right of way	14
Sidewalk/wrong-way riding	23
Disobey traffic control device	11
Lack of nighttime equipment	10

In the police reports, there are no applicable codes for driving or riding on a sidewalk or any other area intended for use by pedestrians. Similarly, there are no codes for lack of headlights, taillights, or reflectors.

Safety Equipment

The face sheet data were examined to determine if the cyclist was using pertinent safety equipment, particularly helmets, lights, reflectors, or retroreflective clothing. Of the 289 collisions involving motor vehicles, only five cyclists were noted to be wearing helmets. Twenty-five cyclists were coded by police as not wearing helmets. In the remaining 259 collisions (90 percent), cyclists' use of safety equipment was coded as either "no safety equipment available" or "not applicable."

In all 29 of the nighttime collisions, the use of appropriate lights, reflectors, or retroreflective clothing by the cyclist was not noted. It is highly probable that these cyclists lacked a headlight and adequate rear reflectors at the time of the collision. The use of a headlight is crucial in preventing many of the intersection collisions, and a taillight and rear reflectors are necessary to reduce overtaking collisions.

METHODS TO EXTEND BICYCLE ACCIDENT DATA SOURCES

The findings of bicycle accident studies on the basis of a review of the literature are reported. These findings are related to the key questions posed earlier. This section also presents possible methods to extend bicycle accident data sources to address the key questions.

Trends in Number of Bicycle Accidents, Amount of Bicycle Travel, and Bicycle Accident Involvement Rates

Police-reported data can be used to identify trends in the number of bicycle–motor vehicle collisions. In most locales, it is possible to obtain these data over several years. To determine the trend in numbers of accidents that do not involve motor vehicles, hospital emergency room surveys would be the primary data source. However, with hospital data, it is often not possible to determine historic trends from previous data. Therefore, efforts to collect hospital data would have to be carried out for several years with a consistent sampling plan.

Determining trends in the amount of bicycle travel is much more difficult, since such data are not collected in most locales. Questions on the type and amount of personal tripmaking by all travel modes could be included in travel surveys. In Great Britain, the Department of Transport monitors the amount of travel and number of casualty accidents for different modes of road travel, including bicycling (*6*). The Department of Transport data have been used to determine historic trends in the bicycling accident rate, as shown in Figure 3. From this figure, the accident rate rose steadily between 1954 and the early 1970s. From the early 1970s to 1987, the rate declined slightly. The accident rate for the general cycling population was approximately 10 times greater than the rate for motoring (*6*).

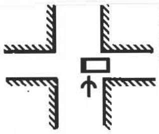
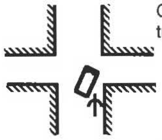
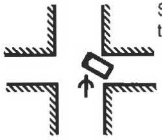
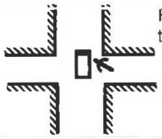
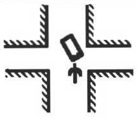
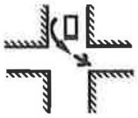
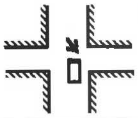
	Configuration		Description	Principal Contributing Factors
A. Mid - block Collisions	1. Rear End 7 (2.4%)		Cyclist strikes rear of stopped or parked motor vehicle.	• Cyclist inattentiveness • Cyclist loss of control
			Rear of cyclist struck by front of overtaking motor vehicle.	• Motorist improper overtaking • Cyclist swerves unexpectedly • Cyclist lack of reflector / taillight
	2. Opening Car Door 15 (6.3%)		Cyclist strikes driver side door.	• Motorist opening door into traffic • Cyclist too close to parked car
			Cyclist strikes passenger door	• Cyclist improper overtaking
	3. Sideswipe same Direction 29 (10.1%)		Cyclist sideswiped by overtaking motor vehicle	• Cyclist swerves unexpectedly • Motorist improper overtaking • Cyclist lack of reflector / taillight
			Motorist changes lane to right	• Motorist improper lane change
			Motorist entering/exiting parking spot	• Cyclist improper over taking • Motorist fails to yield right of way
	4. Sideswipe - Opposite Direction 3 (1.0%)		Cyclist sideswiped by motor vehicle travelling in opposite direction	• Cyclist or Motorist travelling wrong way • Cyclist or Motorist loss of control
	5. Head on 1 (0.4%)		Front of cyclist struck by front of motor vechicle travelling in opposite direction	• Cyclist or motorist travelling wrong way • Cyclist or motorist loss of controll
B. Intersection Collision	6. Right Angle 138 (47.8%)		Cyclist proceeding straight intersection struck by straight through motor vehicle on perpendicular road way	• Cyclist or motorist disobeys traffic control device • Cyclist or motorist fails to yield right of way • Cyclist on sidewalk and / or wrong way • Cyclist lack of head light
	7. Right turn 46 (15.9%)		Cyclist going straight struck by motorist turning right	• Motorist improper turning • Cyclist improper over taking • Cyclist riding on sidewalk and / or wrong way • Cyclist lack of reflectors / taillight
			Straight through cyclist struck by motorist turning right from perpendicular road way	• Motorist fails to yield right of way • Cyclist riding on sidewalk and / or wrong way • Cyclist lack of head light
			Right turning cyclist struck by motorist travelling straight on perpendicular roadway	• Cyclist fails to yield right of way
	8. Left Turn 47 (16.3%)		Straight through cyclist struck by motorist turning left across his path	• Motorist fails to yield right of way • Cyclist riding on sidewalk and / or wrong way • Cyclist lack of head light
			Left turning cyclist struck by overtaking motorist	• Cyclist turning left from curb • Cyclist failure to shoulder check • Cyclist lack of reflector / taillight
			Cyclist turns left across motorist's path	• Cyclist fails to yield right of way

FIGURE 2 Distribution of accidents by configuration, from narrative reconstruction, Winnipeg, 1990.

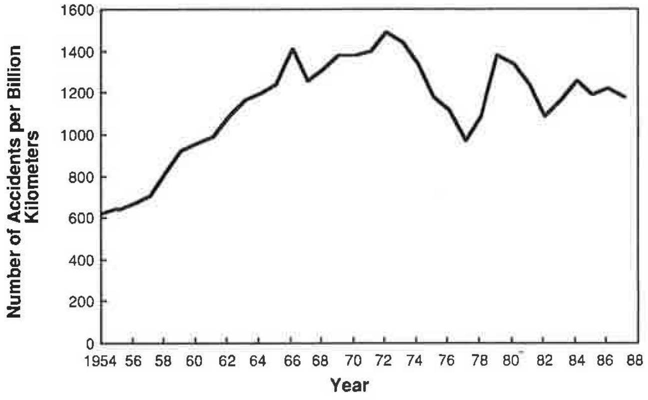


FIGURE 3 Cyclists killed or seriously injured per billion veh-km.

Types of Accidents and Their Severity Levels

In a survey of League of American Wheelman (LAW) members, Kaplan was able to determine the frequency of accidents by type and by injury severity (*7*). In this survey, "serious" was considered to be accidents that required hospital admission. The reported frequencies are given in Table 1.

It is important to note that these frequencies are for a group of highly experienced, club-level cyclists. A survey carried out by Schupack and Driessen of college-age cyclists shows a greater proportion of falls and smaller proportions of collisions with cars and other cyclists (*8*). A survey of elementary school children by Chlapecka et al. indicates a much higher proportion of falls than the LAW members, but only 10 percent with cars (*9*).

Hospital emergency room surveys can serve as the principal source of information on the frequency of bicycle accidents by type and injury severity for the general cycling population.

BICYCLE ACCIDENT INVOLVEMENT RATE AND CYCLIST AGE AND EXPERIENCE

A number of surveys of cyclist accidents have been used to provide general accident rate data. Surveys have been carried out on elementary school children, college adults, and adult club cyclists. The adult club cyclists had a significantly lower accident rate than the first two groups, but they were involved in a somewhat higher proportion of car-bike collisions. The corresponding accident rates by accident type for these groups are presented in Table 2. In these three surveys there was little difference between the accident definitions.

TABLE 1 Accident Types and Frequencies, LAW Members

Type	Percentage of all Accidents	Percentage of Serious Accidents
Fall	44	38
Collision with moving motor vehicle	18	26
Collision with moving bicycle	17	13
Collision with moving dog	8	10
Collision with parked car	4	2
Bicycle defect	3	3
Collision with pedestrian	1	1
Other	5	7

TABLE 2 Accident Rates by Cyclist Type per Million bicycle-mi

	Elementary School Cyclists (*9*)	College Cyclists (*8*)	Adult Club Cyclists (*7*)
Basic accident rate	720	510	113
Fall rate	575	300	50
Car-bike collision rate	72	80	20
Car-bike collision proportion	0.10	0.16	0.18

Cross's Santa Barbara study of accidents not related to motor vehicles has been used to determine the influence of cycling experience on the accident rate (*2*). The annual probability of an accident for cyclists of different annual mileages has been calculated from Cross's data. The relationship between annual mileage and accident rate derived from these calculations is shown in Figure 4. This figure indicates that the accident rate decreases with increasing annual mileage.

In a study of cyclists' behavior in The Netherlands, Maring and von Schagen determined the relationship between a cyclist's age and accident rate per billion bicycle-km for 1983 and 1984 (*10*). The accident rates were developed by using collision data collected by the national traffic accident registration system and relating them to the distances covered by various age groups through annual surveys of the Central Bureau of Statistics. The relationship is shown in Figure 5. From this figure, the accident rates for cyclists younger than 12 and older than 70 are higher than for other age groups.

To determine the relationship between the amount of bicycle travel and accident rates for a particular area, surveys should include questions on the estimated amount of bicycle travel over a specified period and on the number and types of accidents in which an individual cyclist has been involved. To obtain meaningful data, the definition of accident must be consistent. Surveys could be carried out on hospital emergency room cases of bicycle-related accidents or on specific groups of cyclists (e.g., school children and cycling club members).

To distinguish rural from urban and daytime from nighttime accidents, surveys should include questions on light conditions

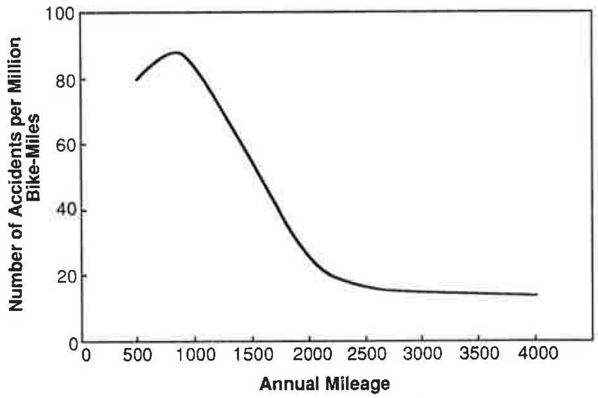


FIGURE 4 Annual mileage and accident rate.

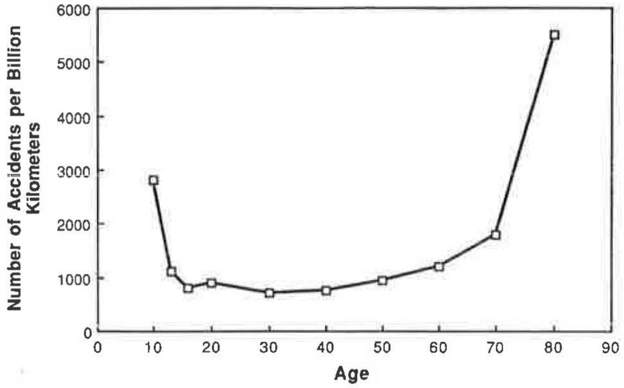


FIGURE 5 Cyclist age and accident rate.

and on urban versus rural settings. However, it may be very difficult, if not impossible, to develop individual accident rates for these variables, since most cyclists do not know the proportion of nighttime or rural travel to total bicycle travel.

To date, no study has been able to demonstrate whether urban cycling is more dangerous than cycling in rural areas.

Bicycle Accident Involvement Rate and Roadway Type

Kaplan's survey of LAW members showed that the accident rate increases with traffic levels (*7*). The distribution of accident rate by roadway type from this survey is given in the following table:

Roadway type	*Accidents per Million bicycle-mi*
Arterial	111
Collector	104
Residential	58
Bike path	292

Off-street bike paths experienced the highest accident rate: 292 accidents per million bicycle-mi, or approximately 2.5 times the rate of arterial roads. This indicates a major safety problem with the design and operation of special bicycle facilities that were intended to improve safety.

CONCLUSIONS AND COMMENTARY

On the basis of this work, the following comments can be made:

- Effective countermeasures require sound knowledge of cycling accidents.
- Bicycle accident information is generally inadequate and covers only a small portion of the accident situation.
- Meaningful information systems require the expansion of the data base to cover accidents that do not involve a motor vehicle and the improvement of the quality of existing data sources.
- The quality of police-reported data is often poor. In particular,
  - Coded data provide an inaccurate description of collisions.
  - Bicycle collisions are often miscoded as pedestrian collisions. Cyclists and pedestrians are two completely different groups of road users with different operating characteristics. Cyclists should be regarded as vehicle operators and collisions should be classified according to the most appropriate configuration code. To assist in this effort, a sketch of all collisions should be made on the diagram provided.
  - A cyclist's use of safety equipment such as helmets, reflectors, and headlights is not noted.
  - Contributing factors on the part of motorists and cyclists are frequently not coded. In describing contributing factors, special codes should be created to describe riding/driving in pedestrian areas and lack of nighttime equipment. Closer attention must be paid to the behavior of the motorist and the cyclist before the collision.
- Opportunities exist to improve the quality of existing bicycle accident data sources and to extend the data base to cover the full range of cycling accidents. Hospital emergency room surveys may be used to develop data on accidents that do not involve a motor vehicle and on the nature and severity of cyclists' injuries. Data on cycling accident experience and bicycle travel can be collected through surveys of specific groups of cyclists. Travel surveys can be used to estimate the amount of bicycle travel in order to develop meaningful exposure data.

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Environmental Benefits of Bicycling and Walking in the United States

CHARLES KOMANOFF, CORA ROELOFS, JON ORCUTT, AND BRIAN KETCHAM

Bicycling and walking are underappreciated modes of mobility in the United States. In an attempt to reassert the benefits of these human-powered transportation modes, the fuel and emissions savings resulting from current levels of bicycling and walking have been estimated. On the basis of high estimates of miles traveled by bicycling and walking, these combined modes displace between 1.2 and 5.0 percent of passenger vehicle emissions of carbon monoxide, nitrogen oxides, and volatile organic compounds. Additionally, bicycling and walking displace as much as 1.6 percent of carbon dioxide emissions from passenger vehicles. The environmental benefits that can be realized from increased bicycling and walking in 2000 are also projected. If federal and state governments go a step beyond the flexible funding provisions of the Intermodal Surface Transportation Efficiency Act of 1991 to direct state and federal funding toward investments in bicycling and walking infrastructure, higher levels of bicycling and walking and thus greater environmental benefits will result by 2000. Bicycling and walking could displace 4 to 15 percent of projected passenger vehicle emissions of carbon monoxide, nitrogen oxides, and volatile organic compounds and 5 percent of passenger vehicle carbon dioxide.

Human-powered modes of transportation—chiefly walking and bicycling—are chronically underreported and understudied in the United States. Unlike driving, which is painstakingly measured and analyzed, or even public transit such as rail, buses, and ferries, whose ridership is diligently recorded, walking and bicycling have been ignored by most energy experts, economists, statisticians, and transportation planners (not to mention policy makers).

From time to time, and increasingly in the past decade, efforts have been made to estimate the amount of bicycling and walking in the United States. These attempts (such as the National Personal Transportation Study conducted every 7 years by FHWA) have sometimes been ingenious and even valuable, but none has been comprehensive. Most measurements of U.S. bicycling and walking have been performed only on a local level, and many have been conducted by grass roots groups, without the funding support and official imprimatur needed for a definitive analysis.

To anyone who has thought seriously about foot- and pedal-powered transportation, this inequality between human-powered and fuel-driven transport should not be surprising. Human power does not use purchased fuels; therefore, it does not figure in energy accounting. Walking and bicycling largely fall outside the transaction economy of gasoline, tolls, and fareboxes that characterizes cars, buses, and trains; thus, human-powered transport hardly enters into the national income categories that make up the gross domestic product. By training, mandate, and institutional tradition, most transportation planners are so focused on cars, highways, and large-scale transit systems that they overlook bicyclists and walkers as practitioners of transportation.

This pervasive bias against human-powered transportation has a parallel in energy analysis. Until recently, small-scale renewable energy was missing from the energy accounting system that tallies Btu's from oil, gas, coal, nuclear, and large-scale hydropower. Even today, there is no systematic accounting of energy contributed by sunlight. As Baer wrote in 1975,

> if you take down your clothesline and buy an electric clothes dryer, the electric consumption of the nation rises slightly. If you go in the other direction and remove the electric clothes dryer and install a clothesline, the consumption of electricity drops slightly, but there is no credit given anywhere on the charts and graphs to solar energy which is now drying the clothes . . . .
>
> If you drive your car to the corner to buy a newspaper, the gasoline consumption appears. If you walk—using food energy—the event has disappeared from sight, for the budget of solar energy consumed by people in food is seldom mentioned. (*1*)

Baer also described the "humiliation" that solar energy advocates experience at being excluded from the "energy pies" that assign slices to fossil, nuclear, and hydro but not to solar, which was too small to appear. "The demoralized reader," wrote Baer, "is then ripe to be persuaded of the necessity of nuclear power plants or offshore drilling. The accounting system shows that he has done absolutely nothing with solar energy. He lacks even a trace of a useful habit or activity that he could build on" (*1*).

To work against the dominant paradigm that ignores the contributions of bicycling and walking to mobility, the authors have quantified the major environmental benefits of these transportation modes.

PUTTING BICYCLING AND WALKING INTO THE PIE: ESTIMATING THE ENVIRONMENTAL BENEFITS OF BICYCLING AND WALKING

Bicycling and walking are the two major forms of transportation that neither use fuel nor pollute in the United States. Millions of Americans ride bicycles or walk for a wide variety of purposes: commuting to work, as part of their job, for personal business such as shopping and visiting, and for pleasure and recreation. For many of these citizens, bicycling and

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walking are an important—and in some cases the prime—means of transportation.

The personal and societal benefits of bicycling and walking are myriad, ranging from thrift and individual health to community building and personal empowerment. The environmental benefits are numerous as well, particularly in relation to the prevailing major mode of transportation in the United States—the private car. Bicycling and walking conserve roadway and residential space; avert the need to build, service, and dispose of automobiles; and spare users of public space the noise, speed, and intimidation that often characterize motor vehicle use, particularly in urban areas.

By far the greatest environmental benefit of bicycling and walking, however, is that they bypass the fossil fuel system to which the American economy has become addicted. Aside from the modest additional food intake that fuels a bicyclist's or walker's incremental expenditure of muscular energy (and the associated energy requirements to grow and deliver those rations and to manufacture bicycles as well), bike riding and walking are free of the environmental damage inherent in extracting, transporting, processing, and burning petroleum or other fossil fuels.

Thus, to the extent that bicycling and walking displace trips that otherwise would have involved the use of motor vehicles, they enable society to reduce consumption of fossil fuels and the associated pollution and other environmental damage. Bicycling and walking also provide a special benefit: people who bicycle and walk instead of drive generally are avoiding driving short distances on a cold, extra-polluting engine.

Accordingly, the key findings of the environmental effects of bicycling and walking concern the amount of fuel consumption and automotive pollution that they avoid by displacing the use of passenger vehicles. Other benefits of bicycling and walking are discussed briefly after this section.

Quantifying the fuel use and pollution avoided by bicycling and walking involved estimating

1. Miles bicycled and walked in the United States,
2. The trade-off of vehicle miles traveled (VMT) for bicycling and walking,
3. Per-mile emissions and fuel consumption of these miles that were not driven for four air pollutants.

Miles Bicycled and Walked

To estimate the miles bicycled and walked in the United States, the authors drew on a range of transportation studies from FHWA's National Personal Transportation Study of 1990 to studies of the modal split in Boulder, Colorado, carried out by a local transportation planning agency. Then the authors developed high and low estimates of annual bicycling and walking for different motivations (e.g., commercial bicycling, recreational walking). Combining bicycling and walking, it is estimated that human-powered miles traveled in the United States ranged between 26.3 and 65.4 billion mi during 1990–1991.

VMT Trade-Off

Estimating the VMT trade-off for bicycling and walking means finding the extent to which miles biked and walked substitute for miles that would have been driven in motor vehicles: the authors account for the fact that not every walking or bicycling trip displaces a motor vehicle trip. Indeed, it is estimated that only about a third (26 to 37 percent) of walking miles displace an automobile mile and that probably a little less than half (38 to 56 percent) of bicycling miles displace automobile miles. The rest of walking or bicycling trips would have been accomplished through carpooling or transit, or would not have occurred at all. Accordingly, passenger vehicle miles displaced by bicycling and walking are considerably fewer than actual miles bicycled and walked.

U.S. passenger vehicles traveled an estimated 2.061 trillion mi in 1991 (*2*). Thus, combined bicycling and walking miles are between 1.3 and 3.2 percent of VMT.

Avoided Per-Mile Emissions and Fuel Consumption

The per-mile emissions and fuel consumption avoided by not driving were estimated for four air pollutants: carbon dioxide (CO_2), which is the primary greenhouse gas responsible for global warming, and the three "criteria" pollutants that apply to motor vehicles—carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs, or hydrocarbons). (Passenger vehicle emissions of the remaining two criteria pollutants, particulate matter and lead, are extremely small relative to CO, NOx, and VOCs. Diesel-engine cars do emit particulates, but diesels account for only about 1 percent of the U.S. passenger vehicle fleet.) For this step, the authors took note of the disproportionately high rate of emissions from short automobile trips, which are precisely the kinds of trips that bicycling and walking most commonly displace. Short vehicle trips are more emission-intensive than longer trips because vehicles emit CO and VOCs at higher rates at the beginning of a trip, when the engine is cold. Additionally, at the end of a trip, engines continue to emit VOCs (via evaporation) after the engine has been turned off, a phenomenon known as hot soak. These two factors lead to higher emissions per mile on short automobile trips than long ones.

Working with low and high estimates—lower and upper bounds of miles bicycled and walked and vehicle miles avoided—the authors developed a low-high range for petroleum and emissions avoided. These estimates are based on current (1990–1991) data for bicycling, walking, and emissions. The results appear in Table 1. Under the high estimate, bicycling and walking annually displace between 1.2 and 5.0 percent of passenger vehicle emissions of CO, NOx, VOCs, and CO_2.

To place this result in context, passenger vehicles account for 20 percent of U.S. energy consumption (this estimate excludes the energy required to manufacture, store, and service the vehicles or the fuel itself) and are responsible for 20 percent of total U.S. CO_2 emissions, 45 percent of CO emissions, 16 percent of NOx emissions, and 25 percent of VOC emissions.

SCENARIO OF EXPANDED BICYCLING AND WALKING FOR 2000

Bicycling and walking are far less common per capita in the United States than in most other industrial countries, the

TABLE 1 Environmental Benefits of Bicycling and Walking, 1990–1991

	Bicycling High	Low	Walking High	Low	Bicycling & Walking High	Low
Bicycling/Walking Miles Traveled (millions)	21,300	5,800	44,100	20,500	65,400	26,300
Passenger Vehicle:						
Miles Displaced (millions)	12,000	2,200	16,100	5,400	28,100	7,600
% Miles Displaced	0.6%	0.1%	0.8%	0.3%	1.4%	0.4%
Petroleum Displaced (millions of gallons)	680	120	910	300	1,590	420
% Petroleum Displaced	0.6%	0.1%	0.8%	0.3%	1.5%	0.4%
Emissions Displaced (metric tons)						
CO_2	6,620,000	1,210,000	8,880,000	2,980,000	15,500,000	4,200,000
CO_2 %	0.7%	0.1%	0.9%	0.3%	1.6%	0.4%
CO	579,000	106,000	777,000	260,000	1,355,000	370,000
CO %	2.1%	0.4%	2.9%	1.0%	5.0%	1.4%
NOx	16,000	2,900	21,500	7,200	37,500	10,100
NOx %	0.5%	0.1%	0.7%	0.2%	1.2%	0.3%
VOC	43,100	7,900	77,600	26,000	120,700	33,900
VOC %	0.9%	0.2%	1.7%	0.6%	2.6%	0.7%

result of a self-reinforcing set of circumstances and policies that includes externalization of many motor vehicle societal costs, social and political biases against public institutions such as transit, and dispersed settlement patterns. Although these phenomena are deeply entrenched, recent developments including enactment of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA); greater attention to health, fitness, and the environment; and improved technology (e.g., the advent of more user-friendly bicycles such as mountain bikes) have kindled interest in expanding opportunities for bicycling and walking.

Accordingly, the authors postulated two scenarios in which U.S. bicycle and walking miles would undergo significant increases between now and 2000. The "low" scenario assumes that many cities and states will use the flexible funding provisions of ISTEA to increase investment in bicycling and walking infrastructure and promotion. Policy-led changes in land-use patterns are modest, however. In the low case, bicycling increases from current levels by a factor of 3 and walking by a factor of 1.5.

The "high" scenario assumes that continuing environmental, quality of life, and transportation problems (e.g., congestion) will lead the federal government to direct dedicated funding to states and cities to increase levels of bicycling and walking. This directed funding path is also motivated by the need to satisfy the air pollution reduction targets in the Clean Air Act Amendments of 1990 and also employs land use planning and automobile disincentives such as fuel taxes and congestion pricing to reduce motor vehicle trips. In the high case, bicycling increases by a factor of 5 and walking by a factor of 2.5. Estimates of the reduced passenger vehicle VMT, fuel consumption, and emissions resulting from these year 2000 scenarios are given in Table 2.

The authors assume that U.S. VMT for motor vehicles could reasonably be expected to increase from 1991 levels by 1.5 percent per year to 2000, to approximately 2.357 trillion mi/year. [Although passenger vehicle VMT would almost certainly differ between the "flexible funding" (low) and "directed funding" (high) scenarios, to simplify the analysis the authors have assumed the same growth in VMT to the year 2000 for both scenarios.] Combined bicycling and walking miles would then range between 2.0 and 9.2 percent of motor vehicle VMT.

Between 1990–1991 and 2000, passenger vehicle per-mile emissions are projected to decrease significantly as new cars with increasingly improved pollution controls replace older vehicles and new, cleaner fuels come into use. The authors project an approximate halving of per-mile emissions of CO, NOx, and VOCs on the basis of projections from the Environmental Protection Agency. Fuel requirements—hence, CO_2

TABLE 2 Environmental Benefits of Bicycling and Walking, 2000

	Bicycling High	Low	Walking High	Low	Bicycling & Walking High	Low
Bicycling/Walking Miles Traveled (millions)	106,500	14,500	132,300	30,750	238,800	45,250
Passenger Vehicle:						
Miles Displaced (millions)	60,000	6,600	40,300	8,100	100,300	14,700
% Miles Displaced	2.5%	0.3%	1.7%	0.3%	4.3%	0.6%
Petroleum Displaced (millions of gallons)	3,050	340	2,050	410	5,100	750
% Petroleum Displaced	2.7%	0.3%	1.8%	0.4%	4.5%	0.7%
Emissions Displaced (metric tons)						
CO_2	29,800,000	3,300,000	20,000,000	4,000,000	49,800,000	7,300,000
CO_2 %	2.9%	0.3%	1.9%	0.4%	4.8%	0.7%
CO	1,260,000	140,000	850,000	170,000	2,110,000	310,000
CO %	9.0%	1.0%	6.1%	1.2%	15.1%	2.2%
NOx	35,500	3,900	23,800	4,800	59,300	8,700
NOx %	2.2%	0.2%	1.5%	0.3%	3.6%	0.5%
VOC	133,200	14,600	120,900	24,300	254,100	38,900
VOC %	3.9%	0.4%	3.6%	0.7%	7.5%	1.1%

emissions per mile traveled—have also been assumed to decline by 10 percent.

Although overall vehicle emissions will be lower in 2000, the authors assume that vehicles will still be stuck in the short-trip, pollution dis-economy trap caused by cold engines and hot soaks. In the year 2000, bicycle and walk trips will continue to deliver "high-power" emissions relief by displacing short automobile trips.

The environmental benefits of bicycling and walking estimated in the year-2000 calculations are highly significant, since they suggest that under an accelerated growth effort such as the directed funding scenario outlined here, bicycling and walking could displace as much as 15 percent of projected passenger vehicle emissions of CO, NOx, and VOCs and 5 percent of passenger vehicle CO_2.

Although a cost comparison is beyond the present scope, the relatively low-cost nature of many walking and bicycling facilities suggests that actions to expand human-powered transportation could reduce air pollution for less per-unit cost than many other approaches (e.g., so-called alternative fuels). When the many other environmental and societal benefits of bicycling and walking are factored in as well, the case for expanding these modes becomes still more compelling.

Other Environmental Benefits of Bicycling and Walking

The focus, thus far, is almost exclusively on the fuel savings and emission reductions arising from the displacement of motor vehicle use by bicycling and walking. Of all of the environmental benefits from human-powered transportation, these are the most obvious, most easily quantified, and probably the most significant. However, bicycling and walking generate a wide array of other important benefits to the environment and to society at large.

Road Space and Congestion

Bicycling and especially walking require far less physical road (or sidewalk) space per traveler than automobiles. This is due to differences in both "vehicle" size and speed. (Although in theory the size of a traffic stream able to pass a given point should be proportional to speed, safe braking distance is proportional to the speed squared, suggesting that in practice the size of the stream is inversely proportional to its speed.)

Thus, human-powered travelers avoid most of the exorbitant need for roadways exerted by motor vehicles, along with associated environmental damage including loss of open space, conversion of farm land, expropriation of valuable urban property, elimination of water and flood drainage, and the various direct impacts from creating, installing, and maintaining pavement surfaces. Similarly, bicycling and walking add little or nothing to congestion—an important point as vehicle use increasingly exceeds roadway capacity, causing chronic congestion. Annual U.S. motor vehicle congestion costs have been estimated at $100 billion or more (*3,4*), suggesting that national VMT and associated congestion displaced by bicycling and walking constitute a significant environmental and economic benefit.

Land Use

Perhaps the most insidious of the various self-reinforcing aspects of motor vehicles is that their "use causes facilities and services to become more widespread often to the point where they are beyond the range of [cyclists and walkers]" (*5*). Or, as Illich put it, "motorized vehicles create new distances which they alone can shrink. They create them for all, but they can shrink them for only a few" (*6*). Moreover, as motor vehicles have expanded into a cultural norm, cities have been either badly compromised through automobile-centered remodeling that undermines urban density or bypassed altogether through suburban and exurban residential and commercial development. In this way, motor vehicles have been both catalyst and creature of dispersed, resource-intensive, nonurban settlement.

Bicycling and walking help counter this dynamic. Although in the popular mind countryside may be more conducive to bicycling and walking, these modes are actually more common in urban areas, where distances are shorter, which favors bicycle and foot travel over motor travel. The converse of this is that bicycling and walking buttress the economic and social vitality of cities; precisely because, in conjunction with public transport, they enable travel to occur without motor vehicles, bicycling and walking in effect make possible the density that defines urban life and commerce. Although quantification of this phenomenon is beyond our scope, the glue that bicycling and walking supply to cities is an important antidote to environmentally and socially destructive sprawl.

Roadway Accidents

Between 45,000 and 50,000 people die in U.S. roadway accidents each year, including roughly 7,000 pedestrians and 1,000 bicyclists. On the basis of the estimates of U.S. miles walked, bicycled, and driven in this report, per-mile fatalities as well as injuries appear to be considerably higher for walking and bicycling. Such a comparison might suggest that the substitution of bicycling and walking for motor vehicle use would increase road accidents, but this conclusion is probably fallacious, for several reasons.

First, most bicyclist deaths and almost all pedestrian deaths occur in collisions with motor vehicles; thus, increases in bicycling and walking and decreases in vehicle use tend to improve safety of "prior" bicyclists and walkers. Second, as mentioned, bicycling and walking help reinforce dense settlement patterns in which trips for work, personal business, and pleasure can be confined to shorter distances; thus, over the long term a mile walked or bicycled can substitute for more than a mile driven—in effect, reducing accident rates per trip or per person, if not per mile. Third, improved bicycling and walking conditions facilitate safety as well as greater mobility for bicyclists and pedestrians by ameliorating traffic signaling and road condition problems that currently cause accidents involving bicyclists only or bicyclists and pedestrians. Fourth, increases in bicycling and walking also tend to give rise to political demand to reduce motor vehicle speed and frequency; thus, growth in pedal and foot traffic can result in declining per-mile casualties, after a period of accommodation.

Road accidents exact enormous costs to American society and the economy through loss of life, lost productivity at work and home, cost and time of rehabilitation, and victim and family pain and suffering. The Urban Institute has estimated these costs at roughly $363 billion/year (1990 dollars) (*7*). A careful, whole-systems analysis of the effect of bicycling and walking on road accidents would contribute profoundly to the understanding of the total environmental benefits of bicycling and walking.

Noise

Roadway traffic generates noise through a variety of mechanical and physical processes, including tires moving over pavement, engine exhaust, operation of engines and related equipment, friction of brake shoes on drums or discs, operation of air brakes, and transmission and drive train friction—not to mention discretionary equipment operated by drivers (e.g., horns and alarms). Noise from motor traffic erodes not only urban civility but also human health and economic well-being.

Although much vehicle noise is from heavy trucks, which are little if at all displaced by bicycling and walking, a considerable part is generated by passenger vehicles. Ketcham and Komanoff estimate annual U.S. health and productivity costs from motor vehicle noise at approximately $22 billion (1990 dollars), on the basis of a 1981 study for the FHWA that inferred a per-decibel estimate of the economic impact of highway noise from property value differences between homes located near and far from urban interstates (*3,4*). In contrast, walking and bicycling generate little, if any, noise.

Other Costs of Motor Vehicle Use

Drilling, shipping, and storing oil cause widespread environmental pollution, ranging from huge oil spills such as the Exxon Valdez in Alaska's Prince Edward Sound to far greater amounts of oil and gasoline routinely leaked and poured into sewers and seeping into groundwater. Petroleum consumption by bicycling and walking is de minimis (i.e., extremely small amounts of lubricants applied to bicycle parts).

Car and truck air conditioning units account for about a quarter of chlorofluorocarbon (CFC) use in the United States. These man-made chemicals are considered responsible for an estimated 14 percent of the greenhouse effect, ranking third behind CO_2 (responsible for about 50 percent) and methane (18 percent) (*8*). CFCs also are destroying the stratospheric ozone layer, thereby exposing life on earth, from humans to vital microorganisms, to excess levels of deadly ultraviolet radiation. In contrast, bicyclists and walkers do not use artificial air conditioning.

Storm water runoff of salts applied to deice highways harms the environment, as do lead and toxic organics from automobile emissions, brake lining wear, and the like. The portion of this due to bicycling and walking is quite small in proportion to their use of road and sidewalk space (and, indeed, municipalities are far less aggressive at removing snow from sidewalks than from roadways).

Approximately 10 million car and truck chassis and 250 million tires are dumped into the environment each year, with little recycling. Analogous impacts from bicycling and walking are merely worn-out bicycles and parts (some of which are recycled internationally by Bikes not Bombs and other mobility-development projects) and footwear.

Motor vehicles contribute to destruction of public property such as parkland, sidewalks, and other facilities through crashes and routine driving and parking in off-road areas. Damage to public and natural areas by hikers and mountain bikers, although a concern to nature and wilderness lovers, is of a lower order of magnitude.

Manufacturing, transporting, and storing vehicles also harm the environment. At least one source estimated the energy requirements of vehicle manufacture at roughly 20 percent of total life-cycle energy (*9*). Analogous impacts from bicycle manufacture are probably proportional to relative vehicle weight (i.e., roughly two orders of magnitude less).

Refining and storing petroleum products pollutes air, land, and water. The authors have excluded such impacts from the quantified estimates, except for adding 10 percent to tailpipe emissions in estimating the emission factor for CO_2.

CONCLUSION

Bicycling and walking, the major modes of renewable transportation, are perhaps in an analogous position to that of solar energy a decade or two ago. If an activity is ignored, so are its benefits. Conversely, if the benefits can be tallied, or at least estimated, then the activity itself may come to be esteemed. This may be of particular value to bicyclists and walkers, who often are not only demoralized but bodily threatened by motorists and motor-oriented planners who, out of carelessness or brutishness, would deny them use of road space.

Today, as the Automobile Century draws to a close, the far-flung damage from motor transportation is finally drawing increasing attention (and opposition)—and none too soon. Bicyclists and walkers suffer damage from motor vehicles not only as citizens and taxpayers, but as victims of a transportation system and motor culture that subject them to constant danger and abuse. It is vital that the environmental benefits of bicycling and walking be appreciated not only by planners and public officials, but by the populace at large.

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Analysis of Traffic Signal Clearance Interval Requirements for Bicycle-Automobile Mixed Traffic

DEAN B. TAYLOR

Clearance intervals (including both the yellow change and all-red clearance intervals) at signalized intersections that are of inadequate lengths for bicycle/rider units may cause accidents. Steps that can be taken to provide safe clearance intervals for bicycles and automobiles are examined. Data on bicycle/rider unit speed, acceleration, and deceleration were collected and analyzed. Using the results of the analysis and an accepted theory for computing safe clearance intervals, a methodology is obtained for computing safe clearance intervals for traffic containing bicycles and automobiles. The clearance interval required by bicycles will probably be somewhat larger than that for automobiles. Providing a single longer clearance interval for both users may cause undue delay or unsafe conditions for automobiles. Therefore, alternatives that provide different warning signals to each user at the appropriate time are presented, and the question of whether this particular signal should be timed for bicycles is answered. A mathematical expression is derived for computing the probability of a bicyclist's being caught in the intersection when the cross-street traffic receives a green. This probability allows one to compute the number of bicycles per hour that will be caught in the intersection. Since traffic engineers require information of this nature to provide safe intersection clearance for both automobiles and bicycles, it is hoped that this and subsequent work will provide methodologies necessary to incorporate into common design manuals, such as AASHTO's *Guide for the Development of Bicycle Facilities* and various state and city manuals.

There are many characteristic differences between the units of a bicycle and its rider and a car and its driver. These differences can have significant safety and operational implications when bicycles and automobiles operate on the same facilities. Bicycles are smaller, offer a rider less protection in the event of an accident, and have different operating characteristics (such as speeds and acceleration and deceleration rates). Because the bicycle offers little protection for the bicyclist, a car-bicycle accident can be very serious. This study investigates the computation of traffic signal clearance interval durations (defined in this paper to be the combination of the yellow vehicle change interval and the all-red clearance interval) required for the safe operation of bicycle-automobile mixed traffic. Inadequate clearance interval duration is considered by Forester to be the "largest identified facility-associated cause of car-bike collisions" (*1*). In addition, an Oregon study reports that "bicyclists disregarding signals" account for 8 percent of all urban bicycle–motor vehicle accidents in that state. The Oregon Department of Transportation's current policy to help alleviate this problem is to add loop detectors in bike lanes to extend the length of the green phase, if a bicyclist is in position to be caught by a clearance interval of inadequate length (*2*).

In order to study this situation, data on bicyclist speed, acceleration, and deceleration were collected. The data are analyzed herein and should prove useful for other analyses. Combining outputs from this data analysis with theory on computing safe clearance intervals yields one of the major outputs of this study: a methodology for computing safe clearance intervals for signals controlling bicycle-automobile mixed traffic.

Inevitably, it will be asked whether a particular traffic signal should be timed for bicycle-automobile mixed use or just for automobile use, since, as is shown herein, accommodation of bicycles will usually require a longer clearance interval, which may increase delay for automobiles. A mathematical expression is derived (computing the probability of bicyclists' being caught in an intersection through no fault of their own) to help traffic engineers answer this question. In addition, data are collected to verify this formula.

Because a bicycle/rider unit is small and normally travels on the far right side of the road, it is less likely to be seen by a motorist entering an intersection on the cross street than a car would be. Undoubtedly many accidents occur because the bicyclist could and should have stopped before the intersection; others occur simply because the clearance interval is too short for some bicycle/rider units to stop before the intersection, but not long enough for them to clear the intersection before the cross-street traffic receives a green. These bicycle/rider units are those caught in the dilemma zone. If caught in the dilemma zone, a bicyclist cannot physically make a correct decision and will therefore be in the intersection when the cross street receives a green. (It should be noted that there is actually no dilemma for the bicyclist. The bicyclist cannot make a correct decision. The term "impossibility zone" might be more appropriate, but dilemma zone is used for historical reasons.)

The dilemma zone is shown pictorially in Figure 1. If the clearance interval is too short, a dilemma zone exists such that no matter what a rider decides to do (stop or proceed), the rider will be caught in the intersection. If the clearance interval is the minimum allowed for safety purposes, then the bicyclist has the opportunity to make a correct decision and there is no dilemma zone. If the clearance interval is greater than this minimum, an optional zone is introduced, in which either decision is acceptable.

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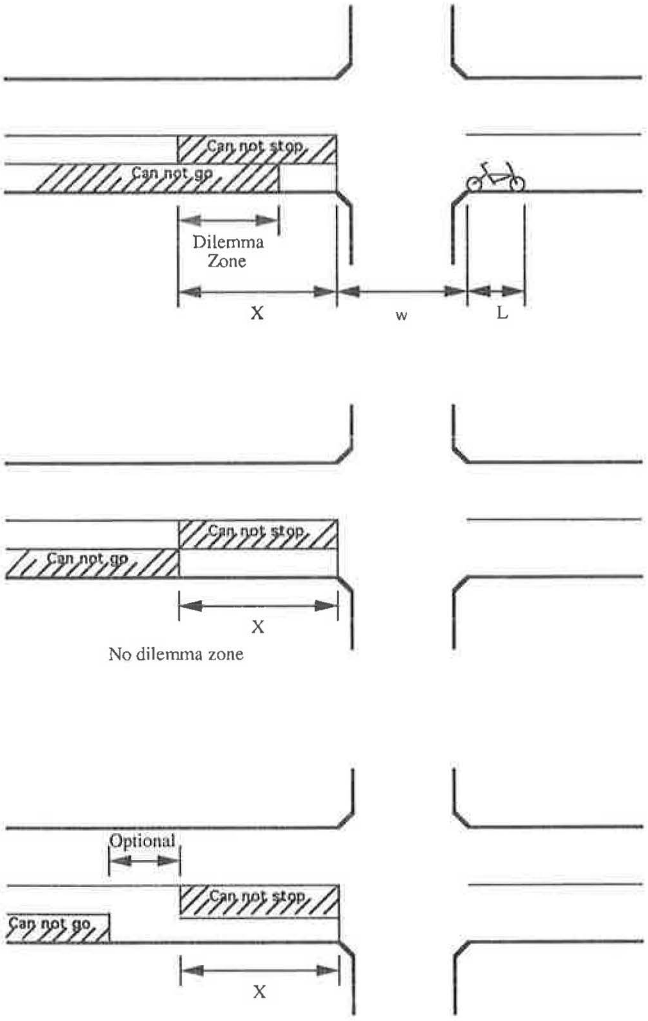


FIGURE 1 **Dilemma zone.**

Keeping a car from being caught in a dilemma zone has been the object of much study (*3–5*). Some information is also available on preventing bicycles from being caught, though, as will be shown later, this information is inadequate (*1,6*). This paper adds to that body of knowledge on preventing this situation for bicycles.

DATA

To analyze clearance intervals, the required data are the normal cruising speeds for bicycle/rider units in mixed traffic (not their fastest speeds), the rates of acceleration that bicyclists would like to use in order to proceed comfortably through yellow lights (not maximum accelerations in emergencies), and the comfortable rates of deceleration for bicycle/rider units while braking to complete stops (again, not emergency stops). Normal and comfortable rates are appropriate, since one does not wish to design for abnormal or uncomfortable situations.

Data were collected and analyzed to obtain these values. The data collection procedures and subsequent data analysis are discussed in the following two subsections. So that the reader may, if desired, skip these two subsections and return to them after finishing the rest of the paper, the results of the data analysis (for level, dry pavement) applicable to the rest of the paper are as follows, where 1 km/hr equals 0.6214 mph and 1 m/sec^2 equals 3.281 ft/sec^2:

	Normal Cruise Speed (km/hr)
7.5 percentile	16.1
Mean	22.5
92.5 percentile	29.0

	Acceleration (m/sec^2)	*Deceleration (m/sec^2)*
15th percentile	0.30	1.22
Mean		2.29

Data Collection Procedure

It is fairly easy to collect speed data without a bicyclist knowing it, but it is not so easy to do for the acceleration and deceleration rates. Since bicycle speed data collected in this manner were available elsewhere, it was deemed more important to collect the latter data, though speed data were also collected.

In the first data collection session, 13 subjects were tested (8 taken voluntarily from city streets, 4 who were friends of the author, and the author). Each subject was asked to make two rides on level pavement (see Figure 2). In Ride 1, subjects were asked to accelerate up to their normal cruise speed (for travel on city streets in Austin, Texas) for about 64 m (210 ft) and remain at that speed for about 46 m (150 ft). When they reached the end of this segment, they were told to accelerate—at a rate that they would use to make it through a yellow light comfortably and safely—for about 50 m (165 ft). Time to traverse the cruising speed segment and times at 18 and 46 m (60 and 150 ft) of acceleration were measured.

A cruising distance of about 46 m (150 ft) was deemed sufficient, because if the human error in timing is off by 2.3 m (7.5 ft), only a 5 percent error in speed is incurred. Acceleration of about 46 m (150 ft) was thought sufficient since it is close to the maximum distance that a bicyclist would have to accelerate to clear a wide intersection.

In Ride 2, the subjects were again asked to accelerate up to normal cruise speed and remain in that speed for 46 m (150 ft). At the end of the segment, they were asked to decelerate comfortably to a stop by braking (never coasting), as if they saw a yellow light and wanted to be sure they stopped before the intersection.

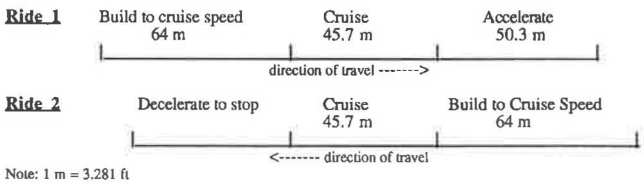


FIGURE 2 **Diagram of rides used to collect data on speed, acceleration, and deceleration.**

After these data were collected and analyzed, it was judged necessary to collect more deceleration data because of their importance in the minimum clearance interval computation methodology. In another data collection session, 15 more subjects were tested (taken voluntarily from city streets). They performed Ride 2 only.

All data were taken on pavement that was level to the human eye and when wind effects were judged to be negligible. Though 24 of the subjects were tested on a narrow, somewhat busy street with cars parked along each side, bicyclists were held until the coast was clear before proceeding. Some interference still may have occurred, but it is not considered significant. The other four subjects were tested in head and tail winds of 16 to 32 km/hr (10 to 20 mph) (estimated by the author); their speeds did show significant differences depending on direction of travel, but the average of the two speeds should adjust for this. The accelerations and decelerations of these four subjects were most likely affected, but they fell within the ranges of the other data and were not adjusted in any way to account for wind effects. It is also important to note that all data were taken on dry pavement.

Data Analysis

Of the 28 total subjects, 5 were female and 23 were male. Ages ranged from 19 to 55, with the average being 29. Statistics on normal cruise speed, deceleration, and acceleration are given in Table 1.

It is interesting to compare these data with previously collected data. Data collected in 1972 show speeds of bicycle/rider units to average about 17 km/hr (10 to 11 mph) and range from 11 to 24 km/hr (7 to 15 mph) (*7*). The data collected for this study show higher speeds, but comparisons are difficult since the conditions under which the 1972 data were collected were not reported. Speed data collected in Mountain View, California, are slightly higher than the data collected in Austin; both Austin and Mountain View can be described as areas where bicycling for both transportation and recreation is popular. The Mountain View data were collected on a level street bike lane in the absence of wind during the entire morning commuting period (conditions that are comparable to those in this study's data collection process, except that the riders in this study knew that they were being timed). For Mountain View, the slowest speed was 19.3 km/hr (12 mph), the median speed was 25.7 km/hr (16 mph), and the 85th-percentile speed was 29.8 km/hr (18.5 mph) (*1*).

No previously collected bicycle acceleration data could be found, so direct comparisons cannot be made. However, comparisons to automobiles provide some insight. Acceleration available to cars can be estimated through Gazis' equation (*3*):

$$a = 4.88 - 0.04034 \cdot v \qquad (1)$$

where a equals acceleration in meters per second squared and v equals speed in kilometers per hour.

TABLE 1 Statistics from Data Collection

Statistic	Speed	Deceleration	Acceleration Over 45.7 m	Acceleration Over 18.3 m
Low	13.2 km/hr	1.15 m/s^2	0.03 m/s^2	0.55 m/s^2
15th percentile	16.9 km/hr	1.28 m/s^2	0.21 m/s^2	--
Mean	22.7 km/hr	2.29 m/s^2	0.43 m/s^2	1.15 m/s^2
Median	23.0 km/hr	2.35 m/s^2	0.40 m/s^2	1.10 m/s^2
85th percentile	26.7 km/hr	2.96 m/s^2	0.58 m/s^2	--
High	33.6 km/hr	3.75 m/s^2	0.91 m/s^2	1.95 m/s^2
# of data points	28	27	12	6

Note: Some statistics are missing (--) due to insufficient number of data points for their computation. 1 km/hr = 0.6214 mph and 1 m/s^2 = 3.281 ft/s^2.

At 22.5 km/hr (14 mph) (the speed of an average bicyclist) a car would be able to accelerate at about 4 m/sec^2 (13 ft/sec^2). As expected, this is greater than a bicycle/rider unit can comfortably achieve at this speed. Even at 64.4 km/hr (40 mph), the car has the ability to accelerate at about 2 m/sec^2 (7.5 ft/sec^2), which is still much greater than the bicycle/rider unit, at 22.5 km/hr (14 mph).

No previously collected data on bicycle deceleration rates were found, but some theoretical information proves interesting for comparative purposes. With tire braking, the maximum deceleration possible is 9.8 m/sec^2 (32.2 ft/sec^2), the acceleration due to gravity, g. This is achievable only if the coefficient of friction between tires and road is 1.0. Actually, the coefficient of friction for vehicles with pneumatic tires varies from about 0.8 (dry concrete) to 0.1 (wet ice), with a value of 0.4 to 0.7 for wet concrete or wet asphalt (*8*). Therefore, the maximum bicycle braking deceleration (under ideal conditions) is about 8 m/sec^2 (26 ft/sec^2).

The center of gravity (in relation to the wheelbase) and weight of a car is such that there is no possibility of flipping over the front wheels while decelerating. This is not the case with a bicycle/rider unit, which is lighter and has a high center of gravity in relation to its wheelbase. This center of gravity moves forward as the rider crouches over the handlebars, which a rider usually does to some extent during braking, since the brakes are usually on the handlebars. The higher and more forward the bicycle/rider unit's center of gravity, the greater its chance of being thrown over the handlebars during braking. Whitt and Wilson computed the maximum deceleration rate achievable by a crouched rider (using dropped handlebars) to be about 0.56 g (*8*). With this as a constraint, the maximum attainable deceleration is about 5.5 m/sec^2 (18 ft/sec^2). In actuality, one would expect riders to decelerate at a rate quite a bit less than this to ensure that they are not thrown.

If one considers braking in wet weather, where the coefficient of friction between tire and road falls to about 0.4, the maximum attainable deceleration is about 4 m/sec^2 (13 ft/sec^2). Again, to be on the safe side, riders would probably brake at rates less than this.

These values hold only if an appropriate force is applied to the rim brake. Therefore, on bicycles on which brakes are not adjusted properly, it is possible that the constraint on maximum deceleration is the amount of force with which the brake block can be pressed against the rim. More research into the actual conditions of bicycle braking mechanisms is required to determine if this actually is the defining constraint.

There is also a coefficient of friction between the brake block and the rim. Under dry conditions this value is near 0.95 and as such should not be a deceleration constraint. Under wet conditions it is possible that this could be a constraint. Using typical bicycle brake block material from 1971, this coefficient of friction was found to drop to about 0.05 when wet (*8*).

Research and development efforts since 1971 have probably improved wet brake coefficients into the range of 0.3 to 0.5, though more research is needed to verify this (*8*).

The deceleration rates obtained in this experiment conform to what is suggested by theory. The maximum rate sampled (3.75 m/sec^2) is less than the "over the handlebar" threshold of 5.5 m/sec^2. Also, the mean and 15th-percentile rates (2.29 and 1.28 m/sec^2, respectively) are significantly less, reflecting either that bicyclists prefer a margin of safety and comfort in their stops or that many bicycle brakes are out of adjustment and riders cannot brake to the "over the handlebar" threshold.

Because of human measurement errors and errors associated with the manner in which bicyclist subjects followed directions, the statistics reported in Table 1 are only approximations. Therefore, for simplicity, those given in the earlier tables are used throughout this study.

SAFE CLEARANCE INTERVAL COMPUTATION

An accepted method for ensuring safe clearance is to allow a minimum clearance interval (which may include an all-red indication after the yellow) such that vehicles that cannot comfortably stop before the intersection have enough time to proceed either into or through the intersection. Only the case of proceeding through the intersection is considered here, because of the safety implications of a bicyclist's being caught in the intersection.

This situation was analyzed by Gazis et al. and presented in the *Transportation and Traffic Engineering Handbook* as follows (*3,9*). To come to a safe stop before the intersection,

$$x = v \cdot t_{p-r} + v^2/(2 \cdot d) \tag{2}$$

where

x = distance required for stopping,
t_{p-r} = perception-reaction time,
v = approach speed, and
d = deceleration.

If a vehicle at distance x from the intersection (when the clearance interval begins) can proceed through the intersection before the clearance interval expires, then there is no dilemma zone (Figure 1). A vehicle can do this without accelerating if the clearance interval (ci) is at least

$$ci_{\min} = (x + w + L)/v = t_{p-r} + v/(2 \cdot d) + (w + L)/v \tag{3}$$

where

$ci_{\min}$ = minimum clearance interval without acceleration,
w = intersection width, and
L = vehicle length.

Since cars are likely to be driving at about the speed limit, they would exceed the speed limit by accelerating through the intersection. For bicycles this is not a problem. Therefore, the minimum clearance interval required for a vehicle to pass through the intersection while accelerating may be applicable to bicycles. This is given by solving the following for $ci_{\min-a}$ using the quadratic equation

$$v \cdot ci_{\min-a} + a \cdot (ci_{\min-a} - t_{p-r})^2/2 = x + w + L$$

or

$$v \cdot ci_{\min-a} + a \cdot (ci_{\min-a} - t_{p-r})^2/2 = v \cdot t_{p-r} + v^2/(2 \cdot d) + w + L \tag{4}$$

yielding

$$ci_{\min-a} = (a \cdot t_{p-r} - v + \{v^2 + 2 \cdot a \cdot [v^2/(2 \cdot d) + w + L]\}^{1/2})/a \tag{5}$$

where $ci_{\min-a}$ is the minimum clearance interval with acceleration, and a equals acceleration.

ANALYSIS OF SAFE CLEARANCE INTERVALS FOR BICYCLE-AUTOMOBILE MIXED TRAFFIC

In cases of mixed bicycle-automobile traffic, a conservative design suggests that minimum clearance intervals be computed for both vehicle types and the largest used. The parameters in the minimum clearance interval equations (Equations 3 and 5) have accepted automobile design values (*9*). For bicycles this is not the case, so it is necessary to analyze what values are appropriate.

The AASHTO *Guide for the Development of Bicycle Facilities* recommends using a bicycle speed of 16.1 km/hr (10 mph) and a perception-reaction time of 2.5 sec, but it says nothing of deceleration or acceleration rates (*6*). Forester recommends bicycle speeds of 24.1 to 32.2 km/hr (15 to 20 mph) for adult transportation routes and 16.1 km/hr (10 mph) for recreation and child routes, a perception-reaction time of 1 sec, and deceleration rates of 4.6 m/sec^2 (15 ft/sec^2) for adult transportation routes and 2.4 m/sec^2 (8 ft/sec^2) for recreation and child routes (*1*).

The noncontroversial values are those for bicycle length (L), 1.8 m (6 ft), and intersection width (w), which changes for each intersection analyzed. Herein, three values are used for sensitivity over narrow, medium, and wide intersections. The values chosen are 9.1, 19.8, and 30.5 m (30, 65, and 100 ft). Perception-reaction times for automobile drivers to perceive a yellow light and react to it by pressing on the brake have been measured, and a design value of 1 sec is normally used (*3–5,9*). However, these times range between about 0.5 and 4.0 sec (*10*). In light of the safety implications for bicyclists, the fact that a bicyclist's perception-reaction time could be different from a car driver's, and the absence of any actual bicyclist perception-reaction data, the author believes that a value greater than 1 sec is called for and recommends that AASHTO's value of 2.5 sec be used.

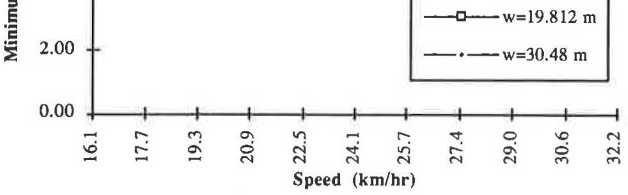
Speeds in the range of 16.1 to 32.2 km/hr (10 to 20 mph) are suggested by the data collected for this study, previously collected data, AASHTO, and Forester.

The higher the design deceleration rate is over the actual requirement for the bicycle/rider population, the smaller the computed minimum clearance interval and the greater a bicyclist's chance of being caught in a dilemma zone. A design value should be chosen to accommodate some percentage of the population of bicycle/rider units on the particular road in question. The author suggests using a value that accommodates about 85 percent of this population. The previous data analysis suggests a value of 1.22 m/sec^2 (4 ft/sec^2). This value is quite a bit less than either of those recommended by Forester (*1*).

Ideally, what is required is the percentage of bicyclists who accelerate through yellow lights. Since it is not known if the percentage of bicyclists who accelerate through intersections is high enough to warrant computing minimum clearance intervals assuming acceleration, the author suggests assuming constant speed. Thus, if one errs it will be on the safe side for bicyclists. Cases with and without acceleration are analyzed herein for comparison. For the former, the previous data analysis concludes that an acceleration of 0.30 m/sec^2 (1.0 ft/sec^2) accommodates 85 percent of the population. Actually, accelerations will probably vary according to intersection width.

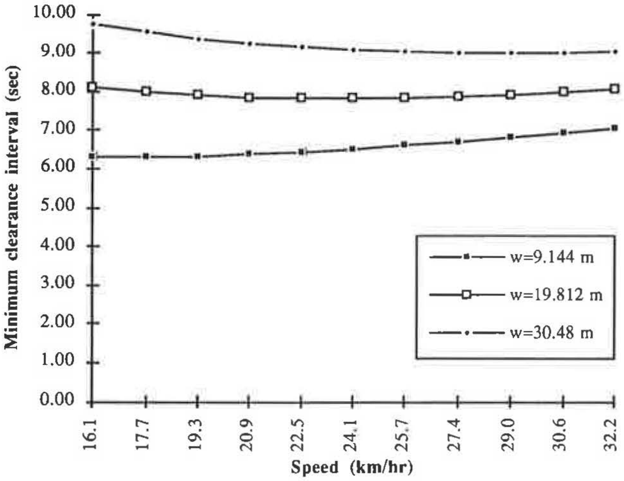
The results of the analysis are shown in Figures 3 and 4. Each figure shows minimum clearance intervals for each of the three intersection widths (w) over the speed (v) range of 16.1 to 32.2 km/hr (10 to 20 mph). Figure 3 is for the case of no acceleration, and Figure 4 assumes acceleration. From these figures one can easily see the magnitudes of the increases in minimum clearance interval required for larger intersection widths and no acceleration versus acceleration. For comparison, the clearance intervals required for automobiles traveling at 56.3 km/hr (35 mph) are 4.5, 5.2, and 5.9 sec for the narrow, medium, and wide intersections, respectively. [These were computed using Equation 3 with the following common automobile design values: d = 3.0 m/sec^2 (10 ft/sec^2), L = 5.8 m (19 ft), t_{p-r} = 1 sec).] These intervals are about 2 to 6 sec less than those required for bicycles, depending on the acceleration assumption and intersection width.

The perception-reaction time used for bicyclists is 2.5 sec. Changes in perception-reaction time result in equal changes to the minimum clearance interval required. For example, assuming a 1-sec perception-reaction time would result in minimum clearance intervals 1.5 sec less than those in Figures 3 and 4. Thus, even for a 1-sec bicyclist perception-reaction time, the minimum clearance intervals required are greater than those for automobiles.



Note: 1 km/hr = 0.6214 mph; 1 m = 3.281 ft.

FIGURE 3 Minimum clearance intervals assuming no acceleration, for three intersection widths (w) and perception-reaction time of 2.5 sec.



Note: 1 km/hr = 0.6214 mph; 1 m = 3.281 ft.

FIGURE 4 Minimum clearance intervals assuming bicycle acceleration of 0.3048 m/sec^2, for three intersection widths (w) and perception-reaction time of 2.5 sec.

The assumptions recommended previously always erred on the conservative side and are reflected in the case of no acceleration and a 2.5-sec perception-reaction time (Figure 3), which leads to the longest minimum clearance intervals. It is interesting to note that with these recommended assumptions, the clearance intervals for wider intersections would need to be more than 7 sec. Clearance intervals of this magnitude are often thought to encourage driver disrespect and possibly increase rear-end collisions (*7*). This problem probably would not occur if the yellow were kept below 5 sec and an all-red used for the rest of the clearance interval, but delay would be added to automobile travel (*9*).

Because the clearance intervals required for bicycle/rider units at the wider intersections (8 to 12 sec) are much larger than those required for automobiles (5 to 6 sec), it may make sense to provide separate warning signals for both users. Pedestrian signals have set a precedent for this. Considering the possible delay costs (if drivers obey a single longer clearance interval) or safety costs (if some do not obey) associated with a single clearance interval warning signal timed for both bicycles and automobiles, the most cost-effective solution may be to provide a separate warning signal for bicyclists. This warning signal could be timed according to the procedures outlined in this paper, while the automobile warning signal would remain timed as before. This separate signal could be an additional light near the current traffic signal (possibly illuminating a yellow bicycle) or a sign upstream from the intersection that lights up a message such as Bicycles Prepare To Stop so that any bicyclist able to view this message should stop before the intersection or risk being caught in the intersection under the red. The principle of the latter signal is the same as that for the Prepare To Stop signs currently used when stopping sight distance is insufficient for a signalized intersection.

It is interesting to note that at different widths, different values of speed yield the highest minimum clearance interval. For example, in the no-acceleration case, a speed of 32.2 km/hr (20 mph) yields the highest minimum clearance interval at the narrow intersection width, while at the two larger intersections, a speed of 16.1 km/hr (10 mph) yields the highest. Since the shapes of these minimum clearance interval-versus-speed curves are convex downward (meaning they have only one minimum), the largest minimum clearance interval is found at either end point of the speed range (16.1 or 32.2 km/hr). By differentiating Equation 3 with respect to v, one obtains the slope of these curves, $1/(2 \cdot d) - (w + L)/v^2$. This slope is negative when v is small and becomes less negative as v increases. The minimum value of $ci_{\min}$ occurs when the slope is 0 or $v = [2 \cdot d \cdot (w + L)]^{0.5}$. For the intersection widths analyzed in Figure 3, these minimums occur at speeds of

- 18.7 km/hr (11.6 mph), narrow;
- 26.1 km/hr (16.2 mph), medium; and
- 32.0 km/hr (19.9 mph), wide.

In this example, computing the minimum clearance intervals for both 16.1 and 32.2 km/hr (10 and 20 mph) and using the highest value would accommodate the bicycle/rider units that would have the most trouble with the intersection width being analyzed. A speed range bounded by the population's lower 7.5 percentile speed and its upper 7.5 percentile speed would accommodate at least the central 85 percent of the population. Obviously, these speed ranges will vary according to intersection location, topography, and the like, but the previous data analysis indicated that this range is about 16.1 to 29.0 km/hr (10 to 18 mph) for relatively flat topography.

METHODOLOGY FOR CLEARANCE INTERVAL COMPUTATION

The following summarizes the previously developed methodology for computing minimum clearance intervals for mixed-use facilities. Compute the automobile minimum clearance interval by an accepted method, such as the one in the *Transportation and Traffic Engineering Handbook*. Compute the bicycle minimum clearance interval as follows, and choose whichever interval is the largest (it or the one computed for automobiles), or use them both and provide separate warning signals for each user. To compute the bicycle minimum clearance interval, the following design values are used in Equation 3: $L = 1.83$ m (6 ft), $t_{p-r} = 2.5$ sec, and $d = 1.22$ m/sec^2 (4 ft/sec^2). Speeds of both 16.1 and 29.0 km/hr (10 and 18 mph) are used, and the largest of the two resulting clearance intervals is chosen. These speeds are valid only for intersections with approximately level grade approaches. If approach grades are significant or any other intersection characteristic affects bicyclists' speeds, different speeds are required.

TIMING SIGNALS FOR BICYCLES

Since bicyclists have the legal right to use almost every roadway, traffic engineers need to time signals for bicyclist safety wherever bicycle volume warrants it. This section deals with how to determine whether bicycle volumes warrant special timing of clearance intervals.

Difficult decisions must be made when considering the trade-offs between possibly increasing delay to motor vehicle traffic and placing bicyclists in danger by creating dilemma zones for them. Should a signal be timed for mixed traffic if only one bicycle a year crosses the intersection? Probably not. What about one bicycle per day, per hour, per minute, or even more frequently? The problem facing the traffic engineer is easy to identify with. The following relationships are intended to help the with this decision.

$$P = D/(v \cdot C) \tag{6}$$

where

P = probability of a cyclist's being caught in dilemma zone,
D = length of dilemma zone,
v = approach speed, and
C = cycle length.

These values assume random bicycle arrivals.

$$D = v \cdot t_{p-r} + v^2/(2 \cdot d) - v \cdot ci + w + L \tag{7}$$

This formulation assumes no acceleration by the bicyclist. The formulation assuming acceleration would include an additional term, $-a \cdot (ci - t_{p-r})^2/2$.

The length of the dilemma zone is the difference between the distance from the intersection where a bicyclist cannot stop and the distance from the intersection where a bicyclist cannot clear the intersection (Figure 1). The distance from the intersection where a bicyclist cannot stop is given by Equation 2. The distance from the intersection where a bicyclist cannot clear is simply the distance that a bicyclist can travel during the clearance interval ($v \cdot ci$) minus the distance required to clear the intersection ($w + L$), yielding $v \cdot ci - w - L$.

The probability (P) is derived assuming the bicycle/rider unit is equally likely to arrive at the intersection at any point in the traffic signal cycle. In other words, the bicyclist's arrival at the intersection is random with respect to the yellow signal. Since the light turns yellow once in every cycle, and the bicyclist can travel the distance ($v \cdot C$) during the cycle, the bicyclist is equally likely to be at any point on the roadway in the distance ($v \cdot C$) before the intersection when the clearance interval begins. This distance ($v \cdot C$) includes the dilemma zone of length D, so the probability of a bicyclist's being caught in the dilemma zone is simply the ratio of D to the distance that the bicyclist can travel during the signal cycle ($v \cdot C$).

P can be computed for any individual bicyclist or, perhaps more important, for the average bicyclist using any intersection. This probability gives one a feeling for how dangerous the clearance interval of the intersection is for bicyclists. A better measure is obtained by multiplying this probability by hourly bicycle traffic volumes to compute the average number of cyclists caught in the dilemma zone (and presumably in the intersection) per hour. Critical values for this average should be determined through future research.

The probability was derived assuming that bicyclists are equally likely to arrive at the intersection at any point in the signal cycle. This is not a good assumption if something upstream of that intersection systematically influences the timing of bicycle arrivals. An example of this would be a series of traffic signals timed for progression. It is also possible that bicyclists might anticipate the yellow by paying attention to how long the light has been green.

To verify Equations 6 and 7, data were collected at an intersection that has considerable bicycle traffic and no upstream impacts that would systematically affect bicycle arrivals. In computing P, average bicyclist characteristics at this intersection are used instead of the design values. The values assumed are t_{p-r} = 1.5 sec, d = 2.3 m/sec^2 (7.5 ft/sec^2), and v = 19.3 km/hr (12 mph). Though 19.3 km/hr (12 mph) is slower than the 22.5 km/hr (14 mph) average speed suggested by the data analysis, it was chosen because the intersection is fairly congested and has on-street parking. Measured parameters for this intersection are C = 75 sec, w = 20.1 m (66 ft), and ci = 4 sec. This measurement of intersection width is as small as possible. It is measured from curbface to curbface, not stopline to curbface or stopline to stopline. With L = 1.83 m (6 ft), the theoretical dilemma zone size is 14.8 m (48.7 ft) for the average cyclist approaching this intersection, and the theoretical probability that the average cyclist is caught in the dilemma zone is 0.0368 (or 3.68 percent of all cyclists will be caught).

A total of 153 cyclists were observed traveling straight through this intersection. Of these, six (or 3.92 percent) were observed to be in the dilemma zone defined by the average cyclist when the light turned yellow, and four of these six were caught in the intersection when the light turned red (and the cross-street light turned green). One bicyclist, who was traveling very slowly, stopped before the intersection. It is very possible that since his speed was much less than 19.3 km/hr (12 mph), he was not caught in his dilemma zone and could therefore stop. Another cleared the intersection. None of the six cyclists appeared to accelerate in an attempt to clear the intersection. Seven cyclists (including the four already mentioned), or 4.58 percent, were actually caught in the intersection when the light turned red. This indicates that three other cyclists were either caught in their individual dilemma zones, or they made incorrect decisions upon viewing the yellow.

These data appear to agree with the theory (Equations 6 and 7). Both the observed percentage of bicyclists caught in the dilemma zone (3.92) and the observed percentage of bicyclists caught in the intersection (4.58) appear to be very close to the predicted percentage (3.68), but are the differences statistically significant or just the result of chance? The sample is large enough to use the normal approximation to the binomial distribution to test the hypothesis that the true percentage of bicyclists being caught in this intersection (or in this dilemma zone) is 3.68, as predicted by the theory. The two-tailed test of this hypothesis is not even close to being significant for either sample percentage (3.92 or 4.58), so one cannot reject the hypothesis or the theory. It is probable that the small differences between the observed and predicted percentages are due only to chance, so the data do tend to verify the theory.

CONCLUDING COMMENTS

This paper presents (a) a methodology for timing traffic signals for bicycle-automobile mixed traffic, including recommendations on design values for speeds, deceleration and acceleration rates, and perception-reaction times, and (b) a mathematical expression for computing the probability of bicyclists' (through no fault of their own) being caught in the intersection when the cross-street traffic receives a green.

It is recommended that further research be performed to

- More accurately quantify bicyclist perception-reaction times and deceleration and acceleration rates,
- Determine how likely it is that bicyclists will accelerate through yellow signals,
- Better relate bicycle speeds at intersections to various attributes of the intersection environment, and
- Set a standard (in number of bicyclists caught in the dilemma zone per hour) for timing signals for bicycle-automobile mixed use.

In addition, recent accident study results should be examined to determine if conclusions such as Forester's (that inadequate clearance interval duration is the "largest identified facility-associated cause of car-bike collisions") are still valid.

Because of the longer (relative to automobiles) clearance intervals required by bicycles at wide intersections, the most cost-effective solution (considering possible delay and safety costs of longer single clearance intervals to automobile drivers) may be to provide a separate warning signal for bicyclists. This warning signal could be timed according to the procedures outlined in this paper, leaving the automobile warning signal timed as before. This separate signal could be an additional light near the current traffic signal (possibly illuminating a yellow bicycle) or a sign upstream from the intersection that lights up a message such as Bicycles Prepare To Stop so that any bicyclist able to view the message should stop or risk being caught in the dilemma zone. It would be interesting to compare these two options (on a cost/benefit basis) with detector schemes, such as those recommended by the Oregon Department of Transportation, that reduce the probability that bicyclists will be caught in the dilemma zone. The study of these and any other options that enable bicyclists to make correct decisions about their safe clearance of signalized intersections is recommended.

It is further recommended that the results of subsequent studies and the results presented herein be used to form accepted procedures and methods for inclusion in common design manuals, such as the *Transportation and Traffic Engineering Handbook*, AASHTO's *Guide for the Development of Bicycle Facilities*, and city and state design manuals. This will offer the guidance that traffic engineers require to design safe facilities for both automobiles and bicycles.

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Intelligent Bicycle Routing in the United States

JOE BETZ, JIM DUSTRUDE, AND JILL WALKER

As bicycling continues to gain popularity as an alternative transportation mode, questions arise as to how transportation departments are going to promote and support bicycle use effectively within the existing infrastructure. Maps are limited; the print medium precludes them from conveying up-to-date information. What is needed is a sophisticated information system that serves a number of main functions: (a) giving bicyclists accurate information on available routes, facilities, bicycling opportunities, safety issues, and registration; (b) providing commuters with more bicycling options, such as linking bicycle use with public transit or carpools; (c) furnishing cyclists with easy-to-use information that is widely accessible and meets cyclists' unique and specific needs; (d) serving as an efficient administrative tool for inventory tracking and demand measurement to help make cost-effective bikeway improvements; (e) promoting efficient and effective bicycle transportation practices and maximizing use of the existing public transportation infrastructure; and (f) becoming an overall support tool for enhancing the quality and quantity of bicycling in the United States. Ways in which an intelligent bicycle routing expert system can play an integral support role in all of these areas are examined.

As environmental concerns and energy conservation take a front seat on many agendas across the United States, bicycling is increasingly viewed as the efficient, practical transportation alternative. Ever-expanding bikeways projects reveal a shift in attention toward the cyclist, and in some U.S. cities, bicycle mode share has reached 23 percent (*1*). In fact, bicycle use is growing at an estimated 4 percent per year. The bicycle causes no pollution, is good exercise, is inexpensive, allows riders to avoid traffic congestion, and requires little parking space—just a few reasons that the bicycle is an attractive alternative to the automobile.

Yet significant factors impede bicycle use from reaching its full potential. The lack of a legible and effective bike route system forces most bike transportation trips, nearly half of all bicycle miles traveled, to take place only on the street system that is legible: urban arterials and collectors, many of which are rated unacceptable for bicycling. Shifting these bike trips to other routes, of which the vast system of residential side streets is a primary component, is mainly a problem of increasing their legibility through effective information systems. Departments of transportation may address this problem with maps, both as a means of conveying bikeway information to consumers and as an administrative tool to priority rank roadway improvements for bicycling. But three fundamental limitations inherent in print communication seriously limit its effectiveness for bicycle transportation purposes:

1. The limitations of paper size and print size preclude maps from conveying the detailed information bicyclists need to make adequate, even safe, route decisions;
2. Roadway characteristics and motor traffic volumes change at a pace that cannot be matched by the medium; and
3. Only one set of assumptions can be reflected on a map, thus limiting its utility to one class in the broad spectrum of bicyclists.

Moreover, the high level of demand for more user-specific route information cannot be accommodated because of the intensive amount of staff time required to convey this "expert knowledge." Referring cyclists to multiple surrogate sources of this information, such as bike clubs, stores, associations, and other cyclists, is not efficient and may not provide an appropriate focus specific to that individual.

What is needed is an information system that can quickly and effectively convey route information while working as an overall support mechanism for the bike community within the existing infrastructure. It is often much easier for people to jump in their cars and drive, even short distances, rather than ride, simply because current road and highway systems are designed specifically to accommodate the automobile. Until effective support mechanisms for the bicycle are in place, bicycle use will not be able to reach its full potential.

A proposed solution is to develop an intelligent bike routing expert system. Such a system would compare specific and accurate information about available road- and bikeways and traffic volumes with the individual bicyclists' travel needs, skill levels, and preferences in order to generate and communicate on demand the most suitable route for each individual's specific needs. Because of the unique ability of this advanced technology system to reflect the intricacies of dual realities, the route generated will have high attractive power and therefore a high probability of being used.

This paper explores the potential of an intelligent bicycle routing expert system, a sophisticated information system that can serve many functions:

- Provide bicyclists accurate, up-to-date information on available routes, facilities, bicycling opportunities, safety issues, and registration;
- Offer commuters more bicycling options, such as linking bicycle use with that of public transport or carpools;

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- Give cyclists easy-to-use information that is widely accessible and meets their unique and specific needs;
- Serve as an efficient administrative tool for inventory tracking and demand measurement to help make cost-effective bikeway improvements;
- Promote efficient and effective bicycle transportation practices and maximize use of the existing public transportation infrastructure; and
- Become an overall support tool for the enhancement of the quality and quantity of bicycling in the United States.

MINNESOTA EXAMPLE

It is hard to overlook the eagerness to ride of residents of Minneapolis/St. Paul, Minnesota. An informal study revealed that on a weekday summer evening at Lake Calhoun in Minneapolis, 360 cyclists pass through a 1-mi stretch of trail per hour. During the day, 2,000 people may bike into downtown Minneapolis, and at least 10 percent of all adults bike to work at least once during the year. Aside from walking, cycling is the most popular form of outdoor recreation in the state. In fact, Minnesota adults are cyclists at nearly twice the national average; there are more people cycling the streets of Minneapolis/St. Paul in winter than in Los Angeles at any time of the year (*1*).

Significant barriers, however, limit the use of bicycles for recreational and transportation purposes throughout Minnesota. An overall lack of awareness of bicycling possibilities and support for cyclists from several fronts impedes maximum usage. For example, Minnesota has approximately 750 mi of trails and 4,600 mi of paved shoulders (*1*), yet many cyclists are unaware of the existing trails and routes available to them. Though many recreational trails are represented in maps, very little information is given to the user, other than the length of the route in miles, the surface of the route, and, in some cases, a vague degree of difficulty. This information is seldom geared to the individual cyclist, which may make him or her somewhat apprehensive about traveling out of the way to use new trails.

For example, one cyclist chooses a 31-mi ride from a 1989 Minnesota trail guide (the last issue of the publication), only to discover while cycling that more than half of the route is on a two-lane highway where 55-mph traffic is at a steady flow. This is not a pleasurable experience for the cyclist; though he is experienced and can ride comfortably with traffic, riding along with constant traffic for a considerable length of time is not what he had in mind. And for a beginner, this route could pose significant hazards.

Bicycle use for commuting is also limited. Those who wish to ride to work face a number of challenges. Everyday city routes—those that get a cyclist from home to work—are seldom represented in current maps. What is reasonably usable [76 percent of urban arterials and corridors have been rated substandard for bicycling in the Twin Cities (*1*)] is not legible, and the cyclist is forced to undergo a trial-and-error method of finding the best path to take. In addition, there is little guarantee that once the cyclist arrives at work, appropriate facilities, such as showers, lockers, even secure bicycle parking, are available. There is simply a lack of corporate awareness as to the priority required for needed improvements. For those who live too far away, bicycling to work, or even part way to work (Bike and Ride), is virtually a nonoption. The result is that even though rush-hour traffic continues to increase, a less-than-desired number of commuters turn to bicycles as the preferred transportation mode.

The bicycle also remains in direct competition with the car. The Twin Cities metro area is neatly designed for the automobile, its elaborate highway system allowing commuters "back door" travel to and from the suburbs, while at the same time creating more far-flung, car-dependent suburban land developers. With few transportation alternatives, people rely on what they know—their cars. This trickles down to other levels as well. Very few cyclists are ever ticketed for breaking bicycle laws; such laws are seldom enforced in the Twin Cities (*1*). And drivers education is just that, *drivers* education; rarely is the bicycle even mentioned in class. The result is that fewer people, motorists and cyclists alike, are aware of the laws and safety issues that directly affect cyclists.

The overall lack of support for and awareness of the widespread bicycling possibilities in Minnesota has made it a less-than-adequate environment for cyclists. In *Plan B, The Comprehensive State Bicycle Plan,* the Minnesota Department of Transportation (Mn/DOT) cites the results of an international study comparing cycling and noncycling cities worldwide. The study found that cities with higher ratios of bicycle mode share are "not notably different, in terms of weather, geography, or standards of living, from their neighboring cities in which bicycles are used much less frequently. . . . The primary factor differentiating the two sets of cities: differences in public policy and levels of government support." In its commitment to maximize the growth potential of bicycle use in the state of Minnesota, Mn/DOT has adopted this perspective: "If you build it, they will come" (*1*).

SUMMARY OF SUPPORT NEEDS

Providing more accurate and up-to-date maps for cyclists and adding facilities to the workplace is only a small portion of what is needed to solve the problems of cyclists in today's urban and rural environments. A number of factors that directly affect cyclists are unique to cyclists and demand the development of full support systems.

First, the bicycle as a vehicle mode is extremely sensitive to the most minute details, details that do not have the same impact on automobiles or pedestrians. For example, a cyclist is intuitively aware of such things as the horizontal distance in fractions of inches between the sections of a bridge deck, the "bump" created where a curb ramp meets the road (sometimes 2 in. high), drain gates, manhole covers, railroad tracks, and expansion and contracting joints. Such small details may go unnoticed by a motorist or pedestrian, but they affect a cyclist's safety and riding experience as well as the condition of the bicycle itself.

Details affecting cyclists also occur over an extremely broad spectrum of parameters, from the smoothness of the road or trail surface to factors that define the attractiveness of a route such as sun, shade, noise, visual scenery, traffic, maintenance, and personal security. Again, the details are tiny. For example, potholes, broken glass and other debris in the street, snow and ice cover in winter, and the safety of the neighborhood itself can influence maintenance and personal security. Although many of these factors are of concern to motorists and pedestrians, they determine whether or not a cyclist can even use a route.

Finally, it is essential for the success of any support system designed for cyclists that it be able to acknowledge the unique needs, capabilities, and desires of each cyclist. This means addressing different levels of skill, strength, assertiveness, and comfort—all of which make the suitability of routes highly variable. In balancing the inextricably tied factors of safety and convenience, a route that will work for one class of cyclists will not work for all cyclists. In effect, the routes must be as unique as the individuals themselves.

Effectively and efficiently serving this set of customers demands sophisticated but easy-to-use communications systems that meet the individual needs of each cyclist as well as administrative tools to inventory, manage, improve, and maintain the bikeway infrastructure. Implementing these information tools means providing cyclists with useful, highly accessible, up-to-date bicycling information on recreational trails and city routes while providing a support mechanism for adequate trail maintenance. By aggressively mining the potential of the infrastructure, creating this support for cyclists can be accomplished with existing information before major investments are required. An intelligent bicycle routing expert system can play an integral role in that "mining" process.

INTELLIGENT BICYCLE ROUTING

Many of the support functions needed to increase bicycle use can be incorporated into an intelligent bicycle routing expert system that helps cyclists find the best route to a given destination on the basis of rider profiles, road conditions, and route availability. The following sections examine the origination of the system concept, the workings of the system, the system capabilities, the ways in which these capabilities address the related factors affecting cyclists and the cycling environment, and the manner in which such a system would integrate bicycling into the rest of the transportation community.

Background

In 1990 PEAKSolutions installed an expert system for Mn/DOT called RouteBuilder. The system supports the entire process of permitting oversize and overweight vehicles, including permit and route generation, the purpose of which is to alleviate the otherwise heavy workload of permitting officials while providing an efficient, consistent approach to the permitting process. The system accounts for all varying vehicle specifications and at the same time strictly complies with state laws and regulations. It has reduced the time that it takes to issue permits from hours to minutes, and it now generates complex routes in less than 45 sec. A significant feature of the system is its built-in "maintenance tools," which provide the ability to update and change data regularly as road conditions are altered by weather, construction, and the like. The use of such tools ensures that only correct, up-to-date information is provided to the system user, thus guaranteeing accuracy in the overall permitting process.

RouteBuilder gave people at Mn/DOT and PEAKSolutions the insight to build a similar expert system geared to cyclists. The system would generate the best route for each individual cyclist on the basis of his or her capabilities, needs, and desires as well as route conditions and availability. Safety issues would be highlighted. Maintenance capabilities would be incorporated into the system to ensure that all information about bicycle routes was accurate and up to date, while providing a forum through which maintenance crews could priority rank those bicycle trails most in need of improvements. This multipurpose tool would serve cyclists and Mn/DOT officials alike. In 1991 PEAKSolutions and Mn/DOT created a "mirage," or design-level prototype, for such a system, which has become the Bike RouteBuilder System Mirage. In the form of a computer program, the mirage demonstrates proposed functionality of an intelligent bicycle routing expert system.

Structure of Program

As a personal computer-based expert system, the intelligent bicycle routing system would proactively lead the user through the program, requiring zero to little training time for the system's operation. The program would work by first helping the user define the rider's profile and preferences and then asking the user to identify the rider's planned destinations and type of route he or she is seeking. For example, the rider may be looking for a specific point-to-point route or for a recreational route within an area. Further still, the rider may prefer the fastest over the most scenic point-to-point route, as is likely the case in a commuter trip. The route would be generated on the basis of information provided by the user and available route information.

To be able to match rider profiles with adequate routes, the intelligent bicycle routing system would require (a) a knowledge base that contains the necessary information associated with those specifications and (b) the ability to maintain the context of the dialogue such that the system can draw appropriate conclusions (i.e., the most suitable route for the user).

Knowledge Base

The knowledge base for this system would contain both profile standards and routing information.

Profile Standards The profile standards could be based on the American Youth Hostel (AYH) guidelines for rating experience levels. It is a simple rating system in which A is advanced, B is intermediate, and C is novice, each level defined by the answers to a set of questions asked of the rider, such as

- Do you ride with children?
- Do you prefer shorter, more relaxed trips?
- Select the category in which most of your rides fall:
  - –0 to 35 mi with frequent stops,

–20 to 75 mi/day with stops every 15 to 30 mi,
–35 to 100 mi/day at 15 to 20 mph with stops every 20 to 30 mi, or
–50 to 200 mi/day at more than 18 mph.

An intelligent bicycle routing system would ask the same questions asked in AYH guidelines to determine the rider's skill level, the first step in recognizing the uniqueness of each individual rider.

Going one step further, the system would also ask the rider his or her preferences. Some examples are as follows:

- How far and where does the rider wish to travel?
- Does the rider want to ride off-road trails only?
- Is heavy traffic a concern?
- Is the steepness of the terrain a concern?
- Does the rider prefer to ride in the sun or the shade?
- Does the rider want to use any facilities en route?

This information, along with AYH experience levels, would define each rider's profile.

One note: the rider's AYH classification could be stored in the system, thus eliminating the need to reevaluate his or her skill level with each use of the system. However, this classification could be reevaluated as desired. For example, if children were to be present for one ride and not for another, the rider's skill level could go from a C to an A, depending on all other related factors. The rider's preferences, on the other hand, would always be reviewed before the generation of each new route. This would ensure that the ever-changing needs and desires of the rider are always considered, since the purpose of each ride varies significantly.

Route Information To match rider profiles with the best routes, the system would be able to store and access descriptive details of the bicycling environment, such as traffic volumes, speed limits, pavement width, grade, and aesthetics. This elaborate routing information could be embedded in the program. Because the collection of data is a highly complex process, existing data would most likely be used in the system, to include any pertinent information related to bicycle routes that is available. For example, most bicycle route maps currently differentiate the degree of suitability associated with the routes by color coding each route and providing a key as a guide. These routes could be represented in the system and identified on the basis of their level of suitability or relative safety. Additional information could come from other maps, reports, charts, maintenance schedules, and the like.

The data used would depend on what is available in each participating state; if plans are to accommodate preferences with regard to steepness of terrain, data associated with steepness of terrain must be available. This issue is of great importance where the minute details affecting cyclists are concerned. It is not likely that applicable data exist for every curb ramp, manhole cover, drain gate, and pothole. Nor is it likely that many data address how sunny or shady a road is. One way to cope with a lack of data would be to allow for related text to be added by anyone using the system. Information could be keyed in by the user, reviewed by an authority, and, if valid, kept on line. For example, next to one portion of a route generated the text may read, "2-in. lip on curb ramp on Washington Avenue over Oak Street." This text would appear every time that portion of a route was generated, informing other users of the potential hazard or inconvenience.

Such built-in maintenance would apply to the changing road conditions due to weather and construction as well. An intelligent bicycle routing system would be most effective if its data were updated regularly, via system maintenance tools, as is done with the RouteBuilder system. A possible function of the data processing or other designated official ongoing maintenance would ensure system accuracy and dependability.

Matching Routes

As an expert system, an intelligent bicycle routing system would be able to maintain the context of each dialogue, allowing it to give the user the most appropriate route on the basis of the rider's profile and available routes best suited to meet the rider's needs. The route could be generated in either list or map form in which its start and finish points would be identified, as would be the direction to follow and the number of miles that make up each stretch of road. The user would be allowed print the route for his or her perusal.

Additional Capabilities

Safety

The vulnerability of cyclists as roadway users is reflected in startling accident rates. In Minnesota fatality rates are more than 3 times the rates for automobiles, and injury rates are more than 41 times those for automobiles; these rates grow per 100 million mi traveled (*1*). Safety information, from hand signals to helmet use, could be provided, possibly as text that offers specific safety tips or rules of the road. The information could be a note as to where a cyclist can pick up a bicycle safety handbook in that area. It could focus on actual bicycle accidents, perhaps those occurring on routes represented in that particular system, exploring possible causes and ways to avoid such incidents. Or it could be provided in some combination of these ideas. Incorporating safety issues into the system promises to increase awareness of potential hazards and safe practices with every use of the system.

Registration

Bicycle registration information could be provided either as text for the system user or as a complete function that enables the user to register the bicycle automatically, similar to the way in which permits are administered in the RouteBuilder system. Facilitating the registration process offers a potential increase in the total number of bicycles registered annually, which would improve cyclist identification, especially in the case of an accident. This would also pose an increase in revenue.

Biker's Bulletin Board

An intelligent bicycle routing system could become a central forum for cyclists, who would be able to glance at the "biker's bulletin board" for equipment for sale, upcoming bicycle tours, day trips, cycling companions, and other notes. An available keyboard would let users input information any time, giving them a new way to find people with similar interests. Social benefits aside, this bulletin board could also serve as a forum through which cyclists offer their feedback, both on the routes and the system itself—an important consideration to those looking to monitor the effectiveness of the tool and provide ongoing maintenance support for its use.

Watchdog

An underlying problem in the bicycle community is the inadequate amount of attention paid to trail and route rehabilitation. This is largely due to limited resources, but also hampering such activity is a lack of knowledge as to which trails are most in need of repair. To be able to maintain bikeways properly, the infrastructure needs certain "watchdog" capabilities that help transportation agency officials determine the order of priority of bikeways targeted for repair. When resources are limited, officials need to expend those resources first on the trails that are used the most.

Feedback on the bulletin board, in combination with data on frequency of routes used, could alert officials to specific areas in need of repair; the expert system could serve as a tracking device, keeping count of the most requested bikeways. Officials could then evaluate route conditions on the basis of whether the route in question is one of the more desirable corridors. Priority ranking to accommodate the most heavily used routes would ensure that funds are allocated to the most appropriate trails and that the most heavily used trails are kept in good condition. Furthermore, identifying these major routes could better position officials to effectively signpost bicycle "highways"—easily recognizable routes with assigned names or numbers that differentiate them from one another, the first step toward truly integrating bikeways into the overall transportation infrastructure.

Linking Intelligent Bicycle Routing and Public Transportation

An intelligent bicycle routing system is an effective means for integrating the bicycle with other modes of transportation. It is envisioned that these bicycle routing capabilities be linked to similar routing tools for public transportation and carpooling programs. Minnesota's Regional Transit Board has already taken the initiative to affix bike racks to the back of University of Minnesota buses in an effort to give students, especially commuters, the opportunity to ride in from longer distances and then turn to their bicycles for better mobility around campus.

The next phase would be to add bus routing software to bicycle routing, providing students with better information on bus services and available bikeways. This link could then occur with all Twin Cities public transport, focusing first on linking express transit stops and then on experimenting with expanded limited-stop routes, which would improve the speed performance enabled by the need for less frequent stops due to increased bicycle use.

A third transportation mode could be added to the routing tool as well: carpools. The same routing needs exist for carpooling as they do in public transit and bicycling, and incorporating all three ensures that the user is given accurate information on multiple transportation modes as well as the flexibility to choose the most suitable transportation mode to fit specific needs. This shifts attention toward the individual and his or her unique desires and capabilities, while shifting attention away from the single-passenger automobile.

Certainly a Bike Share program can be envisioned. Cyclists could create a pool through which one person whose automobile is equipped with a bike rack drives while the others in the group ride, rotating drivers as the group sees fit. This ensures cyclists who bike to work that, should the weather become less than desirable, they will not have to bicycle home. They can ride in the car. The more opportunities that exist, the more bicycle use can be encouraged.

System Access

To generate maximum use, an intelligent bicycle routing system must be usable at the novice level. Developing a system operational from a personal computer is the first step to making it as user-friendly as possible. Touch screens can be explored also, to waive any threat that a keyboard poses to the computer novice. The next step is to design the system so that it leads the user through each step in simple, nontechnical language, generating results quickly and accurately; as an expert system, it operates proactively to guide the user through the task at hand, requiring no knowledge of programming by the user. Finally, the system must be widely accessible.

There are many possibilities for locating an intelligent bicycle routing system: bike shops, tourist information and travel centers, campus unions, libraries, Chambers of Commerce, hotels and motels, shopping centers, state office buildings, and kiosks placed in key areas outdoors, such as at a park or in central downtown. The system may be available for use directly by the cyclist or by an official in charge of entering data and giving the resulting information to the caller or visitor. Outdoor kiosks are prime candidates for touch screen capabilities. Another possibility is to provide a 900 number that people could call for a small fee that puts them in touch with someone operating the system. Home computers could also be used.

PROJECT DEVELOPMENT

Initial implementation of an intelligent bicycle routing system demands that considerable attention be given to selecting target areas with the most impact and designating development phases accordingly, validating the system within a short period of time, and exploring financial opportunities. This section examines each of these areas.

Development Phases

Since the most heavily used bikeways are on or near college and university campuses, and since many students are enthusiastic about the program, initial attention ought to be focused there. (This is based on the overall student response to the Bike RouteBuilder system mirage presented at the Environmental Fairs held at the University of Minnesota–Minneapolis/St. Paul campuses April 21–22, 1992.) In Minnesota, initial target areas include University of Minnesota campuses and central areas of Minneapolis/St. Paul. The program could start with connections to and within the University of Minnesota, then expand to include other Minneapolis/St. Paul colleges and bicycle "hot spots." After that, the system could be made to include downtown Minneapolis and St. Paul, the greater Twin Cities metro area, other urban and popular tourist areas, and eventually the entire state.

PEAKSolutions, the Regional Transit Board, and RideShare (the Twin Cities carpooling organization) have been examining a slightly different approach: one that involves designing a system that integrates bike routes with University of Minnesota bus routes and carpools. This initial prototype system would use a number of preselected routes that would be embedded in the system. The purpose of this approach is (a) to allow involved parties to evaluate the potential use of the system and (b) to test the feasibility of combining mode share in everyday travel. Positive criteria would present a case for expanding the system's capabilities and area.

System Validation

A large university campus, such as the University of Minnesota, could prove to be the most effective test bed for an intelligent bicycle routing system. With so many users concentrated in one area, the potential for more feedback is greatly increased. One method of validating the system would be to select a period of time, such as 3 months, during which the system would be tested. Users would be informed of the system and asked to use it. They would then be asked to evaluate the system, perhaps on a before-and-after basis, providing feedback via the keyboard. The system would also monitor its own use, that is, the number of routes requested daily; the most requested route; the total number of users, both new and repeat; the demographics of the users; and the like. Further performance would be measured by analysis of historical and ongoing accident data, number of bicycle registrations, and other statistics that reveal any significant changes taking place. The overall effectiveness of the system, then, could be evaluated in a relatively short period.

Potential Funding Sources

The Governor's Special Commission on Bikeways stated in 1983,

> The designation of specific funding for bicycling projects and programs has been periodic, temporal, and insufficient, with a net result that planning for bicycling development is exceedingly difficult, if not impossible. Without financial commitment, such development is relegated to a low-priority status and all efforts to improve the situation are severely hampered. (*1*)

Clearly recognizable is the need for adequate funding if any kind of comprehensive overhaul of bike routes is to get under way. Grants (the Intermodal Surface Transportation Efficiency Act of 1991 has a significant amount of federal funds set aside for intelligent vehicle-highway systems and other traffic management systems) and bicycle-related taxes pose opportunities for some states, but an intelligent bicycle routing system poses funding opportunities of its own. First, making bicycle registration more accessible and easier promises to increase the number of people who actually register their bicycles, adding to total registration revenue. Next, the various location options present fee and licensing opportunities that could help pay for the system and generate further revenue from its use. Bicycle shops and hotels and motels could install the system for an initial fee and smaller future licensing payments, the value of which lies in the added service that they could provide their customers.

The system could be operational from a home computer on a low-cost, pay-per-use basis. (It is feasible that an organization that wishes to promote bicycle use and is licensed to use the system may consider allowing users to call in to its system, via modem, at no charge. This could be provided as a service for customers, posing unique financial opportunities for the licensee, i.e., drawing consumers by offering discounts for services or products to those using the system.) Additionally, kiosks could require a small user fee. Each phone call to the 900 number would be charged accordingly. So while installation of an intelligent bicycle routing system demands an initial investment, that investment promises to pay for itself through new revenue sources. Any profits can be channeled into system maintenance and route rehabilitation programs, adding further support to the bicycle community.

SUMMARY OF BENEFITS OF INTELLIGENT BICYCLE ROUTING

Effectively promoting and supporting bicycle use in urban and rural environments entails shifting from the use of current maps to a more sophisticated information and communications system; limitations of the print medium preclude maps from matching the unique and changing needs affecting the bike community. Unless these very specific needs of bicyclists are made the focal point for raising bicycling standards, improvement will be less than desired. The number of those turning to the bicycle as a practical transportation mode will not reach its potential.

An intelligent bicycle routing expert system can address these as well as other significant factors. As an expert system, this computerized program would take into account both sensitivity of detail and the diversity of bicyclists while providing a means for adequately surveying bikeways and priority ranking them for maintenance. It could also serve as a chief integration tool, tying together multiple modes of transportation. In effect, it would equip officials to promote more effective bicycle transportation practices while maximizing efficient use of the existing public transportation infrastructure. This holds the promise of economic advantage and an enhanced quality of life—the optimum result.

If you build it, they will come.

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Study of Bicyclist Characteristics in Phoenix, Arizona

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As of July 1992 the city of Phoenix had a bicycle system of about 300 mi; another 45 mi of on-street bike lanes are planned for fiscal year 1992–1993. The addition of new facilities and encouragement of bicycling as an alternative mode of transportation will lead to greater bicycle accident exposure. Bicycle volumes and use characteristics at select commuter bike lanes during typical commute and noontime hours are summarized. This information will be used to help target bicycle safety education and training in the city. Data were also collected at five sites during the Bike to Work Week in February 1992.

The city of Phoenix has a bicycle network of about 300 mi. This system includes various types of bicycle facilities such as dedicated bike paths, on-street bike routes (signed only), striped bike lanes, and wide sidewalk facilities. The system includes more than 100 mi of on-street bike lanes, and another 45 mi are planned for installation during fiscal year 1992–1993. The ultimate system will eventually have more than 700 mi of bicycle facilities.

Phoenix is encouraging bicycle riding as a nonpolluting and healthy alternative to automobile commuting by adding bike routes, upgrading existing routes, putting bike racks on all city buses, providing showers and bike lockers at some city buildings, and encouraging private industry to do the same. Phoenix has an ideal climate for bicycling during most of the year and wants to make bike travel a viable alternative for motorists to help reduce congestion and clean the air in the valley.

There is a great concern for the safety of bicyclists, especially when higher levels of bicycling are encouraged. In 1991 there were 693 car-bicycle collisions reported in Phoenix, resulting in 646 injuries and eight fatalities. Police accident statistics indicate that the bicyclist was primarily at fault in 71 percent of these collisions. Collisions with motor vehicles are not the only danger to bicyclists, who are also susceptible to falls and collisions with pedestrians, other bicyclists, and fixed objects. The only protection available to bicyclists is head protection in the form of a safety helmet, and the knowledge and skill to avoid problems when riding.

State law defines a bicycle as a vehicle and requires bicyclists to obey the same laws that apply to motor vehicle operators when riding in the street. However, there is no minimum age, skill level, knowledge, or licensing before these vehicle operators (bicyclists) are allowed to use the roadway. Additionally, Phoenix has not conducted a bicycle volume and observation study to evaluate current bicycling practices in the city.

This paper summarizes a study to obtain baseline bicycle usage volumes and riding characteristics on nine bike lanes throughout Phoenix in November and December 1991. The information will be used to help target safety education and training efforts in the city. Data were also collected at five sites during the Bike to Work Week, which was held in the last week of February 1992.

DATA COLLECTION

A trained observer was used to collect 7 hr of bicycle volume and characteristic data at nine locations on typical weekdays under good weather conditions. This study primarily targeted commuter bicyclists (7:00 to 9:00 a.m. and 3:00 to 6:00 p.m.) as well as midday bicyclists (11 a.m. to 1 p.m.) during typical weekdays. Data were collected on bike routes at five traffic signal locations, three Stop sign locations, and one uncontrolled location. Information was also obtained on compliance to these traffic control devices. Two of the signals had special push-button actuators installed for bicyclists. All data collection locations are considered primarily commuter routes that are more likely to be used by adult bicyclists. A decription of each location is given in Table 1.

Data were collected using the form shown in Figure 1. Each bicyclist observation was individualy recorded during the 7-hr study period. Data collected included the time observed, direction of travel, and location where the bicyclist was riding (with traffic in the bike lane, against traffic in the bike lane, or on the sidewalk). Information was not collected for bicyclists on the cross street unless they turned onto the bike lane under observation.

The observer was asked to identify if the bicyclist was a man or a woman and estimate the bicyclist's age. Age was divided into two groups: below 14 years or 14 and older (high school age and older). These categories were selected to differentiate between the two levels of knowledge and experience. The classification of ages was made by oservation only; no one was questioned to verify the observations.

Bicycling is considered to be a social activity, thus the observer was asked to identify whether the bicyclist rode alone or in a group. One of the most important pieces of data collected was helmet use. The observer also recorded if the bicyclist wore special clothing commonly associated with more experienced bike riders.

The observer was to note whether the bicyclist was carryig objects (e.g., books, briefcases) and to identify how the objects were carried. The method that may be considered unsafe is that of carrying an item in one of the hands, which may

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TABLE 1 Data Collection Site Characteristics

Bike Lane	Street Classification	ADT	Traffic Control	Date Established	Route Location
23rd Ave. at Camelback Rd.	Collector	10,000	Actuated traffic signal	February 1991	Northwest Phoenix to Central Business District
Encanto Blvd. at 7th Ave.	Collector	5,000	Actuated traffic signal	February 1991	Continuation of 23rd Ave. route.
7th St. at Broadway Rd.	Major	20,000	Fixed time traffic signal	February 1991	South Phoenix to CBD
Washington St. at 28th St.	Major	45,000	Fixed time traffic signal	October 1991	East Phoenix to CBD
Campbell Ave. at 28th St.	Collector	10,000	Fixed time traffic signal	February 1991	East Phoenix
Encanto Blvd. at 39th Ave.	Collector	5,000	Four-way STOP	February 1991	West Phoenix
Lafayette Blvd. at Arcadia Dr.	Collector	4,500	Four-way STOP	February 1991	East Phoenix
Sweetwater Ave. at 28th St.	Collector	9,000	Four-way STOP	March 1991	Northeast Phoenix
3rd Ave. at Encanto Blvd.	Collector	5,000	None	Originally established in early 1970's. Modified 8/91	Central Phoenix along CBD

reduce the balance and control that the bicyclist has over the bike. The observer recorded the use of the bicyclist push buttons at the two signal locations that were equipped with actuation devices and recorded bicyclist compliance to the Stop signs or traffic signals at eight of the study sites.

Results

Observations were conducted in November and December 1991 during good weather conditions. Sixty-three hours of observations were made, 7 hr at each site, resulting in 480 observations, as presented in Table 2. Only about eight bicyclists were observed per hour throughout the study period. Bicycle volume ranged from a low of 29 on Third Avenue (which is a one-way northbound route) and Sweetwater Avenue to a high of 90 on Lafayette Boulevard.

Bicycle volumes were highest during the afternoon hours and lowest during the noon-time hours. The location with the highest midday volume was 23rd Avenue at Camelback. It is important to note that these counts do not reflect recreational bicycle use during weekends or evening hours or during early commute hours, which may occur before 7:00 a.m., when traffic volumes are lower.

Nearly two-thirds of the bicyclists were observed correctly riding with traffic in the bike lanes. However, 18 percent were observed illegally riding the wrong way in the bike lane (against traffic) and 19 percent were riding on the sidewalk (which is acceptable, but bikes must yield right of way to pedestrians). Even though pavement arrows were placed in the northbound bike lane for Third Avenue (four arrows per mile) to show clearly that bicyclists must ride with traffic, 21 percent of the bicyclists observed on Third Avenue were riding against traffic. The highest pecentage of wrong-way riders was observed on Lafayette Boulevard, which was formerly a two-way bike lane on the south side of the street. The highest sidewalk usage was observed on Campbell Avenue and Washington Street. The highest overall correct use of bike lanes was on Encanto Boulevard at Seventh Avenue, where no bicycists were observed riding the wrong way in the street.

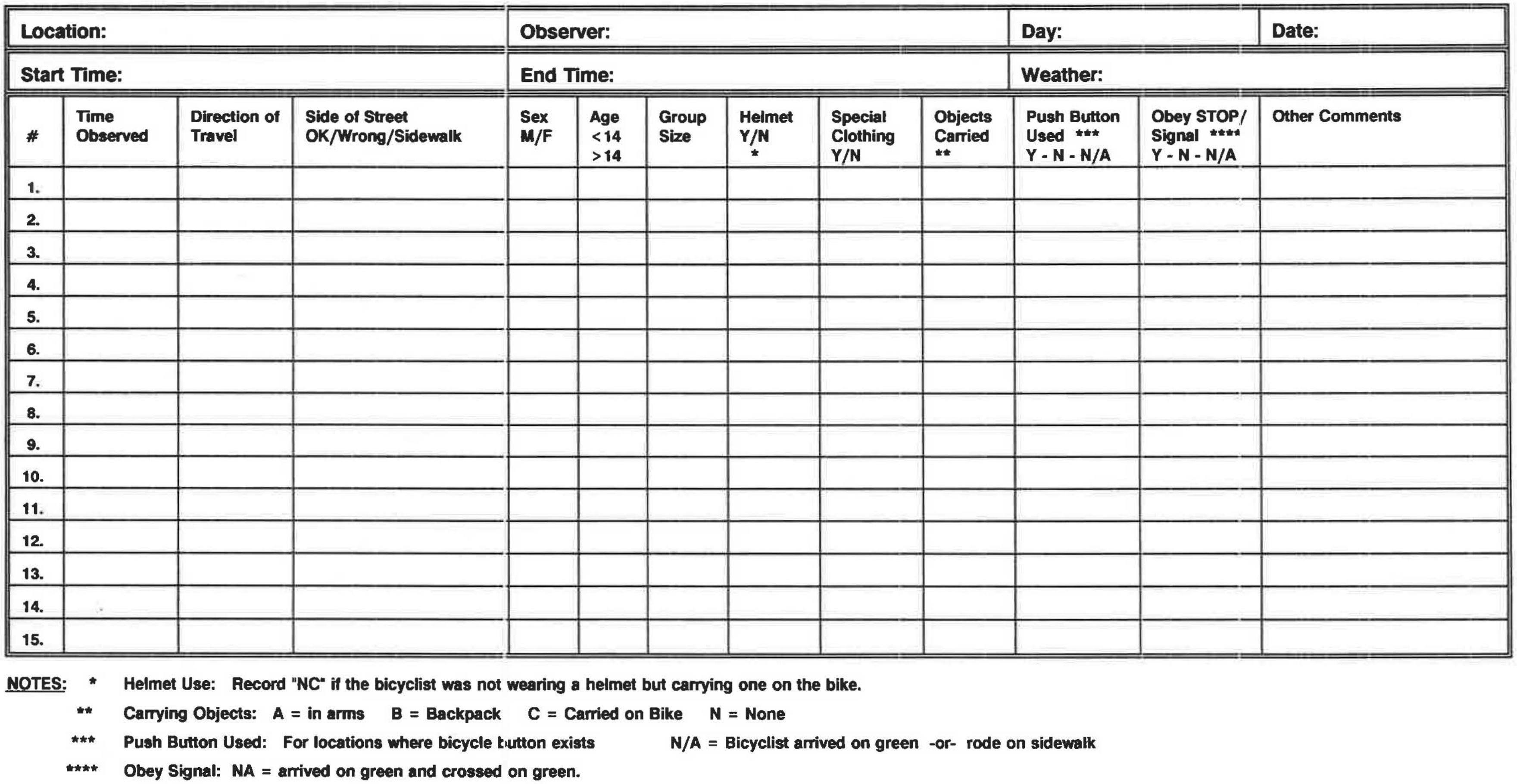
Most of the bicyclists observed were men, and most were high school age or older (classified as adults). Furthermore, most of the bicyclists observed did not ride in groups. This may not be consistent with characteristics of recreational bicycling.

Helmet use was at a disappointing low rate of 15 percent. This ranged from a high of 34 percent on Third Avenue to a low of 0 percent on Sweetwater Avenue. Similarly, only 11 percent of the bicyclists were observed wearing special clothing.

Forty-three percent of bicyclists were observed carrying objects. However, only 2 percent were holding the objects in their hands.

Two of the five signal locations in the study were equipped with bicyclist actuation equipment (push buttons) on the bike lane approach. The vehicle loop detectors at these signals are not sensitive enough to detect bicycles, and the pedestrian push buttons are not easily accessible from the street. The push buttons were marked with special signs and were conveniently located for bicyclists. However, only one-third of the bicyclists who arrived on the red signal used the push button to call the traffic signal.

Compliance with the traffic signal was observed at the five signalized observation sites. For those who arrived on the red signal, 80 percent waited for the green signal light before crossing. This number was highest on 23rd Avenue, where it is very difficult to cross against the signal because of high traffic volumes on Camelback Road. The highest violations of running red lights occurred at Campbell Avenue at 28th Street, where the cross traffic is not substantial and it is easy to cross on the red signal.



Location:	**Observer:**	**Day:**	**Date:**
Start Time:	**End Time:**	**Weather:**	

#	Time Observed	Direction of Travel	Side of Street OK/Wrong/Sidewalk	Sex M/F	Age <14 >14	Group Size	Helmet Y/N *	Special Clothing Y/N	Objects Carried **	Push Button Used *** Y - N - N/A	Obey STOP/ Signal **** Y - N - N/A	Other Comments
1.												
2.												
3.												
4.												
5.												
6.												
7.												
8.												
9.												
10.												
11.												
12.												
13.												
14.												
15.												

NOTES: * Helmet Use: Record "NC" if the bicyclist was not wearing a helmet but carrying one on the bike.

** Carrying Objects: A = in arms B = Backpack C = Carried on Bike N = None

*** Push Button Used: For locations where bicycle button exists N/A = Bicyclist arrived on green -or- rode on sidewalk

**** Obey Signal: NA = arrived on green and crossed on green.

FIGURE 1 Bicycle volume study.

TABLE 2 Summary of Bicycle Observations (7 hr per Location)

Location	Traffic Control	Number Observed	Bikes Per Hour			Bicycling Location			Sex		Age		Group Size		Helmet Use	Push Button Used (When Arrived on Red)	Obey Signal (When Arrived On Red)	Obey STOP Sign
			7-9AM	11AM-1PM	3-6PM	Bike Lane	Wrong Way	on Sidewalk	M	F	Child	Adult	One	Two or More				
23rd Ave at Camelback Rd	Traffic Signal	86	10.5	11.0	14.3	75%	10%	15%	85%	15%	12%	88%	86%	14%	13%	28%	95%	NA
Encanto Blvd at 7th Ave	Traffic Signal	34	4.0	1.5	7.7	94%	0%	6%	74%	26%	9%	91%	68%	32%	29%	41%	71%	NA
7th St at Broadway Rd	Traffic Signal	47	5.0	2.5	10.7	55%	17%	28%	96%	4%	19%	81%	79%	21%	6%	NA	86%	NA
Washington St at 28th St	Traffic Signal	47	7.0	3.5	8.7	58%	4%	38%	98%	2%	0%	100%	100%	0%	19%	NA	80%	NA
Campbell Ave at 28th St	Traffic Signal	60	10.0	4.0	10.7	49%	9%	42%	97%	3%	2%	98%	93%	7%	18%	NA	57%	NA
Encanto Blvd and 39th Ave	STOP Sign	58	6.0	3.0	13.3	46%	27%	27%	74%	26%	45%	55%	59%	41%	3%	NA	NA	8%
Lafayette Blvd at Arcadia	STOP Sign	90	16.0	4.0	16.7	60%	39%	1%	85%	15%	39%	61%	77%	23%	20%	NA	NA	24%
Sweetwater at 28th St	STOP Sign	29	3.5	2.0	6.0	76%	17%	7%	55%	45%	34%	66%	86%	14%	0%	NA	NA	17%
3rd Ave at Encanto Blvd (One-Way)	None	29	3.0	3.0	5.3	72%	21%	7%	72%	28%	3%	97%	86%	14%	34%	NA	NA	NA
Total		480	7.2	3.9	10.4	63%	18%	19%	84%	16%	20%	80%	81%	19%	15%	33%	80%	17%

Compliance at the three Stop signs locations was very low. Arizona state law requires all bicyclists to come to a complete stop before crossing, similarly to motor vehicles. Even though the observer was instructed to give the bicyclists the benefit of the doubt when they came to a near stop, the results show a very high level of noncompliance. Only 17 percent of the bicyclists complied with the Stop sign restriction. The observer noted that many of the bicyclists did not even slow down and completely ignored the Stop sign.

Rider Characteristics by Gender

Table 3 presents various rider summaries by gender. The table shows that the proportion of male/female ridership by time of day and riding location is similar. However, a higher proportion of the female bike riders observed were younger than 14 (43 versus 15 percent for men). Female riders were also more likely to be observed riding with other bicyclists. Helmet use was about equal between men and women, but men were more often observed wearing special clothing.

Female bike riders were more often observed to use the signal push button; however, the sample size is very small. Similarly, women were more likely to obey the traffic signals and Stop signs than men.

Rider Characteristics by Age

Table 4 provides a breakdown of rider characteristics by age for all nine locations. Virtually no young riders were observed during the midday time period (11:00 a.m. to 1:00 p.m.). It is likely that the children were in school during this time.

Younger bike riders were slightly more likely to ride on the sidewalk but much more likely to ride the wrong way in the street than older bicyclists. However, 13 percent of older cyclists rode against traffic while in the street.

Younger bicyclists were about four times as likely to ride with other bicyclists as the older bicyclists. None of the younger

TABLE 3 Bicycle Ridership Characteristics by Gender

	Men (%)	Women (%)
Time of day		
7:00 to 9:00 a.m.	26	33
11:00 a.m. to 1:00 p.m.	16	7
3:00 to 6:00 p.m.	58	60
Riding location		
Bicycle lane	63	61
Wrong way (in street)	17	22
Sidewalk	20	17
Age		
Under 14 years	15	43
14 years or older	85	56
Group size		
Single rider	84	66
Two or more riders	16	34
Helmet use	16	13
Special clothing	12	5
Objects carried		
In arms	2	3
Backpack or bike carrier	39	45
Push button used[a] when arriving on red	28	53
Traffic signal obeyed when arriving on red	79	88
Stop sign obeyed	14	25

[a] 23rd Avenue at Camelback; Encanto Boulevard at 7th Avenue.

TABLE 4 Bicycle Ridership Characteristics by Age

	Less than 14 Years (%)	14 Years and Older (%)
Time of day		
7:00 to 9:00 a.m.	34	25
11:00 a.m. to 1:00 p.m.	1	18
3:00 to 6:00 p.m.	65	57
Riding location		
Bicycle lane	40	68
Wrong way (in street)	38	13
Sidewalk	22	19
Group size		
Single rider	51	89
Two or more riders	49	11
Helmet use	0	19
Special clothing	1	13
Objects carried		
In arms	1	2
Backpack or bike carrier	43	40
Push button used[a] when arriving on red	25	34
Traffic signal obeyed when arriving on red	90	79
Stop sign obeyed	26	12

[a] 23rd Avenue at Camelback; Encanto Boulevard at 7th Avenue.

bicyclists was observed wearing a protective helmet, and only 1 percent wore special clothing. Almost 20 percent of the adult riders wore a helmet.

The older bike riders were more likely to use the push buttons at the two actuated traffic signal locations. Younger bicyclists were more likely to comply with the red traffic signals and were twice as likely to obey the Stop signs than the older riders.

Other Characteristics

Table 5 gives a summary of other characteristics for bicyclists wearing safety helmets. Helmet use was highest during the morning commute period and lowest during the midday hours. Helmet use was higher for bicyclists properly riding the bike lane and was much lower for those riding the wrong way in the street or those on the sidewalk. Helmet use was nearly twice as prevalent for single riders than for those riding in groups.

TABLE 5 Helmet Use by Time of Day, Riding Location, and Group Size

	Helmet Use (%)
Time of day	
7:00 to 9:00 a.m.	21
11:00 a.m. to 1:00 p.m.	10
3:00 to 6:00 p.m.	15
Riding location	
Bicycle lane	22
Wrong way (in street)	5
Sidewalk	3
Group size	
Single rider	17
Two or more riders	9

BIKE TO WORK WEEK

Phoenix participated in the Bike to Work Week (February 24–28), which was sponsored by the Arizona Department of Commerce Energy Office, the Arizona Department of Environmental Quality, Maricopa County, the Phoenix Chamber of Commerce, and the Regional Public Transportation Authority as part of the Clean Air Force Campaign. Commuters were invited to ride their bikes at least one day of that week or drive to one of the valley's 64 park-and-ride lots and pedal the rest of the way to work. Two special group rides were organized for Tuesday of that week. One included a ride with Mayor Paul Johnson from the Metrocenter Transit Center to downtown Phoenix via the 23rd Avenue bike lane. The promotion included a bike fair at Patriot's Park (downtown Phoenix), and bicyclists who registered to ride in before the event were eligible to win prizes.

Bicycle volume and characteristic data were obtained at five of the previous commute routes, as presented in Table 6. Data were collected only in the morning and afternoon commute times and on the same day of the week as the baseline study for four of the five locations, and the 23rd Avenue bike lane was observed on the organized group ride day.

A total of 283 bicyclists were observed in 25 hr of observation (11.3 bicyclists per hour). The number of bicyclists observed was relatively unchanged on the Washington Street, Encanto Boulevard, and Seventh Street bike lanes. There was a 50 percent increase in ridership on the Campbell Avenue route and a 67 percent increase on the 23rd Avenue route that was observed on the special group ride day.

The percentage of female riders was similar to the earlier observations in three of the four study sites; overall, the number of female riders remained low. There was also a higher proportion of adult riders observed during the Bike to Work Week study.

Helmet use doubled during Bike to Work Week, and a large factor was a result of the 23rd Avenue group ride route, which had nearly 50 percent helmet use. In fact, most of the bicyclists riding to work with the mayor were observed wearing a safety helmet. Helmet use increased along the other routes, except Washington Street, where it dropped to 8 percent of bicyclists.

Bicycle push-button use nearly doubled at the two signalized crossings equipped with convenient push-button detectors for bicyclists.

Compliance with the traffic signal was also higher than in the previous observation, except on Washington Street bike lane at the 28th Street signal. This may result from all observations during the peak traffic hours where it is very difficult to cross the major street without the assistance of the traffic signal. In the one exception (Washington Street) the bike lane is on the major street and 28th Street is a lower-volume collector street that is easier to cross. However, the number of bicyclists that arrived on the red signal at 28th Street was small.

Table 7 gives the distribution of helmet use that was observed during the Bike to Work Week. Helmet use increased

TABLE 6 Bicycle Observations During Bike to Work Week (5 hr per Location)

Location	Traffic Control	Number Observed	Bikes per Hour		Bicycling Location			Sex		Age		Group Size		Helmet Use	Push Button Used (When Arrived on Red)	Obey Signal (When Arrived On Red)
			7-9AM	3-6PM	Bike Lane	Wrong Way	on Sidewalk	M	F	Child	Adult	One	Two or More			
23rd Ave at* Camelback Rd	Traffic Signal	100	24.5	17.0	67%	8%	25%	77%	23%	13%	87%	53%	47%	48%	60%	100%
Encanto Blvd at 7th Ave	Traffic Signal	30	4.5	7.0	90%	3%	7%	93%	7%	0%	100%	87%	13%	37%	59%	94%
7th St at Broadway Rd	Traffic Signal	38	5.0	9.3	57%	13%	30%	92%	8%	13%	87%	95%	5%	21%	NA	90%
Washington St at 28th St	Traffic Signal	36	5.5	8.3	43%	3%	54%	94%	6%	0%	100%	89%	11%	8%	NA	33%
Campbell Ave at 28th St	Traffic Signal	79	15.5	16.0	76%	5%	19%	80%	20%	4%	96%	78%	22%	24%	NA	71%
Total		283	11.0	11.5	68%	7%	25%	84%	16%	7%	93%	74%	26%	31%	60%	89%

*Data Collected On The Group Ride Day

for both men and women, and helmet use for women was slightly higher than for men. There were a few younger bicyclists observed wearing helmets, unlike the original observations. Helmet use was only slightly higher for single riders (22 percent compared with 17 percent during the first observations), but it increased six times for those riding in a group of two or more cyclists. Once again this was heavily influenced by the special group ride on the 23rd Avenue route.

CONCLUSIONS AND RECOMMENDATIONS

The level of commuter bicycle travel in Phoenix observed thus far is low, but the city is taking steps to change this. These steps include putting on special promotions and adding bicycle facilities, most notably bike lanes.

There is a major concern with bicycle safety and education, especially where young, inexperienced bicyclists are encouraged to ride on high-speed major streets with cars, trucks, and buses. Although bike helmet use is low (15 percent), a few years ago it was virtually nonexistent. As expected, children were more apt to ride without helmets than adults. Young children are often not exposed to any education or training before riding in the street, and generally they do not realize that they must also obey Stop signs and traffic signals and ride with traffic. It appears from the baseline data that older bicyclists had even lower compliance rates with Stop signs and traffic signals and that education is needed at all age levels.

TABLE 7 Helmet Use During Bike to Work Week

	Helmet Use (%)
Gender	
Male	30
Female	39
Age	
Less than 14 years	5
14 years or older	34
Time of day	
7:00 to 9:00 a.m.	43
3:00 to 6:00 p.m.	24
Riding location	
Bicycle lane	43
Wrong way (in street)	16
Sidewalk	7
Group size	
Single rider	22
Two or more riders	57

The Traffic Safety Plan prepared by the city's traffic safety coordinator has recognized this and recommended a strong public information and education campaign for both adults and children. The Street Transportation Department Traffic Safety Function received funding from the Governor's Office of Highway Safety to provide 10 to 12 bicycle rodeos in various city parks and schools during 1992. These rodeos provide hands-on training by the bicycle detail police officers and free bicycle inspections and tune-ups. Bicyclists are required to wear safety helmets while on the training course, and the city loans helmets to cyclists, when needed, during the training sessions.

Phoenix is continually updating the bicycle system map and distributing it to the public through the parks department and other distribution centers. These maps also provide tips for safe bicycling as well as the rules of the road that all bike operators must follow.

Another avenue to pursue is an increased level of police enforcement. Unfortunately, as with pedestrian violations, it appears that the only time bike enforcement occurs is after a collision. A greater level of police enforcement can be a helpful educational tool. Enforcement need not be a negative experience and result in a citation or fine. An increased level of observation resulting in police warnings or authoritative instructions from police officers may provide better overall results, especially for younger offenders. There already exists a wealth of bike knowledge within the police department due to the Downtown Police Bicycle Detail. These officers can be used to train other officers and identify problems needing correction and to help direct enforcement activities.

It appears that the Bike to Work Week in February 1992 had mixed results. Ridership increased on only two of the five routes and in some cases was slightly lower than the baseline study. The organized group ride was successful and is a concept that should be used more often. Additionally, helmet use was much higher during Bike to Work Week, possibly the result of a greater awareness associated with the Bike to Work Week activities.

Phoenix will continue to pursue a greater level of cycling and concentrate on efforts to increase helmet use and safe riding practices. Although it is unrealistic to expect bicycling to replace the automobile, bikes should and can be used to make a measurable difference in air quality. Good bike corridors are needed to promote this healthy alternative to the single-occupant automobile and help complement carpools and other forms of mass transit. Further observation studies will be made at appropriate intervals to help guide educational efforts and monitor bike ridership, helmet use, and compliance with traffic control devices and rules of the road.

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Determination of Service Levels for Pedestrians, with European Examples

SHEILA SARKAR

Qualitative evaluation of pedestrian precincts is important for providing adequate facilities for the elderly, the physically challenged, and children, who are most inclined to use this mode of travel. Evaluation has been attempted by using the qualitative criteria of safety, security, comfort and convenience, continuity, system coherence, and attractiveness. After the levels of activity and use in the pedestrian environments in Munich and Rome were studied, pedestrian environments have been classified into six service levels.

Walking is often thought to be a simple behavioristic exercise that requires very little effort or experience. This is far from true. Pedestrians process large amounts of sensory input for sophisticated signal exchanges to negotiate rights of way. These sensory inputs also help pedestrians to acquire, over time, valuable knowledge on different aspects of human perception such as peripheral vision, depth perception, judgment of speed and direction, and sound recognition.

Sensory stimulation is normal for adults, who process these inputs much faster than children; however, this process does diminish with age. Besides the slowing of their reflexes, the elderly often suffer from impaired hearing, inaccurate depth perception, decreased lateral vision, and faltering learning capacity. Children receive normal sensory inputs, but owing to their short exposure to such sensory stimulants they are unable to process the information as effectively as adults; this lack of experience causes perceptual difficulties resulting in uncertain reactions when exposed to direct confrontations with traffic. Physically challenged pedestrians require more than normal sensory inputs to compensate for their disabilities; complex processing slows down their reflexes. This is especially true when they are exposed to unsafe and incoherent environments. Braun and Roddin have referred to these groups as "captive pedestrians" (*1*).

In light of these physiological variations among the various groups of pedestrians, the flexibility of the pedestrian as a transportation unit varies considerably. Able-bodied young and middle-aged adults can negotiate through narrow passages, climb over barriers, and overcome hazardous conditions easily. They can "twist, duck, and turn sharply, and . . . can safely extricate themselves in the last few milliseconds before impending impact" (*2*). But "captive pedestrians" find similar situations overwhelming and often threatening, especially when they are exposed to vehicular conflicts. Given these facts, it is important to design pedestrian environments that are coherent and nonthreatening while being stimulating and pleasing for all kinds of pedestrians.

SERVICE LEVEL DESIGN CRITERIA

In the past few decades the pedestrian environment has been besieged by vehicles, and transportation planners and engineers have yielded to the growing demand of space for cars. As a result, the weakest member of the transportation system—the pedestrian—has been severely inconvenienced. On most walkways, designers have ignored the human requirement for space, not only for normal locomotion, but also for visual and psychological interaction (*3*). This unfortunate situation is the outcome of the preoccupation of the engineers and designers with the needs of the vehicular traffic for speed and safety.

Safety accompanied by speed requires wider, smoother, and straighter roads and can become a potent combination, leaving pedestrians and cyclists vulnerable and exposed to vehicular confrontation. This overemphasis on design standards for vehicular traffic stems from the fear of liability. In the United States, roadbuilding agencies accept certain responsibilities for vehicular safety, and design standards help to absolve them from legal battles with road users. These liability issues first surfaced in the late 1950s when motorists injured in accidents sued the roadbuilders, claiming inadequate design or improper construction. Unfortunately, similar issues have not been raised by pedestrians who have been severely inconvenienced by inadequate and hazardous conditions (*4*).

Historically, sidewalks have been the most unregulated part of street rights of way. They are narrow, unevenly surfaced, often in total disrepair, and encroached on by haphazardly placed miscellaneous activities such as convenience stands, gas pumps, cafes, and vending machines. In contrast, every effort has been made to protect the right of way for vehicular traffic and to enhance the comfort and convenience of drivers—allowing right turns on red, wide service and arterial roads, more than adequate turning radii at intersections, shorter red signal phase in the cycle time, and drive-in facilities, to mention a few.

IDEAL PEDESTRIAN ENVIRONMENT

An "ideal" environment would be one where many activities could occur simultaneously without conflicts among users (cyclists, drivers, and pedestrians). There is perfect syno-

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morphism (fitness) between the designed environment and its proposed purpose without spatial interference between activities. In addition to absence of conflicts, the success and failure of the design also depends on the level and the type of use. Insufficient or improper use of the pedestrian facilities is as much of a dysfunction as designed environments with spatial interferences. From this discussion, the success of any pedestrian design can be said to depend on three criteria:

1. *User-friendly environments should offer amenities for various pedestrian groups.* Visual qualities convey powerful emotional messages as to what mode dominates the street scape, and every effort should be made to make it user-friendly for both vehicular and pedestrian traffic. In addition, designers should try to cater to the needs of a pedestrian as a vehicular unit, and to do so they should borrow the functional elements of strip commercial development and introduce them after modification in pedestrian environments. There should also be excellent intermodal connectivity where pedestrians can switch from one mode to the other without much discomfort or inconvenience.
2. *Pedestrian environments should be unique and must blend with the architectural vocabulary of the area.* Standard designs are successful on macro scale when designing for vehicular traffic, but they could be recipes for failure if used in pedestrian environments. Monotonous functional designs of the sidewalk do not help in creating distinct images. Lynch has written about the importance of the "visual quality" or "legibility" of the cityscape—easily identifiable districts and landmarks organized in a coherent pattern in a city (*5*). The same concept applies equally in pedestrian environments. The "legibility" of the surroundings enhances the quality of the pedestrian environments, and the users are offered a plethora of visual stimulation that helps them to create distinct images.
3. *Visually stimulating and exciting environments should capture the spirit of the people and the city.* Pedestrian precincts should be able to provide vignettes of the city, offering users and observers a glimpse of the urban environment. Stimulating environments add character and richness to the streetscape, providing the right ambience for a diversity of activities. The success of the design depends on the perception of the environment, and designers should focus on ways of incorporating excitement and fun in their design while placing the functional elements on the walkways.

To fulfill these three criteria, designers must ensure safety, security, convenience and comfort, continuity, system coherence, and the visual and psychological attractiveness of the environs (*3*). These six qualitative indexes were mentioned by Fruin in *Pedestrian—Planning and Design* and have been used in this paper to develop six service levels.

Vuchic used the term "service quality" as one of the factors that determines the level of service. He defined level of service as the basic element that attracts potential users to the system, and service quality as qualitative elements of service for transit usage (*6*). The same concept is used to define the six service levels for pedestrian usage.

To demonstrate these levels through illustrations, this paper has drawn on examples from different types of walkways that are operational in Munich, Germany, and Rome, Italy. The pedestrians precincts in both cities are used extensively by commuters, tourists, and local residents and provide good examples of pleasant and unpleasant pedestrian environments.

SERVICE LEVEL DESCRIPTIONS FOR WALKWAYS

Service Level A

In Service Level A, the right of way is exclusively for the pedestrians; bicycles may be allowed only when pedestrian areas also encompass roads more than 20 ft wide (Figure 1). There is complete space separation between motorized and nonmotorized transport, eliminating pedestrian-vehicular conflict. The pedestrian network is well-connected, coherent, and comfortable for both able-bodied and captive users.

The built environment is designed and regulated to support diverse human activities and aesthetic experiences. The best way of identifying such environments is by studying the diversity in user activities and the diversity in users.

Safety

There is complete space separation between vehicles and pedestrians in Level A. Bicycles are allowed only when the pedestrian zones also enclose roads more than 20 ft wide, but cyclists are forewarned through prominent signs that pedestrians have first preference. There is no pedestrian-vehicular conflict in such an environment, making it especially safe for physically challenged users.

Security

The security of the pedestrian environment is ensured by the presence of people and police cars. The threat of being caught with very few avenues of escape discourages petty crimes.

FIGURE 1 Service Level A: Marienplatz, Munich—U-bahn and S-bahn stations in pedestrian mall are easily accessed by elevators, enhancing the mall's attractiveness among captive pedestrians.

Convenience and Comfort

The modification in traffic circulation in Service Level A facilitates free pedestrian movement. Large stretches of effective walkway are free from obstacles for easy movement. Ramped curb cuts are provided wherever they are necessary for those who need such assistance.

Underground transit is easily accessible by elevators and escalators. Ticket vending machines and transit information are conveniently located to facilitate the use of transit. Other features that enhance the quality of the environment are the presence of telephone booths, drinking fountains, chairs and benches, and easily accessible public restrooms.

These precincts offer sanctuary from street level noises and air pollution. Pollution-sensitive uses (sitting areas and outdoor cafes) and users (children, elderly, and people with health problems) are protected in such environments. Because the atmosphere is free of vehicular intrusion, the urban ambient sound level varies between 40 and 50 dba.

Continuity

The pedestrian corridor and the major public open spaces appear as a single entity. There are continuous stretches of either space- or time-separated, well-landscaped pedestrian networks connecting historic districts and other places of interests with the shopping areas.

System Coherence

There is excellent connectivity and system coherence brought about by full utilization of the urban space. Streets, transit facilities, shopping areas, and historic buildings are easily distinguishable by their clear visual statements, eliminating the need for constant visual or tactile orientation, and allowing pedestrians to enjoy the sights and sounds about them.

Attractiveness

The pedestrian environment is aesthetically designed and visually pleasing. Street events such as an amateur art sale or acrobatics, and flower shows add vitality to the environment. There is a combination of scale, color, shape, street character, and view to convey the positive visual attributes of the environment.

Service Level B

The right of way in Service Level B is shared by motorized and nonmotorized transportation through physical separation to avoid conflict. Walk widths are more than adequate and free of impediments. The sidewalks are complemented by well-designed components for visual and psychological enjoyment, and special attention is given to the needs of captive pedestrians.

FIGURE 2 Service Level B: Schwabing area on Leopoldstrasse, Munich—effective walkway is wide and uncluttered; ancillary walkway is tastefully landscaped, protecting pedestrians from air and noise pollution while accentuating space separation between pedestrians and cyclists.

The composition in the streetscape design affords a variety of options to the potential users. The landscaping and distance from the vehicular traffic (10 to 15 ft) reduces the noise level to 55 to 65 dba (Figure 2), and the layered arrangement of plants along the broad sidewalks filters the particulate pollutants.

The best way of identifying such environments is by studying the diversity in user activities, and the level of usage by the captive groups.

Safety

Either horizontal or vertical separation among the modes exists to avoid bimodal conflict. Horizontal separation between pedestrians and bicycles or between pedestrians and vehicles may be further pronounced through landscaping, making it even safer for captive users.

Security

The street and sidewalk configurations allow vigilance by pedestrians and patrolling police cars. High lighting levels and unobstructed lines of sight offer very little concealment, thereby reducing the risk of criminal activities.

Convenience and Comfort

The grade-separated pedestrian network with considerable effective walk width free of obstacles provides an ideal environment for walking. In addition, ramped curb cuts are provided wherever necessary for those who need special assistance.

There is excellent intermodal connectivity. Easy access is provided by surface and underground transit, which arrive at short headways. Information on transit schedules and the routes available are posted at each stop for the convenience of transit users; shelters with seating are provided for the comfort of transit users. Bike racks are conveniently placed for those who opt for that mode. Other amenities such as telephone booths, mailboxes, and stamp vending machines are equally accessible from the sidewalks (Figure 3).

FIGURE 3 Service Level B: Isartor, Munich—user-friendly, comfortable pedestrian environment in which facilities such as bus shelters with seating, detailed transit information, and convenience stands nearby make walkway very attractive to users.

Continuity

There are continuous stretches of physically separated, well-landscaped pedestrian networks with more-than-adequate walk widths free of impediments and accessible to captive users.

System Coherence

Excellent system coherence is an important element at Service Level B. The designers afford clear visual statements on the transit facilities, streets, restaurants, and shops, which enable pedestrians (especially the physically challenged) to overcome any directional confusion that may arise and divert their attention to secondary visual inputs such as observing street activities.

Attractiveness

Aesthetic components are not as profusive as in the previous level, as it is very difficult to incorporate all the visually pleasing elements on the ancillary walkways. But within these constraints, much visual variety can be introduced, such as tastefully designed street furniture, interesting patterns on the pavement, and small art pieces.

The positive compatibility components are numerous (*1*). Street furniture is designed to blend with the surrounding architectural vocabulary, and it is arranged to create places where one can step out of the flow of street life for a few moments of rest. Benches and trees, which are classified as passive street furniture, are not placed near the active objects such as mailboxes or telephone booths to afford privacy.

Service Level C

Service Level C right of way is shared by pedestrians and vehicles through physical separation, but the design preference shifts toward vehicular traffic. The walkways have insufficient width to service bidirectional peak traffic flow, and pedestrians must make adjustments to avoid conflicts while walking. The pedestrian environment begins to get uncomfortable and strenuous for the physically challenged, who must make major adaptations to negotiate through the traffic.

The planned changes on the streetscape design have increased service quality for the vehicular road users. The wide roads and turning radii have resulted in higher speeds and greater traffic volumes. But this has harmed the pedestrian environments, introducing higher noise levels (65 to 90 dba) and greater concentration of particulate matter and toxic emissions in the air.

The diversity in user activities (window shopping, sitting, and watching) is considerably limited, and the level of use by captive groups begins to decline in Level C.

Safety

Physical separation still ensures safety from vehicular conflict. But the impediments on the effective walkways accompanied by continual streams of bidirectional flows may intimidate captive users, who must negotiate a far greater number of obstacles to reach their destinations.

Security

The street and sidewalk configuration provides clear lines of sight for patrolling police cars. The pedestrian density is considerable, providing safety in numbers, and the nonconventional users (homeless, panhandlers) do not affect usage; also, the adjacent buildings face the streets, affording a sense of security.

Convenience and Comfort

The walkways are unable to cope with bidirectional peak traffic flow; as a result, minor adjustments must be made by even able-bodied pedestrians. The effective walk width is indistinguishable from the ancillary walk width, and impediments obstruct free flow. A case in point is Figure 4, where

FIGURE 4 Service Level C: Via Navicella, Rome—walkway is incapable of coping with complex pedestrian traffic configuration because of bus stop; at this level, designers' focus has shifted in favor of vehicular traffic; captive pedestrians find such environments arduous and uncomfortable.

the walkway has not been widened to accommodate the changes in traffic configuration resulting from a transit stop. The intermodal connectivity is not as coherent as at the previous level, and pedestrians opting for other modes (transit or bicycles) may be inconvenienced.

Minimum effort is made to upgrade the pedestrian environment. Facilities such as bus shelters, convenience stands, and telephone booths are not available. The comfort levels start to drop because of high noise decibels, air pollution from the vehicular traffic, and poorly surfaced walkways (Figure 4).

Captive users find these walkways uncomfortable and inconvenient. They must make major adjustments to weave through bidirectional flows on uneven pavements, with curb ramps that are few and far between.

Continuity

Continuous stretches of sidewalks exist, but they often have variable widths and poor design standards completely unsuitable for physically challenged users.

System Coherence

The perception of urban space becomes less coherent in Level C, and pedestrians, particularly those with disabilities, feel uncomfortable with the visual statements that guide them. They are primarily concerned with orientation and direction, with limited receptivity to sensory gradients such as color, light, ground slope, smells, sounds, and textures (*3*). This is especially true for physically challenged users and the elderly, who have to weave through bidirectional traffic.

Attractiveness

Mediocre design standards prevail, according very little importance to aesthetic components of walkways. There may be a piecemeal approach to incorporate artistic elements into the street space, but no concerted effort is made to infuse vitality into the pedestrian environment as the primary focus of the designers is to create service quality for the vehicular traffic.

Service Level D

Physical separation still exists for pedestrians and vehicles in Service Level D, but not between pedestrians and bicycles, so there is a greater risk of conflicts between these two modes. The risk factor increases further because of the reduction in effective walk width and the obstructions from street furniture and other impediments. The pedestrian walkways become increasingly inhospitable toward the elderly and the physically challenged users, to the point that many avoid using them. Such situations are illustrated in Figures 5 and 6.

FIGURE 5 Service Level D: intersection of Leopoldstrasse and Schellingstrasse, Munich—effective walk width reduced by improper placement of street furniture and illegal bicycle parking; environment is hazardous for physically challenged pedestrians.

The planned changes on the streetscape design continue to increase service quality for the vehicle road users; the sidewalks are created on leftover spaces and the users must share the narrow right of way with impediments such as gas stations (common in Italy), parking meters, trash cans, and cyclists. The negative compatibility characteristics—such as higher noise decibels (65 to 90 dba), greater concentration of toxic emissions, and poor pedestrian path continuity—become increasingly prevalent.

The diversity in user activities is limited to walking out of necessity, and the level of use by captive groups declines sharply.

Safety

Physical separation between motorized transportation and pedestrians reduces the risk of pedestrian-vehicular conflict, but the streetscape design encourages cyclists to use sidewalks, increasing the odds of pedestrian-bicycle conflicts. Captive pedestrians are particularly at risk owing to their slower reflex actions to imminent conflicts.

FIGURE 6 Service Level D: Schellingstrasse, Munich—pedestrian environment is visually boring, walled up on one side and parked cars on the other; cyclists and pedestrians are using same right of way, making it especially unsafe for captive groups.

Security

The sidewalk configuration and parked cars may inhibit vigilance from the streets at some stretches: however, this is offset somewhat by the presence of other pedestrians during the daytime. But in the evening, sharp turns or bends on the walkways create blind spots along some stretches where pedestrians may be vulnerable to assaults.

Convenience and Comfort

Pedestrians (especially captive users) are inconvenienced because the environment is far from being user-friendly, because of

- Improper placing of street furniture (phone booths, trash cans, mailboxes);
- Obstructions resulting from illegal parking of bicycles and improper positioning of convenience stands, phone booths, and gas stations;
- Inadequate design standards for transit stops and access to the subway;
- Conflicts with bicycles using the same right of way; and
- Lack of ramped curb cuts or clearly marked handicap access areas for those who need assistance.

There is poor intermodal connectivity because switching from walking to any other mode (or vice versa) is not convenient and smooth. This marked drop in convenience and comfort puts stress even on able-bodied pedestrians, and the frequent stops and maneuvers to avoid conflicts increase travel time.

Continuity

The pedestrian corridors are not well connected, and continued stretches of sidewalk are no longer guaranteed. The possibility of several breaches in the pedestrian network, leading to complete disorientation, is highly probable.

System Coherence

The perception of the urban street becomes increasingly incoherent because of confusing directional signs and other visual statements. Confusion and complexity are further heightened by the fear of collision with bicycles. The pedestrian's attention is fully focused on primary visual inputs of orientation and avoidance of impending collision.

Attractiveness

The designers have ignored pedestrians' need for visual and psychological interaction with the milieu. The pedestrian environment is poor in service quality, prohibiting diversity of uses. The mental image and the legibility of the environments are indistinct, and users associate such environments with negativity. Cognitive maps drawn by users indicate their complete disassociation with the milieu.

Service Level E

The streetscape design in Service Level E favors vehicular traffic. The roads are widened at the expense of the sidewalks, reducing the effective walkway width to a bare minimum that does not even support off-peak bidirectional flow without conflict with vehicular traffic. This level exemplifies one of the poorest design standards, in which the needs of captive users have been completely disregarded.

The negative compatibility characteristics—such as higher noise decibels (65 to 90 dba), larger concentration of toxic emissions, poor pedestrian path continuity, increased vehicular traffic, and unpleasant contrast between facilities and the existing architectural styles—become glaringly prominent (Figure 7).

The level of use drops significantly and is limited to walking through these stretches out of necessity. This level also offers one of the poorest examples of intermodal connectivity, and people prefer to use vehicles over other modes.

Safety

All groups of pedestrians feel threatened by the prospect of probable vehicular conflict because of poor service levels on the walkways. The horizontal grade separation is unable to eliminate conflicts with vehicular traffic because the effective walk widths are incapable of supporting bidirectional flow.

Often the continuity of grade separation is breached and pedestrians must negotiate through parked cars or turning vehicles, which are especially formidable obstacles for captive pedestrians (Figure 8).

Security

The proximity to moving vehicles may increase the number of drive-by crimes (purse-snatching, assaults on women), and pedestrians may have very few avenues of escaping such confrontations. Also, infrequent use of the walkways makes these stretches even more susceptible to criminal activities.

FIGURE 7 Service Level E: near Colosseum, Rome—streetscape favors vehicular traffic; bare minimum walkway provided, capable of supporting unidirectional flow in single file; bidirectional flow may result in conflict with vehicular traffic; unsuitable for physically challenged pedestrians.

FIGURE 8 Service Level E: near Roman Forum, Rome—pedestrians must negotiate through parked cars to reach other end of sidewalk; especially hazardous environment for captive pedestrians.

Comfort and Convenience

Facilities that afford comfort and convenience are nonexistent; designers have overlooked the needs of the users and have made no effort to improve the walking conditions. At this level, all pedestrians need to make major adjustments, such as accepting violation of personal space or stepping on to the road to enable bidirectional flows.

Walking is no longer pleasurable and comfortable, and those who do walk are thoroughly inconvenienced by the obstacles, noise, and emissions from the vehicular traffic, along with close confrontations with vehicular traffic.

Continuity

The prevailing design standards prepare pedestrians for the possibility of several breaks in the continuity. Figure 8 shows a distinct breach in the continuity of the sidewalk, where the pedestrians have to negotiate through parked cars to reach the other end of the sidewalk. Such discontinuity causes very poor visual and psychological interaction and may prove to be disastrous for captive pedestrians (especially for the blind).

System Coherence

Pedestrians' perceptions of urban space falter, and pedestrians may devote sensory awareness entirely to the task of restrained locomotion to avoid collision with pedestrians ahead. This occurs mainly because the pedestrians are not assured of their primary concern of orientation and direction, as was seen in Figure 7, where the stream of pedestrians show no interest toward the Colosseum in Rome and appear preoccupied with walking.

Attractiveness

The walkway ceases to be an aesthetic component of the streetscape, offering nothing in the form of diversity and variety. This level exemplifies designers' complete disregard for integrating the pedestrian mode as a major component of the transportation network, thereby overlooking the need to provide the right ambience for walking.

FIGURE 9 Service Level F: near monument of Vittorio Emannuel, Rome—pedestrian needs have been totally disregarded, and pedestrians have been exposed to direct confrontation with vehicular traffic; hazardous for all pedestrian groups.

Service Level F

Service Level F is the worst-case scenario, in which designers have not provided any distinctly separate right of way for the pedestrians, and preference is given only to vehicular traffic. The streetscape design facilitates vehicular movement, placing severe restrictions on pedestrian movement. The safety of pedestrians has been overlooked, and they are either exposed to fast-moving vehicular traffic or forced to negotiate through a maze of parked cars. Captive pedestrians find such environments particularly intimidating and life-threatening. The security for the pedestrians is undermined by the streetscape configuration; physical assaults and hit-and-run accidents are not uncommon.

In such situations the pedestrians feel totally disoriented, confused, and thoroughly inconvenienced. There is complete breakdown in the pedestrian traffic flow, as each pedestrian selects a different route to avoid direct vehicular conflict. They can best produce indistinct cognitive maps of their environs and can share only their experiences of discomfort and intimidation as collective memories (Figure 9).

CONCLUSION

City planners in ancient and medieval times were cognizant of the human need to communicate and interact and made every attempt to enable such social exchange. The architects and planners of those times were equally concerned with convenience and comfort of the pedestrians. The same principles of convenience, comfort, safety, security, and aesthetics are still applicable today.

The best pedestrian environment would accord exclusionary rights to pedestrians: prohibiting vehicular traffic and providing an environment rich in qualitative elements for diversified pedestrian activities. Unfortunately, such ideal conditions can be found only in certain sections of the city and can never be implemented on a large scale. So a more realistic solution would be to foster pedestrian areas with Service Level B, where the right of way is shared by different modes through horizontal and vertical grade separation and attention is given to make the pedestrian environment user-friendly, particularly for captive pedestrians.

Designers should upgrade all pedestrian walkways to Service Level B, and Service Level A where possible. Service Level C can be acceptable only where further improvements would cause major changes in the building configuration and the vehicular traffic flow, but designers should provide ramps on curb cuts and other facilities to ameliorate the conditions for physically challenged users.

Service Levels D and E need major structural and design changes after research and data collection. Service Level F exemplifies the total apathy of transportation planners and designers toward the needs of pedestrians. Such environments should be classified as hazardous areas needing immediate attention.

One of the major problems with streetscape design is that traffic planners and designers ignore the importance of intermodal connectivity and the facilities that enhance such transfers. The service levels proposed in this paper provide a valuable tool to evaluate and improve the most important link for efficient modal transfers—walkways—to ensure an efficient transportation system.

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Modeling Pedestrian Volumes on College Campuses

Laura L. Cove and J. Edwin Clark

A study was undertaken to develop a reliable method for obtaining reasonable estimates of pedestrian volumes on college campuses using short-term volume counts. Pedestrian volume data were collected on the campuses of five colleges and universities in the southeastern United States. The short-term pedestrian volume data collected on the five college campuses were expanded using existing models and analyzed to test the validity of these models. The average sums of the errors between the observed and predicted pedestrian volumes calculated from the existing models were compared with the percentage errors calculated for the additional data collected from the college campuses. The percentage errors were not found to be statistically the same, thus the existing models are not valid for use in expanding short-term pedestrian volume counts on college campuses. Using a random sample of the pedestrian volume count observations from the college campuses, additional expansion models were developed. These models were chosen on the basis of the evaluation of the parameters of the coefficient of determination, R^2, and the standard error about the mean, SE_y. These new models were validated using the remaining data that had not been incorporated into the development of the new models. On the basis of the analysis of the data from the college campuses, the following conclusions were made: (a) existing expansion models were not valid for predicting pedestrian volumes on college campuses, (b) the count interval should be started 10 min before the beginning of class periods, (c) accuracy increased as the volume count period increased, and (d) accuracy increased as the prediction volume range increased.

The increased national awareness on behalf of the pedestrian in recent years has prompted an increase in the amount of research dealing with pedestrian safety issues. However, only a few such research projects were conducted in order to develop a reliable method for measuring pedestrian volumes. Estimates of pedestrian volume counts are needed to evaluate pedestrian safety. To obtain an effective analysis and to determine the relative hazard of various pedestrian behaviors, comparisons must be made between pedestrian behavior during accidents and normal, non-accident pedestrian behavior. The normal, non-accident behavior is designated as pedestrian exposure information. Usually to obtain this exposure information, manual pedestrian volume counts must be taken. Since these counts are typically undertaken for an entire day, they are very labor intensive and thus very costly. Other techniques for obtaining pedestrian volume counts include sampling over shorter time periods and using automated counting devices and analytical methods. However, with the exception of manual pedestrian counting, none of these techniques has been universally accepted by the research or user community.

PURPOSE AND OBJECTIVES

In an attempt to reduce the costs of collecting data on pedestrian volume, a method developed by Mingo et al. uses the practice of making short sample counts of pedestrian volumes that can be expanded to represent daily volumes through the use of appropriate expansion factors (*1*). The purpose of this study was to examine actual daily pedestrian volume counts of pedestrians on selected college campuses and test the validity and reliability of pedestrian volumes obtained through the use of the existing expansion models.

To accomplish the purpose of this study, the following objectives were established:

1. Identify specific sites and collection of field data consisting of pedestrian volumes for 5-min increments at five college campuses,
2. Expand sample field data through the use of existing expansion models based on the count interval and level of accuracy desired,
3. Perform statistical analysis of the actual data and the expanded data to check the validity of the expansion model, and
4. Develop additional expansion models that accurately predict pedestrian volumes on college campuses from short-term volume counts.

METHOD OF INVESTIGATION

The study was conducted by first identifying a particular segment of the population on the basis of one characteristic of the population. This chosen characteristic is age, and the ages being studied range from 17 through 24. The individuals within this age range make up 11 percent of the total population of the nation.

Normally, it is extremely difficult to conduct a study that requires the isolation of a particular segment of the population, including the aforementioned age range. However, most pedestrians 17 through 24 are concentrated on the campuses of colleges and universities throughout the country. According to the *Almanac of Higher Education*, of the 247,732,000 persons in the United States, 12,768,307, or 5.2 percent, attended a 2- or 4-year college or university in 1989 (*2*). The primary mode of travel on the campuses of colleges and

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universities is that of walking, so there is a high density of pedestrian movement at these locations. Pedestrians on campuses exhibit fairly uniform pedestrian characteristics. In addition to similar ages, these pedestrians have common trip purposes and predictable flow variations by time of day on the basis of class schedules. Because of these similar characteristics and the fact that these pedestrians are isolated within a relatively small geographic area of a region, city, or town on a campus, similar traffic patterns exist.

On the basis of similar characteristics, five universities were selected for field data collection: the University of Miami (Coral Gables, Florida), the University of Georgia (Athens), the College of Charleston (Charleston, South Carolina), Clemson University (Clemson, South Carolina), and the University of South Carolina (Columbia).

The data on pedestrian volumes were collected on Fridays during March and April 1991. Pedestrian count volumes were totaled and recorded in 5-min intervals for 12 hr, beginning at 7:00 a.m. and continuing through 7:00 p.m., on each campus. The data were then input into the models developed by Mingo et al., and the percentage errors were calculated by comparing the actual data with the expanded model data (*1*). These errors were then compared with the errors computed by Mingo et al. (*1*). Significance tests were used to determine whether the errors were statistically the same, therefore testing the validity of the models. If the models were not found to be valid, additional expansion models were to be developed using random samples of the observations from the college campuses. The validity of these additional models would be tested using data from the college campuses that had not been incorporated into the development of the models.

METHODOLOGY

Today three methods are generally recognized for measuring pedestrian volumes: mechanical counts, mathematical models, and manual counts. Several mechanical pedestrian counters have been developed and tested, but unfortunately they have not been widely accepted because of their excessive cost and various installation problems. Mathematical models are usually site specific, and the accuracy of the model depends on the type and amount of data collected. As the complexity and accuracy of the model increases, the data collection costs rise rapidly. Thus, the most commonly used method for obtaining pedestrian volume counts is manual counting, a procedure that is labor-intensive and therefore expensive.

College campuses throughout this country and others exhibit a unique problem. Large volumes of pedestrian traffic on these campuses must compete with automobile traffic. Most college campuses are designed with the intention of creating a park-like area within the boundaries of the university community. The presence of automobile traffic presents potential hazards to pedestrians and threatens the relaxed atmosphere.

Pedestrians on college campuses have different characteristics from pedestrians in a central business district or shopping district. The pedestrians' ages generally range from 17 to 24. Their flow variations and the purpose of their trips are predictable depending on the time of day.

Because of the large volume of pedestrian traffic that occurs on most university campuses, special techniques must be applied to provide for safe and efficient movement of persons traveling through the campus by this mode.

COLLECTION OF DATA

Introduction

The data used by Mingo et al. in developing the pedestrian volume expansion models were collected entirely in Washington, D.C., which creates the possibility of a limitation in the models by using data from only one city. There has been no determination that the expansion models are valid when used in another city that exhibits different characteristics than Washington does. To test the validity of these expansion models, data were collected at several sites and then input into the models, thus testing the validity by comparing the percentage errors calculated in the study by Mingo et al. with the percentage errors calculated for the additional data. If these percentage errors are found to be statistically similar, then the models developed previously would be validated. It was decided then to collect pedestrian volume data on the five college campuses in an attempt to verify the validity of the expansion models.

Data Collection Method

Pedestrian volume data were collected on Fridays during March and April 1991 at the five universities. Fruin suggested counting pedestrian volumes on "typical" days, free from the distortions of weather and other seasonal effects (*3*,p.122). Unusually hot, cold, or inclement weather keeps people off the streets and away from the counting area.

The locations of the collection sites at the universities were selected to ensure that pedestrian volumes were large enough to allow enough data to be collected within the limited resources of the study. A 100 percent sample of pedestrians crossing the location was taken at each site during each 12-hr data collection period. These 12-hr samples consisted of continuous counts that were made at each site by one data collector from 7:00 a.m. until 7:00 p.m. Pedestrian volumes were counted for 12-hr periods to ensure that all volumes during the peak travel times would be encompassed within the data. Figure 1 shows the variation in pedestrian volumes by hour of day for each of the campuses. Pedestrian volumes exhibited maximum peaking from 10:00 a.m. to 1:00 p.m.

Pedestrian volumes were recorded every 5 min of the 12-hr period. The crossing volumes were recorded either by crosswalk or by each leg of the intersection, and a total volume for the intersection was then calculated.

ANALYSIS OF DATA

Introduction

The data collected on the five college campuses were expanded using the models developed by Mingo et al. and an-

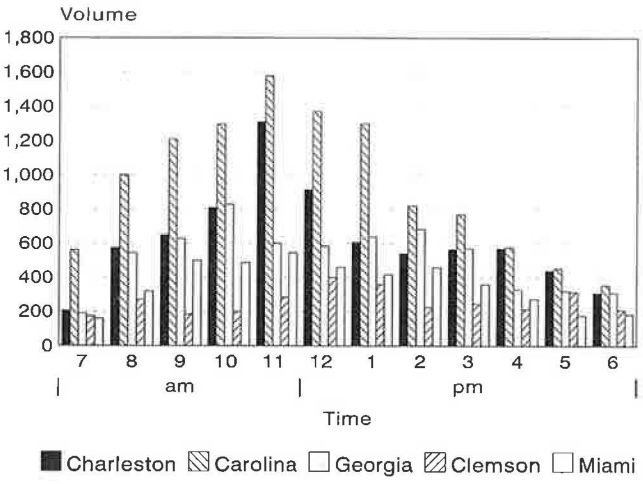

FIGURE 1 Pedestrian activity on college campuses.

alyzed to test the models' validity. The percentage errors calculated in the study by Mingo et al. were compared with the percentage errors calculated for the additional data. If these percentage errors were found to be statistically the same, then the models developed previously would be valid. Because these models did not produce suitable results, additional models were developed using a random sample of the pedestrian volume count observations from the college campuses. The new models were validated using the remaining data from the college campuses that had not been incorporated into the development of the models. Dependent on the results obtained through the use of either the existing models or the newly developed models, a reliable method for obtaining reasonable estimates of pedestrian volumes on college campuses was endorsed.

Pedestrian Volume Count Expansion Procedure

A seven-step procedure was used in the study of the five college campuses to develop the estimating procedure:

1. Select time period to estimate pedestrian volumes.
2. Select the count interval.
3. Develop data collection plan.
4. Collect data.
5. Select expansion model.
6. Compute estimated pedestrian volumes.
7. Determine estimated pedestrian volume ranges.

Verification of Validity of Existing Models

The collection of pedestrian volume data on the five campuses resulted in 60 hr of pedestrian volume data. Data were collected continuously every 5 min for 12 hr at each site, yielding a data base of 720 observations. In testing the validity of the 1-, 2-, 3-, and 4-hr expansion models developed by Mingo et al. (*1*), random intervals of 5, 10, 15, and 30 min were input into the appropriate models and 1–, 2-, 3-, and 4-hr volume predictions were calculated. For various predicted volume ranges, the average percentage differences were calculated for each count interval expansion model.

The research by Mingo et al. evaluated several count intervals and the position of the events within the interval. For all count intervals, the middle event produced a slightly better model since it exhibited the highest coefficient of determination (R^2) and the lowest standard error about the mean (SE_y). Since these models were developed in a large metropolitan area, the pedestrian volumes were fairly uniform throughout the hour and the entire day. On college campuses, the pedestrian traffic is dependent on class schedules, thus it is conceivable that the placement of the interval within the hour could have a significant effect on the accuracy of the expanded count. Haines et al. analyzed pedestrian volumes on the Boulder campus of the University of Colorado and determined that in all the volume counts, the peak periods were from 10 min before the beginning of the class periods until 5 min after classes began (*4*). Because fewer classes are scheduled in the late afternoon than in the morning, the afternoon volumes were less variable and thus a better predictor of normal flow.

On the basis of the recommendation by Haines et al., the placement of the intervals of the 5-min volume counts to be input into the models was selected to be 10 min before the beginning of classes. The predicted volumes were calculated using the expansion models and procedures of Mingo et al. described earlier and then compared with the observed pedestrian volumes. Percentage errors were calculated by subtracting the predicted volumes from the observed volumes and dividing by the observed volumes. The absolute value of the average sums of the errors between the observed and predicted pedestrian volumes for each of the count intervals that corresponded to the given volume ranges was computed. Basically, these factors are percentages that indicate the relative levels of accuracy of an expanded sample crosswalk count.

One method used to test the ability of the expansion models developed by Mingo et al. to predict accurate pedestrian volumes on college campuses is to compare these range factors for both sets of data. If the percentage errors, represented by the range factors, are found to be statistically the same, then the existing models are valid.

Because the sample sizes of the data are different, a statistical test that incorporates sample size had to be used. For the 1-, 2-, 3-, and 4-hr expansion models, hypothesis testing was performed. For the 1- and 2-hr models, z-tests were performed because the sample size was greater than 30, and t-tests were performed for the 3- and 4-hr models because the sample size was less than 30. To determine which of the expansion models were valid, these tests were done for each range factor corresponding to the count interval and the predicted pedestrian volume. Therefore, 27 individual hypothesis tests were performed.

Development of Additional Models

Even though the existing models appeared to produce fairly good results as far as the range factors were concerned, they were not proven to be valid for predicting pedestrian volumes on college campuses. The flow of pedestrians on college campuses is predictable on the basis of variations of time of day, but it is not as uniform as pedestrian flow in a large metropolitan area, such as Washington, D.C., where the existing models were developed. Additional models should be developed with a primary focus on these models' ability to accurately predict pedestrian volumes on college campuses.

In the initial stages of the model development, the data distributions were reviewed and it was determined that all the variables showed positive skewness. In order to perform a regression analysis on the data, the data must be normally distributed. The data could be analyzed using a distribution free nonparametric test, or the data could be transformed so that parametric tests could be performed. The use of parametric tests is more desirable since such tests are more powerful than nonparametric tests. Some statisticians have used transformation processes to normalize their data when normality of data is required, even though other statisticians argue that this transformation process is not completely understood and is nothing more than a manipulation of the data to fit the model. For this study, the logarithms were calculated for all observations for all of the variables in order to transform the data to produce a normal distribution.

Regression analysis was performed on all four count intervals. Two-thirds of the observations of the pedestrian volume data from the college campuses were used to develop these models, and the remaining third were used to verify the models and to develop the range factors associated with the expansion models. The count interval beginning 10 min before classes started was used in the development of all the expansion models. Using the ability of the Quattro Pro software package (*5*) to perform regression analysis, 16 models were developed using the pedestrian volume data from the five college campuses. Table 1 was constructed to examine the R^2 and SE_y for each count interval for all of the models.

By examining the values represented in Table 1, an estimate of how well the data fit the models can be determined. SE_y is the estimated standard error of the y-values and represents the deviation of the observed y-values from the values of the linear combinations represented in the models. R^2 is a statistic that measures the validity of the model. It ranges from 0 to 1, 1 being perfect correlation. It is apparent that as the count interval increased from 5 to 10 to 15 to 30 min, the prediction models became more reliable, as expected since the variation between the count intervals decreased as the count interval increased.

TABLE 1 Regression Output of College Campus Prediction Models

Prediction Model	Count Interval (min)			
	5	10	15	30
1 hr				
R^2	.80	.88	.92	.91
SE_y	.11	.08	.07	.07
2 hr				
R^2	.86	.91	.93	.93
SE_y	.09	.07	.06	.06
3 hr				
R^2	.83	.91	.96	.96
SE_y	.09	.06	.04	.04
4 hr				
R_2	.86	.93	.95	.96
SE_y	.09	.06	.05	.05

RESULTS

Models Developed for Use on College Campuses

Models were developed for the purpose of predicting pedestrian volumes on college campuses by expanding short-term counts. These models were chosen on the basis of the evaluation of the parameters of R^2 and SE_y. The expansion models developed for the count interval beginning 10 min before the start of classes are presented in Figure 2.

Validation of College Campus Expansion Models

To have data available to validate these new models, several observations were excluded from the modeling effort. Twenty observations were used in the validation of the 1-hr models, 10 observations in the 2-hr models, 10 observations in the 3-hr models, and 5 observations in the 4-hr models. All four counting intervals—5, 10, 15, and 30 min—were studied for each model.

The primary use of the validation of the models was to determine the percentage error in the predictions of the pedestrian volume counts. The value of SE_y is used for this purpose, since SE_y bands diverge at the ends of the regression line as the values of X move away from the mean of X ($\bar{X}$). The SE_y bands may become extremely separated when X moves far away from $\bar{X}$, and thus renders the SE_y meaningless. Therefore, the use of percentage change between actual and predicted volume counts was used to determine empirically the error or prediction ranges associated with the expansion models.

For various predicted volume ranges, the average percentage differences were calculated for each count interval in each expansion model. These range factors are presented in Table 2. The volume ranges increased in size as the expansion model increased from 1 to 2 to 3 to 4 hr because of the increase of the volume sizes being predicted and the number of observations per range.

To use these prediction range factors, first select the volume level (row) that corresponds with the count period and the estimated volume from Step 6. Select the sample count interval (column) that was used. Read the prediction range factor, and the estimated volume range will be the estimated volume (Step 6) plus or minus the prediction range factor multiplied by the estimated volume. An example to illustrate this process is shown in the following.

Using a 5-min count, predict the 4-hr pedestrian volume prediction. A 5-min count might be equal to 50 pedestrians, therefore $I5 = 50$. The appropriate expansion model to use for a 4-hr pedestrian volume prediction on the basis of a 5-min volume count from Figure 2 is $V4 = \text{INVLOG}\ [.74408 \log (I5) + 2.047303]$. The estimated volume will be equal to 2,049 persons per 4 hr. The range of values that one may assume the value will actually fall is equal to 2,049 plus or minus 23 percent of 2,049, where 23 percent is obtained from

```
One-Hour Prediction

      PED5M:   V1  = INVLOG [0.709564 log (I5) + 1.5108]
        where  V1  = one-hour prediction in persons per hour
               I5  = the specified five-minute count

     PED10M:   V1  = INVLOG [0.749178 log (I10) + 1.241982]
        where  I10 = the specified ten-minute count

     PED15M:   V1  = INVLOG [0.808811 log (I15) + 0.996939]
        where  I15 = the specified 15-minute count

     PED30M:   V1  = INVLOG [0.902426 log (I30) + 0.55304]
        where  I30 = the specified 30-minute count

Two-Hour Prediction

      PED5M:   V2  = INVLOG [0.743682 log (I5) + 1.749562]

     PED10M:   V2  = INVLOG [0.76066 log (I10) + 1.514637]

     PED15M:   V2  = INVLOG [0.896754 log (I15) + 1.296608]

     PED30M:   V2  = INVLOG [0.897296 log (I30) + 0.864096]
        where  V2  = two-hour prediction in persons per two
                     hours

Three-Hour Prediction

      PED5M:   V3  = INVLOG [0.79884 log (I5) + 1.835829]

     PED10M:   V3  = INVLOG [0.840315 log (I10) + 1.541358]

     PED15M:   V3  = INVLOG [0.879492 log (I15) + 1.325787]

     PED30M:   V3  = INVLOG [0.992658 log (I30) + 0.807528]
        where  V3  = three-hour prediction in persons per
                     three hours

Four-Hour Prediction

      PED5M:   V4  = INVLOG [0.74408 log (I5) + 2.047302]

     PED10M:   V4  = INVLOG [0.762558 log (I10) + 1.811265]

     PED15M:   V4  = INVLOG [0.797503 log (I15) + 1.618377]

     PED30M:   V4  = INVLOG [0.908667 log (I30) + 1.138706]
        where  V4  = four-hour prediction in persons per
                     four hours
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FIGURE 2 Prediction models used for expansion of short-term volume counts on college campuses.

Table 2. The 4-hr pedestrian volume prediction will therefore be between 1,577 and 2,520.

In reviewing the table, it is seen that the percentage error decreased as the count interval increased in all cases but two. As was determined earlier, during the modeling effort, the longer count intervals had higher values of R^2 and appeared to be better predictors of accurate pedestrian volumes. The previous finding was supported here, since the average percentage differences decreased as the count interval increased.

As the volume ranges increased, the percentage error was reduced except for the 3-hr prediction model. At low-volume sites, the flow of pedestrians is often erratic, thus causing large peaks and valleys over short time intervals. Cameron estimated that the probability of sampling at a volume peak or valley was approximately 50 percent, thus decreasing the potential of obtaining a true representative sample of the overall volume (*6*). At a site with high pedestrian volumes, the flow is more uniform from one time interval to the next, therefore a sample taken from a high-volume site is often more representative of the accurate volume than a sample taken from a low-volume site.

It would also appear that as the prediction period increased from 1 to 2 to 3 to 4 hr, the prediction would become less accurate on the basis of the variation that exists with small sample intervals. However, in the college campus prediction models, the opposite was true, and as the prediction period

TABLE 2 Accuracy of Predicted Pedestrian Volumes Using College Campus Prediction Models for 1-, 2-, 3-, and 4-hr Predictions

Pedestrian Volume Level	Range Factor (%)			
	Count Interval (min)			
	5	10	15	30
1-hr prediction				
0–500	33	32	20	16
> 500	22	18	16	8
2-hr prediction				
0–500	27	31	20	10
> 500	25	20	12	10
3-hr prediction				
0–1,500	24	14	6	18
> 1,500	28	27	26	14
4-hr prediction				
0–1,500	23	20	14	11
> 1,500	23	19	11	8

increased, the predictions became more accurate. The reasons for this occurrence are that for a 1-hr prediction, an individual 5-, 10-, 15-, or 30-min interval was input into the expansion model, whereas with a 2-hr prediction, two intervals were averaged and input into the expansion model. For the 3-hr prediction, three intervals were averaged and input into the model, and for the 4-hr predictions, four intervals were averaged and input. This averaging of the intervals practically eliminated the possibility of sampling during a peak or valley, thus reducing the variation of the pedestrian volumes and producing a better estimate of the pedestrian volumes than did the actual volumes.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the use of expansion models in predicting pedestrian volumes on college campuses has shown promise. With respect to practicality, the pedestrian volume sampling method offers a technique that results in a significant savings of time and effort.

On the basis of the results obtained in this study, the following conclusions relative to the use of expansion modeling for accurately predicting pedestrian volumes on college campuses were developed:

1. Expansion modeling from short-term pedestrian volume counts is a promising alternative to direct observation manual counting on college campuses.
2. The counting interval position for use in expansion modeling should be 10 min before the beginning of class periods.
3. The volume predictions became more accurate as the counting period increased from 1 to 2 to 3 to 4 hr.
4. The accuracy of the prediction models also increased as the prediction volume range increased, because at low-volume sites, an erratic occurrence of volume peaks and valleys was apparent.
5. The 1-hr error estimates are fairly high, and thus since 1-hr counts are fairly economical to obtain, direct manual counting for this period is suggested.

On the basis of the study described herein, the following recommendations were developed:

1. Additional research should be undertaken by collecting data at several universities for further testing of the validity of the models developed in this study.
2. Data may also be collected at the five universities selected in the development of this model and used to develop additional models that could be compared to test the reliability of the models developed in this study.
3. The models may also be tested by selecting positions of the counting intervals that have positions different from the recommended period 10 min before the beginning of classes.

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Characteristics of Pedestrian Accidents in Selected Cities of Saudi Arabia

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Pedestrian accidents are a serious safety problem in Saudi Arabia. Statistics indicate that in 1986, 16 percent of motor vehicle accidents in Saudi Arabia involved pedestrians. A lack of detailed local pedestrian accident data makes it difficult to understand the nature of the problem, so a better understanding of the pedestrian safety problem is sought through the analysis of a pedestrian accident data set gathered specifically for such research. The data needed were collected following special arrangements with the traffic police departments of two large cities, Dammam and Riyadh, and two small cities, Qasim and Qatif. The analysis of the data indicated that although some characteristics of the pedestrian safety problem were common to all four cities, each city also had unique problems. Smaller cities appear, in general, to have a more serious problem than larger cities. The Saudi Arabian pedestrian accident experience is markedly different from the U.S. experience in some respects and almost identical in others.

Accidents involving pedestrians and motor vehicles represent a serious safety problem in Saudi Arabia. Existing statistics indicate that in 1986, 16 percent of Saudi Arabian motor vehicle accidents involved pedestrians (*1*). In the United States, pedestrian-related accidents constituted only 0.4 percent of motor vehicle accidents but 18 percent of the motor vehicle fatalities in 1988 (*2*). Although the existing statistics in Saudi Arabia do not indicate the percentage of pedestrian fatalities relative to the total motor vehicle fatalities, it is not difficult to appreciate the seriousness of the pedestrian problem in Saudi Arabia in comparison with the United States.

The lack of detailed pedestrian accident data in Saudi Arabia makes it difficult to understand the nature of the problem and recommend countermeasures. This study was performed as part of a larger study (*3*) related to pedestrian safety and aims to obtain a better understanding of the pedestrian safety problem through the analysis of pedestrian accident data.

DATA COLLECTION

Detailed Saudi Arabian pedestrian statistics are not available on a routine basis because there is no well-developed accident reporting system. Therefore, for this study, the traffic police departments (the entities responsible for collecting accident data) of four cities were asked to provide pedestrian accident data. These cities are the capital, Riyadh, at the center of the country; Dammam and Qatif, which are on the east coast; and Qasim, which is 200 km northwest of Riyadh. The populations and sizes of the cities are given in Table 1.

These cities were selected because they form two contrasting classes. The first class includes Riyadh and Dammam, which are more developed than the cities of the second class, Qasim and Qatif. Furthermore, the former cities have large urban areas and their development pattern is dispersed, unlike Qasim and Qatif, whose populations cluster in remote small villages and densely populated city centers. Therefore, it is expected that urban travel depends on the vehicle in Riyadh and Dammam, whereas walking is more predominant in the urban Qasim and Qatif. These four cities exhibit an equal average automobile ownership rate estimated at 0.6 automobiles per person (*1*,*4*).

The traffic departments in Riyadh, Dammam, and Qasim were able to extract pedestrian accident information from the original accident forms that they began using recently. A special arrangement was made with the Qatif police department, which started collecting pedestrian accident data following the request of the study team.

Because of variations in the methods of accident data collection among the four areas, there are some differences in the levels of detail of accident data as well as the length of the reporting periods. Because of these differences, the common parts of the data were analyzed first and the finer details (which were available in the Qatif and Riyadh data) were analyzed separately. The duration of data collection and total numbers of accidents, together with other information, are given in Table 2.

The authors realize that the analysis periods for all the cities are short and therefore suggest that the results presented should only be considered preliminary, needing further verification with future data analysis. On the other hand, some useful information emerged from the data, as will be explained.

ANALYSIS OF DATA

The analysis of the collected data was performed in two stages for the reasons given earlier. First the analysis of the data for common information is presented, and it is followed by the presentation of some finer details, obtainable for Qatif and Riyadh only.

Analysis of Data Items Common to All Cities

Frequencies of pedestrian accidents recorded on a monthly basis, as well as study durations and some important events during the study periods, are presented in Table 2. Although the study periods are short, and overlapping periods between

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TABLE 1 Characteristics of Selected Cities (*4,5*)

City	Population in 1989 (%)			Area, Hectares (%)		
	Urban	Rural	Total	Urban	Rural	Total
Riyadh	878,540 (62)	538,460 (38)	1,417,000 (100)	53,465 (82)	11,456 (18)	64,921 (100)
Dammam	418,550 (100)	[a]	418,500 (100)	44,000 (100)	[a]	44,000 (100)
Qasim	160,328 (56)	125,972 (44)	286,300 (100)	6,970 (55)	5,659 (45)	12,629 (100)
Qatif	112,350 (42)	155,150 (58)	267,500 (100)	21,460 (58)	15,540 (42)	37,000 (100)

[a] This information was not available, but is regarded as negligible.

the cities are limited, it was possible to make some general comparisons.

The monthly averages of accidents change between 15.7 and 22.1, without too much variation, despite the big differences in populations. The last column in Table 2 shows the average number of pedestrian accidents a month per 100,000 population. This column reveals that Qasim, Qatif, and Dammam have similar pedestrian accident rates and that Riyadh has a much lower rate, approximately one-fifth of the rate of the others. This is probably because of several things: first, Riyadh is a much younger city than the others and is very well laid out, with modern streets using up-to-date planning techniques. Second, it is a very dispersed city and most transportation involves private cars, which minimizes pedestrian activity. Third, most of the shopping that involves concentrated pedestrian activity takes place in well-organized shopping centers that are widely dispersed and that limit the interaction between vehicles and pedestrians.

Table 2 frequency records for Riyadh and Dammam display a peak near December 1987, which was the intersemester school break. Dammam and Qatif records display a tendency for pedestrian accidents to increase toward the end of the academic year, possibly because of increased school activities. The accidents decrease during July and August, which corresponds with school holidays, when many families (especially expatriates, who form a large portion of the population) leave Saudi Arabia. Table 2 also shows that pedestrian accidents increase above their averages for Qasim and Dammam after the schools' summer vacations (September 1987). These observations indicate that pedestrian accidents are somewhat related to school activities.

A last observation from Table 2 is that during April 1988, pedestrian accidents increased in Riyadh, Qatif, and Dammam. This month corresponded to the Muslim holy month of Ramadan. During this month Muslims fast during the day and break their fast at night. People's outdoor activities in Saudi Arabia shift from day to night. Shopping starts after 9:00 p.m., and almost all shops stay open until the early hours of the morning. Families visit each other, sometimes even after midnight, and many families, including children, stay awake until 3:00 or 4:00 a.m. The last meal is eaten before sunrise and then people sleep until very late in the morning. In this month it is common to see children playing in the streets around and after midnight. Because of this increased activity at night when pedestrian visibility is a problem, an increase in pedestrian accidents is not unexpected.

Figure 1 shows the urban and rural accident rates, expressed as pedestrian accidents per 100,000 people for the four cities. The Dammam rural rate was not given because the jurisdiction is almost entirely urban. This figure indicates that risk in urban areas is higher than that in rural areas, as might be expected.

TABLE 2 Pedestrian Accident Summaries for Four Cities

Hijria	Year	1407					1408												1409		Total	Monthly Average	Monthly Accident Rate per 10^5 population
	Month	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2			
Gregorian	Year	1987										1988											
	Month	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9			
Riyadh										29	33	24	9	8	11	8					122	17.4	1.23
Qasim		15	12	19	18	14	21	23	21	16	16	17	11	12							215	16.5	5.78
Qatif															21	14	17	14	12	16	94	15.7	5.28
Dammam							10	13	23	16	28	27	23	20	26	31	31	17			265	22.1	5.86
Events:																							
Ramadan			—												—								
Schools' Summer Vacation					—	—	—										—	—	—				
Schools' Inter-Semester Break											—												

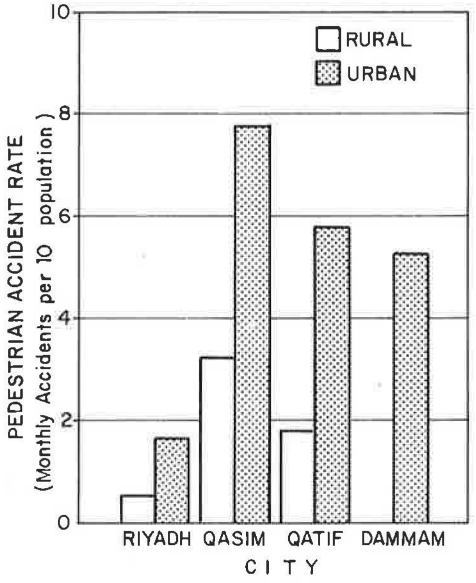

FIGURE 1 Urban and rural pedestrian accident rates for cities.

Figures 2 and 3 indicate that as the urban population and area sizes increase, the pedestrian accident rate tends to decrease. This could be due to many factors: for instance, short travel distances could foster more pedestrian activity in smaller cities.

The percentage distributions of urban and rural pedestrian accidents are presented in the following table:

	Urban (%)	*Rural (%)*
Riyadh	84	16
Qasim	75	25
Qatif	41	59
Dammam	100	0

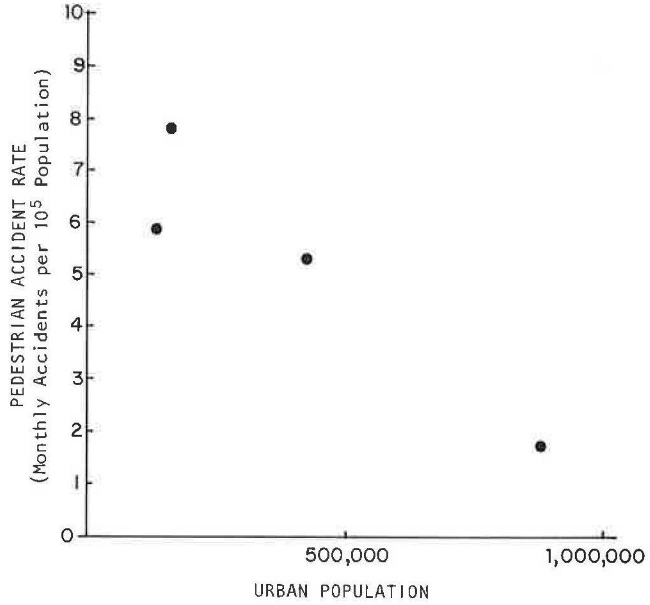

FIGURE 2 Relationship between urban population size and pedestrian accident rate.

The corresponding figures for the United States are 85 percent urban and 15 percent rural (*2*). The table shows that most pedestrian accidents occur in urban areas, with the exception of Qatif where 58 percent of the population lives in areas classified as rural (see Table 1). Qatif is a small agricultural city whose population is mainly involved in the outlying palm gardens and farmlands. Other than in Qatif, the pedestrian accident problem appears to be mainly an urban problem in Saudi Arabia. This is consistent with U.S. experience as demonstrated in the table.

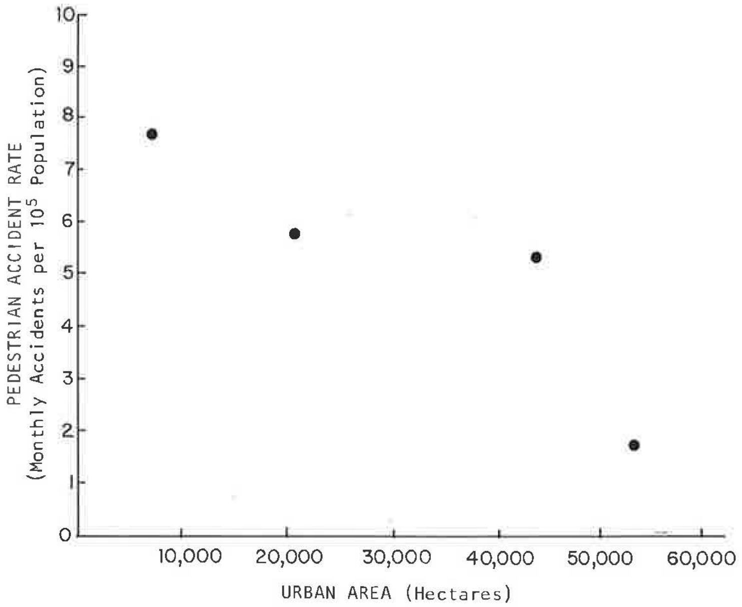

FIGURE 3 Relationship between urban area size and pedestrian accident rate.

TABLE 3 Accident Experience for Age Segments

City	Population Segment[a]	Population Distribution (%)	Pedestrian Accident Distribution (%)	Monthly Pedestrian Accident Rate per 100,000 population
Qasim	Children	62	61	5.68
	Adults	38	39	5.94
Qatif	Children	61	79	7.56
	Adults	39	21	3.19
Dammam	Children	52	71	7.24
	Adults	48	29	3.15

[a]Children: Age ≤ 18 years
Adult : Age > 18 years

Monthly accident rates (per 100,000 population) by gender for three cities are presented in the following table, which indicates that the rate for men is twice as high as that for women:

	Women	*Men*
Qasim	3.56	7.90
Qatif	2.99	8.48
Dammam	3.77	6.20

Given that the ratio of men to women, as indicated by the population census data (*4,5*), is approximately 1:1, it appears that there is a higher incidence of pedestrian accidents among men. This could be explained in cultural terms, given that Saudi Arabian women are more restricted than men in their activities, including walking. In general there are fewer female pedestrians than male pedestrians. However, this difference is also at least partly due to a behavioral difference between the genders. Al-Senan et al. found that male Saudi pedestrians were more aggressive, that they took more risks in their street-crossing behavior than Saudi women (*3*). They reported that on average, a higher percentage of men (54 percent) than women (34 percent) did not stop at curbs. And a higher percentage of men (56 percent) than women (31 percent) crossed signalized intersections in prohibited phases.

Table 3 gives percentage distributions and accident rates for the cities for two age categories: 18 and younger, and older than 18. The Riyadh data were not available for these categories. For Qasim, the percentage distribution is the same for accident frequency as for the population distribution in each age category, implying that risk is the same for these age categories. This fact (for Qasim) is supported by the fact that the monthly accident rate per 100,000 population in each category is nearly equal. Rates for Qatif and Dammam show that the younger population is more at risk (about twice) than the older group. It appears that at least in two of three cities, the younger pedestrian population is more at risk.

TABLE 4 Pedestrian Accident Percentage Distribution

City	By Severity		By Time of Day	
	Fatal	Injury	Day	Night
Riyadh	9.8	90.2	69.7	30.3
Qasim	14.9	85.1	55.3	44.7
Qatif	16.0	84.0	19.1	80.9
Dammam	4.9	95.1	60.4	39.6
U.S.[a]	11.0	89.0	N/A[b]	N/A

[a]Source: Ref. 2
[b]N/A : Not Available

Table 4 presents the percentage distribution of fatalities and injuries. It appears that the large cities (Dammam and Riyadh) have the smallest fatality percentages. Riyadh's fatality and injury percentages are very similar to the average percentages in the United States, which are 11 and 89 percent for fatalities and injuries, respectively, in 1988 (*2*). Dammam's low fatality rate is due to the fact that it does not include rural accidents (as seen earlier) and, as is well established (*2*), rural pedestrian accidents are more severe than urban ones and adequate or timely medical attention is less likely. Rural accidents near Dammam are mostly included in the nearby cities such as Qatif.

Day and night distributions of pedestrian accidents are presented in Table 4. For all cities except Qatif, most pedestrian accidents occur during the day. The Qatif area is less developed than the other cities, and most of its streets are very poorly illuminated at night, which might lead to this situation. Furthermore, a significant portion of Qatif's working people work in nearby cities and return only during the late afternoon. Considering that 80 to 85 percent of average daily traffic occurs in the daytime hours in Saudi Arabia cities (*3*), the percentages of night pedestrian accidents are still too high. This, to a great extent, can be attributed to the visibility problem at night.

Analysis of Qatif Accidents

Qatif pedestrian accidents were collected for 6 months following the request of the study team. Although the period is short and the sample size is small, the records include some finer details and therefore are separately analyzed here.

Table 5 gives the frequency distributions of population and pedestrian accidents by age group. The most critical age categories are 4 years and less and 5 to 9 years, as these experience a disproportionately high percentage of fatalities and injuries in comparison with their population percentages. Children 4 and under are not usually allowed out unaccompanied by an adult; therefore, they suffer relatively fewer injuries than 5 to 9 year olds. However, the accident percentages for both categories are still high, which would appear to be mostly the result of a lack of adult supervision. It is very common to see very young children, even in those 4 and

TABLE 5 Percentage Distribution of Age and Percentage Pedestrian Casualties in Qatif

Age	Population in Age Category[a] (%)	Pedestrian Accidents in Each Category (%)		
		Fatality	Injury	Total
4 and less	17.2	26.7	25.0	25.6
5-9	17.3	26.7	44.0	41.5
10-14	14.4	20.0	6.3	8.5
15-19	12.0	0	3.8	3.2
20-39	22.0	26.6	8.9	11.8
40-59	12.1	0	3.8	3.2
60 and more	5.0	0	8.2	6.4
Total	100	100	100	100

[a] Based on the latest census available, *(5)*.

TABLE 6 Severity Distribution by Age in United States (*2*)

Age	Killed or Injured (%)
4 and less	7.3
5 - 9	17.0
10-14	11.2
15-19	10.6
20-24	9.1
25-44	26.1
45-64	11.0
65 and over	7.7

under, playing in busy streets unaccompanied by an adult. In particular, 5 to 9 year olds are in the most at-risk group.

The age category of 10 to 14, although still critical because it has a high fatality percentage, is not as critical as the younger categories. The category of 15 to 19 does not appear to have a pedestrian problem. The very active and productive age category of 20 to 39 appears to receive a disproportionately low percentage of pedestrian fatalities, perhaps because of the emotional maturity and physical well-being of those in this group. The category of 60 years and up appears to have only a slightly higher percentage in injury accidents than its population percentage. A larger sample of data is needed to verify all of these findings. But in general, age categories between 10 to 59 have lower percentages in total accidents than their population percentages. Striking differences are revealed when these accident percentages are compared with the ones from United States, which are presented in Table 6. The accident percentage in the categories of children 9 years and younger in Qatif (67.1 percent) is much higher than the percentage in the United States (24.3 percent). This indicates a much higher risk for these children in Saudi Arabia than in the United States.

Fatalities and injuries in rural and urban areas are compared in the following table:

	Fatality	*Injury*
Urban	27	43
Rural	73	57
Total	100	100

On one hand, almost three times as many fatalities occur in the rural part of Qatif than in the urban part. On the other hand, considering that 58 percent of the Qatif population lives in the rural areas, the fatality share of the rural areas is disproportionately high. The injury distribution (43 percent urban and 57 percent rural) is similar to the population distribution, so it appears that rural accidents are more severe than urban accidents. A logical cause could be the higher speeds of vehicles in the rural parts. Another factor may be the greater time involved in getting medical attention.

The hourly distribution of Qatif accidents is shown in Figure 4. A definite peak occurs between 4:00 and 9:00 p.m. In Qatif, as in other parts of Saudi Arabia, shops open at 4:00 p.m. (they are closed between noon and 4:00 p.m.). This peak accident period therefore corresponds to the period of con-

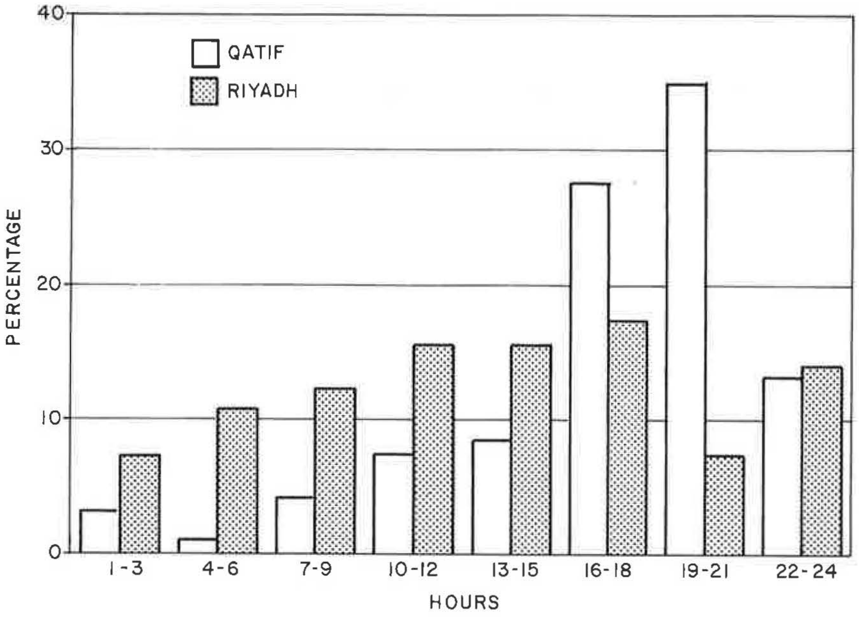

FIGURE 4 Hourly distribution of pedestrian accidents in Qatif and Riyadh.

centrated shopping activity. Furthermore, during the hot season (which starts as early as April and continues to November), children usually go out after 4:00 p.m. to play. Similarly, many adults limit their activities in this period to avoid the heat of the day. It should be noted that all the Qatif data were collected during the hot season. Finally, Qatif is an area with close social contacts where relatives and friends live near each other and children go out to play with others in the neighborhood. All these factors create a very high peak for Qatif. A different pattern will emerge for Riyadh, however.

Analysis of Riyadh Accidents

The Riyadh accident data were collected during 7 months, from November through May. During this period the weather is very pleasant.

Figure 4 shows the hourly distribution of pedestrian accidents in Riyadh. Obviously these accidents are more evenly distributed than those from the Qatif area. This consistency can be attributed to many things. First, because the period of data collection corresponds to a very pleasant time of the year, people can carry out their activities throughout the day. Second, Riyadh is a large and dispersed city lacking close-knit neighborhoods, so child activity in the streets is much less than in Qatif. Children usually play inside well-protected housing compounds and within their own gardens. Still, however, a slight peak occurs at 4:00 to 6:00 p.m., when shopping activity starts.

The daily distribution of pedestrian accidents for Riyadh is shown in Figure 5. It should be noted that the normal working days are Saturday through Wednesday in Saudi Arabia. The weekend corresponds to Thursday and Friday. It can be seen that Wednesday, which is the end of the normal working week, has the highest percentage of accidents. A similar trend is reported for the United States (*6*). What is unique about the Riyadh data is the occurrence of a second peak on Fridays, which is the second day of the weekend. One reason for this may be that most of the low-income expatriate workers, who usually work on Thursdays, do their shopping during this day. These workers do not own cars and are usually brought to shopping areas by buses. This creates a significant amount of pedestrian activity. Furthermore, most of these workers have low education levels and are not familiar with the rules of the road.

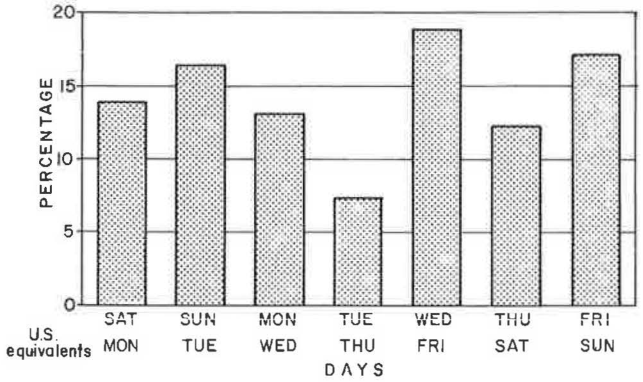

FIGURE 5 Daily distribution of pedestrian accidents in Riyadh.

Table 7 shows the distribution of pedestrian accidents by action. Most accidents occurred while pedestrians were crossing at midblock (64 percent); this was followed by the number of accidents while pedestrians were crossing at intersections (11.5 percent). For the United States, the percentages are 34.5 and 23.3 (*2*) for midblock and intersection accidents, respectively. Apparently there is a higher percentage of midblock accidents in Riyadh than the United States, which makes Riyadh pedestrian accidents more serious, because, as shown in the literature (*6*), vehicles at midblocks have higher speeds, and pedestrian crossings at midblocks are not normally expected.

Riyadh streets are usually very wide. Twelve-lane arterials (four lanes for service roads and eight for the main road) are very common in the city. This increases the exposure time of pedestrian crossings. Furthermore, many of the signalized intersections in Riyadh, as well as everywhere else in Saudi

TABLE 7 Pedestrian Accidents by Action in Riyadh and United States (*2*)

Action	Percentage		
	Riyadh		U.S.
Midblock crossing	62.4		34.5
Midblock dart in front of a parked car	1.6		
Sub Total		64.0	
Crossing at Intersection			
Near side	3.3		
Far side	3.3		
With right-turning vehicles at Intersection	3.3		
With left-turning vehicles at Intersection	1.6		
Sub Total		11.5	23.3
While walking to or from a bus stop		0.8	
While walking on the side of road		2.5	
While walking on sidewalk		1.6	
With a reversing car		5.7	
Unknown		13.9	
Total		100	

Note: For U.S. data, the only reported percentages are shown.

Arabia, operate with unidirectional phases (i.e., a separate phase for each approach) and usually have very long cycles (180-sec cycles are common). This leads to very long waiting times for pedestrians to cross signalized intersections legally. Therefore, many pedestrians either avoid crossing at intersections or violate the signals at intersections and do not use refuge islands. Al-Senan et al. report that 56 percent of male pedestrians and 32 percent of female pedestrians cross signalized intersections in the prohibited phase (*3*). Special arrangements are needed, such as selecting signal phasing schemes that accommodate pedestrians or providing over- or underpasses for pedestrian passing at busy locations.

SUMMARY AND CONCLUSIONS

The summary of the main research findings are as follows:

1. In general, pedestrian accidents tend to increase during the school intersemester breaks and decrease during the summer months; these times correspond with school holidays, when many families, especially the expatriate families that make up a major portion of the population, leave Saudi Arabia for vacation. This indicates that pedestrian accidents are somewhat related to school activities.
2. During the holy month of Ramadan an increase in pedestrian accidents was observed. This could be attributed to the shift of activities from day to night during this period.
3. It was found that more accidents occur in urban areas than the rural areas, which is similar to the experience of the United States.
4. The pedestrian accident rate appears to decrease with an increase in the urban population and the size of the urban area.
5. There is a higher incidence of pedestrian accidents among men than women. This is partly due to the greater exposure of men to traffic. However, it could also be attributed to the more aggressive behavior of men as pedestrians than women.
6. In general, the younger pedestrian population (younger than 18) appears to be more at risk than the older category (older than 18).
7. Fatality percentages in large cities are much smaller than those of the smaller cities. It appears also that the severity of pedestrian accidents is higher in smaller cities.
8. For all the cities, except for Qatif, most accidents occur during the day. But when exposure is considered (i.e., the percentage of traffic occurring during the day), the percentage of night pedestrian accidents is still disproportionately high. This discrepancy may be attributed to poor visibility at night.
9. In Qatif, the age categories most at risk were found to be 5 to 9 year olds, followed by 4 and younger. This result was attributed to a lack of adult supervision. The economically active age category of 20 to 39 year olds was found to have a disproportionately low percentage of accidents: this group makes up 22 percent of the population but accounts for only 11.8 percent of the accidents, half of what would be expected.
10. Almost three times as many fatalities occur in the rural part of Qatif than in the urban part. The injury distribution is similar to the population distribution. Higher severity rates occur in rural areas because vehicular speeds in rural areas are higher and medical care is not as readily available.
11. Qatif shows a very high peak of pedestrian accidents during shopping and after-school hours from 4:00 to 9:00 p.m. Although Riyadh had a similar peak during the same period, it was not as high as Qatif. This was attributed partly to the different periods of data collection in the two cities. However, it could also be due to the different characteristics of these two cities.
12. The daily distribution of pedestrian accidents in Riyadh indicates that Wednesday is the peak working day equivalent to Friday in the United States. But a second peak was recorded on Friday, which is the second day of the weekend. The occurrence of this latter peak was partly attributed to increased pedestrian shopping activity by low-income expatriate workers.
13. Compared with the United States, a much higher percentage (62.4 versus 34.5 percent) of pedestrian accidents occur at midblocks in the Riyadh area. This was attributed, apart from some possible behavioral differences, to the very wide arterial streets (many with 12 lanes), which increase pedestrian exposure to traffic. It was also noted that the present unidirectional signal phasing and long signal cycles encourage illegal pedestrian crossing at intersections or at points other than intersections.
14. Although there are some shared characteristics of the pedestrian safety problem, each city also has unique problems. These individual areas can and should be studied in more depth in small-scale local studies.
15. Finally, more research is needed in the pedestrian safety area in Saudi Arabia. The results of this study should be considered preliminary since they are based on a very limited sample of pedestrian accidents.

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Analysis of Elderly Pedestrian Accidents and Recommended Countermeasures

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A study was carried out to create a better understanding of the causes and characteristics of motor vehicle crashes involving older pedestrians and to present information on appropriate interventions to reduce the problem. Detailed analyses by pedestrian age were carried out on more than 26,000 pedestrian crashes occurring in North Carolina over 11 years. A parallel analysis was also conducted on more than 70,000 fatal pedestrian crashes nationwide from the *Fatal Accident Reporting System.* Results showed that on a population basis, older pedestrians (65 or older) are slightly less likely than younger pedestrians to be struck by a motor vehicle; however, this statistic does not take into account the amount of walking, accident location, and so forth. Once struck, older pedestrians have a much higher likelihood of being killed—20 percent, compared with 5 to 10 percent for younger age groups. Pedestrians 65 or older are overrepresented in crashes during daylight hours, on weekdays, and in winter. Older pedestrians are also overrepresented in intersection crashes (particularly involving turning vehicles) and in crashes involving wide street crossings. Alcohol involvement, however, was less likely for older pedestrians than for most younger age groups. Results of the analysis were used to target specific countermeasures. A variety of educational, enforcement, and roadway improvements were recommended to reduce the annual toll of injuries and fatalities to older pedestrians.

Pedestrian–motor vehicle crashes are a serious problem in the United States and many other industrialized countries. A total of 6,468 pedestrians were reported killed in motor vehicle crashes in the United States in 1990 (*1*). These deaths accounted for 14.5 percent of the 44,529 motor vehicle deaths nationwide. An estimated 109,000 pedestrians were injured or killed in motor vehicle collisions, representing 3.2 percent of the 3.4 million total persons injured in traffic crashes (*2*).

Of the pedestrians injured or killed in 1990, approximately 10,000, or 9 percent, were 65 or older. This is lower than their 13 percent representation in the overall population. However, adults 65 or older made up 23 percent of pedestrians killed in 1990. Thus, the elderly are less likely than other pedestrians to be involved in a crash, but once in a crash they are more likely to be killed. Pedestrians 65 or older have a fatality rate of 4.8 per 100,000 population, nearly twice the rate of 2.6 per 100,000 found in the overall population.

The percentage of Americans who are 65 or older has tripled from 4 percent in 1900 to an estimated 13 percent in 1990 and is projected to increase to 17 percent by 2020 (*3*), which translates into a 62 percent increase in the absolute number of older Americans between 1990 and 2020. If the injury rate remains the same, the number of older pedestrians killed and injured will also increase by 62 percent, and the current annual count of 10,000 elderly pedestrian injuries and fatalities will grow to more than 16,000. Serious efforts are needed to better understand the causes and characteristics of elderly pedestrian–motor vehicle crashes and to develop appropriate interventions to address this problem.

As a group, older persons show declines in health, vision, hearing, and speed of reaction (*3*). Perceptual and cognitive problems facing many of the elderly include a reduced ability to maintain general attention, difficulty in separating important from unimportant information, decreases in the speed and accuracy of information processing, diminished problem-solving ability, and declines in short-term memory (*4*).

This study presents the results of an analysis of more than 26,000 pedestrian–motor vehicle crashes occurring in North Carolina during an 11-year period (January 1980 through December 1990). Included in the total are nearly 1,800 pedestrian victims 65 or older. Similar findings are reported from an analysis of 71,000 fatal pedestrian–motor vehicle crashes occurring nationwide during 1980–1989 and identified from the *Fatal Accident Reporting System* (FARS) data base. During the 10 years spanned by this data base, about 15,000 pedestrians 65 or older were killed. In addition to the results of the data analysis, recommendations are given for a number of interventions to reduce the frequency and severity of elderly pedestrian crashes and injuries.

METHOD

To obtain a better understanding of the causes and characteristics of motor vehicle crashes involving older pedestrians, analyses were carried out on two computerized data bases:

- The North Carolina motor vehicle crash file, containing information on all police-reported motor vehicle crashes in the state. For the current study, all crashes involving one or more pedestrians during the period 1980–1990 were extracted for analysis.
- FARS data, a computer file of all fatal police-reported motor vehicle crashes nationwide. For the current analysis, all fatal motor vehicle crashes involving a pedestrian were extracted during the 10-year period 1980–1989.

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One of the primary objectives of the analysis was to determine what roadway and environmental factors are associated to a larger degree with accidents involving older pedestrians (i.e., those 65 or older) as compared with those involving younger age groups. For example, are older persons more likely to be struck at intersections, during conditions of darkness, or on weekdays than younger persons? Answering such questions involved analyzing the distribution of crashes by pedestrian age categories for these and other factors. The age categories selected for the analysis included 0 through 4, 5 through 9, 10 through 14, 15 through 24, 25 through 44, 45 through 64, 65 through 74, and 75 and above. These age groups were chosen on the basis of what is known about age-related differences in pedestrian behavior and crash experience. For example, 5- to 9-year-old boys are particularly at risk for crashes resulting from darting out into the street, whereas persons 25 to 44 years old have a high incidence of alcohol-related injuries and deaths.

The data analysis first involved computing pedestrian crash rates and fatality rates (per 100,000 population) by age, gender, and race. Next, the percentage of pedestrian crashes was determined within each age group as a function of each accident variable of interest. These included time factors (i.e., season, month, day of week, time of day), light condition (dark, light, dawn or dusk), crash location (intersection, midblock), area type (urban, rural), number of traffic lanes, roadway class, road surface condition (dry or wet), crash type, alcohol involvement, and others.

RESULTS

Description of Data

A total of 26,260 pedestrian–motor vehicle crashes were identified from the 1980–1990 North Carolina motor vehicle crash files. This averages nearly 2,400 crashes a year over the 11-year period (Table 1). The number of crashes has been higher in recent years, averaging more than 2,500 crashes a year during 1986–1990 compared with fewer than 2,300 a year during 1980–1985. The slight increase in accidents in the most recent 5 years could be the direct result of increased population and motor vehicle travel in the state, as well as increased urbanization. The number of elderly pedestrians in North Carolina crashes has also increased, reflecting the statewide trend.

Nationwide, pedestrian fatalities have shown a decline, dropping from 8,070 in 1980 to 6,468 in 1990. The reason for this decline is not clear. Possible factors may include some combination of improved pedestrian safety programs now under way in many states along with improved medical care and treatment. The death rate within the older pedestrian population, however, has not declined as much as that for the overall population.

TABLE 1 Summary of Pedestrian Crashes in North Carolina and Pedestrian Fatalities Nationwide by Year

	North Carolina Pedestrian Crashes		U.S. Fatal Pedestrian Crashes	
Year	65 and Older	All Ages	65 and Older	All Ages
1980	152	2,338	1,728	8,070
1981	151	2,189	1,628	7,837
1982	145	2,413	1,449	7,331
1983	132	2,227	1,388	6,826
1984	175	2,324	1,460	7,022
1985	150	2,095	1,448	6,799
1986	157	2,512	1,422	6,772
1987	179	2,530	1,482	6,746
1988	177	2,521	1,596	6,870
1989	176	2,618	1,466	6,552
1990	164	2,493	1,501	6,468
Total	1,758	26,260	16,568	77,293

Crash and Injury Rates

A general issue of concern involved determining whether older adults are overrepresented in pedestrian crashes. Crash involvement rates (crashes per 100,000 population) by age category and gender are given for North Carolina in Figure 1. Five- to 9-year-old boys clearly have the highest involvement rates (85.3 per 100,000 population), followed by 15- to 24-year-old men (61.2). At all age levels, men have a higher crash involvement rate than women. Rates for older persons (65 through 74 and 75 or older) are lower than for most other age groups (although it is interesting to note the upswing for those 75 or up). This finding agrees with much of the literature and may reflect greater caution on the part of older persons (e.g., fewer darting out in midblock, less walking at night), as well as reduced exposure.

Although older pedestrians are generally less likely than younger persons to be struck by motor vehicles, they are more likely to be killed if they are struck. As shown in Figure 2, 10 percent or fewer of the crashes for each of the age groups under 45 years result in death, compared with 18.6 percent of the crashes to pedestrians 65 through 74 and 25.1 percent of crashes involving those 75 or older. These percentages support the view that older adults are more vulnerable to injury and do not recover as easily as younger people.

Pedestrian Crash Factors

Dozens of specific crash factors were analyzed by age group to identify abnormally high trends among those 65 or older. This included analyses of both the North Carolina files and the nationwide FARS data on fatal pedestrian crashes. As will be discussed, the factors of greatest significance were those related to time, light condition, location (urban versus rural), road surface condition, relation to intersection, vehicle maneuver, and alcohol use.

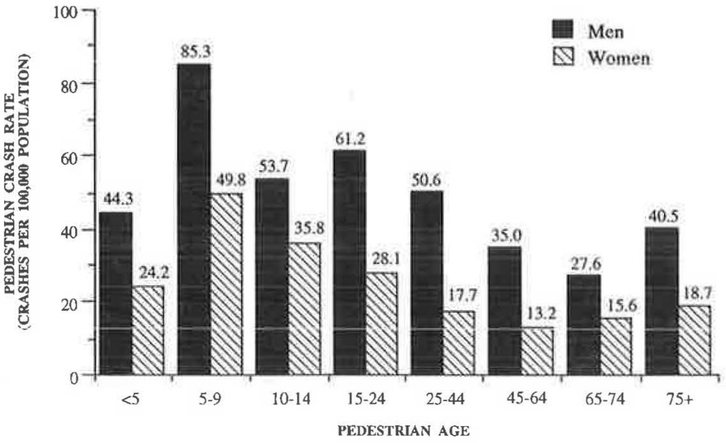

FIGURE 1 Pedestrian crash rate per 100,000 population by age and gender, 1980–1990 North Carolina data.

Time Factors

Examination of seasonal crash characteristics on the FARS data base revealed that deaths to older pedestrians are more likely to occur during fall and winter than spring and summer (Figure 3). According to the national data, persons 65 or older experience 60 percent of their fatalities from September through February. North Carolina crash data also revealed higher overall crash frequencies among persons 65 or older during the fall and winter months than among younger pedestrians. Younger pedestrians (particularly 9 years or younger) experienced a greater percentage of injuries and deaths during spring and summer months.

The trend of overinvolvement among older pedestrians in winter crashes agrees with an earlier U.S. Department of Transportation study (*5*). One of the theories cited for this trend is that elderly pedestrians often wear dark clothing in winter. On dark cloudy days, they may be difficult to distinguish against a dark background such as the shadow of a tall building. Also, many of these wintertime accidents to older adults involve left-turning drivers, who are paying attention to oncoming through traffic. When an adequate gap in the traffic is found, these motorists accelerate into their left turn, striking the poorly visible elderly pedestrian, who also may not be able to react or move out of the way quickly enough.

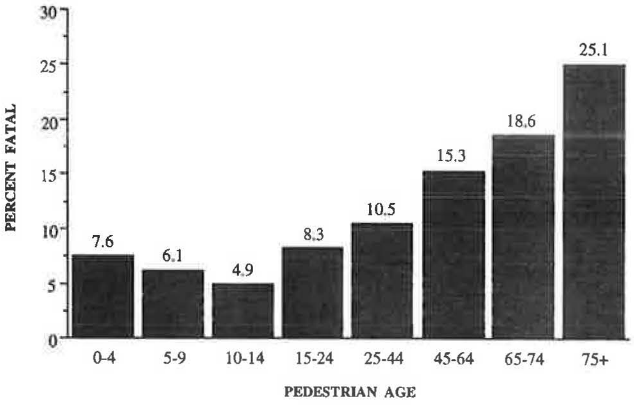

FIGURE 2 Percentage of pedestrian-motor vehicle crashes resulting in death, by pedestrian age, 1980–1990 North Carolina data.

Another time factor involves the day of the week when older adults are struck. North Carolina data revealed that persons 65 or older had a lower percentage of their accidents on weekends (Saturday and Sunday) than other age groups (Figure 4). In fact, weekend accidents accounted for only 21.3 percent of accidents to pedestrians 65 through 74 and 19.6 percent for pedestrians 75 or older. This compares with between 23 and 34 percent for other age groups.

FARS data showed that persons 5 through 9 and 75 or over had the lowest percentages of fatal accidents on weekends (24.1 and 22.7 percent, respectively). By contrast, nearly 45 percent of fatal accidents involving pedestrians between 15 and 24 years occurred on weekends.

The lower involvement of the elderly in weekend than other age groups is most likely due to different lifestyles and walking patterns. Older adults, particularly those who are retired, tend to walk for exercise and for shopping trips and other errands on weekdays, whereas people 15 through 44 are at work or in school. Thus, the crashes of the elderly may be more uniformly distributed throughout the week than the crashes of younger people, who may be most active on weekends.

The time-of-day factor was reviewed primarily on the basis of light condition. Results for the nationwide FARS data are presented in Figure 5. They show that next to young children, older adults have the highest percentage of fatal crashes occurring during daylight hours. Forty percent of fatalities to 65- to 74-year-old adults and 54 percent of fatalities to those 75 or older occurred during daylight, which compares with only 33 percent for all ages combined.

The North Carolina data show a similar trend. Overall, 54.3 percent of the state's reported pedestrian crashes occur during daylight, but this percentage increases to 62.4 percent for persons 65 through 74 and to 72.9 percent for those 75 or older. The only age groups with higher daytime percentages are those 14 and younger.

These results reflect to a large extent the walking habits for the various age groups. Children 14 and younger engage in much outdoor activity and thus experience a greater proportion of their crashes during daylight conditions. Young and middle-age pedestrians (ages 15 through 64) tend to walk

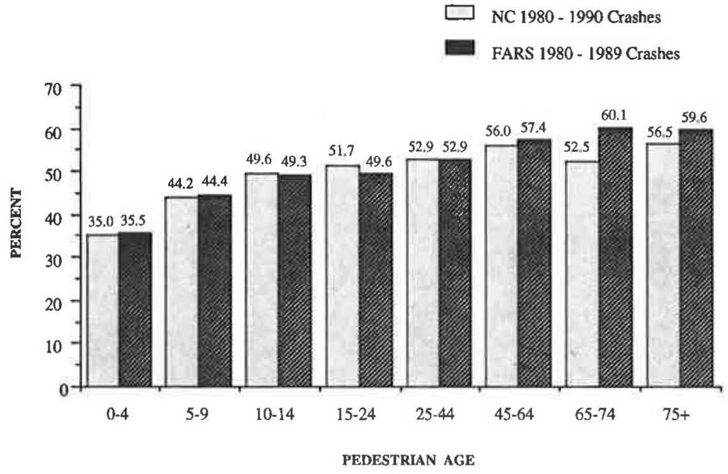

FIGURE 3 Percentage of pedestrian crashes occurring in fall or winter months (September–February).

more at night and therefore experience more of their crashes—particularly fatal crashes—at night. Older adults may walk more often at night than children, but less often than younger adults. And their slower reaction times, wearing of dark clothing, and reduced nighttime vision may make their nighttime walking particularly hazardous.

Roadway and Location Factors

The analyses revealed that, as expected, pedestrian crashes occur more often in urban than in rural areas. Overall, 65.9 percent of fatal pedestrian crashes on the FARS data base occurred in urban areas. Compared with other age groups in the national FARS data, older adults have the highest percentage of fatalities occurring in urban areas: 75.1 percent for those 65 or older, which compares with 57 to 69 percent for the other age groups.

Urban Areas In North Carolina, 60.3 percent of all pedestrian crashes occur in developed urban areas, 21.2 percent in rural areas, and 18.5 percent in areas of mixed development. The North Carolina data did not show older pedestrians to be overinvolved in urban accidents when compared with the other age groups. This is probably because a slightly lower percentage of North Carolina's elderly population lives in cities than the percentage in other states.

Wet Roads The analyses revealed problems for older pedestrians on wet roads. In particular, pedestrians 65 or older experienced 17.2 percent of their fatalities on wet roads, which is higher than the percentages of persons 15 through 44 (13.9 percent) or 14 years or younger (7.5 percent). However, in terms of all pedestrian crashes (fatal and nonfatal) on North Carolina roads, older adult crashes were not overrepresented on wet roads.

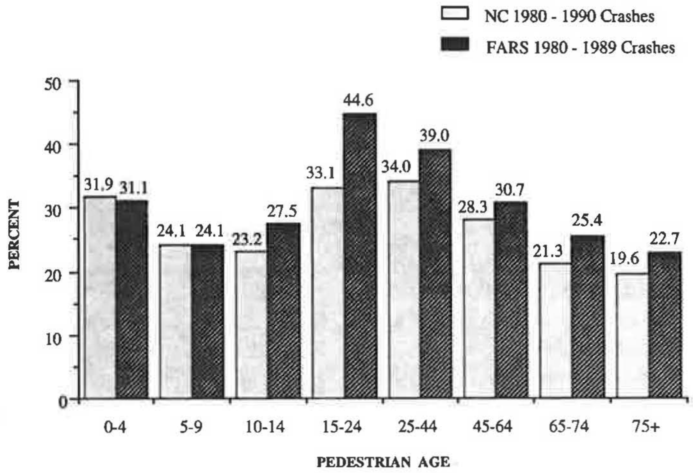

FIGURE 4 Percentage of pedestrian crashes occurring on weekends (Saturday or Sunday).

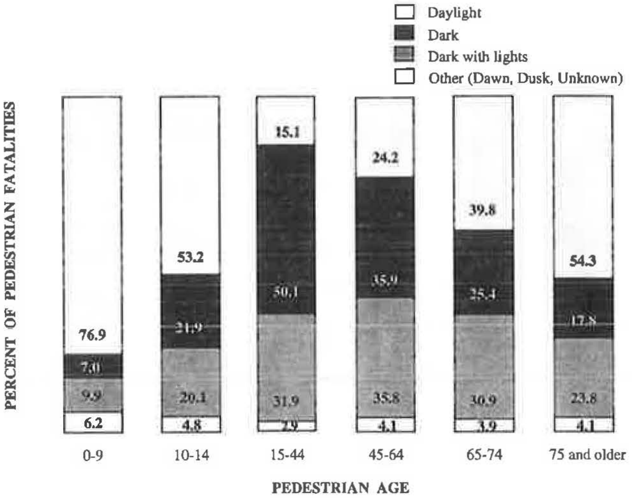

FIGURE 5 Distribution of pedestrian crashes by light condition, 1980–1989 FARS data.

Although these trends are not totally clear, the results could indicate that older adults are less likely to venture out into the rain to walk than other groups. However, when they do walk in the rain, they may be more at risk of getting into a serious crash because of their reduced maneuverability and the limited visibility associated with rainy days. Also, some older adults may direct more of their attention to their footing (and the fear of slipping and falling on wet roads) than to motor vehicle traffic.

Location The location where pedestrian crashes occur is important for identifying the specific roadway characteristics that cause problems for older adults and situations in which roadway improvements are needed. There is evidence from the literature that older adults are overinvolved in crashes while crossing streets at intersections when compared with younger pedestrians. This was, in fact, supported in the authors' analysis of the national FARS data, where intersections accounted for 32.2 and 35.3 percent of deaths for the age groups 65 through 74 and 75 and above, respectively, compared with 22 percent or less for the younger age groups (Figure 6).

Figure 6 also shows higher intersection involvement rates for older pedestrians from the North Carolina crash file, although percentages for this sample of combined fatal and nonfatal crashes are not as great as from the FARS data. These trends could result from an increased incidence of intersection crossings by older adults, but they might also indicate problems in understanding or reacting to the more complex traffic movement and signalization at intersections.

A final locational feature of interest involves the number of traffic lanes. Older persons may be less able to safely negotiate wide streets because of their slower walking speeds and diminished abilities to handle complex traffic conditions. In fact, North Carolina pedestrians 45 and older had high percentages of accidents on roadways with four or more lanes (26.6 to 29.0 percent). This compares with 6.9 to 22.2 percent for those 24 years or younger. The higher trends among older pedestrians at intersections and wide streets suggest the need for specific interventions that will be discussed later.

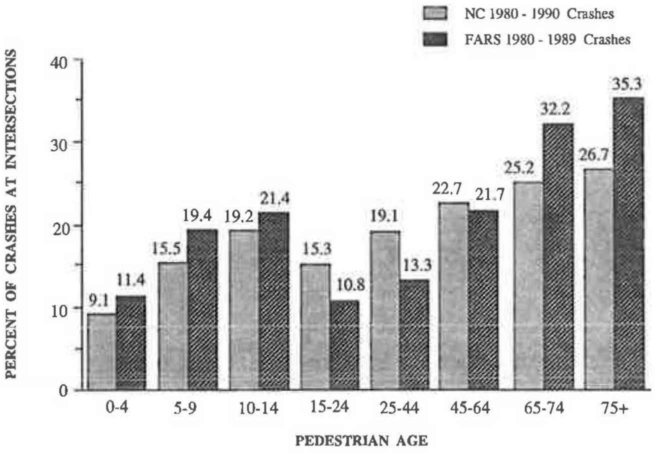

FIGURE 6 Percentage of pedestrian crashes related to intersections.

Vehicle Maneuvers

The 65 or older age groups were overrepresented in fatal crashes in which a left-turning vehicle struck a pedestrian. This type of crash occurred in 5.4 percent of fatal crashes in the United States involving pedestrians 65 or older but in only 0.7 percent of cases involving pedestrians under 45. The corresponding percentages in the North Carolina file for fatal plus nonfatal crashes are 6.5 percent (ages 65 or up) and 2.5 percent (younger than 65).

Older pedestrians are also overrepresented in right-turn crashes, including right turns on red. Right-turn crashes accounted for 2.2 percent of fatal crashes in the United States involving pedestrians 65 or older but only for 0.6 percent of those involving pedestrians under 45. In the North Carolina file, this type of crash accounted for 5.0 percent of crashes to pedestrians 65 or older, compared with 2.0 percent for pedestrians under 45.

A surprisingly high 9.5 percent of North Carolina's older pedestrian crash victims were struck by a backing vehicle, compared with only 3.9 percent for younger age groups (under 45). Thus, older pedestrians are more likely to be involved in crashes involving turning and backing vehicles than are other age groups.

Alcohol Involvement

Alcohol has been shown to be a contributing factor in pedestrian fatalities. From the North Carolina data base, crashes were classified as involving drinking on the basis of the police officer's judgment at the time of the crash. Overall, 20.5 percent of North Carolina pedestrian crashes involved drinking. However, the percentage was considerably lower for older pedestrians: 15.4 percent for those 65 to 74 and only 3.2 percent for those 75 or older (Figure 7). Pedestrians 25 through 44 years old had the highest alcohol involvement rate at 36.4

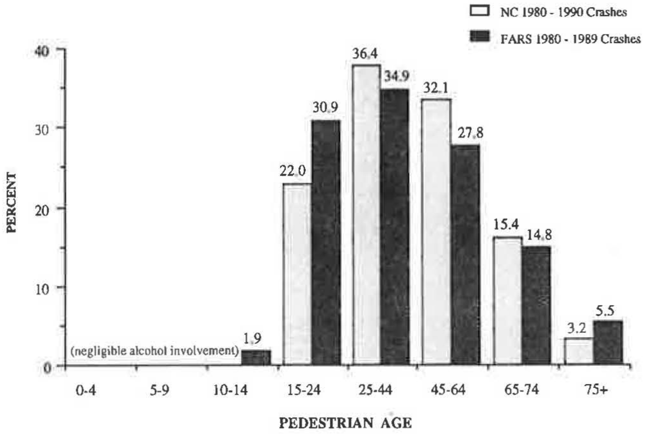

FIGURE 7 Percentage of crashes involving alcohol.

percent and were followed closely by those 45 through 64, at 32.1 percent.

Alcohol use among fatally injured pedestrians nationwide was reasonably close to the North Carolina numbers, as also shown in the figure. Of all U.S. pedestrian deaths, 22.1 percent involved drinking by the pedestrian. Again, those 25 through 44 had the highest rate of use (34.9 percent), followed by those 15 through 24 (30.9 percent) and 45 through 64 (27.8 percent). Alcohol involvement was similar between the FARS and North Carolina data for those 65 through 74 (14.8 percent versus 15.4 percent) and for those 75 or older (5.5 percent versus 3.2 percent).

These percentages confirm alcohol use as a major contributing factor in crashes involving pedestrians 15 years and older. Since alcohol can affect judgment and reaction time, its use may be particularly hazardous to older pedestrians already experiencing age-related limitations in some of their physical abilities. And even relatively small amounts of alcohol can have exaggerated effects when used with some prescription medicines commonly taken by older adults.

Although there has been considerable effort directed in recent years to reduce drunk driving, there has not been a comparable effort put forth to reduce the occurrence of drinking and walking. In fact, efforts to reduce drunk driving, such as revoking one's driver's license, may convert a drunk driver to a drunk pedestrian. It may not be as great a problem for the older age groups, but alcohol use nevertheless constitutes a serious pedestrian safety problem for which effective and immediate interventions are needed.

INTERVENTIONS FOR REDUCING ELDERLY PEDESTRIAN CRASHES AND INJURIES

The data and a review of the literature suggest a number of interventions that health care practitioners, law enforcement personnel, city planners, state and local traffic engineers, and others could implement to help reduce the annual toll of injury and death to elderly pedestrians. The rest of the paper will highlight some of the most promising interventions, focusing on education, enforcement and regulation, and roadway improvement countermeasures and program activities.

Educational Interventions

Most pedestrian–motor vehicle crashes are caused by unsafe pedestrian actions, and older adults (along with young children) are among the most common violators (*6*). Educational measures can help to correct unsafe behavior and thereby reduce the likelihood of being struck by a motor vehicle. Measures directed at the older pedestrian most often rely on printed materials, presentations at senior centers, public service announcements, and other media outlets to convey key safety messages. The Walk Alert Pedestrian Safety Program, developed by the National Safety Council and the U.S. Department of Transportation, suggests the following messages (*7*):

- Proper search behavior: always stop at the curb and look left, then right, then left again before starting to cross, continuing to search while crossing.
- Being seen: wear bright clothing during the day and carry a flashlight and wear retroreflective materials that outline the body at night.
- Traffic signals, signs, and markings: search for traffic, even if crossing with a walk signal or in a marked crosswalk; understand the meaning of the flashing Don't Walk signal.
- Disabled vehicle: pull off the roadway as far as possible, activate emergency flashers, walk facing traffic, and be seen.
- Intersection crossing: check for turning vehicles.
- Visual screens: move out beyond the parked or stopped vehicle far enough to again stop and search for traffic before crossing.

The analyses of crash data reinforce the importance of many of these measures for the elderly pedestrian—particularly the need to follow proper search behavior at intersections and to wear bright clothing to increase conspicuity. In educating older adults about pedestrian safety, it is important to remember the concerns that they themselves might have about their safety on the roadway. Many older adults, for example, are concerned that they will not be able to complete their crossing of an intersection before the signal changes. As a result, they may be too quick to step off the curb and begin their crossing. The first few steps are often the most critical, though, since it is when just entering an intersection that the pedestrian is most vulnerable to being struck. Older adults (and pedestrians of any age) should always search left-right-left before entering a roadway, even if they have been given a Walk signal. This is particularly important when crossing multilane roadways, where research indicates older pedestrians are at particularly high risk.

Enforcement and Regulation

Regulations and enforcement programs are additional tools for modifying unsafe pedestrian behaviors. Because their impact is generally short lived, long-term sustained efforts are needed. Successful enforcement programs target both pedestrians and motorists and incorporate public information and education.

When the ingredients are not in place for a full-scale pedestrian law enforcement program, police can sometimes be encouraged to implement selective enforcement strategies.

Selective law enforcement targets particular actions, locations, or times associated with greatest risk. For example, a particularly dangerous intersection near a senior center or shopping area might be targeted. Such tailored programs have been applied successfully in many areas of traffic law enforcement and could benefit elderly pedestrians as well.

The elderly can also benefit from local laws and ordinances designed to protect pedestrians. For example, the bus stop ordinance requires that bus stops be relocated from the near side to the far side of an intersection so that alighting passengers will more likely cross the street behind the bus where they can be seen by passing motorists (*6*). The model parking ordinance bans parking within 50 ft of a marked crosswalk or 60 ft of an unmarked crosswalk, thereby eliminating a visual screen (*6*). Given their greater likelihood of being struck at intersections, elderly pedestrians may be particularly helped by such countermeasures.

Roadway Improvements

Besides educational and enforcement measures, traffic and roadway improvements can also be made to increase the level of safety for all ages of pedestrians. Some of these improvements are discussed in the following.

Sign-Related Measures

A variety of roadway signs may be used that relate to pedestrians, as specified in the *Manual on Uniform Traffic Control Devices* (*8*). For example, Walk on Left Facing Traffic signs can reduce the likelihood that a pedestrian will be struck while walking along the road. The relatively high incidence of crashes to older pedestrians involving right- and left-turning vehicles may be reduced at certain locations with No Left Turn or No Turn on Red signs, where appropriate. Guide signs may be helpful to direct pedestrians to sidewalks, walkways, bus stops, trails, overpasses, or other facilities.

Sidewalks

The installation of sidewalks or walkways in residential and suburban areas can be highly beneficial to pedestrians of all ages, and particularly to older pedestrians, since these areas provide a space in which to walk separate from traffic. Older persons with reduced vision and limited mobility especially need sidewalks to offer protection from motor vehicle traffic. Sidewalk curb ramps at street crossing locations can facilitate movement for wheelchair users. Many elderly or handicapped people who do not use wheelchairs have difficulty in traversing curbs of any height and therefore rely on curb cuts. With curb cuts, however, visually impaired pedestrians may not notice the ramp and may walk unknowingly into the street (*9*).

Street Furniture

The safe and efficient movement of pedestrians on sidewalks requires the proper placement of street furniture (e.g., newspaper racks, telephone booths, benches). Signs, signal poles, and telephone poles should be located so as not to obstruct pedestrian movement or block the view of pedestrians and motorists. Such obstacles not only create hazards for visually impaired pedestrians, but also provide unnecessary barriers for pedestrians with mobility problems. When possible, an area at each street corner should be set aside for the placement of street furniture and for pedestrians waiting to cross the street.

Signalization

One of the key factors found to be associated with crashes to pedestrians 65 or older was the existence of an intersection-related crossing. The addition of traffic signals can be helpful to pedestrians, especially older or handicapped individuals, at intersections with an insufficient number of adequate gaps in traffic for pedestrians to cross safely. Traffic signals create artificial gaps in traffic flow that allow pedestrians to cross. In addition, a protected left-turn phase reduces conflicts between pedestrians and left-turning vehicles. Since many older and handicapped people have slower walking speeds, signals must be timed to provide adequate crossing time. Proper timing is particularly important on wide, high-speed roadways where elderly pedestrians were found to be at particularly high risk.

When used in conjunction with traffic signals, pedestrian signals (i.e., Walk/Don't Walk signals) may be beneficial to pedestrians. Many elderly and handicapped pedestrians could also be assisted by the use of pedestrian push-button devices. When pushed, these devices extend the crossing period or stop traffic so that pedestrians may cross the street (*10*).

For visually impaired pedestrians, signals that use a voice, buzzer, or other sound may be helpful to indicate when the Walk signal is actuated. Audible signals have been installed in many U.S. cities. In San Diego audible signals installed at intersections frequented by blind and visually impaired people use different sounds depending on the direction of travel (north-south or east-west) (*11*).

However, the audible signal only indicates when the Walk interval is activated; it does not guarantee that motorists will not run red lights or turn across a pedestrian's path from a side street. Some organizations providing services to the blind are opposed to audible signals, since such signals may cause pedestrians to pay less attention to other traffic cues (*11*).

Pedestrian Refuge Islands

In the current analysis, older pedestrians were found to be overrepresented in crashes when crossing wide streets of four or more lanes. One possible solution is to install pedestrian refuge islands (or safety islands), which are areas between opposing traffic lanes within an intersection that may consist of pavement markings only or a raised island. They are particularly helpful to those who have difficulty crossing a wide street without stopping. The use of channelized right-turn lanes (with a pedestrian refuge island separating the right-turn lane from the other travel lanes) can reduce right-turn-on-red crashes with pedestrians; it also shortens crossing distances.

Roadway Lighting

Although older pedestrians are generally underrepresented in nighttime crashes, one-fourth of deaths to pedestrians 65 through 74 do occur under dark conditions. The installation of adequate street lighting has been found to reduce pedestrian crashes by as much as 43 percent. Many cities such as Seattle, Washington, currently install lighting at midblock locations and at pedestrian activity centers to improve safety (*12*,*13*).

Overpasses and Underpasses

Overpasses and underpasses are facilities that allow for the free-flowing movement of vehicles and pedestrians and can greatly reduce the crash risk to older pedestrians crossing wide streets with high speeds and heavy volumes of traffic. In such facilities, a passageway for pedestrians is located one or more levels above or below the vehicle level (*6*). The effectiveness of grade-separated crossings, however, depends on how much they are used. Thus, the selection and proper placement of overpasses is essential. In addition, however, the facilities must be designed with gradual ramps leading onto and off of them to be of practical use to people with mobility limitations.

Pedestrian Malls

As found in the analysis, pedestrian crashes in general are primarily an urban problem, particularly for older pedestrians. The closing of streets to motor vehicles to provide for environments partially or totally for pedestrians is an ideal solution for improving pedestrian safety and movement. Although the development of pedestrian malls and other automobile-free zones in downtown areas is usually the result of efforts to revitalize the area, it can have the added benefit of substantially increasing safety for younger and older pedestrians alike.

CONCLUSIONS

Motor vehicle crashes represent a serious threat to the elderly pedestrian. Older pedestrians generally limit their exposure to the extent that, on a per-person basis, they are no more likely than other age groups to be involved in a pedestrian collision. However, once in a collision, the elderly are much more vulnerable to injury, so that they have the highest pedestrian fatality rate of any age group.

Much can be learned through the analysis of motor vehicle crash data about the particular factors involved in elderly pedestrian crashes. This information can, in turn, be used for more effective targeting of intervention strategies toward this vulnerable age group. Drawing from the literature and from a decade of North Carolina and U.S. pedestrian crash data, the present study has recommended a number of educational, enforcement, legislative, and roadway countermeasures for preventing motor vehicle crash injuries to elderly pedestrians.

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Factors Associated with Driving Performance of Older Drivers

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A 2-year study of older drivers was conducted at the University of Nebraska to develop and evaluate methods for improving the safety of older drivers. During the first year, data on several characteristics including driving performance of older drivers were collected. The correlation between driving performance and measured characteristics was investigated to provide a basis for the design of the countermeasures, which were evaluated in the second year. The results of the analysis of the factors associated with the driving performance of older drivers are presented. Several factors relative to the physical and mental status of 105 drivers between the ages of 65 and 88 were measured. In addition, their driving knowledge and on-street driving performance were evaluated. Pearson product-moment correlation coefficients were computed to measure the relationships between on-street driving performance and the other factors. In addition, stepwise multiple regression analysis was used to determine the combination of factors that accounted for the most variability in the on-street driving performance. A number of factors associated with vision, visual perception, cognition, and driver knowledge were found to correlate significantly with the driving performance of older drivers. The results of the analysis suggest that a number of methods can improve the safety of older drivers; among them are (a) physical therapy to improve range of motion, (b) therapies or exercises to improve visual perception and cognition, and (c) driver education to increase driving knowledge pertinent to the accident situations in which older drivers are overinvolved.

During the past few decades research has provided insight into some of the deficiencies in the abilities of older people that affect their driving performance. As related to the driving task, these deficiencies may be classified into five categories:

- *Sensory*, which includes any deficiency in human senses that may affect the amount or quality of information received while driving;
- *Perceptual*, which is related to the human ability to identify objects presented while driving;
- *Cognitive*, which is related to the human ability to match the perceived information with past experience and decide on the proper action to be taken;
- *Physical,* which is related to the functional ability of the human body to perform the driving task; and
- *Driving knowledge*, which is related to the driver's understanding of how to drive in response to prevailing roadway and traffic conditions.

These factors have been evaluated as possible discriminators between young and old drivers. All of them have been found to exhibit some age differences (*1*,*2*). However, the degree of discrimination was not the same for all factors. It was dependent on the type of task and the age difference between the younger and older drivers being considered. Because driving is a highly visual task, it is important to note that many adults tend to have significant deficits in visual functioning (*3*). However, contrary to intuition, published research has failed to establish a link between vision and driving in elderly persons (*4–6*). Considerable published evidence suggests a decline in the cognitive functioning of aging individuals (*7*,*8*). Many studies have shown that intact cognition is a necessary component of safe driving (*9–11*). Also, people of the same age usually exhibit differences with respect to these five factors for reasons other than the age. Consequently, age alone has not been found to be a reliable indicator of driving ability.

A 2-year study of older drivers was conducted by the University of Nebraska to develop and evaluate methods to improve the safety of older drivers. During the first year, the problems of older drivers were analyzed to provide a basis for the design of the countermeasures. The results of the analysis of the factors associated with the driving performance of older drivers are presented in this paper.

METHODOLOGY

Several factors relative to the physical and mental status of 105 drivers between the ages of 65 and 88 were measured. In addition, their driving knowledge and on-street driving performance were evaluated. Pearson product-moment correlation coefficients were computed to measure the relationships between on-street driving performance and the other factors. In addition, stepwise multiple regression analysis was used to determine the combination of factors that accounted for the most variability in the on-street driving performance.

SUBJECTS

The subjects who participated in the study were active individuals who drive regularly. The average age of the 105 drivers was 71.4 years. Fifty-four were women, with an average age of 70.5 years, and 51 were men, with an average age of 72.2 years. The distribution of the subjects by age and gender is shown in Table 1. Thirty-six of the subjects have taken a driver education course within the past 10 years. All of the subjects

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TABLE 1 Distribution of Subjects by Age and Gender

Age	Male	Female	Total
65 - 69	19	22	41
70 - 74	17	24	41
75 - 79	9	6	15
80 - 84	4	2	6
85 - 89	2	0	2
Total	51	54	105

were volunteers, and they were each paid $25 for their participation in the study.

FACTORS

The characteristics of older drivers evaluated in this study were vision, visual perception, cognition, reaction time, range of motion, and driving knowledge. The methods used to measure each of these factors are described in the following.

Vision

Keystone telebinocular testing device was used to measure the vision of each subject. These measurements included far and near acuity, depth perception, left and right peripheral vision, color vision, and lateral and vertical phoria. Although these measures were recorded, they were not expected to be good correlates of driving (*6*).

Visual Perception

The motor-free visual perception test (MVPT), designed and standardized on children by Colarusso and Hammil (*12*), was used in this study to assess the visual perception of older drivers. The test is composed of 36 questions, divided into the five groups, that assess the following aspects of visual perception:

1. *Spatial relationship*, which is the ability orient one's body in space and perceive the positions of objects in relation to oneself and other objects;
2. *Visual discrimination*, which is the ability to discriminate dominant features in different objects;
3. *Figure-ground,* which is the ability to distinguish an object from its background;
4. *Visual closure*, which is the ability to identify incomplete figures when only fragments are presented; and
5. *Visual memory,* which is the ability to recall dominant features of one stimulus item or to remember the sequence of several items.

A modified version of MVPT has been used to evaluate brain-damaged people (*13*), but the use of MVPT to evaluate elderly people has not been reported in the literature. However, because the test does measure the aforementioned cognitive factors, it was used in this study.

The MVPT was administered by occupational therapists according to the standard procedure. Two scores were obtained for each subject for each of the five visual-perception measures. One was the mean time required for the subject to answer the questions pertaining to the given measure (response-time score), and the other was the number of questions answered correctly (error score). Overall response-time and error scores were also computed.

Cognition

Three tests were used to measure the cognitive ability of a subject: the mini-mental state (MMS) examination, the trail-making test Part A (TMA), and the trail-making test Part B (TMB). Because other factors besides cognition were being tested, the cognitive tests had to be restricted to MMS, TMA, and TMB.

MMS is a simplified cognitive status examination devised by Marshal et al. (*14*). Compared with other cognitive performance tests such as Withers and Hinton's or Wechsler adult intelligence scale, MMS concentrates only on the cognitive aspects of mental functions. It excludes questions concerning mood, abnormal mental experiences, and the form of thinking, but includes questions on orientation. Normal, healthy elderly people have been found to score well on the MMS (*15*), and it has been found to be a predictor of driving (*1*).

TMA and TMB are both composed of 25 circles distributed randomly on an 8- × 11½-in. sheet of white paper. In TMA, the circles are numbered randomly from 1 to 25. The time required for the subject to correctly draw a line connecting the 25 circles in numerical order is measured. In TMB, there is either a number (from 1 to 13) or a letter (from A to L) written inside each circle, and the time it takes the subject to correctly draw a line connecting the circles in alternate numerical and alphabetical order (from 1 to A to 2 to B, etc.) is measured. TMA is a general measure of visuospatial scanning ability and motor sequencing skills. TMB requires some abilities in addition to those required for TMA. Alternating between numbers and letters requires more language skills of the subject and the ability to switch flexibly between numbers and letters. The tests were found to be 81 percent effective in diagnosing brain-damaged subjects and were also found to be sensitive to age (*7*).

Reaction Time

The brake reaction times of the subjects were measured with a Doron L225 driving simulator. The stimulus was a display composed of two rectangular red lights, each 2 × 3 cm, mounted 4 cm apart on the dashboard of the simulator. The lights flashed in alternating fashion. When both lights turned on at the same time, the subject was to release the gas pedal and push the brake pedal as fast as possible. Six trials were obtained from each subject, and the mean was taken to represent subject's brake reaction time.

Range of Motion

Flexibility is an essential component of the physical fitness of older people (*2*). Movement of the upper extremities plays a vital role in driving (*16*). Decreased head and neck mobility impair the ability of the older driver to perform driving tasks such as scanning the rear, backing, and turning the head to observe blind spots (*17*). Complex arm, leg, and head movements while driving tend to be limited among the elderly (*18*). In a survey of the problems of the elderly, 21 percent of the older drivers reported difficulty in turning their heads and looking to the rear when driving (*19*).

Range-of-motion measurements were taken both in the clinic and in the car. The measurements in the clinic were taken with the subject seated upright in a straight-backed chair with both feet on the floor. The following range-of-motion measurements were taken in the clinic: neck flexion, neck extension, neck rotation to the left, neck rotation to the right, neck lateral bend to the left, neck lateral bend to the right, left shoulder flexion, right shoulder flexion, trunk rotation to the left, and trunk rotation to the right.

The in-car measurements were taken with the subject seated behind the steering wheel. The subject's seat belt was fastened, and the subject's hands were in their normal driving position on the steering wheel. The following range-of-motion measurements were taken in the car: neck flexion, neck extension, neck rotation to the left, neck rotation to the right, neck lateral bend to the left, and neck lateral bend to the right. Three measurements of each motion were taken, and the average of the three was used.

Driving Knowledge

To drive safely, drivers must know how to drive their vehicles under a variety of roadway and traffic conditions. In addition, they must know the rules of the road, the traffic laws and regulations, and the meanings of the traffic control devices. Previous studies have found that older drivers are often less knowledgeable about driving than younger drivers (*20,21*). McCoy et al. found that scores on the driving-knowledge portion of the Nebraska driver's license examination were lower for older drivers, and the average score of drivers over 75 years old was below the 80 percent required to pass the test (*22*).

A 50-question multiple-choice test was used to measure the driving knowledge of the subjects. The test was designed to determine their driving knowledge pertinent to the types of accidents in which older drivers in Nebraska were overinvolved. The distribution of the questions on the test was according to the distribution of collision types and contributing circumstances reflected in the accident experience of older drivers in Nebraska. The distribution of the test questions is given in Table 2. For example, 25 of the 50 questions pertained to left-turn collisions involving failure to yield the right of way. The percentage of the questions answered correctly was used as the measure of driving knowledge.

DRIVING PERFORMANCE

The driving performance of the subjects was evaluated using the on-street driving performance measurement (DPM) technique developed at Michigan State University (*23*). This technique provides a systematic approach to the design of an on-street DPM route and a reliable method for rating driving performance as satisfactory or unsatisfactory on the basis of observable driver behavior patterns composed of search, speed control, and direction control. The pilot studies conducted in Michigan showed that the DPM technique is a reliable and valid measure of safe and skillful driving. The subjects were evaluated by a driver education expert trained and experienced in the use of the DPM technique. The evaluator scored the driving performance of the subjects while riding with them in the front passenger seat of the vehicle. The evaluator did not have any information on the performance of the subjects in the other tests. The evaluation was done two times. Within-evaluator reliability was established through a *t*-test done on the score of the two road tests. The two road test scores were not different from each other. Similarly, because two evaluators were used, between-evaluator reliability was also established through a *t*-test. Road test scores on a sample of drivers evaluated by each of the evaluators were tested against each other, and they showed to be insignificant. The subjects drove their own vehicles.

DPM Route

The DPM route was designed to evaluate the subjects in the situations that are most often involved in the accidents of older drivers. The results of an analysis of accidents in Nebraska indicated that older drivers were overrepresented in left-turn and right-angle collisions at controlled intersections in urban areas on weekdays between 9:00 a.m. and 3:00 p.m. (*14*). Therefore, the route featured the evaluation of the subjects at urban intersections.

The DPM route was a 19-km circuit in Omaha, Nebraska. The driving performance of the subjects was evaluated at seven intersections on the route. The subjects were required to make left turns at five of the intersections and right turns

TABLE 2 Distribution of Driving Knowledge Test Questions

Contributing Circumstance	Accident Type								Total
	Right Angle	Rear End	Side Swipe	Head On	Left Turn	Other Turn	Right Turn	Pedes-trian	
Failure To Yield	4[a]/2[b]		1/1		50/24	4/2	1/1	4/2	64/32
Disregarded Traffic Signal	10/4			1/1	1/1				12/6
Improper Turn Signal						1/1			1/1
Made Improper Turn			1/1	1/1	4/1	1/1			7/4
Following Too Close		11/5							11/5
Improper Lane Change			5/2						5/2
Total	14/6	11/5	7/4	2/2	56/27	5/3	1/1	4/2	100/50

[a] Percent of older-driver accidents.

[b] Number of driving-knowledge test questions.

at the other two intersections. Four of the left turns were made from left-turn lanes on four-lane divided arterial streets in suburban areas and one was made from a left-turn lane on a two-lane two-way street in an outlying business district. Two of the left turns were controlled by protected/permitted left-turn signal phases, two were controlled by permitted left-turn signal phases, and one was uncontrolled. One of the right turns was on a turning roadway at a signalized intersection on a four-lane divided arterial street in a suburban area. The other right turn was made from a stop-sign controlled approach at an intersection of two, two-lane two-way local streets in a residential area. The speed limits were from 35 to 45 mph on the arterial streets and 25 mph in the outlying business district and residential area.

Evaluation

Each of the seven turning maneuvers evaluated was divided into three segments: (a) the approach to the intersection, (b) the turning maneuver itself, and (c) the departure from the intersection. The performance of the subject in each segment was evaluated as being satisfactory or unsatisfactory. One point was given for each "satisfactory" score and zero points were given for an "unsatisfactory" score. Therefore, the best driving performance score that a subject could receive for each trip around the route was 21 points, and the worst was 0 points. The criteria for determining satisfactory or unsatisfactory performance were in terms of the subject's search pattern and control of the vehicle's speed and direction.

The subjects made two trips around the route. Therefore, 42 was the maximum score that they could receive. The measure of driving performance used in the analysis was the driving performance score expressed as a percentage of 42. It usually took the subjects about an hour to complete two trips around the route.

RESULTS

Correlation Analysis

The data were initially checked for possible outliers, and the check was followed by a correlation analysis. The results of the correlation analysis are presented in Table 3. Among the vision factors, depth perception and right visual field showed the highest correlations, of .35 and .22, respectively. They were also the only significant correlations (p-values $< .05$) with the driving performance among the vision factors.

Among the visual perception factors, the following scores were correlated significantly (p-values $< .05$) with the driving performance: spatial relationships error score (.21), visual discrimination error score (.26), visual discrimination response-time score (-0.22), figure-ground response-time score (-0.28), visual closure response-time score (-0.24), visual memory response-time score (-0.38), overall error score (.26), and

TABLE 3 Correlation Between Driving Performance and Factors

Factor	Correlation Coefficient	P-Value
Vision		
Far Acuity	0.18	0.0577
Near Acuity	0.15	0.1347
Depth Perception	0.35	0.0002
Right Visual Field	0.22	0.0238
Left Visual Field	0.12	0.2354
Color Vision	0.07	0.5016
Lateral Phoria	-0.03	0.7681
Vertical Phoria	0.16	0.1001
Visual Perception		
Spatial Relationships Error Score	0.21	0.0276
Spatial Relationships Response Time	-0.14	0.1591
Visual Discrimination Error Score	0.26	0.0071
Visual Discrimination Response Time	-0.22	0.0250
Figure-Ground Error Score	0.05	0.5967
Figure-Ground Response Time	-0.28	0.0036
Visual Closure Error Score	0.18	0.0595
Visual Closure Response Time	-0.24	0.0113
Visual Memory Error Score	0.10	0.3059
Visual Memory Response Time	-0.38	0.0001
Overall Error Score	0.26	0.0079
Overall Response Time	-0.32	0.0008
Cognition		
Trail-Making Test Part A	-0.03	0.7329
Trail-Making Test Part B	-0.42	0.0001
Mini-Mental Status Exam	0.24	0.0123
Brake Reaction Time	-0.15	0.1182

(continued on next page)

overall response-time score (−0.32). As expected, the negative correlations were associated with the response-time scores and the positive correlations were associated with the error scores.

Among the cognitive measures, TMB and MMS showed the highest correlations, of −0.42 and 0.24, respectively. They were also the only significant ones. In fact, it is interesting to note the difference in correlation between TMA and TMB. For some unexplainable reasons TMB has turned out to be a reasonably decent predictor of driving performance. The main difference between the two tests is that TMB had both alphabets and numbers in the map that the subjects traced, whereas TMA had only numbers in the map. Further research is needed in this area. TMB had the highest correlations of any of the factors included in the analysis.

The driving knowledge test score (.27) was also significantly correlated with driving performance.

None of the range-of-motion measures was significantly correlated with the driving performance. All of these measures had relatively low correlations except the in-clinic measures of trunk rotation to the right (.17), trunk rotation to the left (.14), and neck lateral bend to the right (.15).

Other factors included in the analysis were age, gender, and whether the subject had a driver education course within the past 10 years. None of these had significant correlations with driving performance.

TABLE 3 *(continued)*

Factor	Correlation Coefficient	P-Value
In-Clinic Range of Motion		
Neck Flexion	0.08	0.4290
Neck Extension	0.10	0.2875
Neck Rotation to the Left	0.01	0.9161
Neck Rotation to the Right	-0.07	0.4507
Neck Lateral Bend to the Left	0.03	0.7617
Neck Lateral Bend to the Right	0.15	0.1156
Shoulder Flexion to the Left	0.08	0.4306
Shoulder Flexion to the Right	0.13	0.1724
Trunk Rotation to the Left	0.14	0.1562
Trunk Rotation to the Right	0.17	0.0744
In-Car Range of Motion		
Neck Flexion	0.04	0.6822
Neck Extension	0.13	0.1803
Neck Rotation to the Left	-0.11	0.2425
Neck Rotation to the Right	0.08	0.4087
Neck Lateral Bend to the Left	-0.04	0.6798
Neck Lateral Bend to the Right	-0.01	0.8868
Driving-Knowledge Test Score	0.27	0.0053
Other		
Age	-0.11	0.2651
Gender	0.04	0.7087
Taken Driver Education Course Within Past 10 Years	0.04	0.7100

Multiple Regression Analysis

The results of the stepwise multiple regression analysis are presented in Table 4. All factors investigated in this study were included the stepwise procedure of the regression analysis at the .05 level of significance for the entry and removal of variables from the model. TMB, trunk rotation to the right, TMA, overall visual perception response-time score, and spatial relationship error score were the only significant factors. Together they accounted for 45 percent of the total variability in the driving performance. According to the signs of the regression coefficients in the model, better driving performance was associated with better cognition as measured TMA and TMB, better range of motion in trunk rotation, and visual perception.

DISCUSSION OF RESULTS

Vision

Depth perception and peripheral vision are among the most important aspects of vision needed for safe driving. Depth perception is important for estimating distances, especially those of moving objects. Driving requires the continuous estimation of distances. Since many of the cues in driving come from the roadside, peripheral vision is also helpful. Narrow visual fields limit the ability of the driver to receive timely information. Rotation of the head and eyes to compensate for deficiencies in peripheral vision increases the time required to receive the information. Both of depth perception and peripheral vision showed significant correlations with the driving performance of the older drivers.

TABLE 4 Regression Analysis Summary

Factor	Sign of Regression Coefficient	Partial R^2	Model R^2	F-Value	P-Value
Trail-Making Test Part B	-	0.23	0.23	19.80	0.001
Trunk Rotation To The Right	+	0.07	0.30	9.82	0.028
Trail-Making Test Part A	-	0.05	0.35	7.90	0.0078
Visual Perception Response-Time Score	-	0.07	0.42	10.92	0.0013
Spatial Relationships Error Score	+	0.03	0.45	5.15	0.0256

Visual Perception

Better driving performance was associated with better visual perception, especially with visual memory and figure-ground discrimination. Visual perception is an indicator of the ability to manipulate objects so that they are recognized quickly and accurately. Compared with the correlations of the vision factors, visual perception has a greater bearing on driving performance among older drivers. Some older drivers may have good vision but cannot use it effectively.

Cognition

The results of the analyses indicate the importance of the general cognitive state of older drivers in relation to their ability to drive safely. Most highly correlated with driving performance were the aspects of cognition measured by the TMB and MMS tests such as language skills, orientation, memory, attention, and ability to follow verbal and written instructions.

Range of Motion

None of the range-of-motion factors correlated significantly with the driving performance. These factors are important for driving, especially the neck and trunk rotation. However, it is not surprising that these factors did not correlate significantly with the driving performance as measured in this study. These factors are most important for safe driving in high-volume, high-speed traffic such as that on a freeway. The lane-changing, passing, and collision avoidance maneuvers required under these conditions demand more head rotation. But older drivers usually avoid driving under these conditions. Therefore, the DPM route did not include these conditions.

Driving Knowledge

The driving knowledge of older drivers showed a significant and reasonably high correlation with their driving performance, which appears logical. Knowing how to drive properly is a prerequisite to driving properly.

Other Factors

Age and gender did not have large or significant correlations with driving performance. Of course, only drivers between the ages of 65 and 88 were evaluated. The narrow age range may account for the lack of correlation between age and driving performance. It is noteworthy that chronological age did not predict driving performance. This would help argue against age cutoffs for licensing. But the subjects were about evenly divided between men and women. Therefore, gender may not be a factor in the driving performance of older drivers.

With respect to driver education, whether the subject had taken a driver education course within the past 10 years had a very small correlation with driving performance. However, most of the subjects who had taken a driver education course within the past 10 years had taken it more than 5 years ago. Consequently, the results cannot be considered applicable to the drivers who had taken a course within the past 5 years.

CONCLUSION

A number of factors associated with vision, visual perception, cognition, and driver knowledge were found to correlate significantly with the driving performance of older drivers as measured by the on-street DPM technique. The results of the analysis suggest a number of methods for improving the safety of older drivers. The positive correlation found between driving performance and the vision factors of depth perception and peripheral vision indicates that older drivers need to be aware of ways to compensate for deficiencies with respect to these factors. Search patterns and maintenance of margins of safety that compensate for these deficiencies are typically included in education courses for older drivers. Therapies designed to improve the visual perception of older drivers are suggested by the correlations found between driving performance and visual perception. Likewise, measures designed to improve cognition are indicated as possible ways to improve the driving performance of older people.

The results of the regression analysis indicate that physical therapy designed to improve range of motion may benefit older drivers. A driver education program designed specifically to improve spatial scanning, visual information processing skills, and cognitive functioning skills may improve the driving performance of the older driver. A caveat is in order here: although this study had 105 subjects, when distributed over 40 factors the number of subjects per factor became low. Therefore, a validation study is definitely needed before any generalization can be made.

As a result of the analysis, the countermeasures designed for evaluation during the second year of the research were physical therapy, perceptual therapy, driver education, and traffic engineering improvements. The results of the evaluation of the effects of these countermeasures on the performance of older drivers are reported elsewhere (*24*).

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Evaluation of Countermeasures for Improving Driving Performance of Older Drivers

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A 2-year study of the problems of older drivers was conducted by a team of researchers from the disciplines of traffic engineering, gerontology, physical therapy, occupational therapy, and driver education. The objective of the research was to develop and evaluate countermeasures for improving the safety of older drivers. During the first year, the problems of older drivers were examined and countermeasures were designed to address these problems. The countermeasures designed were physical therapy, perceptual therapy, driver education, and traffic engineering improvements. In the second year, the countermeasures were evaluated by measuring their effects on the driving performance of older drivers. The results of the evaluation of the countermeasures are presented. A total of 105 older drivers between the ages of 65 and 88 were used to evaluate the effects of the countermeasures on the driving performance of older drivers. The subjects were randomly assigned to six experimental groups that received different countermeasures. The on-road driving performance of the subjects was measured using the driver performance measurement technique developed at Michigan State University. All of the countermeasures significantly improved the driving performance of the older drivers by an average of 7.9 percent. The results of the cost-effectiveness analysis indicated that traffic engineering improvements would be most cost-effective on high-volume roadways and that the other countermeasures would be most cost-effective on low-volume roadways.

A 2-year study of the problems of older drivers was conducted by a team of researchers from the disciplines of traffic engineering, gerontology, physical therapy, occupational therapy, and driver education. The objective of the research was to develop and evaluate ways to improve the safety of older drivers. During the first year of the study, the problems of older drivers were examined and countermeasures designed to address these problems. The problems of older drivers, which are reported elsewhere (*1*), were defined in terms of the accident situations in which they are overinvolved, deficiencies in their knowledge of driving, and deficits in their physical, perceptual, and cognitive abilities. The countermeasures designed to address these problems were

- Physical therapy,
- Perceptual therapy,
- Driver education, and
- Traffic engineering improvements.

In the second year, the countermeasures were evaluated by measuring their effects on the driving performance of older drivers. The procedures and results of this evaluation are presented in this paper.

SUBJECTS

The older drivers who participated in the study were volunteers solicited through the AgeWell Program at Immanuel Hospital in Omaha, Nebraska. Letters of invitation to participate in the study were sent to 1,500 members of the AgeWell Program who were 75 years or older. The letters explained the objective of the study, the eligibility requirements for participation in the study, the study procedure and time requirements, and the benefits of participation. The eligibility requirements were as follows:

- Age 75 years or older,
- Good health,
- Valid driver's license,
- Driving on a regular basis,
- Evidence of financial responsibility,
- Vehicle to use,
- Not taken an older driver training course, and
- Medical release from physician to participate.

Potential subjects were offered $25 and a free older driver training course in return for participating in the study. Two weeks later, a second letter was sent the 1,500 members reminding them of the request to participate in the study and the registration deadline. About 20 members volunteered to participate in the study. However, this was much too small a sample size for the purposes of the research.

The minimum age requirement was initially set at 75 years, because the results of the first year of the research indicated that drivers 75 years and older had the most serious driving problems (*1*). But to obtain a sufficient sample size, it was

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necessary to reduce the minimum age requirement to 65 years. Letters were then sent to 1,000 members of the AgeWell Program who were between 65 and 75 years old. As a result, a total sample size of 105 drivers 65 years and older was obtained.

The 105 subjects ranged in age from 65 to 88 and averaged 71.8 years. There were 51 men and 54 women. The men ranged from 66 to 88 years, with an average age of 72.6 years. The women ranged from 65 to 84 years, with an average age of 70.9 years. The distribution of the subjects by age and sex is shown in the following table:

Age	*Men*	*Women*	*Total*
65–69	19	22	41
70–74	17	24	41
75–79	9	6	15
80–84	4	2	6
85–89	2	0	2
Total	51	54	105

DRIVING PERFORMANCE TEST

The driving performance of the subjects was measured on the road using the driver performance measurement (DPM) technique developed at Michigan State University (*2,3*). The results of the first year of the research indicated that older drivers were overinvolved in multivehicle collisions at intersections in urban areas. Therefore, the DPM route was designed to measure the driving performance of the subjects relative to the maneuvers often involved in older-driver accidents at intersections in Omaha, Nebraska. The driving performance of the subjects was evaluated at seven locations on the 19-km route. Five of the locations involved left turns, one involved a right turn, and the other involved an approach to an uncontrolled intersection. Four of the left-turn locations were at signalized four-leg intersections on four-lane divided arterial streets at which the left turns were made from left-turn lanes. Three of the four left turns were controlled by protected/permitted phasing and the fourth by permitted phasing. The fifth left turn was at an unsignalized T-intersection on a four-lane divided arterial street intersecting a four-lane undivided arterial street at which the left-turn maneuver was made from a left-turn lane. The right turn was at a signalized intersection of two four-lane divided arterial streets.

A certified driver education expert trained in the DPM technique conducted the evaluation. The evaluator scored the driving performance of the subjects while riding with them in the front passenger seat of their vehicles. At each of the seven locations on the DPM route, the evaluation of a subject's driving performance was based on search, speed control, and direction control criteria, which were each scored as either satisfactory or unsatisfactory. One point was given for satisfactory performance, and zero points were given for unsatisfactory performance. A maximum score of three points was possible at each location. Therefore, a total of 21 points was possible on the DPM route.

The DPM tests were conducted during the off-peak hours between 9:00 a.m. and 3:00 p.m. Monday through Saturday, which were the times when older drivers were found to be overinvolved in traffic accidents (*1*). The subjects drove their own vehicles so that the DPM scores would not be influenced by the subjects' unfamiliarity with the vehicles that they drove during the tests. To improve the reliability of the test scores, each subject drove around the DPM route twice and the mean of the two DPM scores was used in the data analysis. All of the subjects were from the Omaha area and were familiar with the streets on the DPM route.

COUNTERMEASURES

Four countermeasures were selected for evaluation during the second year of the research: physical therapy, perceptual therapy, driver education, and traffic engineering improvements. These countermeasures were designed to address the problems of older drivers that had been defined during the first year of the research (*1*).

Physical Therapy

The physical therapy was a set of self-administered home-based exercises designed to improve posture, trunk rotation, neck flexibility, and shoulder flexibility. The therapy consisted of seven exercises. The exercises were to be done four times a week for 8 weeks. Before the start of their exercise program, the subjects were given a 1-hr training session. During the training session, the subjects practiced all of the exercises. They were also given brochures containing instructions for doing the exercises and diaries in which to record the dates on which they did the exercises. The subjects were encouraged to contact the researchers whenever they had any questions. After 4 weeks the researchers contacted the subjects to check their progress and answer any questions.

Perceptual Therapy

The perceptual therapy was a set of self-administered home-based exercises designed to improve the following five components of visual perception:

- Spatial relationships,
- Visual discrimination,
- Figure-ground,
- Visual closure, and
- Visual memory.

The therapy consisted of 568 exercises. The exercises were to be done for 20 min four times a week for 8 weeks. Before the start of the exercise program, the subjects were given a 1-hr training session. During the training session, the subjects practiced the exercises for each of the five components of visual perception. The subjects were given workbooks that contained the exercises and instructions for doing them. They were also given diaries in which to record the dates on which they did the exercises. The subjects were encouraged to contact the researchers whenever they had any questions. After 4 weeks the researchers contacted the subjects to check their progress and answer any questions.

The exercises in the workbook were organized into five sections, one for each component of visual perception. The exercises in each section of the workbook were arranged in order of degree of difficulty, progressing from the simplest to the most difficult. The subjects were to do the exercises in order, spending about 4 min on each section during a 20-min session. They were to do as many exercises as possible, working at their own pace. If they completed the exercises in one of the sections before the end of the 8 weeks, they were to start the section over from the beginning.

Driver Education

The results of the evaluation of the driving knowledge of older drivers (*1*) indicated that they have deficiencies in their driving knowledge with respect to right-of-way rules and procedures for crossing and turning left at intersections, safe following distances, correct lane positioning and selection, and proper procedures for backing and parking maneuvers. Therefore, driver education to correct these deficiencies was selected as one of the countermeasures to be evaluated.

There are three nationally prominent older driver education programs:

- *Coaching the Mature Driver*, National Safety Council (NSC);
- *55 Alive/Mature Driving*, American Association of Retired Persons (AARP); and
- *Safe Driving for Mature Operators*, American Automobile Association (AAA).

All three programs were examined and found to provide adequate coverage of the information needed to address the driving knowledge deficiencies of older drivers and the accident situations in which they are overinvolved. Therefore, it was not necessary for the research team to develop another older-driver education program.

The AAA *Safe Driving for Mature Operators* was selected as the driver education countermeasure to be used in the second year of the research. It was one of the lowest-cost programs. In addition, AAA was the most willing of the program sponsors to have its program used in the research. The course was taught by one of the officers of the Nebraska State Highway Patrol who normally teaches the AAA course in the Omaha area. The course consisted of 8 hr of classroom instruction presented in 1 day. Each subject received a course manual (*4*) that covered the information presented by the course instructor.

Engineering

The traffic engineering improvements were incorporated into the DPM route at the seven locations where driving performance was evaluated. Because the DPM route was designed to measure the driving performance of the subjects relative to the maneuvers often involved in older-driver accidents at intersections, the traffic engineering improvements were designed to improve the performance of older drivers in making these maneuvers. Therefore, traffic engineering improvements were installed to facilitate left-turn maneuvers at five of the locations, right-turn maneuvers at one location, and the approach to an uncontrolled intersection at the other location. The improvements were limited to signs, pavement markings, and traffic signal displays because of the time and budget constraints of the research. The improvements were selected to address the particular operational and safety problems observed at each location. These problems were reviewed with the traffic engineering staff of the city of Omaha to determine the most appropriate improvements for each location. The final selection was made in cooperation with the city of Omaha.

EXPERIMENTAL DESIGN

The subjects were tested before and after the countermeasures were implemented. The tests examined the following subject attributes: vision, visual perception, cognition, range of motion, brake reaction time, driving knowledge, and on-road driving performance. The change in the DPM scores was the primary measure of the effectiveness of the countermeasures. The changes in the other test scores were used to monitor and control for changes in the physical and mental condition and driving knowledge of the subjects.

Initial Design

The subjects were divided randomly into six study groups. Each group received a different countermeasure. The first group received the physical therapy program, the second group received the perceptual therapy program, and the third group received the driver education program. The fourth and fifth groups received a combination of therapy and driver education: the fourth group received the physical therapy and driver education, and the fifth group received the perceptual therapy and driver education. The sixth group was the control group, which did not receive either of the therapies or the driver education program.

The traffic engineering improvements were incorporated into the DPM route. Therefore, the subjects in each of the six study groups were divided randomly into two subgroups. The subjects in one of the subgroups were given both their before and after DPM tests before the traffic engineering improvements were installed on the DPM route. The subjects in the other subgroup were given their first DPM test before the traffic engineering improvements were installed and their second DPM test after the traffic engineering improvements were installed.

The subjects were assigned randomly to the 12 subgroups. In an effort to avoid a biased assignment with respect to driving performance, the subjects were first ranked according to their scores on their before DPM test and divided into four quarters. The subjects were then assigned randomly to the 12 subgroups using the four quarters as a blocking factor. The number of subjects assigned to each subgroup is given in Table 1. A Kruskal-Wallis test of the DPM scores indicated that there were no significant differences among the subgroup mean DPM scores at the .05 level of significance.

TABLE 1 **Sample Sizes**

Countermeasure	Second DPM Test Run[a] A	B	Total
1 - Physical Therapy	9	9	18
2 - Perceptual Therapy	9	8	17
3 - Driver Education	8	9	17
4 - Physical Therapy and Driver Education	9	8	17
5 - Perceptual Therapy and Driver Education	9	9	18
6 - None	9	9	18
Total	53	52	105

[a] A - Before traffic engineering improvements were installed.
B - After traffic engineering improvements were installed.

Revised Design

The 105 subjects were given the before tests and assigned to the 12 study groups. However, 11 of the subjects did not complete their participation in the study for various reasons. Two of the 11 subjects became ill, and the others had personal business or scheduling conflicts that prevented them from continuing their participation in the study. Thus only 94 subjects completed study. The revised sample sizes are presented in Table 2.

Some of the subjects who were initially assigned to Group B2, who were to receive perceptual therapy and take their DPM test after the traffic engineering improvements had been installed on the DPM route, were inadvertently sent information about the schedule for the driver education course that was intended for the subjects in Group B5, who were to receive both perceptual therapy and driver education and take their second DPM test after the traffic engineering improvements had been installed on the DPM route. Consequently, there were only 4 subjects left in Group B2 instead of the 8 originally assigned to it, and there were 11 subjects instead of 9 in Group B5.

There was one other change to the original experimental design shown in Table 1. The subjects originally assigned to Control Groups A6 and B6 were combined into one control group in order to increase the sample size used to evaluate the traffic engineering improvements. The driving performance of these subjects was tested three times instead of twice. The first time their driving performance was tested was at the beginning of the study when all of the other subjects were first tested. The second time was 2 months later, before the traffic engineering improvements had been installed on the DPM route. The third time was another 2 months later, after the traffic engineering improvements had been installed. The difference between their first and second DPM scores served as the control for the study, and the difference between their second and third DPM scores served to measure the effects of the traffic engineering improvements.

EVALUATION

The effects of the countermeasures on the driving performance of the 94 subjects were computed by subtracting the subjects' DPM scores before implementation of the countermeasures from their DPM scores after implementation of the countermeasures. The mean differences in the DPM scores were then computed for each study group. The results of these calculations are shown in Table 3.

TABLE 2 **Revised Sample Sizes**

Countermeasure	Second DPM Test Run[a] A	B	Total
1 - Physical Therapy	9	9	18
2 - Perceptual Therapy	6	4	10
3 - Driver Education	8	7	15
4 - Physical Therapy and Driver Education	8	7	15
5 - Perceptual Therapy and Driver Education	8	11	19
6 - None			17[b]
Total			94

[a] A - Before traffic engineering improvements were installed.
B - After traffic engineering improvements were installed.
[b] Subjects in this group made three DPM test runs.

TABLE 3 DPM Scores

Countermeasure	DPM Score[a] (%) Before	DPM Score[a] (%) After	Mean Difference (%)
A - After DPM Score on DPM Route Before Traffic Engineering Improvements Installed			
1 - Physical Therapy	82.9	89.7	6.8
2 - Perceptual Therapy	88.1	95.8	7.7
3 - Driver Education	87.8	91.5	3.7
4 - Physical Therapy and Driver Education	85.2	93.9	8.7
5 - Perceptual Therapy and Driver Education	82.9	96.8	13.9
6 - None	84.1	83.7	-0.4
B - After DPM Score on DPM Route After Traffic Engineering Improvements Installed			
1 - Physical Therapy	86.7	93.1	6.4
2 - Perceptual Therapy	89.9	92.2	2.3
3 - Driver Education	85.4	91.7	6.3
4 - Physical Therapy and Driver Education	85.9	95.6	9.7
5 - Perceptual Therapy and Driver Education	85.7	94.8	9.1
6 - None	83.7	92.1	8.4

[a] Maximum possible DPM score = 100.0%.

The mean differences for all of the study groups except one were positive, indicating an improvement in driving performance. The only group that did not experience an improvement in driving performance was the control group A6. This group did not receive physical therapy, perceptual therapy, or driver education. The mean difference for this group was computed using the first and second DPM scores, which were obtained before the traffic engineering improvements were installed on the DPM route.

Kruskal-Wallis tests were used to test the equality of the group means. The Kruskal-Wallis test indicated that the group means were not equal ($p = .001$). Therefore, a Kruskal-Wallis multiple pairwise comparison test was conducted to determine which means were significantly different from one another. The results of the pairwise comparison test are shown in Table 4.

The p-values in Table 4 indicate that all of the groups that received a therapy or driver education or that were exposed to the traffic engineering improvements, except Group B2, showed statistically significant ($p < .015$) improvements in driving performance relative to Group A6. (The fact that Group B2 did not show a significant improvement could probably be attributed to its small sample size.) However, none of the other comparisons was statistically significant ($p < .015$).

COST-EFFECTIVENESS

The cost-effectiveness of the countermeasures was evaluated. The mean improvement in DPM score used was the measure of effectiveness. However, the results of the Kruskal-Wallis multiple pairwise comparison test in Table 4 indicated that there were no statistically significant differences among the mean improvements of the countermeasures. Therefore, the mean improvement for all of the countermeasures was the average improvement experienced by the subjects in the study groups that received countermeasures. The average improvement for the subjects in these groups was 7.9 percent.

The costs of the therapies included the 1-hr training sessions and the instructional brochures and exercise workbooks. The cost per older driver was computed by dividing the total cost of the training and instructional/exercise materials by the number of subjects receiving the therapy. The cost of the physical therapy was $5.35 (per person), and the cost of the perceptual therapy was $11.50. The cost of the driver education was the standard registration fee for the AAA course *Safe Driving for Mature Operators*, which was $7.00. The total cost of the engineering countermeasures was $3,066, which included the costs of materials, equipment, and labor. The cost per older driver would depend on the traffic volume and the percentage of older drivers in the traffic stream.

The cost-effectiveness of the countermeasures is shown in Table 5. The countermeasures were equally effective, each providing a 7.9 percent improvement in the driving performance of older drivers. Therefore, the most cost-effective countermeasure was the one with the lowest cost, which was the physical therapy. The cost-effectiveness of the traffic engineering improvements would depend on the number of older drivers exposed to the countermeasures, which in turn would depend on the traffic volume and percentage of older drivers in the traffic stream. To compare the traffic engineering improvements with the other countermeasures, the average daily traffic (ADT) volumes at which the traffic engineering improvements would be equally cost-effective with the other countermeasures were computed. The calculation of these breakeven ADTs was based on the following assumptions: (a) each countermeasure had a service life of 1 year and (b) the traffic volume had 10 percent older drivers. The breakeven

TABLE 4 ***p*-Values for Kruskal-Wallis Multiple Pairwise Comparison Test**

Group[a]	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5
A1	-										
A2	0.8444	-									
A3	0.9442	0.7972	-								
A4	0.8910	0.9607	0.8432	-							
A5	0.1147	0.1804	0.1083	0.1784	-						
A6	0.0069	0.0065	0.0113	0.0110	0.0001	-					
B1	0.8041	0.9699	0.7556	0.9299	0.1720	0.0031	-				
B2	0.4098	0.3434	0.4482	0.3760	0.0448	0.2831	0.3122	-			
B3	0.8543	0.9899	0.8062	0.9699	0.1768	0.0068	0.9594	0.3483	-		
B4	0.1911	0.2861	0.1798	0.2797	0.7565	0.0002	0.2780	0.0723	0.2806	-	
B5	0.3316	0.4753	0.3102	0.4597	0.4377	0.0001	0.4726	0.1199	0.4670	0.6337	-
B6	0.7505	0.6109	0.8168	0.6664	0.0515	0.0074	0.5557	0.5243	0.6205	0.0919	0.1641

[a] A - Subjects in the "A" groups were not exposed to the engineering countermeasures.
B - Subjects in the "B" groups were exposed to the engineering countermeasures.
1 - Subjects in the "1" groups received physical therapy.
2 - Subjects in the "2" groups received perceptual therapy.
3 - Subjects in the "3" groups received driver education.
4 - Subjects in the "4" groups received physical therapy and driver education.
5 - Subjects in the "5" groups received perceptual therapy and driver education.
6 - Subjects in the "6" groups did not receive any countermeasures.

ADTs for the traffic engineering improvements with respect to the other countermeasures are shown in the following table:

Countermeasure	*Breakeven ADT*
1—Physical therapy	5,730
2—Perceptual therapy	2,670
3—Driver education	4,380
4—Physical therapy and driver education	2,480
5—Perceptual therapy and driver education	1,660

The relative cost-effectiveness of traffic engineering improvements is shown in Figure 1. The three lines represent the breakeven ADTs for traffic engineering improvements with respect to the other countermeasures for annual costs of traffic engineering improvements up to $150,000/year. If the point of intersection of the annual cost of a traffic engineering improvement and the ADT exposed to it is above the breakeven line, the traffic engineering improvement would be cost-effective with respect to the other countermeasure. If the point of intersection is below the breakeven line, the traffic engineering improvement would not be cost-effective with respect to the other countermeasure. For example, if a traffic engineering improvement that costs $50,000/year was installed at a location where 60,000 vehicles per day were exposed to it, it would be cost-effective with respect to perceptual therapy but not with respect to physical therapy or driver education. If a program of traffic engineering improvements was implemented at several locations at a cost of $50,000/year and the sum of the traffic volumes exposed to the countermeasures at all locations was 60,000 vehicles per day, the program of traffic engineering improvements would be cost-effective with respect to perceptual therapy but not with respect to physical therapy or driver education.

TABLE 5 Cost-Effectiveness of Countermeasures

Countermeasure	Mean Improvement in DPM Test Score (%)	Cost ($/older driver)	Cost-Effectiveness ($/older driver/%)
1 - Physical Therapy	7.9	5.35	0.68
2 - Perceptual Therapy	7.9	11.50	1.46
3 - Driver Education	7.9	7.00	0.89
4 - Physical Therapy and Driver Education	7.9	12.35	1.56
5 - Perceptual Therapy and Driver Education	7.9	18.50	2.34
6 - Traffic Engineering Improvements	7.9	N.A.[a]	N.A.

[a] N.A. - Value would depend on traffic volume and percent of older drivers.

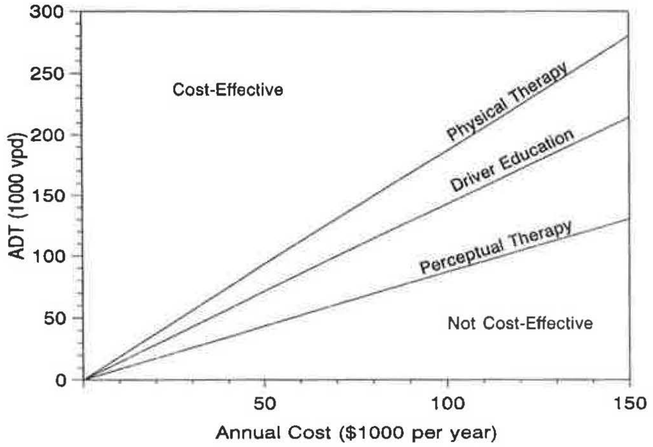

FIGURE 1 Relative cost-effectiveness of traffic engineering improvements.

CONCLUSION

Physical therapy, perceptual therapy, driver education, and traffic engineering improvements were all found to significantly improve the driving performance of older drivers. Combining driver education with physical or perceptual therapy tended to increase the improvement in driving performance, but none of the increases was statistically significant. Likewise, although the traffic engineering improvements were effective in improving the driving performance of older drivers, they did not add significantly to the improvement that was achieved by the other countermeasures. However, there were no statistically significant differences among the improvements provided by the countermeasures either individually or in combination. The average improvement provided was 7.9 percent. Therefore, it was concluded that the countermeasures and their combinations are equally effective and provide a 7.9 percent improvement in the performance of older drivers.

Since the countermeasures were equally effective, the most cost-effective countermeasure was the one with the lowest cost. The costs per driver of the countermeasures evaluated in the research were (a) $5.35 for physical therapy, (b) $11.50 for perceptual therapy, (c) $7.00 for driver education, and (d) $3,066 total cost for the traffic engineering improvements. Among the first three countermeasures, physical therapy was the most cost-effective because it had the lowest cost per older driver. The combination of these countermeasures provided the same level of effectiveness at a higher cost and therefore was less cost-effective. The cost of the traffic engineering improvements per older driver was a function of the number of older drivers exposed to them, which in turn was dependent on the traffic volumes and percentage of older drivers on the roadways where the improvements were installed. Assuming 10 percent older drivers and a 1-year service life for all countermeasures, the ADTs at which the traffic engineering improvements were as cost-effective as the other countermeasures were computed. To be as cost-effective as physical therapy, the sum of the ADT exposed to the traffic engineering improvements would have to be 5,730 vehicles.

Direct comparison of traffic engineering improvements with the other countermeasures is difficult. Traffic engineering improvements are different in nature than the other countermeasures: traffic engineering improvements are site-specific, whereas the other countermeasures are driver-specific. The effects of traffic engineering improvements are limited to the locations where they are installed, but the effects of the other countermeasures are realized wherever the subjects drive. Likewise, the effects of the other countermeasures are limited to the drivers who receive them, but the effects of the traffic engineering improvements are realized by all drivers who travel through the locations where they are installed. Nevertheless, the relative cost-effectiveness of traffic engineering improvements with respect to the other countermeasures shown in Figure 1 indicates that traffic engineering improvements would be most cost-effective on high-volume rural highways and urban streets, and programs of older-driver education and instruction in physical and perceptual exercises would be most cost-effective in rural areas with low-volume streets and highways.

LIMITATIONS OF RESEARCH

The limitations of the research should be noted when considering the application of the results. These limitations are discussed in the following.

Subjects

The subjects who participated in the study may not have been representative of the older driver population. They were not selected at random. Instead they volunteered to participate in the study. Consequently, they may have been more highly motivated than the general older-driver population to improve their driving performance.

The subjects were generally in very good mental and physical condition. Their range of motion, visual perception, mental status, and reaction times were about the norms for their age group. In addition, they were good drivers. The effectiveness of the countermeasures observed in this research may be different for older drivers who are not in good physical or mental condition or are not good drivers.

Driving Conditions

The driving performance of the older drivers was evaluated at intersections on urban streets during off-peak hours. The driving maneuvers evaluated were left turns and right turns at signalized intersections and approaches to unsignalized intersections. Although these are the conditions and maneuvers most often involved in older-driver accidents, the effectiveness of the countermeasures may not be the same for different driving conditions or maneuvers.

Driving Performance

The driving performance of the subjects was evaluated using the DPM method developed at Michigan State University (*2,3*). Although it has been found to be a reliable indicator of safe driving performance, it is not a direct measure of accident experience. Therefore, the 7.9 percent improvement in driving performance attributed to the countermeasures is only an indication of the resultant improvement in the safety of older drivers. It is not necessarily the reduction in older drivers' accidents provided by the countermeasures.

Traffic Engineering Improvements

The traffic engineering improvements were composed of signs, pavement markings, and traffic signal displays that were designed to improve the safety of the maneuvers most often involved in older-driver accidents at intersections. They were designed in compliance with the *Manual on Uniform Traffic Control Devices* (*5*) to address particular operational and safety problems observed at the intersections where the driving performance of the subjects was evaluated. Their designs were based on the application of conventional traffic engineering principles to facilitate the driving task involved in the maneuvers being evaluated. The traffic engineering improvements were not intended to be universal solutions to the problems of older drivers. Instead, they were to represent ways to improve traffic control and highway design to account for the limitations of older drivers.

Therefore, the improvements in driving performance provided by the traffic engineering improvements should be viewed as indicative of that provided by the application of traffic engineering design principles to the problems of older drivers at particular locations. The specific traffic engineering improvements evaluated in this research should not be expected to provide the same level of effectiveness at other locations with different operational and safety problems than those observed at the locations where the traffic engineering improvements were installed in this study.

Cost-Effectiveness

The cost-effectiveness analysis was based on a number of assumptions that may limit the general applicability of the results. First, the countermeasures were assumed to have equal service lives of 1 year. In other words, the effects of physical therapy, perceptual therapy, driver education, and the traffic engineering improvements were all assumed to last for 1 year, after which the countermeasure would have to be repeated or replaced at the same cost. However, it is conceivable that the countermeasures actually have different service lives. For example, the costs of the therapies might be one-time costs. Once the exercise instructions and workbooks have been purchased, the exercises could be repeated indefinitely without additional cost or lost of effectiveness. Similarly, the driving knowledge acquired in the driver education course could be effectively retained for much longer than 1 year, and some of the traffic control devices used in the engineering improvements could be effective for 5 to 10 years without replacement.

The costs of the countermeasures used in the analysis were those paid for the countermeasures during the conduct of the research. Other than the need to comply with the research budget, no special efforts were made to minimize the costs of the countermeasures. The costs of the driver education and engineering countermeasures were representative. The cost of the driver education course was the registration fee charged by AAA for the *Safe Driving for Mature Operators* course, and the costs of the traffic engineering improvements were those normally incurred by the city of Omaha for the installation of traffic control devices. However, the costs of the physical and perceptual therapies may not have been representative. These exercise programs were new programs, and the most efficient methods of preparing the materials and providing the instruction had not been developed. Therefore, it is very likely that these countermeasures could be implemented at a lower cost, which would improve their cost-effectiveness.

The relative cost-effectiveness of the traffic engineering improvements with respect to the other countermeasures was computed assuming that traffic was composed of 10 percent older drivers. Although about 10 percent of all drivers are 65 years or older (*6*), this figure may not be appropriate for all communities or all locations on the highway system. Many communities in the rural midwest region have nearly 15 percent older drivers (*7*). Even within larger metropolitan areas some streets and highways have higher percentages of older drivers because they are in the vicinity of older residential neighborhoods, medical facilities, senior centers, and other land uses that attract older people. Therefore, the relative cost-effectiveness of traffic engineering improvements may be higher or lower than that found in this study depending on the location where the improvements are to be implemented.

Suboptimal Designs

The countermeasures evaluated in this research were satisfactorily designed to meet the needs of older drivers. However, they were not the optimal designs because of the limited resources available to the research for the design of the countermeasures. Therefore, if their designs were optimized, the countermeasures could probably provide even greater improvements in the driving performance of older drivers than those observed in this study.

FURTHER STUDY

Further study is needed to overcome the limitations of this research. Similar studies should be conducted using older subjects who are not as physically and mentally fit as the subjects in this study. Also, research should be conducted to determine the long-term effects of the countermeasures on the driving performance and accident experiences of older drivers. Although the countermeasures were all found to be effective in improving the driving performance of older drivers, further research should be conducted to optimize the design of the countermeasures and maximize their effectiveness. Physical and perceptual therapies should be examined to determine the optimum combination of exercises that would maximize their positive effect on driving performance and facilitate their use by older drivers. Additional research is needed on the design and application of traffic control devices to meet the needs of older drivers more effectively.

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Signs of Deficiency Among Elderly Drivers

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Most referrals of older drivers to motor vehicle departments for reexamination are made by police. A sample of 1,000 completed referral forms used by police was obtained from five states and analyzed to identify the bases of referral. Accidents were found to serve as the leading source of contact between police and older drivers, closely followed by traffic violations. The bases of referral for reexamination (in order of decreasing frequency) were sensory deficiencies, mental states, attentional deficiencies, medical conditions, motor deficiencies, cognitive deficiencies, other aberrant behavior, physical deficiencies, a history of driving problems, and the testimony of others. The relative involvement of these referral bases were constant over the age range represented by older drivers except for sensory deficiencies (vision and hearing), which increased in frequency with age, and medical conditions, which declined in frequency. Although significant differences were observed among states, the differences are outweighed by the similarities, and the results from the five states provide a reasonably reliable estimate of the bases for reexamination referral across the country. The preponderance of problems that would not be readily apparent to medical practitioners points to the need for routine, periodic reexamination as a means of ensuring the safety of both older drivers and the motoring public.

The overinvolvement on a per-mile basis of elderly drivers in automobile crashes is well established. The elderly have a higher accident rate than any other age group except beginning teenagers. Their absolute number of accidents is kept in check by the lower number of miles that the elderly travel.

The most vexing aspect of the elderly driver population is its heterogeneity: for every deficient driver there are many more who are safer than they ever were. The challenge in regulating the access of elderly drivers to the public highways is distinguishing the safe from the unsafe. The ordinary periodic renewal licensing process is not well equipped to handle this, and even if society allowed motor vehicle departments to call in all of the elderly for a more intensive examination, it might be too expensive.

One way to identify potentially unsafe elderly drivers is through traffic law enforcement. When an elderly driver is stopped for a violation or involved in an accident, police have an opportunity to observe signs of incompetence that often lead to referral to the state licensing agency for reexamination. Indeed, it appears that in most jurisdictions, police are the primary source of referrals. For example, police are responsible for three-fourths of Michigan's 5,000 annual referrals.

Law enforcement is the primary source of reexamination referral, but it is a source that is far from fully used—witness the large number of law enforcement agencies and officers that make very few referrals, if any at all. Either they are extremely fortunate in rarely encountering deficient drivers or they are simply not prepared to take action when they do.

One reason that law enforcement agencies and personnel may not make more referrals is that they are unable to identify deficient drivers when they see them. Either they do not know the signs of deficiency or they are not secure enough in their knowledge to be willing to act. Unfortunately, the scientific community is not in a position to be of much help. Most of what we know about elderly drivers comes from research using laboratory testing techniques that are not available to the police on the highway.

OBJECTIVE

The objective of the exploratory study described here was to identify the signs of driver deficiency that enforcement personnel have used as a basis of referral for reexamination. The signs include (a) unsafe behaviors observed by officers, including those that form a basis for traffic citations; (b) unsafe behaviors underlying accidents investigated by officers; and (c) signs of deficiency observed in drivers by officers in the course of issuing citations or investigating accidents that do not themselves point to deficiencies. This study addresses the following questions:

- What are the specific signs that alert law enforcement officers to the possibility that elderly drivers are deficient with respect to the functions required for safe driving?
- Which signs, or combinations of signs, appear often enough to warrant their becoming elements of a referral process?
- What differences exist across age levels within the elderly driver population?

METHODS

The means by which signs of driver deficiency were identified is through documented records created by law enforcement officers as part of the referral process. A number of jurisdictions provide forms on which police can record the observations that led to the referral of individual drivers. The forms may be distributed by the state licensing agency, the law enforcement agencies, or both.

It is the enforcement officer's description of observations that provides probable cause to request drivers to report for reexamination. The amount of detail in which the cause is described varies enormously, from a few words to several paragraphs. The degree of detail appears to depend more on the insight and the meticulousness of the officers than it does on the characteristics of the drivers themselves. For this reason, any review for research purposes could be confined to

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those states providing the more detailed descriptions, without introducing significant bias into the outcome.

Selection of Sample

Five states participated in the study: California, Maryland, Massachusetts, Michigan, and Oregon. These states met the following three criteria: that they be able to readily identify older drivers, that they be able to single out drivers referred by police, and that the referral forms contain a narrative from which it would be possible to extract the information forming the basis for the police referral.

Each state was asked to provide approximately 200 randomly selected copies of older driver referrals with identifying information deleted. Referrals that were not sufficiently detailed to determine the signs of deficiency that triggered them, or that pertained to drivers younger than 60, were eliminated. After the selection process was complete, the data consisted of 1,000 usable referral forms. The breakdown by state is given in Table 1.

Data Entry

The following data were entered from each police referral form into a computer data base for analysis:

- State of subject residence,
- Age and gender of subject,
- Narrative description of accident or circumstances that caused police officer to come into contact with the subject, and
- Narrative description of each cue that the officer noted pertaining to the subject.

Data Analysis

Since there was no predetermined classification of referrals, the first 100 entries were studied in order to arrive at appropriate categories. These categories involved the basis of initial contact, the behaviors leading to the contact, and the deficiencies that served as a basis of referral.

Basis of Contact

The incident that brought the subject to the officer's attention was coded for analysis in the following categories:

- Accident,
- Violation,
- Observation, and
- Outside sources.

TABLE 1 Breakdown of Subjects by State

State	Gender Male	Female	Total
California	125	72	197
Maryland	146	68	214
Massachusetts	141	91	232
Michigan	88	57	145
Oregon	123	89	212

Contributing Behaviors

At the time that an officer interacted with an aging driver, the specific behavior contributing to that contact was identified. These behaviors included

- Driving the wrong way or on the wrong side of the street;
- Driving off the road;
- Rear-ending a vehicle;
- Failing to yield right of way or come to a complete stop at a stop sign;
- Infringing on the rights of a pedestrian or cyclist;
- Turning across the path of oncoming vehicles;
- Crossing lane markings;
- Backing improperly;
- Operating at low speed; and
- Other behaviors.

Basis of Referral

After initial contact with an older driver, enforcement officers reported a number of deficiencies that served as a basis for referral. The referral signs were broken down into the following general categories:

- Aberrant behavior,
- Attentional deficit,
- Cognitive deficit,
- History of problems,
- Licensing irregularities,
- Medical problems,
- Mental problems,
- Motor-related deficits,
- Physical problems,
- Sensory-related deficits, and
- Testimony of others.

RESULTS

The true "results" of the data collection effort were a set of older driver characteristics taken from the narratives of police referral forms. Only a review of these individual entries will reveal the actual basis for driver referral, but some insight into the patterns of driver characteristics exhibited can be gained by examining the categories of referral cues, along with the frequencies associated with each.

Basis of Initial Contact

The following table provides a breakdown of contacts with elderly drivers according to the nature of the incident that called the driver to the officer's attention:

Source of Contact	N	*Percent*
Accident	486	48.1
Violation	443	43.9
Observed behavior	70	6.9
Outside referral	11	1.1

The leading source of contacts is accidents in which the older drivers were involved, followed closely by violations committed by the older driver. The simple observation of aberrant behavior was responsible for relatively few contacts, and a small percentage involved someone else calling the officer's attention to the individual driver. Most referrals from relatives, friends, physicians, or others are made directly to the motor vehicle department rather than to the police. Relatively few referrals by police officers were based on the characteristic of accidents or violations themselves. Instead, they resulted from an officer's evaluation of a driver's appearance or behavior during the interaction that followed.

Contributing Behaviors

A summary of the specific behaviors involved in accidents, violations, and observed driving is given in Table 2. The primary behaviors that brought drivers to the attention of officers were driving the wrong way down a one-way street or on the wrong side of a two-way street, which contributed to many violations but few accidents; operating off the paved surface, which contributed to many accidents, but few straight violations; and failing to yield or stop for other traffic, which contributed to significant numbers of accidents and violations. Making unsafe turns across the paths of oncoming vehicles, a mistake in which older drivers are generally recognized as being overrepresented, was half as frequent as the behaviors just described and was found equally often in accidents and in violations that do not involve accidents. Other contributing behaviors were driving very slow, rear-ending another vehicle, backing improperly, failing to observe lane markings, and not yielding to pedestrians and bicyclists.

Basis for Referral

The older driver characteristics that served as a basis for reexamination referral are presented in Table 3. Since more than one observed characteristic may have led to the referral, the total frequency across all characteristics adds up to more than 1,000 incidents.

TABLE 2 Frequency of Behaviors Contributing to Accidents, Violations, and Observations of Officers

Behavior	Accident	Violation	Observation	Total
Wrong way	29	149	13	191
No yield/stop	74	114	3	191
Off road	176	8	1	185
Turning across traffic	46	43	0	89
Slow speed	0	56	9	65
Rear-ender	49	0	1	50
Backing	32	1	1	34
Crossing lane marking	5	25	0	30
No yield to pedestrian or cyclist	16	5	3	24
Miscellaneous/ missed	58	43	39	140

TABLE 3 Basis for Referring Elderly Drivers for Reexamination by Police

Characteristic	*N*	Percentage
Sensory deficiency	358	15.9
Mental state	354	15.8
Attentional deficiency	312	13.9
Medical condition	236	10.5
Motor deficiency	228	10.1
Cognitive deficiency	225	10.0
Aberrant behavior	199	8.9
Physical condition	174	7.7
Personal history	110	4.9
Testimony of others	51	2.3
Total	2,247	100

Sensory Deficiencies

A total of 358 incidents involved apparent sensory deficiency, the overwhelming majority of deficiencies being visual. Deficiencies included impaired vision (149), impaired hearing (93), poor depth perception (47), degraded night vision (41), and vision problems related to medical conditions such as cataracts or recent surgery (28).

Mental States

Most of the deficiencies discussed involve driver abilities. Several other mental and physical characteristics involve what might be better described as "states" or "conditions." Mental states associated with referral for reexamination include being confused (170), disoriented (98), lost (46), "senile" (15), drowsy or fatigued (12), and other problems of a mental sort (13).

Attentional Deficiencies

The category attentional deficiencies involves incidents in which the officer noted behavior indicative of attentional deficiencies. In many cases, drivers themselves acknowledged attentional lapses. Specific conditions included admission of being generally unaware or inattentive (171), failure to notice another vehicle (73), failure to notice a traffic control (30), and not being aware of what they had done that resulted in a violation or accident (38).

Medical Conditions

A variety of diagnosed medical conditions were identified as the bases of driver difficulties leading to referral for reexamination. They include complaints of "blacking out" (67), diabetes (26), heart condition (22), stroke (18), Alzheimer's disease (13), fainting or dizziness (13), arthritis (9), Parkinson's disease (8), seizure (4), epilepsy (3), and other medical problems (28).

Motor Deficiencies

This category included deficiencies in motor behavior that were not related to apparent medical conditions or physical shortcomings. The most frequently mentioned deficiency was what appeared to be slow reaction time or slowed reflexes (110), followed by inappropriate manipulation of controls, such as stepping on the gas instead of the brake (84), and generally poor motor coordination (34).

Cognitive Deficiencies

Four categories of information-related deficiency involve lack of recall (123), inability to comprehend (51), failure to know the rules of the road (26) and inability to process information in making sound decisions (15).

Aberrant Behavior

The category aberrant behavior does not include all instances of aberrant behavior, just those in which the investigating officer could not identify any other underlying problem or deficiency. The 199 instances divided themselves as follows: taking too long to pull over despite the officer's use of lights and sirens (120), having difficulty in producing identification when requested (40), failing to stop and identify themselves after an accident (36), and driving off after stopping for the officer and having to be chased down (30). Such behavior probably involves some of the deficiencies making up the rest of Table 3, but it was not obvious to the officer, or from the officer's description, which of the deficiencies were involved.

Physical Conditions

Those physical conditions resulting in referral include observed difficulty in walking (63), shaking or tremors (55), physical disability or handicap (35), general weakness (16), and extremely short stature (5).

Other Characteristics

The remaining two bases of referral involve the testimony of a relative, physician, neighbor, or other that would give rise to concern over the driver's ability to operate safely (38) and some specific prior history of driving problems that has come to the attention of the officer (6).

Twenty-seven elderly drivers were referred to licensing agencies because of licensing irregularities rather than any identified shortcomings to the drivers themselves. These irregularities included not wearing glasses, and claiming not to need them, despite license restriction requiring that glasses be worn (14) and issues related to vehicle registration, driver's license, or insurance (13).

Police also recorded 122 instances of unusual affect on the part of the elderly driver, although in no case did it serve as a basis for referral. Sixty instances of strange, bizarre, erratic, or other unusual behavior were also noted even though they were not basis for reexamination.

The referral bases are not broken down separately by accidents and violations because, for the most part, the deficiencies noted in connection with accidents followed the same pattern as those found in violations without accidents. The two exceptions were the following:

- Aberrant behavior, which made up 14 percent of the signs associated with violations alone (as opposed to 4 percent of the signs noted in connection with accidents) and 6 percent of instances in which officers stopped a driver for observed behavior without even an accident or violation.
- Medical conditions, which accounted for 14 percent of the signs associated with accidents but only 5 percent of signs associated with violations and 7 percent of signs associated with observed behavior.

In no other case did the percentage of accidents involving a particular deficiency differ more than 3 points from the percentage of violations involving that deficiency.

Driver Deficiencies by Age

Although all of the drivers referred for examination were elderly and referred because of age-related problems, differences among drivers in the age categories represented are, for the most part, small and easily attributed to chance. However, four categories of deficiencies show substantial age-related trends. They are given in Table 4.

All of the comparisons in the table are statistically significant. Because they have been selected from a large number of comparisons, they must be treated as hypotheses instead of conclusions. Nevertheless, the very large differences involved provide some assurance that they represent true age relationships.

Two of the comparisons involve bases of referral, and the others involve behaviors leading to the driver being stopped. The most startling finding is the marked decline in the incidence of medical problems as age increases. Since the percentages reported are all relative to other types of deficiencies, the decline cannot be attributed to reduced total driving. These findings do not necessarily mean that medical problems decline with age, but they could mean that drivers affected with these conditions are less willing or able to drive as they become older. The increasing relative incidence of sensory problems with age reflects what might be an expected decline in sight and hearing with increasing years.

TABLE 4 Selected Deficiencies by Age Group

	Age					
Characteristic	< 75 (%)	75–80 (%)	80–85 (%)	> 85 (%)	χ^2	p
Sensory	9.3	14.9	19.0	15.9	26.1	< .001
Medical	19.8	8.0	5.2	2.8	130.4	< .001
Wrong way	23.3	19.9	18.4	12.3	9.6	.05
Off road	26.5	17.4	13.2	14.2	20.5	< .001

NOTE: Deficiencies expressed as percentage of all deficiencies within age group.

There is no ready explanation for the decline in incidence of driving the wrong way or off the road with increasing age. They may reflect changing exposure to various road and traffic conditions instead of changes in drivers themselves. No significant differences were found between the relative involvement of accidents, violations, or observations as the basis of enforcement contact ($\chi^2 = 13.88, p = .13$).

Consistency of Results

The ability to generalize results from the five participating states to the nation as a whole can be estimated from the consistency of collected data. If the five states show similar patterns of results, it is likely that the sample provides a reasonably accurate estimate of population patterns.

A simple and direct measure of the agreement among samples would be the correlation among states and the frequency with which various characteristics were observed. The intraclass correlation among states, representing the average correlation between all possible pairs in the five states, was .66 both for the behaviors contributing to the initial contact and for the basis of referral. This correlation represents moderately high agreement in each case. The estimated correlation between pooled results for the five states and those of another set of five states selected in the same manner is .91. Even though there are substantial differences among states, they are outweighed by their similarities, and the totals presented in Tables 2 and 3 provide reasonably good estimates of what will be found in the nation at large.

Since the basis of initial contact only involves three categories, relationships are not well expressed in terms of correlation but can be readily grasped by mere inspection. Table 5 presents the breakdown of accidents, violations, and observations by state, expressed in percentage to facilitate comparison.

Marked differences can be seen from one state to another. For example, three-quarters of the contacts with elderly drivers from Michigan arose from accidents, whereas accidents accounted for one-third of the contacts in Oregon. These differences are probably due to variation in enforcement policies and practices rather than state-to-state variation in characteristics of elderly drivers.

DISCUSSION OF RESULTS

The true results of the study that has been described lie in the inventory of specific signs used by police in referring elderly drivers to motor vehicle departments for reexamination, but the summary statistics generated from these results are illuminating. Although substantial differences appeared among the states relative to the behaviors contributing to an accident or the violation giving rise to a referral as well as among the deficiencies that served as the basis of referral, the similarities outweighed the differences. What differed substantially among the states was the degree to which referrals arose from accidents versus violations, a difference that is probably due more to enforcement practices than to characteristics of drivers.

TABLE 5 Basis of Contact by State

	Percentage					
Basis of Contact	CA	MA	MD	MI	OR	Total
Accident	45	57	40	75	34	49
Violation	50	31	54	16	59	44
Observation	5	11	6	5	6	7
Total	100	100	100	100	100	100

One finding of interest is the role that functional deficiencies involving attentional, sensory, cognitive, and motor deficiencies play in the incidents leading to referral. Currently, much of the effort in dealing with elderly drivers is focused on diagnosed medical problems, with hospitals and rehabilitation clinics attempting to serve the needs of the afflicted as well as the driving public. A sharp decline in the relative involvement of medical conditions beyond age 75—dropping from 19.8 to 2.8 percent—suggests that the efforts of the health practitioners to control the various medical conditions, or driving under their influence, are generally successful. By contrast, the relative involvement of sensory deficiencies in police referrals increases from 9.3 to 15.9 percent. Such deficiencies tend to be the result of gradual deterioration and are therefore not likely to come to anyone's attention except through some sort of periodic screening process.

From the data available, it is not possible to assess the accuracy of police in identifying driver deficiencies. Descriptions of events preceding a referral provide insight into the nature of driving deficiencies, but follow-up investigation is needed to identify the specific nature of conditions giving rise to the deficiencies described. Yet, given descriptions of behavior that accompany referrals, it is clear that the law enforcement community is providing a valuable service, both in bringing driver deficiencies to the attention of the licensing authority and in providing information that can help guide further examination.

That almost half of the referrals arose in the course of investigating an accident is cause for concern, even though there is no evidence of the degree to which identified deficiencies of aging driver actually contributed to the accidents. It appears advantageous to the health of elderly drivers and the safety of the motoring public to detect deficiencies of elderly drivers through some other means than their involvement in accidents. These results underscore the potential advantage of screening measures that would permit deficient drivers to be identified through the licensing process before they come to the attention of law enforcement officers. Most of the deficiencies that have been described lend themselves to diagnoses through available testing techniques. The task will be to find ways of adapting testing techniques to the limited time available for driving screening.

CONCLUSIONS

On the basis of the data collected as a part of this study, the following conclusions can be reached:

1. Behaviors leading to identification of deficient drivers include, in order of generally decreasing frequency, driving the wrong way, failing to yield or stop, leaving the roadway, turning across oncoming traffic, driving excessively slowly,

having rear-end collisions, backing, crossing lane markings, and failing to yield to pedestrians or bicycles.

2. Driver characteristics contributing to these behaviors included, in order of generally decreasing frequency, sensory deficiencies, mental states, attentional deficiencies, medical conditions, motor deficiencies, cognitive deficiencies, testimony of other parties, observed aberrant behavior itself, physical conditions, and information concerning a driver's personal history.

3. The relative frequency of various behaviors and driver characteristics showed little variation over the elderly age range except for a gradual increase in sensory problems and a marked decline in medical problems.

4. Although the enforcement community appears to be successful in identifying substantial numbers of deficient drivers, the fact that almost half of the referrals resulted from accidents points to the need for greater use of routine screening as a part of the licensing process.

5. Research is needed to devise methods of identifying deficient drivers that (a) are effective in distinguishing deficient from qualified drivers, (b) can be practically implemented as a part of the license renewal process, and (c) will lead to licensing actions that are appropriate to the specific deficiencies identified.

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