TRANSPORTATION RESEARCH

RECORD

No. 1438

Safety and Human Performance

Research Issues on Bicycling, Pedestrians, and Older Drivers

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1994

Transportation Research Record 1438
ISSN 0361-1981
ISBN 0-309-05519-9
Price: $25.00

Subscriber Category
IVB safety and human performance

Printed in the United States of America

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Transportation Research Record 1438

Contents

Foreword

The papers in this volume cover three areas of considerable interest and importance to highway and traffic planners, designers, and operators. The first four papers, sponsored by the TRB Committee on Bicycling and Bicycle Facilities, will be of use to bicycle facility designers and planners. The long-standing problems of pedal power and use of the roadway by motorized vehicles are addressed, and tools to aid in resolving these dilemmas are presented. The fifth paper on bicycling, in which bicycle accidents are described in some detail, should be of value to the traffic safety community. Since data on these types of crashes are underreported, this paper helps fill that gap.

Sponsored by the Committee on Pedestrians, the next four papers in this volume concern pedestrians and pedestrian facilities. The papers by Khisty, Virkler and Elayadath, and Bandara et al. will be useful to planners and designers trying to improve pedestrian movement and facilities in new or existing infrastructure. Bowman and Vecellio provide information on pedestrians that is necessary in the design process and also relate this information to pedestrian safety.

The Committee on Safety and Mobility of Older Drivers sponsored the final three papers. A question of great interest to the safety community has been whether older driver performance can be changed through training. Janke addresses the Mature Driver Improvement Program in California, one of the first empirical evaluations of this question. Driver visual performance has always been a concern of the highway and traffic safety community: Wood and Troutbeck give insight into difficulties surrounding a specific type of vision problem. Finally, Benekohal et al. provide data about the much-discussed hypothesis that older drivers voluntarily modify where, when, and how much they drive.

PART 1

Bicycles and Bicycle Facilities

Bicycle Interaction Hazard Score: A Theoretical Model

BRUCE W. LANDIS

A calibrated and transferrable model is needed to estimate bicyclists' perception of the hazards of sharing roadway segments with motor vehicles. Such an interaction hazard (perception) model would help overcome one of the barriers to the development of a sequential bicycle travel demand simulation or forecasting model. An interaction hazard model would also greatly aid planners in the priority ranking of competing roadway segments for on-road bicycle facilities by providing an objective and stable supply-side measure of bicycle facility need. In addition, a model would assist planners to objectively assess the overall bicycle "friendliness" of their road networks as well as provide a uniform tool to assist in the development of bicycle suitability maps. The theoretical interaction hazard score (IHS) model described in this paper represents an opportunity, after statistical calibration (and the possible incorporation of roadway grade and curvature terms for application in hilly terrain), to fulfill the aforementioned needs. On the basis of consensus group evaluation, the IHS model incorporates the appropriate exposure variables that describe actual and perceived interaction hazards to bicyclists sharing parallel facilities with motor vehicles.

Very few calibrated and transferrable models exist to estimate bicyclists' perceived hazard of sharing specific transportation facilities with motorized vehicles. Likewise in short supply are calibrated and transferrable models to estimate road segments' potential hazard of use by bicyclists. There are several urgent application needs for a single calibrated and transferrable model that addresses both of the aforementioned problems. These needs range from bicycle planning tools such as travel demand forecasting and objective measures of the urban area's road bicycle-friendliness to end-user products such as priority ranking of construction projects and bicycle (route) suitability maps.

One of the most urgent needs for a bicyclist-motorist interaction hazard model is to overcome one of the current barriers to developing a sequential bicycle travel demand simulation or forecasting model. This barrier is resident in the trip assignment step of the classic four-step transportation system model. Unlike the relatively straightforward trip assignment algorithm for motorized vehicles, which includes impedance factors such as travel distance and (if selected) capacity constraint, route selection by bicyclists is not influenced by capacity constraints but is strongly influenced by the perceived hazards of sharing the roadway (i.e., interaction) with motorized vehicles. This essential component of the trip assignment algorithm can only be implemented by the systemwide use of a data-based, segment-specific "travel penalty" or impedance-type measure such as an interaction hazard score.

As the bicycle mode share of travel increases as a result of new facility construction (*1,2*), increased funding of bicycle improvements is likely. Currently, even some of the most advanced priority-ranking systems for on-road bicycle facilities suffer from not having the capability to differentiate among projects with equal use demands. Often the choice between projects is made in the absence of an objective evaluation of perceived motorist-bicycle interaction hazard, a major factor (in addition to a demand evaluation) in determining the need for a parallel on-road bicycle facility. Because significant construction of bicycle facilities is possible with recently increased funding sources such as the 1991 Intermodal Surface Transportation Efficiency Act and the 1990 Clean Air Act Amendments, a more defined, objective, and defensible supply-side evaluation component is needed to rank bicycle project priority.

Finally, an objective tool to assist in the development of bicycle suitability road maps is needed. Current practice includes the subjective evaluation of roadways to determine their "friendliness" to bicycle use. Consistent evaluations of the roads is virtually impossible without the same people being involved in subsequent years. A numerical and objective evaluation tool is needed.

THEORETICAL STRUCTURE OF MODEL

There has been some work in recent years both in modeling the *actual* hazard of road segments for bicycle use and in estimating bicyclists' *perceived* hazard of sharing specific road segments with motorized vehicles. The first modeling effort, the Auburn-Chattanooga bicycle safety evaluation index (*3*), also known as the Davis model (see Figure 1), sought to predict bicycle accidents (or crashes) using variables such as average annual daily traffic, number of travel lanes (to establish curb-lane volume), and pavement and location (land use intensity) factors. Its failing in meeting the goal of predicting accidents [as evidenced by a low correlation coefficient (*4*)] was its lack of incorporating bicycle volumes as a normalizing, or exposure, variable. However, it is considered a pioneering effort in that it provided the genesis of thought that led to modeling efforts to estimate bicyclists' perception of the hazard of sharing specific road segments with motorized vehicles. Both modeling efforts are typified by the initial version of the Broward County Bicycle Facilities Network Plan roadway condition index (RCI) (*4*) and the Florida Bicycle Coordinator's recently consensus-developed segment condition index (SCI) model. Their equations are nearly identical to that of the Davis model. Their shortcoming is in the subjective methodology used to assign values to variables, particularly in the estimation of pavement and location factors. Common also to both these modeling initiatives is the lack of research funding for statistical calibration.

The model described in this paper is called the interaction hazard score (IHS) model. Its theoretical forebears include the RCI

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AADT/ (L*2500) ÷ S/35 ÷ (14-W)/2 + PF + LF = SAFETY INDEX

AADT =   AVERAGE ANNUAL DAILY TRAFFIC
L    =   NUMBER OF TRAVEL LANES
S    =   SPEED LIMIT (MPH)
W    =   WIDTH OF OUTSIDE LANE (W > 14, FACTOR = 0) (FEET)
PF   =   PAVEMENT FACTOR
LF   =   LOCATION FACTOR

                    PAVEMENT FACTOR VALUES

              1.   Cracking              0.50
              2.   Patching              0.25
              3.   Weathering            0.25
              4.   Potholes              0.75
              5.   Rough Edge            0.75
              6.   Curb & Gutter         0.25
              7.   Rough RR Crossing     0.50
              8.   Drainage Grates       0.75
                                  PF =    SUM

                    LOCATION FACTOR VALUES

   1.   TYPICAL SECTION
        A.  Angle Parking                0.75
        B.  Parallel Parking             0.50
        C.  Right Turn Lanes             0.25
        D.  Physical Median          (-) 0.25
        E.  Center Turn Lane         (-) 0.25
        F.  Paved Shoulder           (-) 0.75
   2.   ALIGNMENT
        A.  Grades, Severe               0.50
        B.  Grades, Moderate             0.25
        C.  Horiz. Curves, Frequent      0.25
        D.  Restricted Sight Dist.       0.50
   3.   ENVIRONMENT
        A.  Numerous Drives              0.50
        B.  Industrial Land Use          0.50
        C.  Commercial Land Use          0.25
                                  LF =    SUM
```

FIGURE 1 Davis roadway segment formula (3).

and SCI models. The IHS model was developed primarily because the aforementioned models lack complete consideration of the exposure variables, and they incorporated substantial subjectivity in their methodology in estimating the values of some variables. Although the first shortcoming is significant, the second is devastating: if the same data collection personnel are not employed year after year to provide their assessment of roadway conditions, considerable distortion in the outputs of the aforementioned models can occur, severely limiting priority ranking and other annual or repetitive applications. Accordingly, the IHS model was developed to avoid these shortcomings.

Modeling Factors

In order to effectively simulate the potential hazards to a bicyclist sharing the roadway with motor vehicles, a model must consider two components. They are longitudinal and transverse interaction components of the on-road bicycling environment.

In the longitudinal roadway environment, several interactions are present and thus affect the bicyclist's perception of hazard. First there are the volume, speed, and characteristics (5) of the motor vehicles using the shared right-of-way and their perceived effect on the bicyclist. As the volume, speed, and size of motor vehicles increase, so does the bicyclist's perception of interaction hazard. Second is the proximity of the bicyclist to these motor vehicles. As width of the outermost roadway lane decreases, forcing together the bicyclist's and the motor vehicle's travel paths, the perceived hazard increases. Finally is the pavement condition or hazards affecting the travel line of the bicyclist. As pavement condition deteriorates, the bicyclist is required to pay more attention to the immediate travel line; thus, the perceived hazard increases.

In the transverse environment, uncontrolled vehicular movement (i.e., roadway access and on-street parking) presents a hazard to the bicyclist using a shared right-of-way. Representative roadway features include driveways and parallel or on-street parking.

These transverse features represent a similar "turbulence" or hazard to the bicyclist as to motor vehicle operators, which has been acknowledged in recent highway access management policy development (*6*). Accordingly, as the number of driveways or on-street parking increases, a corresponding increase in the perceived hazard to the on-road bicyclist is expected. Affecting this perception of hazard is the driveway traffic frequency and the rate of turnover in on-street parking.

Model Terms

On the basis of the aforementioned bicyclist interaction factors and incorporating some terms from the Epperson-Davis version of the RCI model (*4*), the IHS model has been developed with the following general form:

$$IHS = \left\{ \frac{(ADT)}{L} \times \left(\frac{14}{W}\right)^2 \times \left[a_1 \frac{S}{30} \times (1 + \%HV)^2 + a_2 PF \right] + a_3 LU \times CCF \right\} \times \frac{1}{10} \qquad (1)$$

where

ADT = average daily traffic,
L = total number of through lanes,
W = usable width of outside through lane (includes width of any bike lanes; measured from pavement edge, or gutter pan, to center of road, yellow stripe, or lane line, whichever is less),
LU = land use (intensity) adjoining the road segment (commercial value = 15, noncommercial value = 1),
CCF = curb cut (or on-street parking) frequency, a measure of uncontrolled access (i.e., turbulence per unit of distance),
PF = pavement factor [the reciprocal of FHWA Highway Performance Monitoring System (HPMS) PAVECON factor (*7*)],
S = speed limit,
HV = presence of heavy vehicles (e.g., trucks) expressed as decimal, and
a_1–a_3 = calibration coefficients initially equal to unity.

One of the strengths of the IHS model is its data format. The data needed for the model are collected objectively and economically. As shown in Table 1, the field data collection is standardized, requiring a minimum of subjective evaluation and technical skills.

TABLE 1 Data Inventory Guidelines

W=	Useable width of outside through lane [includes width of any bike lanes; measured from pavement edge, or gutter pan, to center of road, yellow stripe or lane line, whichever is less]
Bike Lane=	(Y or N) Only indicate "Yes" if there is a bona fide bike lane OR if the paved shoulder is 1.2 meters (4 feet) wide or greater
Comm. Land Use =	Indicate "Yes" only if there is at least thirty (30) percent of commercial uses adjoining the road segment. For the purposes of a windshield survey and this data's use in the Interaction Hazard scoring, "Commercial" land use is defined as any land uses other than single family residential (or agricultural).
Total Curb Cuts =	Record the number of non-controlled access points and on-street parking spaces of each segment
PAVECON =	Evaluate the pavement condition according to the FDOT's Roadway characteristics Inventory Feature 230 - Surface Description). If a bike lane is present, record that surface condition, not that of the auto lane.
	5.0 Very good - Only new or nearly new pavements are likely to be smooth enough and free of cracks and patches to qualify for this category.
	4.0 Good - Pavement, although not as smooth as those described above, gives a first class ride and exhibits signs of surface deterioration.
	3.0 Fair - Riding qualities are noticeably inferior to those above, may be barely tolerable for high speed traffic. Defects may include rutting, map cracking, and extensive patching.
	2.0 Poor - Pavements have deteriorated to such an extent that they affect the speed of the free-flow traffic. Flexible pavement has distress over 50 percent or more of the surface. Rigid pavement distress includes joint spalling, patching, etc.
	1.0 Very Poor - Pavements that are in an extremely deteriorated condition. Distress occurs over 75 percent or more of the surface.

TABLE 2 IHS Model Sensitivity

$$IHS = \left\{ \left(\frac{ADT}{L}\right) \times \left(\frac{14}{W}\right)^2 \times \left[a_1 \frac{S}{30} \times (1+\%HV)^2 + a_2 PF\right] + a_3 LU \times CCF \right\} \times \frac{1}{10} \quad (2)$$

Baseline Inputs:

ADT = 15,000 vpd	% HV = 0
L = 2 lanes	PF= 0.25 (good condition pavement)
W = 12 ft	LU = 15 (commercial area)
S = 45 mph	CCF = 42 per mile

and calibration coefficients $a_1 = a_2 = a_3 = 0.01$, 0.01, and 0.024 respectively

		IHS	% Change
Baseline Interaction Hazard Score (IHS)		19.3	N/A
Lane Width Modifications to Segment			
W = 11	(substandard)	22.7	18% increment
W = 12	(standard)	19.3	no change
W = 14	(wide outside lane)	14.5	24% reduction
W = 16	(dedicated bike lane)	11.5	40% reduction
Speed Control Measures			
S = 55		22.7	18% increase
S = 45	(baseline value)	19.3	no change
S = 40		17.6	9% reduction
S = 30		14.2	26% reduction
Traffic Volume Reduction Measures			
20,000		25.3	31% increase
15,000	(typical LOS D volume)	19.3	no change
10,000		13.4	31% decrease
5,000		7.5	61% decrease
1,000	(typical collector threshold)	3.8	80% decrease
Pavement Surface Conditions			
PF = 1.0	(PAVECON*= 1.0 very poor)	27.0	40% increase
PF = 0.5	(PAVECON = 2.0 poor)	21.9	13% increase
PF = 0.33	(PAVECON = 3.0 fair condition)	20.1	5% increase
PF = 0.25	(PAVECON = 4.0 good condition)	19.3	no change
PF = 0.20	(PAVECON = 5.0 new)	18.8	3% decrease
* The FDOT/HPMS Pavement Condition rating (see description in Table 1)			
Access (curb cut or on-street parking) Management			
CCF = 220	(Continuous Parallel Parking)	25.7	33% increase
CCF = 100	(Typical CBD Condition)	21.3	11% increase
CCF = 42	(Spacing = 125 ft)	19.3	no change
CCF = 22	(Spacing = 245 ft)	18.6	4% decrease
CCF = 12	(Spacing = 440 ft)	18.2	5% decrease
CCF = 8	(Spacing = 660 ft)	18.1	6% decrease
CCF = 4	(Spacing =1320 ft)	17.9	7% decrease
Truck Route Control			
%HV = 20%	(truck route-extremely high)	26.1	35% increase
%HV = 15%	(truck route-high)	24.3	26% increase
%HV = 10%	(truck route-typical)	22.6	17% increase
%HV = 5%	(typical of arterial)	21.0	9% increase
%HV = 2%	(typical of collector)	20.0	4% increase
%HV = 0%	(typical of local road)	19.3	no change

1 Km = 0.6 mi
1 m = 3.28 ft

Equation Adjustment and Sensitivity Analysis

Two nonstatistical adjustments were performed during the initial development of the IHS model: an inter-term and an overall equation. The inter-term adjustment was conducted first. Using the baseline inputs (representing a typical two-lane minor arterial) as shown in Table 2, the calibration coefficients a_1, a_2, and a_3 were adjusted to 0.01, 0.01, and 0.02, respectively. The final speed, pavement condition, and transverse terms compose 79, 13, and 8 percent of the equation's value, respectively. The first two terms, after mathematical distribution, are magnified by common volume, laneage, and lane width factors. On the basis of both consensus group meetings and interviews with bicyclists representing design cyclist Groups A, B, and C (*8*) (see definitions in Table 3), these percentages represent a consensus on the terms' reflection of bicyclists' perceptions.

Second, a total sensitivity analysis was conducted to adjust the equation with respect to changes in the variables. Table 2 also shows the corresponding IHS model values and their percentage change for various traffic and roadway conditions. Again, the consensus group and interview technique confirmed the appropriateness of the values of the constants a_1, a_2, and a_3 of this prestatistically adjusted version of the model.

SUGGESTED STATISTICAL CALIBRATION AND VALIDATION METHODOLOGY

Although research funding requests for statistical calibration of the IHS model are currently being made, the model is being used in several metropolitan areas with the initially adjusted calibration coefficients. Already, it has been well received by bicycle planners, who have expressed interest in its statistical calibration for transferability to other metropolitan areas.

The proposed calibration and validation methodology of the IHS model includes the use of a policy-capturing study (or Lens model). The following is the suggested design:

1. Randomly select 30 (the number of calibration coefficients multiplied by 10) road segments with inventoried geometric, traffic, and environmental conditions.
2. Obtain 90 volunteer bicyclists [at least 30 from each rider group (*8*)] and schedule the riding of the test road segments during common traffic periods.
3. Have the volunteers complete questionnaires designed to quantify their perception of the riding hazard of each segment, resulting in the availability of 2,700 observations for regression analysis.
4. Use the following statistical technique: (*a*) Multiple regression analysis will be made. (*b*) If the perceptions are statistically significant, separate model forms (calibration coefficients) will be established. (*c*) Otherwise, a single model form establishing the values of the calibration coefficients a_1, a_2, and a_3 will be adequate. (*d*) Determination of whether there is a statistical difference among the perceptions of the rider groups will be made.
5. Videotape a rider's view of all road segments. The same volunteers participating in Steps 2 and 3 will complete questionnaires to assist in the determination of whether correlation is strong between actual riding perception versus video-viewing per-

TABLE 3 Design Cyclist Groups

- Group A - Advanced Bicyclists: Experienced riders who can operate under most traffic conditions, they comprise the majority of the current users of collector and arterial streets and are best served by the following:
  - Direct access to destinations usually via the existing street and highway system.
  - The opportunity to operate at maximum speed with minimum delays.
  - Sufficient operating space on the roadway or shoulder to reduce the need for either the bicyclist or the motor vehicle operator to change position when passing.
- Group B - Basic Bicyclists: These are casual or new adult and teenage riders who are less confident of their ability to operate in traffic without special provisions for bicycles. Some will develop greater skills and progress to the advanced level, but there will always be many millions of basic bicyclists. They prefer:
  - Comfortable access to destinations, preferably by a direct route; either low-speed, low traffic-volume streets or designated bicycle facilities.
  - Well-defined separation of bicycles and motor vehicles on arterial and collector streets (bike lanes or shoulders), or on separate bike paths.

Group C - Children: Pre-teen riders whose roadway use is initially monitored by parents, eventually they are accorded independent access to the system. They and their parents prefer the following:

- Access to key destinations surrounding residential areas, including schools, recreation facilities, shopping, or other residential areas.
- Residential streets with low motor vehicle speed limits and volumes.
- Well-defined separation of bicycles and motor vehicles on arterial and collector streets, or on separate bike paths.

ception. If the correlation is strong, then the video-based approach in other geographic areas will provide for relatively inexpensive validation studies for model transferability.

6. Finalize the IHS model equation and publish the report.

Comments from reviewers and attendees at the 73rd Annual Meeting of the Transportation Research Board suggest that (*a*) the denominator in the speed term should be 10 mph instead of 30 mph to reflect the AASHTO design for bicyclists and (*b*) research indicates that pavement condition does not affect the bicyclist's perception of hazard. During the statistical calibration of the model, these issues should be investigated.

ACKNOWLEDGMENT

The author expresses his gratitude to the following for their information or input that led to the development of the IHS model described in .this paper: Alex Sorton, Mark Horowitz, Bruce Epperson, Russell Ottenberg, and Gordon Waugh; the Hillsborough County Metropolitan Planning Organization staff; and the Bicycle Advisory Committee.

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Publication of this paper sponsored by Committee on Bicycling and Bicycle Facilities.

Evaluating Suitability of Roadways for Bicycle Use: Toward a Cycling Level-of-Service Standard

BRUCE EPPERSON

Since 1965, traffic engineers and planners have used a measurement known as level of service (LOS) to describe the operating conditions within a traffic stream and their perception by motorists, passengers, or both. Although the most recent edition of the publication that defines these standards, the *Highway Capacity Manual*, does contain a short section on bicycles, it is more concerned with the effects of bicycles on traffic flows within intersections than with the ability of various types of roads and traffic conditions to provide quality of service to cyclists. In the last several years, some researchers and planners interested in bicycling issues have made attempts to develop an index of roadway operational conditions important to bicycle users. Although there have been several different approaches to the problem, recent work has centered on a method based on five descriptive factors: per-lane traffic volume, speed of traffic, right-hand-lane width (including the width of bicycle lanes or road shoulders), overall pavement quality, and the generation of conflicting travel paths. Taken together, these efforts have come close to developing a practical and meaningful roadway LOS standard for bicycle use. Work remains to be done in several areas: the relationship between LOS values and the perception of various cyclists as to the quality of service provided by a roadway, the role of level of service in cyclist route selection, and the applicability of the methodology to bicyclists with different skills and use needs.

Since 1965, traffic engineers and planners have used a measurement known as level of service (LOS) to describe how well a roadway is operating. The LOS concept is an outgrowth of highway capacity analysis, and the publication defining these standards is still called the *Highway Capacity Manual* (*1*). Originally, researchers had hoped to create a mathematical formula to determine the capacity of roads to carry traffic loads. It quickly became apparent, however, that the ultimate capacity of a road was far less important than the quality of service it provided at various volumes of traffic. Therefore, level of service evolved from a measure of absolute traffic-carrying capacity into

> a qualitative measure describing operational conditions within a traffic stream, and their perception by motorists and/or passengers. A level-of-service definition generally describes these conditions in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety. (*1*)

Level of service is broken down into six categories, denoted by the letters A through F. An LOS A road is free flowing with light traffic, whereas an LOS F road is totally jammed. Level of service is calculated using several variables, including type of road (freeway, arterial, collector); roadway geometrics and physical conditions (number of lanes, lane widths, severity of grades); traffic conditions (number of heavy vehicles, direction and distribution of traffic, weather conditions); and control conditions (frequency of driveways and intersections, traffic signal timing, special turn lanes). In fact, level of service is now such a complex measurement that computers are usually used to calculate it on a regional or citywide basis.

LOS standards have more recently been developed for transit and pedestrians. The transit LOS standards are based on the number of persons per seat in a bus or rail car, and the pedestrian standard is determined by the square feet per pedestrian on sidewalks and in elevators. Both are essentially measures of crowding, which affects comfort and, in the case of pedestrians, also affects the speed of forward travel.

The *Highway Capacity Manual* has a short section on bicycles, but it is more concerned with the effects of bicycles on traffic flows at intersections than with the ability of various types of roads to provide quality of service to bicycle users. There is no attempt to formulate an LOS standard for bicycles or to suggest what roadway or traffic conditions contribute to the safety, comfort, or convenience of cyclists.

DEVELOPMENT OF BICYCLING LEVEL OF SERVICE: A HISTORY

Davis Bicycle Safety Index Rating

The first systematic attempt to develop some sort of measurement of the operational condition of roadways for cycling was made in 1987 by Davis at Auburn University. He sought to "develop a mathematical model for indexing bicycle safety to physical roadway features and other pertinent factors" (*2*). His bicycle safety index rating divided roadways into segments with similar roadway and traffic conditions. Each segment was evaluated using a roadway segment index (RSI). Major intersections along the road were also evaluated using a separate intersection index.

Roadway Segment Index

The RSI was calculated using the following function:

$$RSI = [ADT/(L * 2500)] + (S/56) + [(4.25 - W) * 1.635] + \Sigma PF + \Sigma LF$$

Miami Urbanized Area Metropolitan Planning Organization, Office of the County Manager, 111 N.W. First Street, Suite 910, Miami, Fla. 33128.

where

ADT = average daily traffic,
L = number of traffic lanes,
S = speed limit (km/hr),
W = width of outside traffic lane (m),
ΣPF = sum of pavement factors, and
ΣLF = sum of location factors.

Pavement Factor Values Pavement factors are a series of points assessed for poor pavement surfaces and surface conditions that present a hazard to cyclists, such as rough railroad crossings, drainage grates, or potholes. Pavement factor values used in the RSI are as follows:

Factor	*Value*
Cracking	0.50
Patching	0.25
Weathering	0.25
Potholes	0.75
Rough road edge	0.75
Curb and gutter	0.25
Rough railroad crossing	0.50
Drainage grates	0.75

Location Factor Values Location factors are a series of points assessed against road segments that contain conditions that contribute to the generation of cross traffic, limit sight distance, or restrict the operation of bicycles. Location factor values used in the RSI are as follows:

Factor	*Value*
Angled parking	0.75
Parallel parking	0.50
Right-turn lanes	0.25
Raised median	−0.25
Center turn lane	−0.25
Paved shoulder	−0.75
Grades, severe	0.50
Grades, moderate	0.25
Curves, frequent	0.25
Restricted sight distance	0.50
Numerous drives	0.50
Industrial land use	0.50
Commercial land use	0.25

A lower RSI score indicates a better road for bicycling. To say that location factors are "assessed against" road segments is somewhat inaccurate because, unlike pavement factors, location factors are both positive and negative. Negative location factors indicate a feature that improves the quality of the roadway for cyclists, such as raised medians (which restrict left-turning cross traffic) and paved shoulders.

Intersection Evaluation Index

Davis also evaluated each major (i.e., signalized) intersection along a route using a function he called the intersection evaluation index (IEI), which was calculated using the following formula:

$$IEI = [(VC + VR)/10{,}000] + [(VR * 2)/(VC + VR)] + \Sigma GF + \Sigma SF$$

where

VC = cross street volume (ADT),
VR = traffic volume on route being indexed,
ΣGF = sum of geometric factors, and
ΣSF = sum of signalization factors.

Geometric Factor Values Geometric factor values used in the IEI are as follows:

Factor	*Value*
No left-turn lane	0.50
Dual left-turn lane	0.50
Right-turn lane	0.75
Two through lanes	0.25
Three or more through lanes	0.50
Substandard curb radii	0.25
Restricted sight distance	0.50

Signalization Factor Values Signalization factor values used in the IEI are as follows:

Factor	*Value*
Traffic-actuated signal	0.50
Substandard clearance interval	0.75
Permissive left-turn arrow	0.25
Right-turn arrow	0.50

As with the RSI, a lower IEI score is better. The geometric and signalization factors are analogous to the pavement factors and location factors in the RCI. There are no negative GF or SF terms.

Davis combined the RSI and IEI figures to achieve a final product, the bicycle safety index rating (BSIR). The BSIR is calculated using a weighted average of the means of the RCIs and the IEIs along the route under examination. For example, if Oak Street has three roadway segments with RCIs of 5.4, 4.8, and 6.1 and two signalized intersections with IEI scores of 6.8 and 4.6, the average of the three RCIs is 5.4 and the average of the two IEIs is 5.7. The BSIR would then be 27.6 ≈ 5 = 5.5.

This would place Oak Street in the middle of the "fair" category. A score of 0 to 4 would indicate an excellent rating; 4 to 5, good; 5 to 6, fair; and 6 and over, poor. The classification criteria used by Davis are given in Table 1.

The Oak Street example can also be used to point out some of the shortcomings in the Davis system. If Oak Street had only one signalized intersection but an IEI rating of 6.5, the BSIR rating for the entire street would climb to 5.7. This result conflicts with some studies of pedestrian accidents, which suggest that the number of conflicting travel paths (points where the permitted travel paths, pedestrians, and cars cross) is as important as the volume of vehicles or pedestrians traveling along those paths (*3*). If this is the case for bicycles, then an appropriate safety rating would include not only the average danger ratings of intersections, but also the frequency with which signalized intersections occur.

An analogous argument can be made for the RSI. Returning to the Oak Street example, assume that the street is divided into three segments with RSI scores of 5.4, 4.8, and 6.1. The BSIR weights these three segments equally, even though they may entail a much larger or smaller share of the road's total length. If, for instance, the roadway segment rated 6.1 made up most of Oak Street's length, the final BSIR rating of 5.5 is too low. The opposite would be true if the middle segment (RSI = 4.8) made up the bulk of Oak Street's length.

TABLE 1 Rating Classifications for Davis Bicycle Safety Index Rating

Index Range	Classification	Description
0 to 4	Excellent	Denotes a roadway extremely favorable for safe bicycle operation.
4 to 5	Good	Refers to roadway conditions still conducive to safe bicycle operation, but not quite as unrestricted as in the excellent case.
5 to 6	Fair	Pertains to roadway conditions of marginal desirability for safe bicycle operation.
6 or above	Poor	Indicates roadway conditions of questionable desirability for bicycle operation.

Another problem with the Davis model is the use of location factors and pavement factors in the RSI evaluation. Davis claimed to have structured the RSI so that "the coefficients were configured to give slightly more significance to the objective variables such as volume, speed limit, and lane width" (*2*). However, on the seven Chattanooga roads that Davis evaluated as a test of his method, the combined LF and PF values accounted for an average of 30 percent of the total evaluation score, with some road sections receiving as much as 53 percent of their total score in LF and PF values. This tended to dilute the focus of the evaluation model on the three critical factors of roadway speed, per-lane volume, and lane width. A similar problem exists with the use of geometric factors and signalization factors in the IEI.

In addition to these technical considerations, the Davis BSIR suffered from an inability to meet its stated goal: the prediction of major bicycling accidents. Davis did not attempt to calibrate his model by comparing the safety rating of roadways with their rate of bicycling accidents. An attempt to account for the location of bicycle and motor vehicle accidents in one Florida city using a variation of the Davis BSIR revealed that it explained less than 20 percent of the variation in accidents between different road segments (*4*).

These problems, however, should not detract from an appreciation of what was a significant conceptual leap. For the first time, Davis identified the three critical factors that affect the comfort, convenience, and perception of safety common to virtually all bicycle users: per-lane traffic volume, traffic speed, and lane width. He then used a quantitative method to distill these factors into a single rating. Although the Davis BISR may have left something to be desired as an accident prediction tool, it came very close to being a workable tool for describing a cyclist's perception of "the operational conditions within a traffic stream," and thus can lay claim to being the progenitor of a true LOS rating for bicycles.

Florida Roadway Condition Index

Since the mid-1980s, the state of Florida has maintained a system of county and local bicycle coordinators partially funded through, and guided by, a state bicycle coordinator's office within the Florida Department of Transportation (FDOT). In the late 1980s the coordinator's office circulated copies of the Davis monograph to its local counterparts. In 1991, the bicycle programs in Broward County and the city of Hollywood coordinated a joint application of two variants of the Davis index. (Hollywood is located in Broward County, which also includes Fort Lauderdale.)

The two projects were contrasts in terms of their scope. Broward County, with a population of over 1.2 million and a land area of almost 5,200 km^2, presented a much different problem than Hollywood, with its 125,000 population and 65 km^2. The roadway system in Broward County contained over 750 segments, many of which were over 2 km long. Hollywood, on the other hand, had fewer than 120 segments, only one of which was over 1 km long (*5*).

Both jurisdictions used similar variations of the Davis RSI, which eliminated both the IEI and the averaging of individual road segments into an overall roadway rating. Each road segment was identified by the cross streets that bounded it and retained an individual score. The final product for each segment was termed the roadway condition index (RCI), primarily to indicate that its goal was not to predict accident locations.

Also, the LF and PF values were modified so that they played a smaller part in the determination of segment scores. For the most part, this was successful, because the combined LF and PF values averaged 9 percent of total RCI scores in Hollywood and 11 percent in Broward County.

In addition to these changes, Hollywood alone modified the Davis RSI to place greater weight on segments where narrow lane widths and high vehicle speeds occurred simultaneously. This was done by multiplying the lane width term by the speed limit term, in effect doubly penalizing road segments that combined narrowness with high speeds. The denominator in the speed limit term was also decreased from 56 to 48, augmenting the effect. To compensate for the inherent tendency of the modified formula to inflate the final index, the denominator in the ADT factor was raised from 2500 to 3100, the upper limit of LOS C for two-lane collector roads in Florida. The so-called Epperson-Davis modification resulted in this formula:

$$RCI = [ADT/(L * 3100)] + (S/48) + \{(S/48) * [(4.25 - W) * 1.635]\} + \Sigma PF + \Sigma LF$$

The pavement factors and location factors used in the Epperson-Davis variation are given in Table 2. Broward County continued to use the less modified Davis RSI. As was explained earlier, the

TABLE 2 Epperson-Davis RCI as Applied in Hollywood, Florida

RCI = (ADT/(L*3100)) + (S/48) + (S/48*((4.25-W)*1.635)) + PF + LF

ADT	= Average Daily Traffic	W	= Width of Outside Lane (meters)
L	= Number of Travel Lanes	PF	= Pavement Factor
S	= Speed Limit (KPH)	LF	= Location Factor

Pavement Factor Values	
1. Cracking	.50
2. Patching	.25
3. Weathering	.25
4. Potholes	.25 to .50, depending on severity
5. Rough road edge	.25 to .50, depending on severity
6. Railroad Crossing	.25
7. Rough or Angled RR Crossing	.50
8. Drainage Grates	.50
Location Factor Values	
1. Cross-Movement Generation	
a. Angle Parking	.75
b. Parallel Parking	.25
c. Right-turn lane (full length)	.25
d. Raised median (solid)	-.50
e. Raised median (left turn bays)	-.35
f. Center Turn Lane (scramble lane)	-.20
g. Paved shoulder or bike lane	.75
2. Alignment	
a. Severe grades	.50
b. Moderate grades	.20
c. Horizontal curves, frequent	.35
d. Restricted sight distance	.50
3. Environment	
a. Numerous drives	.25
b. If Commercial, ADD	.25
or	
c. If industrial, ADD	.25

Evaluation Totals			
0-3	Excellent	4-5	Fair
3-4	Good	5+	Poor

city of Hollywood is contained within Broward County. Because of this, the road sections within the city were indexed independently by both jurisdictions, presenting an opportunity to compare the final results of the two derivations. In general, the differences were not large. Some examples of these differences are presented in Table 3. Overall, the Epperson-Davis version, as would be expected, was more sensitive to differences in lane width and speed and less sensitive to changes in ADT.

In general, the less altered Broward County version seems better suited to situations in which a large survey scope or limited resources make it difficult to get exact lane width measurements. In smaller areas with more frequent changes in the characteristics of road segments, the Epperson-Davis variant appears to more accurately capture the combined effects of small changes in two or more variables simultaneously.

As mentioned earlier, the Epperson-Davis RCI was tested for its ability to predict bicycle and motor vehicle accidents. For a 20-month period during 1990 and 1991, the location of all such accidents in Hollywood was plotted by road segment. Each accident was assigned a weight of 1 to 5 depending on the severity of injury to the cyclist (5 indicated a fatality). These scores were totaled for each segment and converted to a per-mile basis to compensate for different length segments. The accident score for each segment was then compared with its RCI rating using linear regression analysis. The analysis indicated that the RCI rating explained only 18 percent of the variation in accident scores between different road segments.

There are several explanations for this effect, the most likely being that different road segments had markedly different levels of bicycle use, with the pattern of accidents heavily influenced by the bicycle use patterns. A road segment with several accidents could be explained either as a very dangerous stretch of road or one that had a very high level of bicycle use. This suggests that the successful prediction of bicycle accidents must include bicycle traffic counts and an analysis of land use patterns as well as an evaluation of roadway characteristics.

TABLE 3 Comparison of Roadway Segments in Hollywood, Florida, Using Davis RSI (Broward) and Epperson-Davis RCI (Hollywood)

	No. Lns.	ADT	Speed Limit	Rt. Ln. Width	Holly-Wood	Broward County	Percent Difference
Taft Street (Collector)							
72 Ave to 64 Ave.	4	19900	56	3.7	4.44	4.66	5
64 Ave. to S.R. 7	4	27300	56	3.4	5.37	5.90	10
S.R. 7 to 56 Ave.	2	11400	56	3.4	5.26	5.95	13
56 Ave. to Park Rd.	2	8800	48	3.4	4.42	5.26	19
Park Rd. to I-95	2	12000	48	3.7	4.44	4.90	10
I-95 to 26 Ave.	2	13000	48	3.4	5.10	5.90	16
26 Ave. to 21 Ave.	2	7500	48	3.4	4.21	4.50	7
21 Ave. to US 1	2	6000	48	3.4	4.47	4.45	0
Pembroke (Major Arterial)							
66 Ave. to SR 7	4	30000	65	3.7	6.09	6.58	8
SR 7 to 56 Ave.	4	29900	65	3.7	5.58	6.07	9
56 Ave. to Park Rd.	4	35000	72	3.7	5.82	6.25	7
Park Rd. to I-95	4	42100	72	3.4	7.40	7.13	4
I-95 to 26 Ave.	4	31200	56	3.4	5.93	6.54	10
26 Ave. to 21 Ave.	4	31200	56	3.4	5.93	6.79	15

A second problem in accident prediction is the heterogeneous nature of bicycle users, resulting in distinct clusters of cyclist types, each experiencing widely different accident types. Children, occasional adult cyclists, and experienced recreational bicyclists have radically different operational characteristics, and as a result, the accidents experienced by each group result from very different causal circumstances (*6*). A safety evaluation methodology that yields good results for experienced, adult cyclists would probably be less accurate in predicting the location of accidents occurring to young children.

Dade County Bicycle Facilities Plan

In the summer of 1993, the Metropolitan Planning Organization of Dade County, Florida (which includes the Miami-Hialeah Urban Area), undertook a more ambitious application of the RCI. Whereas Broward County and the city of Hollywood used the RCI as a way of establishing existing cycling conditions in anticipation of future bicycle plans, Dade County's goal was the establishment of a true multimodal evaluation of the county's transportation network. Given Florida's growth management regulatory structure, such a methodology may prove critical to the future development of the area.

In 1985, Florida adopted the Local Government Comprehensive Planning and Land Development Regulation Act, which required local and regional plans to conform to the goals and objectives of both state and regional comprehensive plans. The state plan was based on the concept of guaranteeing the availability of public facilities and services needed to handle new growth and development. In short, if municipalities are at or approaching their maximum capacity in certain forms of infrastructure—including roads—they lose the ability to grant developers permission to build.

In the early years of the act, FDOT defined this mandate as requiring counties and municipalities to maintain LOS D or better on all arterials and on certain collectors designated by the state. Failure to meet this mandate usually led to development restrictions along the affected roadway links. However, realizing that this would eventually lead to a situation where most development would be driven to the urban fringe, Dade County proposed a two-tier system in which roadways inside a designated Urban Infill Area (UIA) would be allowed to degrade beyond the threshold between LOS D and E. The system, known as the Concurrency Management System, was accepted by the state in 1989 (*7*).

In 1992, the county wrote an updated comprehensive plan element that proposed a similar graduated scale but one that not only included location within the county (in or out of the UIA), but also incorporated the level of transit service available along a corridor. Transit service was broken down into two categories: standard, defined as line-haul service on headways of 20 min or less in peak periods, and extraordinary, defined as having very short peak period headways, express service, or rapid rail availability. A breakdown of these standards is presented in Table 4.

A primary goal of the 1993 Dade County Bicycle Facilities Plan was to incorporate the measurement of a roadway segment's suitability for bicycle travel into its overall capacity evaluation in a manner analogous to that for transit service. Thus, a roadway segment with good transit service and a high suitability for cycling would be defined as providing adequate transportation capacity, even if its vehicular level of service was below existing standards.

A modified version of the Epperson-Davis RCI function was used. Several of the changes were influenced by the work being done for a bicycle facilities plan for Hillsborough County, Florida, by Sprinkle Consulting Engineers of Tampa (see paper by Landis in this Record). The new function was of the form

$$RCI = [ADT/(L * 3100)] * (S/48) * (4.25/W) * [(1 + HV)]1.8 * [1 + (0.03 * PF) + (0.02 * LF)]$$

where the terms are as previously defined.

TABLE 4 Existing Long-Term LOS Standards for Dade County, Florida

Location	No Transit service	20 minute headway transit service within .8 km	Extraordinary transit service (rapid rail or express bus) within .8 km.
Outside UIA	LOS D	100% LOS E	120% LOS E
Inside UIA	100% LOS E	120% LOS E	150% LOS E

The pavement factors (weight 0.03) are as follows:

Factor	*Value*
Excellent pavement surface	0
Good pavement surface	1
Fair pavement surface	2
Poor pavement surface	3

The location factors (weight 0.02) are as follows:

Factor	*Value*
Little cross-traffic generation	1
Moderate cross-traffic generation	2
Heavy cross-traffic generation	3

The evaluation totals are as follows: 0 to 3, excellent; 3 to 4, good; 4 to 5, fair; 5+, poor.

Although the form of the equation appears much different from those used earlier by the city of Hollywood and Broward County, it functions in a similar manner and yields equivalent results in most circumstances. In general, there were three primary changes:

1. The pavement factors and location factors were each simplified to a single 0-to-3 scale, with each factor point assigned a weight of 0.02 or 0.03. The sum of the location factor and the pavement factor would then be multiplied by the remainder of the RCI term. For example, a roadway segment with a PF rated 2 and an LF rated 1 would score $(2 * 0.03) + (1 * 0.02) = 0.08$. If the remainder of the RCI function was 3.75, the final score for the link would be $3.75 * 1.08 = 4.09$. This change was made to prevent the location and pavement factors from weighing more heavily, in proportional terms, for roadway segments that had better characteristics of traffic speed, volume, and right-lane width.

2. The extra roadway width created through the placement of bicycle lanes or road shoulders was incorporated into the roadway width term instead of being included as a separate pavement factor value. As the role of pavement factors and location factors continued to be reduced, it became necessary to find an alternative method of incorporating these facilities in a manner that was more flexible and that accurately reflected the importance of these width-enhancing measures. To allow for this procedural change, the right-lane width term was modified so that it could consider widths greater than 4.25 m. In older versions, right-lane widths greater than 4.25 yielded nonsensical (i.e., negative) results. In the new version, an unlimited right-lane width input is possible, but combined lane and shoulder widths greater than 4.25 m yield proportionately less benefit. This accurately captures the effect of very wide lane-shoulder combinations offering a decreased advantage to cyclists because of the collection of road dirt and debris as one moves progressively away from the travel lanes.

3. Whereas previous versions of the index added the per-lane traffic volume, speed, and lane width terms together to achieve a final result, the new variant multiplied them. This increased the interaction of the three terms that was introduced in the Davis-Epperson version. Multiplicative terms also allowed the use of an exponential scalar: in this case, 1.8. The scalar was used to accentuate changes to the index at the top and bottom of its range, in effect "bending" the function line at values below 3 and above 5. This was done to improve the fit of the index on low-volume roads while not significantly affecting the evaluation of roads closer to the urban core. Although the method did inflate the index on roads rated above 5 or 6, this was of little concern since these roads were identified as being deficient in either case.

A roadway link rated 4.0 or lower was determined to provide an adequate level of service for less experienced cyclists or children and will be used in the future to evaluate roadways on the neighborhood level, to facilitate school accessibility planning, and to evaluate the potential for nonmotorized access to transit. A rating of 5.0 or lower was judged to provide an adequate level of service for more experienced cyclists and for travel on an intracounty scale, the scope of the present study. On the basis of this evaluation, the modifications outlined in Table 5 have been proposed to the Concurrency Management System to include bicycle accessibility considerations in the county's growth management strategy.

ISSUES FOR FURTHER CONSIDERATION

Is LOS Measurement for Bicycles Meaningful?

Given the great disparity of evaluation methodologies used in the relatively short history of the bicycling LOS procedure to date, one must ask: is there really such a thing as a meaningful level of service for bicycles?

One important difference between the level of service for motor vehicles and that for bicycles is the fact that the bicycling level of service is determined by exogenous variables such as roadway and traffic characteristics (particularly motor vehicle speed and volume), whereas the motor vehicle level of service is largely determined by the volume of the vehicles themselves. It would be hard to find a roadway in this country so heavily used by bicycles that the volume of bicycle traffic significantly affected the operation of other bicycles. However, recalling the full definition of level of service as given in the introduction to this paper, it becomes more apparent that level of service is a concept with specific meaning to bicycle operators. Most cyclists are able to identify—at least in a general way—which streets they consider "better" or "worse." In recent literature on bicycle planning, much has been made of a supposedly deep and irreconcilable

TABLE 5 Proposed Long-Term LOS Standards for Dade County, Florida

Outside Urban Infill Area

Bicycle LOS	No Transit service	20 minute headway transit service within .8 km	Extraordinary transit service (rapid rail or express bus) within .8km.
Inadequate	LOS D	100% LOS E	120% LOS E
Adequate	100% LOS E	110% LOS E	130% LOS E

Inside Urban Infill Area

Bicycle LOS	No Transit service	20 minute headway transit service within 1/2 mile	Extraordinary transit service (rapid rail or express bus) within 1/2 mi.
Inadequate	100% LOS E	120% LOS E	150% LOS E
Adequate	110% LOS E	135% LOS E	170% LOS E

schism in bicycle planning between casual and experienced cyclists (*8*). However, even a cursory survey of both groups reveals an agreement on the basic characteristics of a desirable riding environment: wider pavement surfaces to allow easy passing by overtaking motor vehicles, lower traffic volumes, and slower motor vehicle speeds. The so-called schism is not a debate about the virtue of these factors, but is instead a different propensity for various types of cyclists to trade off a pleasant riding environment for the higher average speeds, directness, and right-of-way preference accorded to roads with a high functional classification (*9*).

Much of the evolution in cycling-related evaluative methods has been the result of a refinement in thinking about what these methodologies are and what they are expected to do. Starting as a tool to predict accident exposure, the BSIR/RCI gained increased interest when it was used as a way of aggregating important roadway characteristics into a single, easily understood index number, and it has evolved into a method of replicating cyclists' own evaluative behavior in selecting travel path alternatives. As some researchers have noted (see the paper by Landis in this Record), this type of application functions much like the trip assignment module of a typical regional travel demand model. This could ultimately prove to be the most valuable application of an LOS-style method, with the development of an integrated travel demand model for bicycle use proving to be the breakthrough that ushers in a new era of nonmotorized transport planning. It is conceivable that such a model could be incorporated into the transportation forecasting models now used to plan roadway and transit networks, facilitating a true multimodal transport development framework.

What Further Work Is Required?

To facilitate such an application, work that more accurately relates the LOS standards to empirical data and the perception of cyclists will be required. One method of gathering these data would be to isolate a destination center that attracts a significant number of cyclists, such as a school, university, or employment center. Cyclists arriving at this location would be asked to identify the origin of their trip and the route that they chose to use, as well as the reason that led them to select this route over other alternatives. This method would allow the collection of both subjective and objective information. The subjective information would be revealed by the cyclists' responses to interview questions about the reasons behind their route choice. Objective data would be provided by measuring, either in time or distance, the deviation from the shortest or fastest route selected by a given cyclist. This method would thus have the advantage of allowing a pattern of subjective judgments to be somewhat quantified.

For example, with the destination interview, it would be possible to say that occasional cyclists are willing to make their trip X percent longer to gain a Y percent improvement in average trip level of service. Although this would be extremely useful knowledge for the planning of cycling route networks, it does go beyond the traditional use of the LOS methodology. For motor vehicles, level of service is assumed to affect route choice only in cases where the level of service on the preferred route is very low: E or F. On the other hand, bicyclists are exposed to impositions on their comfort and convenience to a much greater extent than are motor vehicle operators, who are primarily affected by trip length and time.

Another method would be to use a video camera to record conditions along several different road sections. These sequences could then be shown to groups of cyclists, who would be asked to evaluate them on, for example, a scale of 1 to 10. This method is being used to aid in the development of the next generation of motor vehicle LOS standards and would be an inexpensive method of comparing proposed standards with the perceptions of large groups. However, although such a method would be useful for comparing an overall roadway index for a road segment with the perceptions of cyclists, it would be harder (when compared with the destination interview) to use it as a quantification of the index itself.

CONCLUSION

As a result of the intervention of cycling activists and the adoption of recent legislation mandating a multimodal transportation approach, bicycling has gained new acceptance by mainstream transportation engineers and planners. However, these professionals are now demanding the development of the same type of quantitative tools that have long been the staple of traditional transportation planning. It is necessary that those involved with the development of alternative modes become familiar with these tools and work to adapt them to the needs of both cyclists and pedestrians.

Knowing bicycling is no longer enough. Just as cycling advocates have long been demanding that transport professionals broaden their vision, it is now time that bicycle advocates and planners become more catholic in their knowledge and learn the procedures and methods of transport analysis and use this new knowledge to develop the tools being demanded by the transport profession. The alternative to refusing to do so may prove to be either the removal of bicycle planning responsibilities from those with a particular interest in the field and a transferral to others with less understanding or sympathy for the area, or a continued neglect by municipal and state agencies of alternative modes planning.

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Publication of this paper sponsored by Committee on Bicycling and Bicycle Facilities.

Bicycle Stress Level as a Tool To Evaluate Urban and Suburban Bicycle Compatibility

ALEX SORTON AND THOMAS WALSH

The available information for establishing criteria to determine the bicycle compatibility of roadways is limited. Existing bicycle-compatible roadway procedures do not provide a complete picture of bicycling conditions from the different points of view of the various types of bicyclists. Such procedures also fail to account for the varying levels of difficulty bicyclists experience under different traffic conditions. The authors have employed *bicycle stress level* as a method to supply this missing information and thus provide the full range of criteria needed to determine the bicycle compatibility of roadways. Bicyclists on streets seek to minimize mental stress. They want to avoid conflict with motor vehicles and the strain of having to concentrate for long periods of riding along narrow, high-speed, high-volume roads. The authors have established bicycle stress levels ranging from 1 to 5 to account for traffic variables of volume, speed, and curb lane width. Level 1 indicates no problems for bicyclists; Level 5 suggests major problems. The highest and lowest stress levels are based on a thorough review of traffic engineering literature, the rationale being that if conditions are bad for motorists, they will be worse for bicyclists. Stress Levels 2 to 4 were prorated between the two extremes. The stress levels defined in the present study were validated by a group of volunteer bicyclists who watched videotaped segments showing a wide range of on-street traffic conditions and rated them according to the traffic variables described above.

Allocating portions of the existing street network for bicyclists represents a potentially cost-effective means of developing a bicycle network. The use of existing streets, wherever feasible, would provide bicyclists with the most direct and convenient access available. Identifying, analyzing, and selecting the best streets and design treatments, however, is a complex task because of the complexity of combined motor-vehicle and bicycle operation. To arrive at sound decisions on the appropriate locations of bicycle usage, it is necessary to

1. Identify the major factors affecting bicycle and motor vehicle operation,
2. Arrive at a general understanding of the basic interrelationships between these factors, and
3. Establish a process or methodology by which to record and evaluate existing conditions with respect to these factors (*1*).

There are no empirical data available to establish uniform location and design criteria for bicycle-compatible roadways. This gap in current principles and guidelines can only be filled by conducting comprehensive research projects and monitoring activities. Meanwhile, there is a pressing need to establish a methodology by which the key factors affecting bicycle and motor vehicle use can be recorded and analyzed. Decisions can then be made based on prudent professional judgment, taking into consideration widely varying local conditions and the widely varying abilities of bicyclists.

Two categories of bicycle-compatibility roadway analysis procedures have been established:

1. Procedures that assume that bicyclists are unable to share the roadways with motor vehicle traffic except under low volume and speed conditions; these procedures were developed by transportation professionals, in most cases nonbicyclists, and tended to try separating the bicyclist from the road or street (*2*); and
2. Procedures that assume that experienced bicyclists can share the roadway with motor vehicle traffic because they can tolerate higher volume and speed conditions; these procedures were developed by experienced bicyclists who rode their bicycles on the roadway with motorized traffic (*3*).

These procedures have several shortcomings:

1. They fail to recognize that there are different types of bicyclists with differing roadway riding preferences and abilities.
2. They use average daily traffic (ADT) as a variable in the analysis procedures. ADT may not be a good indication of whether a roadway is bicycle compatible because it is a measure of the road's daily volume, which fluctuates from hour to hour. Peak hour volume (PHV) is a better indicator. If bicycles can share the roadway during the peak hours, then off-peak hours will be even less of a problem (*4*).
3. There is no rational basis for these procedures. They cite neither documented research nor operating experience. They are entirely subjective, based on the authors' opinions.
4. The procedures make no distinction between urban and rural roadways. In urban and suburban areas, the average bicycle trip is usually under 5 mi long. Rural bicycling trips are usually made for recreation and touring and are usually longer than 5 mi. On rural roads, bicyclists cannot readily divert to other roadways as easily as they can on urban streets because the distances between intersecting and parallel roads are much greater. Other variables that must be considered in rural areas include higher vehicle speeds, truck turbulence, passing sight distances for motor vehicles, and riding times longer than 20 to 30 min, to mention only a few (*1,5*).

To be of the widest use, a bicycle-compatible road analysis procedure should provide ratings based not only on road charac-

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teristics but also on the full range of bicycling competency. The ratings should be easily understood by all types of bicyclists and nonbicyclists, and data for all bicycle road compatibility procedures must be readily available. Existing bicycle-compatible roadway procedures do not meet these criteria. A procedure is needed that satisfactorily explains the effects of traffic volume, speed, and curb lane width on the different types of bicyclists wanting to use the roadway.

BICYCLE STRESS LEVEL CONCEPT

The concept of *bicycle stress* was first developed by the Geelong Bikeplan team in Australia (*6*). The team evaluated lane-sharing width on high-traffic-volume roads, but their analysis did not provide a complete picture of road bicycling from the bicyclist's point of view. In particular, the lane-sharing analysis failed to measure the extent to which roads are difficult or harassing to ride along, relative to traffic speed, volume, and curb lane width. The only measure used in the evaluation was a simple "adequate" or "inadequate."

Providing this information would have enabled the Geelong team to pinpoint those roads that are least comfortable to bicycle on. Measures to provide improvements or alternative routes according to this priority could then have been proposed.

In this paper, the idea of bicycle stress has been used to provide these data.

It is well known that bicyclists choose routes that will cost them the least amount of effort. They save energy by following the flattest route, one that will enable them to avoid stopping and slowing as much as possible.

However, conserving physical effort is only part of the story. Bicyclists also seek to avoid conflict with motor vehicles, harassment from heavy traffic, and the strain of having to concentrate for long periods while riding along narrow, high-speed, high-volume roads. In other words, they want to minimize not only physical effort but also mental stress.

The Geelong Bikeplan did not reflect the different stress levels of individual roadway variables, nor did it consider the different types of bicyclists. To overcome this deficiency, the authors propose to identify the stress levels for each roadway variable, as well as for the different types of bicyclists. They will also indicate how the roadway variables can predict the stress levels experienced by the different types of bicyclists.

Types of Bicyclists and Definition of Stress Levels

Bicyclists can be divided into clearly defined categories (*1,7*):

1. Child (recreation or play, primary school): The cognitive skills of primary school children are not fully developed. Children under the age of 10 have little knowledge of traffic laws and should only ride under supervision when they are on or near streets.
2. Youth (secondary school): The bicycling skills of secondary school students vary greatly. For older students (14 years and over), most bicycling takes place on the street.
3. Casual (recreation, utility, shopping, etc.): Casual bicyclists tend to give high priority to avoiding congested, heavily trafficked streets. Nevertheless, some will use busy streets if there are compensating conditions, such as bike lanes or wide curb lanes.
4. Experienced (commuting, touring and recreation): The on-street bicycling skill level of experienced bicyclists allows them to use the most direct and convenient routes, which often are the arterial or collector streets.

Bicycling stress levels range from 1 to 5, which bicyclists can relate to varying traffic conditions. (Children under age 10 should not be considered in this analysis process.) Stress Level 1 indicates that the traffic variables are so favorable that all types of bicyclists should have little or no problem. Stress Level 5 suggests that the traffic variables are so poor that all types of bicyclists will perceive the road or street as presenting a major problem.

Table 1 relates the five bicycling stress levels to the types of bicyclists appropriate for each on the basis of their riding competency and preferred riding environment. Again, this analysis is not intended for use with bicyclists under 10 years of age, who should only ride under supervision when on or near streets.

Applying Urban and Suburban Stress-Level Evaluation Methodology

The process for evaluating an existing street system can be viewed as a series of three steps:

1. Select those physical roadway variables that are most significant in affecting bicycle use. On two-way roads, data should be collected for each direction of travel.
2. Evaluate the suitability of all street segments for bicycle use on the basis of the variables identified above. This is done by finding the stress level for each variable for on-street segments. The overall average stress level can then be determined.
3. Select and rank all street segments on the basis of the future improvements needed to fit bicycle traffic and on the type, cost, and political feasibility of those improvements. This selection is accomplished by relating the overall average stress level of the road segment variables to the relevant bicyclist type and then determining what improvements, if any, should be made.

Given the increasing demands on staff personnel in recent years, local public agencies need to develop an accurate rating and evaluation mechanism that will require the minimum possible effort (*1*).

PRELIMINARY ASSESSMENT OF MAJOR CORRIDORS AND CANDIDATE STREETS

A first step in planning and designing bicycle-compatible roads is to identify the corridors through which bicycle travel is likely to be greatest. Analysis of area riding environment and bicycle user information should enable satisfactory identification, evaluation, and preliminary analysis of appropriate corridors or streets.

Typical corridors in which the provision of bicycle-compatible roads and facilities should be considered will cover an area two to six blocks wide, depending on local conditions. There are two key factors in identifying corridors with respect to bicycle movement.

TABLE 1 Suggested Interpretation of Bicycling Stress Levels

Stress Level	Interpretation
1 (Very Low)	Street is reasonably safe for all types of bicyclists (except children under 10).
2 (Low)	Street can accommodate experienced and casual bicyclists, and/or may need altering* or have compensating conditions** to fit youth bicyclists.
3 (Moderate)	Street can accommodate experienced bicyclists, and/or contains compensating conditions** to accommodate casual bicyclists. Not recommended for youth bicyclists.
4 (High)	Street may need altering* and/or have compensating conditions** to accommodate experienced bicyclists. Not recommended for casual or youth bicyclists.
5 (Very High)	Street may not be suitable for bicycle use.

* "Altering" means that street may be widened to include wide curblane, paved shoulder addition, etc.

** "Compensating condition" can include street with wide curb lanes, paved shoulders, bike lanes, low volume, etc.

1. As is the case with motorists, most trips bicyclists make are "destination" trips. All riders tend to seek the most direct, convenient route. Therefore, existing primary motor vehicle travel corridors may already be oriented to destinational riding.
2. Traditionally, bicyclists do not care to deviate more than two blocks out of their way in order to use a street or facility (*8*).

The three-step rating methodology proposed earlier can be carried out in two phases (*1*).

Phase I (Primary Variables)

Phase I is a rapid initial assessment of potential bicycling corridors to determine the general implications of allowing bicycle access on candidate streets. Three primary variables—curb lane traffic volume, speed of motor vehicles, and curb lane width—are evaluated to determine their effects on bicyclists.

Phase II (Secondary Variables)

Phase II is a more detailed evaluation of selected variables on alternative streets within a corridor to determine the bicycle compatibility of candidate streets. These secondary variables are number of commercial driveways per mile along the street, parking turnover, and percentage of heavy vehicles using the road. Heavy vehicles include trucks, buses, and recreational vehicles.

Because of limited funds, the present research was conducted for the three primary variables only. This paper will therefore include discussion of the development of the methodology, how the research was conducted, and the results of the research.

PROPOSED METHODOLOGY: PRIMARY VARIABLES

The proposed methodology was extrapolated from transportation engineering literature covering motor vehicles and then related to the bicycle stress level process. (The logic behind this extrapolation is that if there are problems for motor vehicles, these will be bigger problems for bicycles.)

As mentioned earlier, a curbside lane-sharing evaluation should take account of the following primary variables: traffic volume in the curb lane, curb lane width, and traffic speed. These three primary variables will determine the street compatibility rating for the different groups of bicyclists on the basis of stress level.

Traffic Volume Versus Stress Level

The quantity and character of motor vehicle traffic flow in the curb lane are primary determinants of bicycle compatibility.

The ADT on a given street in a given 24-hr period can and does fluctuate dramatically. In determining the number of lanes required for motor vehicles, traffic engineers and designers usually carry out a capacity analysis using the peak hour volume (PHV) or an operational check of existing conditions. The same must be done in a bicycle compatibility roadway analysis (2). Traffic planners use ADT, which is usually based on the PHV. Since the authors are traffic engineers who evaluate streets under peak hour conditions, PHV is used here. ADT can be substituted, since PHV is directly related to ADT. The direct relationship between ADT and PHV can be delineated by applying the K-factor, or that portion of the ADT that occurs during the peak hour. A typical K-factor for an urban area is 10 percent. The PHV in vehicles per hour (vph) is computed as shown below (2). The worst-case scenario for bicyclists occurs during peak periods. Therefore, peak periods must be used to determine whether bicyclists can use a given street.

$$PHV\ (\text{vph}) = ADT \times K\text{-factor}$$

Curb lane volume is determined by dividing the PHV by the number of through lanes on the street. This assumes a 50/50 split on a two-way street. If the directional split is different, as is often the case during the peak hours, the known split should be used for the analysis.

Example: Two-Lane Urban Street (Two-Way)

ADT = 10,000

K-factor (urban condition) = 0.10

PHV = 10,000 × 0.10 = 1,000 vph two way

Curb lane volume = 1,000/2 lanes (50/50 split) = 500 vph

Determining the amount of traffic volume that a bicyclist is willing to tolerate in the curb lane can be described in the form of stress level. Curb lanes on urban streets are at maximum capacity or maximum traffic flow volume when there are 450 to 800 vehicles per hour per lane (vphpl) (*2,9*). To be on the conservative side, in this study 450 vphpl was considered to result in a stress level of 5. When the motor vehicle volume is low (less than 50 vphpl), the condition can be described as Stress Level 1. A two-way residential street may have an ADT of 1,000 vpd. This is equal to 50 vphpl (1,000 × 0.10)/2 = 50 vphpl.

Shown below are the suggested stress levels for volumes in the curb lane:

Stress Level	*Curb Lane Volume (vphpl)*
1	≤50
2	150
3	250
4	350
5	≥450

Curb Lane Width Versus Stress Level

Curb lane width is a critical variable because it delimits the bicyclist's operating space. Curbside lane width is the distance from the joint between the curb and gutter and the first full travel lane adjacent to it. With parked vehicles it is measured from the side of a parked car to the first lane line. Where on-street parking exists, it is assumed that 2.4 m (8 ft) is required; the curb lane is determined by measuring from the 2.4-m mark to the first lane line. When a paved shoulder is adjacent to the travel lane, the curb lane width is the travel lane plus the width of the paved shoulder.

Research by the Maryland Department of Transportation suggests that a curb lane width of 4.6 m (15 ft) or greater can accommodate bicyclists and cars in the same lane for speeds of 65 kph (40 mph) and less. This includes a 0.3-m (1-ft) curb and gutter section (*10*). The *Highway Capacity Manual* (*4*) indicates that on urban streets with a curb lane of 4.3 m (14 ft) or wider, bicycles do not affect motor vehicle traffic when sharing the same lane. On a lane width of 3.3 m (11 ft) or less, a bicycle is equivalent to one passenger car because the car has to leave the curb lane to pass the bicycle (*2*). Thus for a 4.6-m curb lane (not including the gutter), the stress level is considered 1, and for a 3.3-m curb lane (not including the gutter) the stress level would be 5. Gutter sections tend to vary in width and are not considered part of the total curb lane width.

Applying the stress level concept to the curb lane width results in the following suggested relationships (1 m = 3.3 ft):

Stress Level	*Curb Lane Width (m)*
1	≥4.6
2	4.3
3	4.0
4	3.7
5	≤3.3

Traffic Speed Versus Stress Level

The high-speed effect of vehicles passing too close to a bicycle can cause loss of control and is especially unpleasant when accompanied by spray in wet weather. The degree of the speed effect on bicyclists on narrow curbside lanes depends on motor vehicle speed and size. The speed that is used in the evaluation should be the actual 85th-percentile speed no matter what the posted speed limit is (*2*). At a speed of 75 kph (45 mph), the turbulence of large motor vehicles starts to affect the stability of bicyclists using the roadway (*8*). It is recommended that at speeds of 75 kph or higher, the stress level be considered 5. On residential streets posted for speed limits of 40 kph (25 mph), the stress level is 1.

Motor vehicle speed as it relates to bicycle stress level is shown below (1 kph = 0.6 mph):

Stress Level	*Motor Vehicle Speed (kph)*
1	≤40
2	50
3	60
4	65
5	≥75

Example

The following example analysis will explain the stress level concept as discussed previously. For this example, assume a two-lane suburban arterial street (two way), 3.7-m (12-ft) lanes, ADT =

15,000 vpd, and speed = 75 kph (45 mph).

PHV (street) = 15,000 × 0.10 = 1,500 vph

PHV (curb lane) = 1,500 vph/2 = 750 vphpl

Curb lane width = 3.7 m (12 ft)

Motor vehicle speed = 75 kph (45 mph)

Volume stress level =	5
Curb lane stress level =	4
Speed stress level =	5
TOTAL =	14
Overall stress level = 14/3 =	4.7

This street does not seem to be compatible with young and casual bicyclists. It also may not be compatible for experienced bicyclists.

VALIDATION OF BICYCLE STRESS LEVEL PROCEDURE

The city of Madison, Wisconsin, Traffic Engineering Division was interested in validating the bicycle stress level procedure for bicyclists who use their city streets. The city applied for and received a $4,000 grant from the Wisconsin Department of Transportation to carry out the validation study. The grant money was used to pay a technician to collect the data. The authors agreed to donate their time to develop the process and survey instrument and to analyze the survey results.

It was decided that only the primary variables would be studied (motor vehicle volume, motor vehicle speed, and curb lane width). Twenty-three Madison street segments were selected, representing the range of variables bicyclists encountered when using the street system. After various options had been explored, it was decided that the selected segments would be videotaped. Taking 35-mm slides was considered, but the idea was discarded because a still picture cannot show movement or speed of vehicles. Videotaping from the front passenger seat of a motor vehicle was tried and abandoned because the video camera could not be held steady enough. The survey vehicle also blocked vehicles behind it from passing in the same lane. Finally, the video camera was mounted on a tripod that was placed behind the curb of the street segments being studied. It was positioned so that it could record the traffic in the curb lane in the downstream direction—the same direction in which a bicyclist would be moving if he or she were using the street.

The primary variables on the 23 street segments were as follows. The speeds on the selected streets ranged from a low of 40 kph (25 mph) to a high of 75 kph (40 mph). The widths of the curb lane ranged from 3.3 m (11 ft) to 5.5 m (18 ft). The curb lane volume ranged from a low of 60 vph to a high of 670 vph.

A questionnaire was developed. The first part contained questions about the bicyclist to determine his or her type, age, and sex; typical bicycle trips made; riding environment used; and the number of trips and miles traveled during an average week (*11*).

The second half of the questionnaire dealt with the 23 videotaped street segments. For each street segment, the participants were asked to respond to a specific question about one of the primary variables. Participants were asked to watch a video clip of each segment of the selected streets and then rate a specific primary variable on the basis of the bicycle stress level concept. Participants then rated the vehicular volume in the curb lane for eight street segments. The next seven segments, different from the previous eight, dealt with speeds of motor vehicles. The last eight segments dealt with the width of the curb lane.

Before watching each video clip, participants were instructed to indicate how comfortable they would feel with a specific primary variable that they would be asked to evaluate in the clip. They were told that a 1 would indicate that they were very comfortable riding with this variable condition and a 5 would indicate that they would not want to ride with this variable condition under any circumstances. They were further instructed to rate the specific variable condition between 2 and 4 for conditions they believed did not meet the extremes.

The 40 adult bicyclists who volunteered to take part in the survey were employees of the Wisconsin Department of Transportation in Madison. The remaining 21 bicycle participants were members of a Madison church youth group, ranging in age from 10 to 15. After the 61 participants were stratified into the three types of bicyclists, the sample sizes of two groupings were deemed not large enough to achieve statistically valid results. Thus, the results that were achieved for the street segments were merely indicators of the different types of bicyclists' perceptions of traffic conditions.

SURVEY RESULTS

There was an interesting outcome of the analysis of the survey results. Although the respondents were divided into three types of bicyclists (youth, casual, and experienced), over two-thirds of the total indicated that they were experienced when asked, "What type of bicyclist do you consider yourself, experienced or casual?"

This was highly unlikely, since experienced bicyclists make up only approximately 5 percent of the total bicyclist population. Thus, other items on the questionnaire were used to categorize bicyclists by type. Bicyclists were considered experienced if they commuted regularly, rode on arterial and residential streets, rode frequently, and bicycled more than 20 mi per week. According to those guidelines, eight bicyclists were experienced. Bicyclists were categorized as casual if they did not ride on arterial streets, used the bicycle for recreation, used sidewalks, rode infrequently, and rode less than 5 mi per week. There were 32 casual bicyclists. Youth bicyclists, or those between the ages of 10 and 15 years, numbered 21.

The respondents' stress level ratings of all 23 street segments were combined and averaged within each category of bicyclist. The differences in overall average stress level among the three types of bicyclists are shown below:

Stress Level	*Average Value*
Proposed	2.61
Experienced	2.54
Casual	2.82
Youth	2.82

The proposed average stress level is lower than the average stress level of either the casual or youth bicyclists but slightly higher than that of the experienced bicyclists. This suggests that the proposed average stress level of each primary variable may have to be modified for each type of bicyclist. Casual and youth bicyclists seem to have the same perception of roadway primary variables. In an effort to verify this finding, each primary variable was analyzed for each type of bicyclist and compared.

Shown below are the average stress levels by type of bicyclist for motor vehicle volume on eight street segments:

Stress Level	*Average Value*
Proposed	2.89
Experienced	2.32
Casual	2.42
Youth	2.52

The results suggest that the three types of bicyclists vary in the way they perceive stress levels for traffic volume and that the proposed stress level for volume may be too low. Bicyclists in all three categories might be willing to accept higher volumes for a given stress level, which in turn might require increasing the curb lane volume for each stress level.

A linear regression line is a straight line that runs through or past the data points on a path while staying as close as possible to all of them. Regression analysis determines how an independent variable (such as volume, speed, or curb lane width) affects a dependent variable (such as stress level). It can be used to identify data that may have predictive capabilities. R-squared represents the validity of the relationship between the independent and dependent variables. The closer to 1 this value is, the better the independent variable predicts the dependent variable. A value close to zero means that the independent variable is not a useful predictor of the dependent variable.

Figure 1 shows the plots of the linear regression lines for the average stress level versus curb lane volume for the different types of bicyclists. These plots indicate that stress level versus curb lane volume for all types of bicyclists is upwardly linear from low to high volume. The R-squared values for the regression lines are 0.94, 0.95, and 0.91, respectively, for experienced, casual, and youth bicyclists. This seems to indicate that the differing types of bicyclists can correlate the varying volumes to the stress level ranges. All bicyclist types gave a higher stress level rating to curb lane volumes above the 450-vphpl limit proposed in this study. This suggests that the volumes for the stress levels may have to be raised.

The average stress levels for curb lane width on six street segments are shown below. Two street segments containing bicycle lanes were not used because this would have biased the results; such streets had lower stress levels for all types of bicyclists than did streets without bicycle lanes (but having similar volumes, speeds, and curb lane widths).

Stress Level	*Average Value*
Proposed	2.25
Experienced	2.68
Casual	3.21
Youth	2.81

Again, experienced bicyclists show higher tolerance for narrower lanes than do either casual or youth bicyclists, who may need a wider lane. The proposed average stress level for curb lane width is much lower than the stress level for either of the other variables. This suggests that the proposed lane widths versus stress level may have to be adjusted.

Figure 2 shows plots of the linear regression lines of the average stress level versus curb lane width for the different types of bicyclists. The R-squared values for the regression plots are 0.47, 0.36, and 0.13 for experienced, casual, and youth bicyclists. These values indicate that all three types of bicyclist are experiencing difficulty in correlating width with stress levels using this procedure. Again, the number of segments is very low for this type of analysis. It would be desirable to look at a larger number of street segments to see if the results might be similar. The position of the video camera might have prevented the video image from showing vehicle width properly. It would be worth experimenting with different camera positions to determine whether this can be

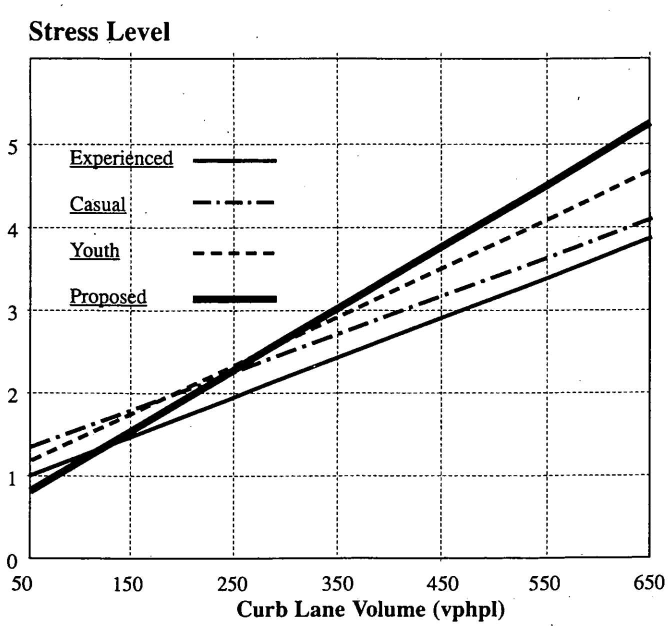

FIGURE 1 Volume versus bicycle stress level.

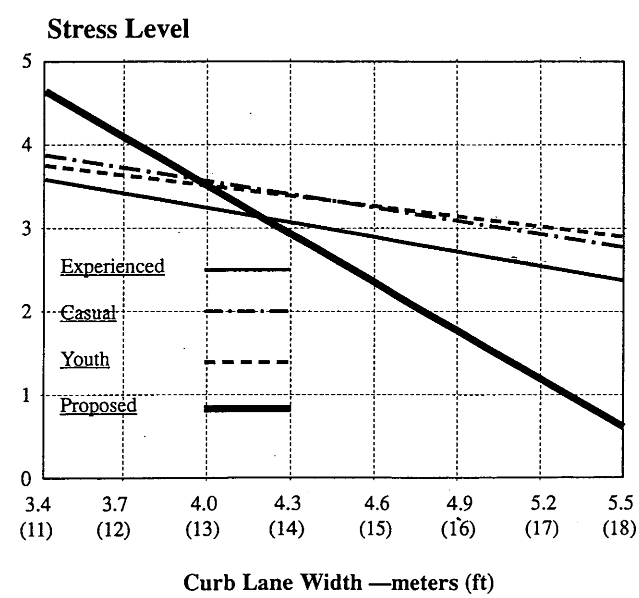

FIGURE 2 Width versus bicycle stress level.

improved upon. Again, these plots show that stress level versus width is upwardly linear from wide to narrow. The plots also indicate a difference in perception between the experienced and casual bicyclist for narrow lane widths and a lesser difference for wide lanes. The perceptions of the youth bicyclist fall somewhere between those of the casual and experienced bicyclists.

The results of the speed stress level for five street segments are shown below. Again, two street segments containing bicycle lanes were not used in this analysis, for the reasons stated earlier.

Stress Level	*Average Value*
Proposed	2.40
Experienced	3.00
Casual	3.34
Youth	3.01

These results show a difference between the experienced bicyclist and the casual bicyclist in their perception of speed, with little if any difference between experienced and youth bicyclists. There are several possible reasons for this unexpected result: (*a*) there were too few street segments for this analysis, (*b*) youth bicyclists may have higher risk-taking behavior characteristics, and (*c*) youth bicyclists may not be able to judge speeds as competently as experienced drivers of vehicles. The proposed average stress level is lower than that shown for all three types of bicyclists. This suggests that the proposed stress level for speed might have to be modified upward.

Figure 3 shows the plots of the best-fit regression lines of average stress level versus speed for the different types of bicyclists. The plots indicate an apparent difference between casual and experienced bicyclists at lower speeds. At higher speeds the lines converge at 75 kph (45 mph). The youth bicyclist regression line is almost the same as that of the experienced bicyclist. The *R*-squared values of these regression plots are 0.80, 0.64, and 0.90 for the experienced, casual, and youth bicyclists, respectively. There is fairly high correlation for speed and stress level for the experienced and youth bicyclists but the correlation is not quite as high for the casual bicyclist. It is surprising that youth bicyclists had the highest *R*-squared value. This may be due to the low number of street segments evaluated.

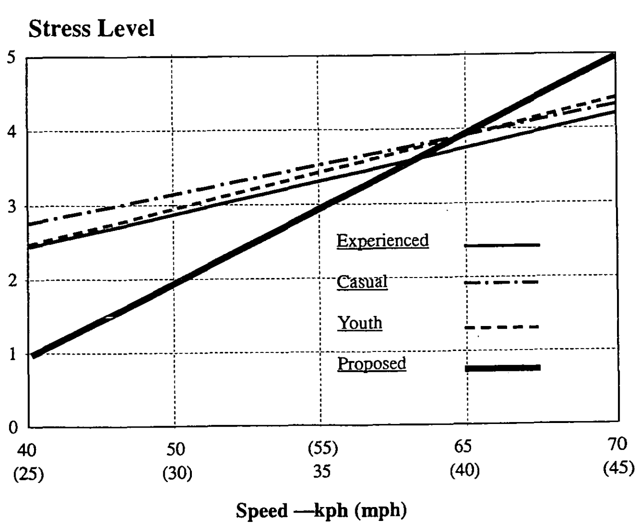

FIGURE 3 Speed versus bicycle stress level.

CONCLUSIONS

The following conclusions were drawn:

1. The bicycle stress level analysis procedure shows promise in evaluating urban and suburban streets for bicycling compatibility.
2. This procedure seems to indicate that different types of bicyclists can recognize the variation in the three primary on-street traffic variables from low to high. Bicyclists apparently relate their perception of the variation in the form of stress level.
3. The hypothesis that there are differences in how the various types of bicyclists perceive primary on-street variables could not be confirmed or rejected. The sample sizes of the three types of bicyclists were not large enough to be validated statistically, nor was the number of street segments used to evaluate the three primary variables.

FUTURE RESEARCH

Future research should be as follows:

1. The same survey should be conducted with a sufficient number of bicyclists in each of the three bicyclist categories to ensure that the results can be statistically analyzed. All 23 street segments should be analyzed for all three primary variables by all the bicyclists.
2. Similar surveys could be conducted in cities having larger or smaller populations than Madison, Wisconsin. It may be that bicycle stress level depends on the population size of urbanized areas.
3. Several of the Madison streets with wide curb lanes used in this study have been restriped to include bicycle lanes. It would be of interest to determine whether striping a bicycle lane on an existing street with wide curb lanes lowers bicycling stress levels. The present research indicates that stress levels for all types of bicyclists with respect to speed and width variables seem to drop for street segments with bicycle lanes as compared with similar segments without bicycle lanes.
4. It should be determined at what specific overall stress levels the different types of bicyclists would stop utilizing streets as well as the distances they would be willing to ride on the basis of the overall stress levels of streets.
5. The videotape stress level procedure should be validated by surveying bicyclists riding on streets with differing variables.

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Publication of this paper sponsored by Committee on Bicycling and Bicycle Facilities.

Environmental and Travel Preferences of Cyclists

CATHY L. ANTONAKOS

Current recommendations for designing bicycle facilities are most often based on experience rather than on findings from scientific inquiry. This study pools cyclists' opinions on environmental design issues, substantiating experts' knowledge about designs for cycling environments. The study examines the influence of personal characteristics, travel resources, and travel constraints on cyclists' environmental preferences, evaluations of cycling conditions, and decisions to bicycle for transportation. Questionnaires were distributed to 552 cyclists at four recreational bicycle tours in Michigan during the summer of 1992. Analysis of variance and correlations were used to investigate relationships of interest. Cyclists indicated their preferences for different types of cycling facilities and the importance that they placed on environmental factors such as traffic volume and surface quality when choosing cycling routes. Age was positively correlated with preference for on-road facilities (striped bike lanes, wide curb lanes), with importance placed on surface quality, scenery, and bike safety education. Age was negatively correlated with preference for bike paths separated from the roadway. Safety, scenery, terrain, and bike safety education were more important to women on average than to men. As expected, cycling experience was negatively correlated with preference for off-road facilities and concerns about safety, traffic, and terrain. Bike safety education was rated almost as high as the need for bike lanes, to improve community cycling conditions. Thirty-two percent of the cyclists surveyed commute by bicycle; 68 percent run errands by bicycle. Commute distance was strongly associated with the likelihood and frequency of commuting by bicycle.

The Intermodal Surface Transportation Efficiency Act of 1991 sets aside funding for the development of nonmotorized transportation, indicating a growing awareness of the need for a more diversified transportation system and, perhaps, a new approach to transportation planning in the face of budget constraints. But the American landscape is imprinted with infrastructure for automobiles, often to the exclusion of pedestrians and bicyclists. Research is needed to determine how to integrate pedestrians and cyclists safely into the automobile-dominated transportation system. This study focuses on bicycling, examining issues related to efforts to design environments for bicycling. Cyclists were surveyed to determine the importance they place on environmental factors theorized to affect cycling conditions.

THE CASE FOR BICYCLING

Enthusiasm for bicycling has grown in the United States during the past decade, evidenced by a steady increase in bicycle ridership (*1*). Bicycling has the potential to fill many travel needs (*2*), to reduce pollutants from automobile emissions, and to increase mobility for people without access to automobiles. Reducing motor vehicle congestion is a major public policy objective, and every decision to substitute other travel modes for single-occupancy vehicles contributes to reducing congestion. Bicycling must be developed within the constraints of existing land use patterns and infrastructure and the distance limitations of the bicycle. In many areas, discontinuous bike routes, rough pavement, and heavy traffic thwart potential cyclists. Knowledge of how to integrate cyclists safely into the stream of motorized traffic is not widespread and usually not familiar to local planners and engineers responsible for implementing change in travel environments.

To date, bicycle transportation planners and engineers have relied heavily upon the American Association of State Highway and Transportation Officials standards (*3*) when designing bikeways. The tendency in the United States to treat bicyclists as pedestrians, keeping them on sidewalks or bike paths, has angered some bicycling advocates, who claim that riding on sidewalks or separate pathways does not solve all safety problems. The League of American Wheelmen recommends educating bicyclists about proper riding techniques and retaining cyclists' full rights to use the roadway (*4*). Treatments to integrate all traffic modes, and to separate modes, have been used successfully in redesigned street environments in Europe in conjunction with traffic calming.

STUDY PURPOSE

This study was conducted to contribute to a sparse base of knowledge on cyclists' opinions of how to improve cycling conditions. Data were collected from cyclists at four recreational bicycle tours in Michigan during the summer of 1992. The sampling design made it possible to survey large numbers of cyclists at fixed locations such as rest stops along tour routes, reducing the time and cost required for data collection. The sample thus excludes cyclists who bicycle only for transportation and noncyclists, although studies of these groups are needed also.

Cyclists were questioned on a number of issues that planners consider as they develop bicycle plans. Are bike paths, bike lanes, or wide curb lanes preferred? Do these "route corridor preferences" differ for recreational and commuting cycling? Do surface quality, traffic volume, traffic speed, and scenery influence a cyclist's choice of recreational and commuting bike routes? Do preferences vary by age and sex or with different levels of cycling experience? Do cyclists on road bikes have different preferences than cyclists on mountain bikes or hybrids? What influences a person's decision to ride a bicycle for transportation?

TRAVEL BEHAVIOR THEORY FOR CYCLING

Most of the publications on cycling date to the 1970s, when the oil embargo led the United States to take a long look at alternatives

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TABLE 1 Factors Studied in Research on Cyclists' Travel Behavior

	Environmental Factors	Personal Characteristics
Stated Preferences *(12)*	Pavement Quality Bicycle Facility Traffic Distance/Travel Time	Age Gender Socioeconomic Status Auto Availability
Mode Choice *(13)*	Traffic Secure Parking Climate Terrain	Age Gender Type of School Availability of Bicycle Desire for Companionship on the Way to School
Travel Behavior *(14)*	Number of Establishments within 1 Km of Home	Age Gender Employment Status Travel Mode Activity

to the automobile. Because cyclists' demand for better facilities, traffic congestion, and the number of car-bike collisions have increased, the topic of cycling has reemerged. Recent publications cover issues related to planning and designing bicycle facilities, including street designs that channel or favor bicycle traffic *(5–11)*.

A few studies have examined cyclists' travel behavior and environmental preferences, using personal and environmental characteristics as explanatory variables *(12–14)* (Table 1). In particular, Bovy and Bradley *(12)* established the importance of a limited set of personal and environmental factors in cyclists' commuting route preferences. This study tests the influence of personal characteristics, travel resources and constraints, and environmental characteristics on cyclists' environmental preferences, evaluations of cycling conditions, and cycling for transportation (Table 2). Numerous explanatory and outcome variables are included to test the model of cyclists' travel behavior shown in Figure 1 and to expand on earlier studies, though the list of factors tested is not all inclusive. Weather and climate are not measured, nor are many factors that might influence a person's decision to commute by bicycle, such as safe bicycle parking at destinations.

Many of the factors in Table 2 relate to traffic and transportation infrastructure, implying constraints imposed or opportunities presented by the built environment. Bicycle facilities (bike paths off the roadway and striped bike lanes on the road) are often major components of community bicycle plans. Natural features, such as scenery and hills, may affect a cyclist's enjoyment of a bicycle route and the level of physical effort required. Most of the environmental attributes relate to both recreational and commute cycling, though some are most relevant for commuting. Pathway design options for off-road cycling are more diverse than options for on-road cycling; they are incorporated as well.

If preferences are shown to be associated with easily measured personal characteristics, planners who are familiar with cyclists in their communities may be better able to provide facilities and programs to suit those cyclists. Age and sex may determine, in part, a cyclist's physical strength and in turn how tolerant a cyclist is of rough pavement or difficult terrain. More experienced cyclists, who are more confident of their cycling skills, may prefer riding in the street rather than on a separate bike path. Cyclists who ride mountain bikes or hybrids may be less affected by rough

TABLE 2 Factors Theorized To Influence Cyclists' Environmental Preferences

Personal Characteristics	Travel Resources and Constraints	Environmental Factors	Type of Route Corridor
Age Gender Cycling Experience	Type of Bicycle Auto Availability Commute Distance	Safety Traffic Volume Traffic Speed Pavement Quality Scenery Hilliness Traffic Stops Pavement Markings Road Signs Direct Route Quick Route Convenient for Errands	Bike Lane Wide Curb Lane Bike Path Trail Dirt Road Sidewalk

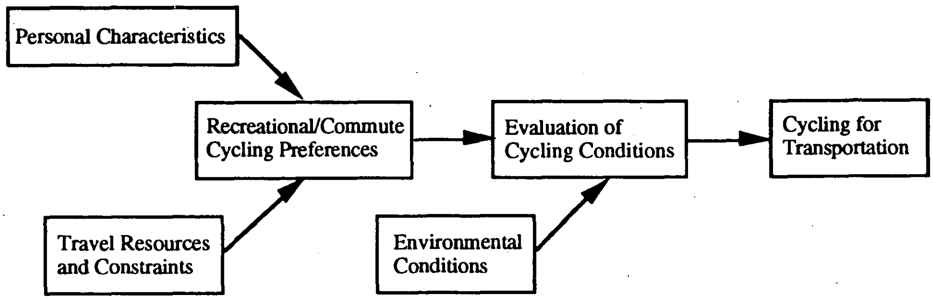

FIGURE 1 Theory of travel behavior for cycling.

pavement. Cyclists without access to automobiles and cyclists who live close to work may be more likely to commute by bicycle. The relationships shown in Figure 1 are summarized below.

1. Environmental Preference: Personal characteristics and the type of bicycle used are expected to influence environmental preferences for cycling.
2. Environmental Evaluation: Environmental preferences are expected to influence evaluations of cycling conditions.
3. Cycling for Transportation: Personal characteristics, travel resources and constraints, and environmental preferences are expected to influence cycling for transportation.

DATA COLLECTION METHODOLOGY

To test the relationships of interest, data were required from cyclists with diverse personal characteristics, cycling experience, and travel resources and constraints. Recreational bicycle tours provided an opportunity to survey a large group of cyclists at a single location, limiting the cost and time required for data collection. Bicyclists on recreational bicycle tours are fairly diverse in age and sex. Some bicycle tours are billed as challenging and fit intermediate or avid cyclists, and others attract cyclists of all abilities. Cyclists were surveyed at four bicycle tours in lower Michigan in the summer of 1992 (Figure 2). Three of the tours were on-road tours. One off-road tour was included to capture cyclists on mountain bikes.

Surveys were conducted where large crowds of cyclists were expected to assemble, such as at planned rest stops. Over 100 questionnaires were distributed and collected at each site in 2 to 3 hr. Cyclists required 5 to 10 min to complete the questionnaire. A total of 552 cyclists were surveyed at a cost of approximately $500 for travel to and from the data collection sites and printing expenses. Response rates at all of the tours were very good. About 95 percent of the questionnaires distributed were returned. The rate of missing data was 5.6 percent on average for survey items asked of all participants. The timing of surveys was critical to achieve a low refusal rate and low rate of missing data: cyclists are best approached when they are relaxing or resting, not at the end of a tour when their thoughts are on packing. The questionnaire length was appropriate for the circumstances, judging by the low rate of missing data.

Farm Lake Tour

The Farm Lake Tour (June 7, 1992)—a one-day tour held in the Plymouth, Michigan, area each year—attracts many less-than-avid cyclists. Approximately 900 cyclists participated in the 1992 tour. Three routes—32, 52, and 100 km (20, 32, and 64 mi)—are offered each year. Cyclists were approached at a rest stop common to all three routes and asked to participate in a brief survey. Then 114 questionnaires were distributed and collected. The refusal rate was less than 5 percent.

Pedal Across Lower Michigan (PALM) Tour

The Pedal Across Lower Michigan (PALM) tour (June 20–26, 1992) is an annual 6-day tour across the state of Michigan, attracting families and intermediate or avid touring cyclists. Two routes—a north and a south route—cross the state of Michigan from west to east. The routes converged on the next-to-last day of the tour. That evening, questionnaires were distributed to cyclists attending a general meeting, and the response was very positive: 150 questionnaires were distributed and 136 were returned.

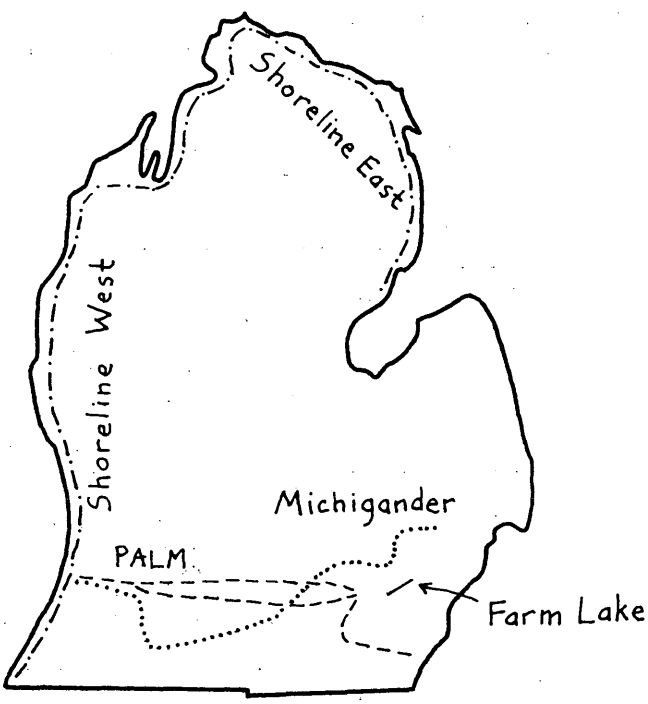

FIGURE 2 Recreational tour locations in lower Michigan.

Shoreline Tour

The Shoreline Tour (August 1–8, 1992) offers challenging east and west routes along the coast of northern lower Michigan. About 800 cyclists from Michigan, Illinois, Ohio, and other U.S. states, and from Canada participated in 1992. The tour is known for its scenery, hilly terrain, and the long distances traveled each day. Cyclists were surveyed as they ate lunch at the final destination of the two routes in Traverse City. The refusal rate was much higher for this tour because cyclists were preparing to collect their belongings, pack, and travel home. Approximately 200 questionnaires were distributed, and 177 collected.

Michigander Tour

The Michigander Tour (August 17–22, 1992)—a 6-day, cross-state, mostly off-road tour—was chosen for this study to determine whether the preferences of cyclists on mountain bikes differ from those of cyclists on road bikes and to examine issues relevant to designing off-road recreational trails for bicycling. Cyclists were surveyed on the fourth day of the tour in the afternoon, shortly after arriving in camp and setting up tents for the night. The refusal rate at this tour was very low (less than 5 percent). A total of 125 questionnaires were distributed and collected.

SAMPLE CHARACTERISTICS

Most of the cyclists in the sample had had considerable cycling experience. It would have been difficult to capture less-experienced cyclists than these in this sample using recreational bicycle tours as a field, although sampling methodologies (such as surveys at recreational bicycling paths along riverfronts) could be devised to capture novice recreational cyclists.

The sample provided a fair distribution on age, sex, and cycling experience (Table 3). As expected, cyclists at the Farm Lake and Michigander tours had less cycling experience than those on the PALM and Shoreline tours. Approximately 70 percent of the cyclists in the on-road tours were using road bikes, whereas in the Michigander Tour—the off-road tour—about 96 percent of the respondents were on mountain bikes or hybrids. Compared with estimates of cycling in the general population (*1*), the rate of cycling for transportation among this group of cyclists is very high: 32 percent commute by bike and 68 percent run errands by bike. Approximately 17 percent of the survey respondents had been involved in a car-bike collision.

ANALYTICAL METHODOLOGY AND FINDINGS

Summary statistics and findings from analyses conducted to investigate the theoretical model shown in Figure 1 are presented in this section. Descriptive statistics summarize cyclists' preferences and evaluations of cycling conditions in their communities. Statistics generated to test relationships in Figure 1 are also presented. An index of cycling experience used in the bivariate analyses was created by collapsing and summing three interval-scaled variables, "miles cycled past month," "miles cycled past year," and "years bicycled over 100 miles," to create a nine-category cycling experience index, referred to as "Cycling Experience" in some of the following tables. Missing values and "don't know" responses were coded zero.

Environmental Preferences for Recreational and Commuting Cycling

Cyclists rated their preferences for different types of cycling corridors using a five-point scale ranging from 1 (not at all preferred) to 5 (very preferred) (Table 4). Cyclists also indicated the importance they place on particular route characteristics when choosing a cycling route, using a five-point scale ranging from 1 (not at all important) to 5 (extremely important). Bike lanes, wide unmarked

TABLE 3 Characteristics of Survey Participants

Cyclist Characteristics			
Personal Characteristics	Age	40.8 Years (ave.)	Range: 11 to 77 Years
	Gender	44% Female, 56% Male	
	Km Cycled Past Month	560 (ave.)[a]	Range: 0 to 2580 Km[b]
	Km Cycled Past Year	1951 (ave.)[a]	Range: 0 to 15323 Km [b]
	Years Cycled > 62 Km	8.8 (ave.)	Range: 0 to 40 Years
	Commute by Bike	32%	
	Run Errands by Bike	68%	
Travel Resources and Constraints	Commute Distance - All Respondents	20.0 Km (ave.)	Range: 0.3 to 177 Km.
	Commute Distance - Bike Commuters	10.8 Km (ave.)	Range: 0.3 to 53 Km.
	Access to Automobile	96.6%	
	Type of Bicycle	Road Bike	59.8%
		Mt. Bike/Hybrid	39.3%

[a] 1 km = 0.6 mi.
[b] Some respondents on the Farm Lake Tour were on their first cycling trip of the season, and did not include the tour mileage when calculating distance cycled.

TABLE 4 Environmental Preferences for Recreational and Commuting Cycling

Recreation		Commuting	
Corridor Type	(ave. score)	Corridor Type	(ave. score)
Bike Lane	3.9	Bike Lane	4.1
Wide Curb Lane	3.6	Wide Curb Lane	3.8
Bike Path	3.4	Bike Path	3.1
Trail	2.4	Trail	2.0
Dirt Road	1.8	Sidewalk	1.9
Sidewalk	1.5	Dirt Road	1.7
Off-Road Corridors[a]	(ave. score)		
Prepared Trail	4.0		
Paved Trail	3.7		
Unsurfaced Trail	3.4		
Route Characteristic	(ave. score)	Route Characteristic	(ave. score)
Safety	4.4	Safety	4.2
Traffic Volume	4.1	Quick Route	3.9
Smooth Pavement	4.1	Direct Route	3.8
Scenery	3.9	Smooth Pavement	3.8
Slow Traffic	3.6	Low Traffic Volume	3.6
Few Stops	3.0	Slow Traffic	3.3
Few Hills	2.7	Convenient for Errands	3.2
		Avoid Hills	2.2
		Scenery	2.0

Items were rated on a scale from 1 (not at all preferred/not at all important) to 5 (very preferred/extremely important).
[a] Opinions about off-road corridor types were not asked in the context of commute cycling.

curb lanes, and bike paths are most preferred for recreational and commuting cycling. For off-road recreational cycling, prepared trails (surfaced and widened) are preferred over paved (asphalt) and unprepared (unimproved) trails. Scenery is important for recreational cycling but not for commuting by bike. Traffic, surface quality, and scenery are the most important factors for choosing recreational cycling routes, whereas safe, quick, and direct routes with smooth pavement are important for commuting.

Tables 5 through 7 summarize the results of analyses conducted to determine the strength of association among age, sex, cycling experience, type of bicycle, and environmental preferences for cycling. Highlights of the findings are discussed in the context of recreational and commuting cycling.

Recreational Preferences

Cycling experience and age are negatively associated with preference for bike paths, sidewalks, dirt roads, and trails for recreational cycling. Cycling experience is positively correlated with preference for wide curb lanes. Women rate bike lanes and bike paths higher, and their ratings for dirt roads are lower, on average, compared with men's ratings. Cyclists on road bikes and cyclists who use mountain bikes or hybrids both rate bike lanes high. Cyclists on road bikes also rate wide curb lanes high, and cyclists on mountain bikes or hybrids give comparatively higher scores to bike paths, trails, and dirt roads.

Age is positively correlated with importance placed on pavement quality and scenery and negatively correlated with few stops along a route in the choice of a recreational cycling route. Age is not associated with concerns about traffic and safety. Women and men both rate traffic and safety high, though women give higher ratings to those items on average than men. Women rate scenery and few hills higher as well. Not surprisingly, cyclists on road bikes place more emphasis on surface quality than cyclists on mountain bikes. Safety and traffic speed are more important to cyclists on mountain bikes than to cyclists on road bikes. For off-road cycling, older cyclists prefer paved (asphalt) trails (Table 6). Prepared (surfaced and widened) trails receive higher scores from women on average than from men.

Commuting Preferences

Age and cycling experience are negatively correlated with preference for bike paths, sidewalks, and dirt trails for commuting (Table 7). Women and men both rate bike lanes and wide curb lanes high. Wide curb lanes received higher ratings from cyclists on road bikes than from cyclists on mountain bikes, though both groups rate bike lanes high.

Age is positively correlated with consideration of convenience for errands in the choice of a commuting bike route. Cycling experience is negatively correlated with concerns about safety and low traffic volume. Safety, few hills, and convenience for errands are, on average, more important to women than to men. Surface quality for commuting, as it is for recreational cycling, is more important for cyclists on road bikes than cyclists on mountain bikes and hybrids.

TABLE 5 On-Road Recreational Cycling Preferences, Personal Characteristics, and Type of Bicycle

	Age	Cycling Experience	Gender			Type of Bicycle		
Corridor Type[a]	(Pearson r)	(Pearson r)	Male (ave.)	Female (ave.)	(eta)	Road Bike (ave.)	Mt. Bike (ave.)	(eta)
Bike Lane	.06	.00	3.8	4.0	.12[b]	3.9	3.8	.05
Wide Curb Lane	.09	.14[b]	3.5	3.6	.03	3.8	3.3	.21[b]
Bike Path	-.11[b]	-.20[b]	3.2	3.5	.11[b]	3.0	3.9	.28[b]
Trail	-.11[b]	-.15[b]	2.5	2.3	.05	1.8	3.3	.50[b]
Dirt Road	-.13[b]	-.02	1.9	1.5	.15[b]	1.3	2.3	.48[b]
Sidewalk	-.10[b]	-.25[b]	1.4	1.6	.06	1.3	1.7	.23[b]
Route Characteristic[a]								
Safety	.04	-.09[b]	4.3	4.5	.13[b]	4.3	4.5	.12[b]
Traffic Volume	-.01	-.02	4.0	4.1	.06	4.0	4.2	.08
Surface Quality	.10b	.08	4.0	4.1	.09	4.2	3.9	.17[b]
Scenery	.11b	.02	3.8	4.0	.13[b]	3.9	3.9	.00
Traffic Speed	.01	-.14[b]	3.5	3.8	.11[b]	3.5	3.8	.18[b]
Few Stops	-.14[b]	-.04	2.9	3.0	.04	3.1	2.8	.10[b]
Few Hills	.04	-.15[b]	2.5	3.1	.23[b]	2.7	2.8	.02

[a] Items were rated on a scale from 1 (not at all preferred/not at all important) to 5 (very preferred/extremely important).
[b] Significant at alpha equal to .05, two-tailed.

Evaluation of Cycling Conditions

Community Conditions

Survey respondents indicated the importance of different means to improve cycling conditions in their communities using a five-point scale ranging from 1 (not at all important) to 5 (extremely important). Education for bicyclists of all ages and improved awareness on the part of motorists were rated about as high as the need for bike lanes (Table 8). Road signs, pavement markings, and slower traffic speed were less favored improvements.

Age and cycling experience are positively correlated with improving motorist awareness and negatively correlated with perceived need for bike paths (Table 9). Cycling experience is also negatively correlated with preference for slower traffic. Motorist awareness, bike safety education, bike lanes, and road signs were rated higher by women than by men. Cyclists on mountain bikes gave lower ratings to surface quality and higher ratings to bike paths and slower traffic than did cyclists on road bikes.

Tour Route Terrain

One part of the questionnaire collected cyclists' evaluations of routes they had ridden earlier in the day. For one route characteristic—hilliness—objective data were compiled from topographic maps to create slope profiles of the routes for comparison with cyclists' evaluations of route hilliness. Several metrics for hilliness were devised to quantify the difficulty of climbs, steepness of descents, and variation in terrain. Overall, the routes were found to be relatively flat, and cyclists' evaluations of them showed little variance. A more complete discussion of the analysis of route terrain has been provided elsewhere (*15*).

Cycling for Transportation

As expected, commute distance is negatively correlated with the likelihood and frequency of commuting by bicycle (Table 10). (Reasons respondents gave for not commuting by bicycle included

TABLE 6 Off-Road Cycling Preferences and Personal Characteristics

	Age	Cycling Experience	Gender		
Route Corridor[a]	(Pearson r)	(Pearson r)	Male (ave.)	Female (ave.)	(eta)
Paved Trail	.16	.06	3.6	4.0	.16
Prepared Trail	-.03	-.09	3.8	4.4	.29[b]
Unsurfaced Trail	-.40[b]	.08	3.5	3.0	.18

[a] Items were rated on a scale from 1 (not at all preferred) to 5 (very preferred).
[b] Significant at alpha equal to .05, two-tailed.

TABLE 7 Commute Cycling Preferences, Personal Characteristics, and Type of Bicycle

	Age	Cycling Experience	Gender			Type of Bicycle		
Corridor Type[a]	(Pearson r)	(Pearson r)	Male (ave.)	Female (ave.)	(eta)	Road Bike (ave.)	Mt. Bike (ave.)	(eta)
Bike Lane	.08	.06	3.9	4.2	.13[b]	4.2	3.9	.11
Wide Curb Lane	.06	.02	3.6	4.1	.25[b]	4.0	3.5	.21[b]
Bike Path	-.20[b]	-.17[b]	3.1	3.1	.01	2.8	3.3	.17[b]
Trail	-.15	-.16	2.0	1.9	.06	1.7	1.9	.08
Sidewalk	-.31[b]	-.30[b]	1.9	1.7	.06	1.4	2.1	.34[b]
Dirt Road	-.27[b]	-.23[b]	1.8	1.5	.12	1.7	2.2	.21[b]
Route Characteristic[a]								
Safety	.05	-.15	4.1	4.5	.19[b]	4.2	4.3	.00
Quick Route	-.10	-.05	3.9	3.7	.05	3.7	4.0	.12
Direct Route	.01	.04	3.8	3.8	00	3.7	3.9	.10
Surface Quality	.08	.07	3.7	3.9	.09	3.9	3.6	.13
Traffic Volume	-.09	-.10	3.7	3.7	.00	3.8	3.6	.09
Traffic Speed	.06	-.03	3.4	3.3	.04	3.5	3.2	.10
Convenient for Errands	.16[b]	-.02	3.0	3.3	.12	3.0	3.3	.10
Few Hills	-.01	.01	2.1	2.4	.13	2.2	2.2	.01
Scenery	.04	.01	1.9	2.1	.07	2.2	1.8	.20[b]

[a] Items were rated on a scale from 1 (not at all preferred/not at all important) to 5 (very preferred/very important).
[b] Significant at alpha equal to .05, two-tailed.

unsafe roads, dress code at work, traveling before or after daylight, and commute distance.) More experienced cyclists are more likely to commute and run errands by bicycle. Age is not associated with cycling for transportation. A significantly higher percentage of male respondents commute and run errands by bicycle (40 and 73 percent, respectively) as compared with female respondents (30 and 58 percent, respectively). Respondents without access to automobiles are more likely to bicycle for transportation, though the number of survey respondents in this analysis who do not have access to an automobile on a regular basis is so small (n = 17) that this finding may be unreliable.

TABLE 8 Evaluations of Needed Community Improvements

	(Ave. Score)
Bike Lanes	4.5
Motorist Awareness Should Increase	4.4
Child/Youth Bike Safety Education	4.2
Surface Quality	4.2
Adult Bike Safety Education	4.1
Bike Paths	3.8
Road Markings	3.4
Road Signs	3.3
Slower Traffic	3.2

Items were rated on a scale from 1 (not at all important) to 5 (extremely important).

POLICY IMPLICATIONS FOR PLANNING

Findings presented in the preceding sections show that personal characteristics and travel resources and constraints are associated with environmental preferences, evaluations of cycling conditions, and cycling for transportation. Recreational and commuting cycling preferences were found to be similar in this study, suggesting that knowledge of recreational cycling preferences may be useful for planning commuting cycling environments.

Bike Lanes and Bike Paths

The cyclists surveyed rated bike lanes highest for recreational and commuting cycling. This preference holds true among cyclists with different personal characteristics and levels of cycling experience. On the basis of these findings, bike lanes may be desirable in communities, and they are much less expensive to install and maintain than bike paths. Yet less experienced cyclists and cyclists on mountain bikes also rate bike paths high. A mix of facilities is thus likely to best satisfy the needs of different types of cyclists.

Bike Safety Education

Respondents indicated that increasing motorists' awareness of cyclists and providing bike safety education for bicyclists of all ages are important means to improve cycling conditions in communities. However, efforts to inform the public of safe driving practices

TABLE 9 Community Cycling Conditions, Personal Characteristics, and Type of Bicycle

Community Improvement[a]	Age	Cycling Experience	Gender			Type of Bicycle		
	(Pearson r)	(Pearson r)	Male (ave.)	Female (ave.)	(eta)	Road Bike (ave.)	Mt. Bike (ave.)	(eta)
Bike Lanes	-.02	.03	4.4	4.7	.18[b]	4.5	4.6	.05
Motorist Awareness Should Increase	.11[b]	.10[b]	4.4	4.6	.14[b]	4.4	4.4	.01
Youth Bike Safety Education	.22[b]	.06	4.1	4.5	.18[b]	4.3	4.2	.05
Surface Quality	.04	.05	4.1	4.2	.04	4.3	4.0	.16[b]
Adult Bike Safety Education	.17[b]	.06	4.0	4.4	.19[b]	4.2	4.1	.04
Bike Paths	-.10[b]	-.22[b]	3.6	3.8	.08	3.6	4.2	.25[b]
Road Markings	.05	-.08	3.5	3.7	.05	3.4	3.6	.08
Road Signs	.01	-.08	3.3	3.7	.15[b]	3.2	3.4	.07
Slower Traffic	.00	-.11[b]	3.1	3.3	.07	3.1	3.3	.09[b]

[a] Items were rated on a scale from 1 (not at all preferred/not at all important) to 5 (very preferred/very important).
[b] Significant at alpha equal to .05, two-tailed.

TABLE 10 Cycling for Transportation, Personal Characteristics, and Travel Resources and Constraints

	Commute by Bike	Errands by Bike
Age	-.04	.08
Cycling Experience	.16[a]	.19[a]
Gender	.10[a]	.09[a]
Commute Distance	-.25[a]	NA
Auto Availability	.16[a]	.08

Coefficients are Pearson's correlations.
[a] Signifiant at alpha equal to .05, two-tailed.

for interactions with cyclists and to educate cyclists about safe cycling are often lacking in bicycle programs. Educational efforts in communities can be instituted at low cost and have much potential to benefit cyclists.

Cycling for Errands

Efforts to increase cycling for transportation often focus on the commute trip. In this study, the percentage of respondents who run errands by bicycle is much larger than the percentage who commute by bicycle, indicating that "errands by bike" should be a major element of pro-bike programs. Trips made for shopping and banking, for instance, are not as constrained with respect to destination, distance, time of departure, and dress as commuting trips. Providing bicycle facilities to link residential areas with nearby shopping may be a more effective way to increase the proportion of trips made by bicycle than efforts to create a more extensive but fragmented network of bicycle facilities.

CONCLUSION

This study substantiates knowledge held by experts familiar with planning environments for bicycling. Further work is needed to determine the preferences of different types of cyclists, such as those who bicycle only for transportation and those who bicycle for recreation but do not participate in bicycle tours, and to determine the characteristics of a truly representative sample of cyclists in the United States. More in-depth studies of bicycle transportation are needed to provide precise evaluations of cycling conditions, which would further aid transportation planners and other professionals interested in improving environmental conditions for cycling.

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Publication of this paper sponsored by Committee on Bicycling and Bicycle Facilities.

Bicycle Accidents in Maine: An Analysis

PER GÅRDER

In the United States, little thought has traditionally been given to bicyclists in the design of roadways. Measures to improve bicycle safety should be introduced where they give optimal effect. It is therefore important to know where the problems are the greatest. In total, over 2,000 police-reported bicycle accidents were analyzed. A limited number of hospital-reported accidents were also included. An analysis shows that of 44 patients admitted and treated for major trauma caused by bicycle accidents, only 6 (14 percent) showed up in the police statistics. The vehicle driver involved in a bicycle accident most commonly has not violated any formal highway law, whereas the bicyclist commonly has. There are many reasons for this: lack of knowledge, youth and inexperience, and disrespect for regulations. Bicyclist training and information could influence a high percentage of the accidents (up to 80 percent). Vehicle drivers also need education. Being within the highway code is not always enough to avoid an accident. Nine out of 12 fatal bicycle accidents in Maine during 1988–1991 were caused by collisions with automobiles. Separating bikes and cars from one another is a possible option. Mixed environments can also be made safer, for example, by reducing speed limits or modifying intersections to make them safer for bicyclists. The influence of physical measures is hard to evaluate conclusively because of lacking exposure data. Fatalities are typically caused by head injuries. Increased use of helmets should therefore be a primary short-term safety goal.

Measures to improve bicycle safety should be introduced where they give optimal effect. In order to do this, it is important to know where the problems are greatest and to understand which measures have the potential to be most beneficial. This study focuses on identifying the problematic areas in bicycle safety for a mostly rural state.

BACKGROUND

In the United States, the design of roadways has typically emphasized the safe and efficient movement of motor vehicles. Little thought has normally been given to bicycle riders. In recent years, about 2 percent of all road accident fatalities involved bicycle riders (*1*). This percentage may not seem high, but the risk—measured in fatalities per mile traveled—is high in comparison with other modes of transportation.

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) was passed by the U.S. Congress. This legislation encourages bicycling and walking as serious transportation options. The result may be that bicycling will become more common. Bicycling is basically a sound and environmentally friendly mode of transportation. However, increased volumes of cyclists may also increase the number of accidents if a safe infrastructure is not provided.

Possible solutions include building bike paths. In order to get a high percentage of bicycle riders to use them, the paths ought to closely follow the roads and highways used by motorists. Otherwise, unprotected road users do not feel safe, especially at night when the risk of being attacked is perceived as high on bike paths that are isolated from major roads. Such bike-roads may also remain unknown to the person who usually goes by car, but who may on occasion want to use his or her bike.

In rural areas bike paths as a rule are beneficial to safety. However, European experience has shown that bike paths along major roads in built-up areas surprisingly often generate more accidents per bicycle-mile than mixed-traffic environments. This is because in urban or suburban areas lacking bike paths, roughly three out of four accidents involving a bicyclist happen at intersections. When a bike path is built, the mid-block risks are generally reduced. What happens at the intersections is quite different. Cycling through a "normal" intersection layout—in which the bike path is about 3 to 6 m (10 to 20 ft) from the parallel road—presents higher risks for the adult cyclist than cycling in mixed traffic. This is partly because turning motorists do not observe the cyclist as easily as when they share the same right-of-way and partly because the angle of collision typically increases from almost parallel to about 90 degrees when the bike path is installed. These differences result in more serious accidents. The overall effect of building bike paths along streets in built-up areas is therefore typically an increase in risk, unless the intersections are grade separated or built in other safe ways (*2,3*).

ACCIDENT DATA

The primary data source is made up of all police-reported accidents occurring in the state of Maine from 1986 through 1991 that involved one or several bicyclists and at least one motorized vehicle, in total 2,059 accidents. According to state law, an accident is reportable to the police if damages are more than $500 or if there is any personal injury and the accident takes place on a public roadway or other place where public traffic may reasonably be expected. These data came from the Maine Department of Transportation's Transportation Integrated Network Information System (TINIS) and were obtained on computer disks and downloaded for analysis. TINIS also gave access to data files containing the geometric layout and vehicle volumes for all locations with reported bicycle accidents. The results presented in this paper are based on the TINIS data base, unless otherwise specified.

Besides the information that can be extracted from this computerized system, a subset of almost 400 actual police reports, which sometimes included supplemental report sheets, was examined. (All fatal accidents and all 1991 accidents were examined in this way.) In these reports, a narrative, as well as a sketch, supplements what is covered in the computerized systems. Besides being more complete, the original reports provide less risk of error. However, it must be kept in mind that even the original data are based on the interpretation of each reporting officer and that

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one of the parties involved in the accident may have had a reason to fabricate a story.

Hospital statistics provided a final source of information. Two hospitals are currently participating in the Maine Trauma Registry: Maine Medical Center (MMC) in Portland and Eastern Maine Medical Center (EMMC) in Bangor. MMC provided a report covering patients injured in bicycle accidents and admitted to MMC between January 1, 1990, and June 30, 1993. Patients are included if they stay in the hospital more than 3 days, die, or require transfer in or out of the hospital. In total, 42 patients were included in this report. A similar report was obtained from EMMC covering January 1, 1991, to April 30, 1993, which included 10 bicycle victims. MMC also provided a statewide report on 1991 accidents. A special grant enabled the recruitment of emergency nurses in each of 35 hospitals, who voluntarily completed a trauma form on patients identified with major trauma, including 30 patients treated for bicycle accidents in 1991. Information on nine of these was duplicated by information in the MMC and EMMC registries. After these duplicates had been eliminated, the hospital file contained a total of 73 bicycle accidents.

A risk analysis should typically be based on expected accident rates. The denominator for calculating this rate should be number of road users or number of miles traveled. Therefore, to estimate bicyclists' risk with respect to a given factor, it is necessary to know either the number of cyclists passing a location or the number of miles ridden along a section. Because statewide bicycle counts have only been initiated recently, several essential risk estimates cannot be calculated at this time.

ANALYSIS OF BICYCLE ACCIDENT DATA

Number of Accidents

According to TINIS, there were 2,059 bicycle accidents between 1986 and 1991. Fourteen of these were fatal, and 117 were noninjury accidents.

The hospital statistics analyzed in this study show that 22 of 63 admitted patients (35 percent) were treated for collisions with motor vehicles. (The 10 accidents reported by EMMC are of an unknown type.) For these, the average length of stay in the hospital was 9.2 days. The average length of stay in the hospital for patients injured in single-bicycle accidents was 4.6 days.

An analysis of 1990 and 1991 hospital data shows that of 44 patients admitted and treated for major trauma caused by bicycle accidents, only 6 (14 percent) showed up in TINIS. These numbers indicate that the approximate number of severe injury (bicycle) accidents in Maine is around 2,500 per year (2,059/6/0.14), or 0.2 percent of the entire state's population. Of 13 accidents involving motor vehicles, 6 showed up in TINIS (46 percent).

It can therefore be assumed that close to half of the more serious bicycle accidents involving motor vehicles are reported to the police. Whether the portion not being reported is of the same type as those that have been reported can only be left to speculation. Probably the nonreported accidents are somewhat less severe on average and may also be more likely to involve children and occur in rural areas and on private property.

Characteristics of Accident Situation

Population Density

Two of three accidents (68 percent) are reported in an urban environment. A location is classified as urban if it is within a compact area that has a population of more than 6,000. Of the 14 fatal accidents, 9 were rural and 5 urban.

Time of Year

It is natural to assume that most bicycle accidents occur when ridership is high—during the time of year when the weather is favorable to riding a bike, which in most years is from late April through October. The data support this assumption and show that 40 percent of all bike accidents happen in July and August, the vacation months (Figure 1). This indicates that bicycling is primarily a recreational or leisure activity rather than a means for everyday transportation. However, it has to be kept in mind that Maine's population increases considerably during the summer months because of tourism and summer residences.

Weekday of Accident

If bicycling is mostly a leisure activity, the majority of accidents ought to occur on Saturdays and Sundays. Figure 1, however, shows that this is not the case. Saturdays have roughly 20 percent fewer accidents than regular weekdays, and Sundays have 45 percent fewer. This does not necessarily mean that there are fewer people riding bikes on weekends than weekdays. It may also indicate that there is less conflicting vehicle traffic on weekends or that people are in less of a hurry on weekends and therefore are less likely to collide, or both.

Time of Day

Figure 1 also shows that almost half (44 percent) of all accidents happen between 3:00 p.m. and 7:00 p.m. Surprisingly few accidents happen during the morning peak hour.

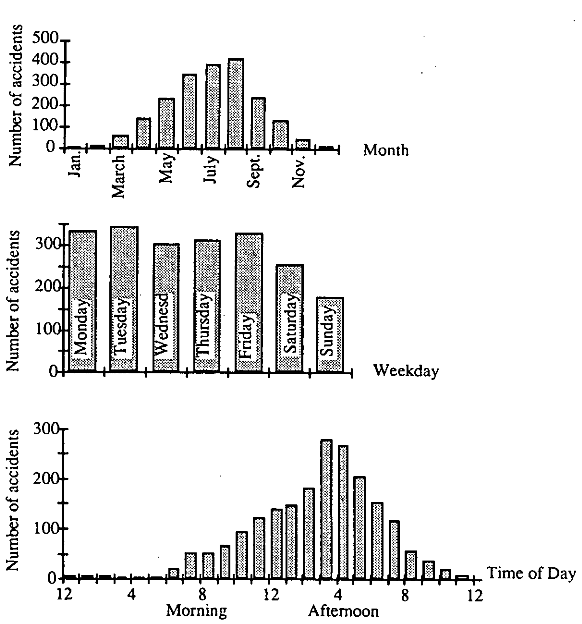

FIGURE 1 Bicycle accidents by time of occurrence.

Characteristics of Bicyclists Involved in Accidents

Age

As can be seen from Figure 2, children 10 to 15 years old are especially prone to having bicycle accidents, but many accidents also involve those in their early twenties, as well as younger children. Figure 2 also shows the age of significant trauma patients admitted for care as a result of bicycle accidents. The median age of the 14 fatally injured bicyclists was 16.

Sex

Male bicyclists are involved in 77 percent of all accidents, and 12 of the 14 fatalities were male. According to the hospital statistics, 71 percent of the patients admitted because of bicycle accidents were male.

Type of Injury

The primary analysis covers 58 of the hospital-reported accidents (those reported directly from EMMC and MMC). The most common areas of the body injured were the head, skull, and face [26 accidents, including the only fatalities (*2*)]; chest (9 accidents); legs (7); internal areas (6); arm and elbow (4); entire body (2); spinal cord (2); ankle (1); and hand (1). Data provided indicate that none of the patients seemed to have been wearing a helmet, although in a few cases helmet status was uncertain.

Behavior of Bicyclists Involved in Accidents

Bicyclists' Contribution to Accidents

In 20 percent of the accidents, the police officer did not cite any contributing factor on the part of the bicyclist. In the other 80 percent, the rider contributed to the accident in the opinion of the reporting officer. In 29 percent of the cases, the bicyclist showed inattention or was distracted, and in 18 percent the bicyclist failed to yield the right-of-way. Other common causes were other human violations, 20 percent; driver inexperience, 5 percent; disregard of traffic control device, 4 percent; riding left of center line, 3 percent; unsafe speed, 3 percent; and improper turn, 3 percent. The most common bicycle defect was defective brakes (4 percent). In less than 1 percent of the accidents is it noted that the bicycle had defective lights.

Bicyclists' Movement in Intersection Accidents

It is often assumed that most intersection accidents happen when the cyclist is turning left. The data show that this is not the case. In 84 percent of the cases, the bicycle rider was going straight through the intersection, in 11 percent turning left, and in 5 percent turning right. Note that there are typically more bicyclists going straight through than turning left at an intersection, so the percentages just given cannot be interpreted as risk per bicycle passage. The bicyclist was riding on the sidewalk in about 20 percent of the accidents.

Bicyclists' Choice of Route and Driveway Accidents

A manual analysis of 83 accidents happening at driveways in 1991 shows that of those involving a car entering or leaving the driveway, it was not uncommon that the bicyclist was riding on the sidewalk (29 percent of the cases) or on the left-hand side of the road (18 percent).

Bicyclists Riding With or Against Traffic Flow

One issue often debated among bicyclists is whether it is safer to ride with or against the general flow of traffic. The prevailing opinion is that it is safer to ride on the right side with the general traffic flow. The data here support that opinion.

Since it is not known what percentage of non-accident-involved cyclists ride on the left versus the right side, all that can be done is to study accident numbers. The following analysis is based on 595 accidents—those that were coded in TINIS with respect to

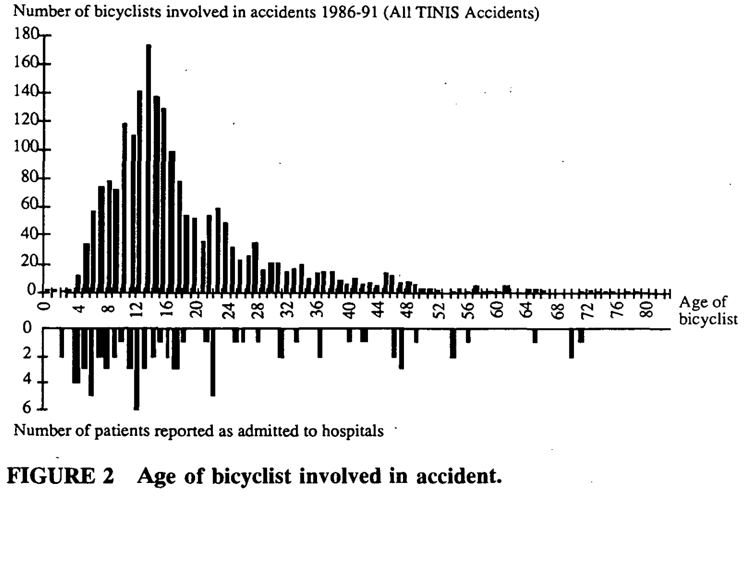

FIGURE 2 Age of bicyclist involved in accident.

what side of the street the bicyclist was riding on. Starting with roadway sections between intersections, a total of 128 accidents were recorded in which the bicyclist was riding with the traffic and 41 accidents in which the rider was going against the traffic. For accidents in passing through four-leg intersections, there were 43 in which bicyclists were riding against the traffic and 55 in which they were with the traffic. If it is now first assumed that riding on sections between intersections is equally dangerous on both sides [which is a conservative assumption for cyclists riding on the right side, since many accidents happen when bicyclists are crossing driveways, for which it is definitely safer to be on the right side (*4*)], this means that there are at least 3.1 times (128/41) as many bicyclists using the right side compared with those using the left. If it is next assumed that cyclists stay on the same side of the road when crossing intersections as when riding between them (also a conservative assumption, because cyclists ought to use the right side, particularly in complicated environments with many intersections), going through a four-leg intersection on the left side becomes at least 2.5 times as dangerous as going through on the right side; 43 accidents were reported for cyclists riding on the left, although no more than 17.7 (55/3.1) would be expected if the risk were the same as that on the right side.

Characteristics of Vehicle and Driver Involved in Bicycle Accidents

Type of Vehicle

A question frequently asked is whether trucks often are involved in bicycle accidents. Only 46 of the accidents (2.3 percent) involved a truck or bus; trucks and buses together account for about 9 percent of the miles driven in the state (*5*), although many of these miles are driven on roads with light or no bicycle traffic. Pickup trucks (including larger vans) were involved in 20.7 percent of the accidents and about 26 percent of the miles driven. Motorcycles accounted for 1.3 percent of the accidents and about 0.8 percent of the miles driven in the state. The remaining accidents (75.7 percent) involved a regular passenger car, station wagon, or smaller van. They account for about 65 percent of the mileage driven (*5*).

Age of Driver

Another question often asked is whether older drivers are a threat to bicyclists' safety. Seen from a public health aspect, older vehicle drivers are not a threat. Older drivers (those 70 years and older) may have higher accident rates per mile than middle-aged drivers, but in absolute numbers it is not older drivers but younger ones who typically are involved in bicycle accidents (see Figure 3).

Sex of Vehicle Driver

Male vehicle drivers account for 58 percent of the accidents. The average distance driven by car also tends to be slightly higher for men, so in terms of accidents per mile driven it appears that men and women are approximately equally safe.

Influence of Alcohol or Drugs

According to the information given in the police reports, the vehicle driver was under the influence, had been drinking or using other drugs, or both in only 26 cases. This represents just over 1 percent of the accidents. Typically, a much higher percentage of accidents is attributed to alcohol. One explanation for the low number of accidents reported as alcohol related—with respect to the vehicle driver—is that bicyclists usually ride in the daytime, whereas alcohol and driving is a combination more common in the evening or night. (Over 90 percent of the accidents were reported between 7:00 a.m. and 8:00 p.m.) In 32 cases it is unknown whether the vehicle driver was impaired.

An in-depth analysis of vehicle drivers involved in fatal accidents does not show that these drivers deviate from "good behavior" in any obvious way. The driver in every case was sober and had a valid license and a violation-free driving record.

Behavior of Vehicle Driver Involved in Bicycle Accidents

Vehicle Driver Contribution

In most accidents (60 percent) the police officer has noted "no improper driving" in the report. In 20 percent, inattention or distraction is given as a contributing factor to the accident; in 10 percent, failure to yield the right-of-way; and in 6 percent, obscured vision.

Action of Vehicle Driver Before Accident

In 964 accidents (47 percent of the cases), the vehicle driver was going straight ahead on the roadway. In 293 (14 percent), the driver was turning right, and in 269 (13 percent), the driver was turning left. Other actions resulting in accidents were starting (7 percent), stopping or slowing in traffic (4 percent), avoiding objects or other road users (4 percent), and backing in traffic (1 percent). Legally parked cars were involved in 2 percent of the accidents.

Intersection Accidents and Movement of Vehicle Hitting Bicyclist

A specific analysis of movement was done for accidents occurring at intersections. In more than half of these, the vehicle was turning (in 27 percent to the left and in 30 percent to the right). Manual

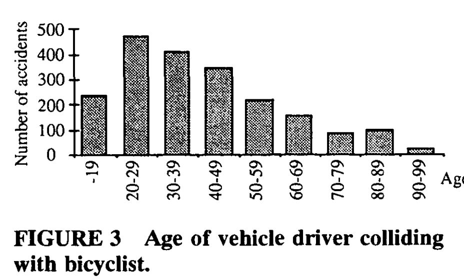

FIGURE 3 Age of vehicle driver colliding with bicyclist.

analysis of 205 accidents reported at intersections in 1991 shows that the two parties entered the intersection at right angles in the majority of cases (70 percent). About 10 percent of the accidents were caused by left-turning cars colliding with bicyclists riding in the opposing direction. Right-turning cars cutting off bicyclists going straight through the intersection accounted for 9 percent of these accidents.

Characteristics of Accident Location

Accident Distribution at Intersection or Roadway Section

Roughly half of all accidents occurred at intersections (48 percent according to TINIS; 55 percent according to a manual analysis of 370 accidents from 1991). Of these, about 55 percent occurred at three-leg intersections, 42 percent at four-leg intersections, and 3 percent at five-leg intersections. Roughly half of the accidents between intersections involved a vehicle or bicycle moving in or out of a driveway (50 percent according to the manual analysis of the 1991 accidents). Only 9 percent of all accidents involved a bicyclist and a motorist traveling along the road in the same direction away from intersections and driveways. In 3 percent, the parties were traveling in opposing directions away from intersections and driveways. The bicyclist was crossing the road away from intersections and not coming from a driveway in 10 percent of all accidents. An analysis of 1991 accidents that occurred at a driveway entrance or exit shows that most often the accident involved a car that was leaving the driveway (34 percent of the cases) or just entering the driveway (26 percent). There were also many cases involving bicyclists who were riding into the street from a driveway (34 percent) compared with heading for the driveway (6 percent). However, some of the accidents that seem to have happened away from intersections and driveways may have involved a bicyclist crossing the road with intent to go into a driveway. This intent is usually impossible to determine from the police report.

Out of the 14 fatal accidents examined in depth, only 3 accidents happened at intersections. In three cases the bicyclist was crossing a major road coming from a driveway, and in two other cases the bicyclist was crossing a major road away from any intersection or driveway. In one case the bicyclist rode along the road in the direction opposite to the vehicle traffic, and in three other cases, the bicyclist was going straight along the road in the same direction as the vehicle. In two of these cases, the bicyclists for some reason lost their balance and fell in front of the vehicle.

Intersection Control

In the state of Maine, the practice is to have Stop signs on nearly all minor approaches at nonsignalized intersections. Four-way and other all-way stop controls are uncommon. Yield signs are used very sparingly, mostly for right-turn-only lanes in rural environments. Only very minor streets intersecting with other local streets have no signed control.

At three-leg intersections, 1 percent of the accidents occurred at all-way stops, 50 percent at other stops, 2 percent at Yield signs, 8 percent at traffic signals, and 37 percent where there was no control. At four-leg intersections, 3 percent of the accidents happened at four-way stops, 43 percent at other stops, 38 percent at signalized locations, and 14 percent where there was no control. At intersections with more than 25,000 vehicles entering per day, 51 out of 57 accidents happened at signalized intersections. Although the lack of bicycle counts again makes it impossible to calculate risks, they may be higher at signalized intersections because of higher traffic volumes and speeds, as well as an increase in turning movements.

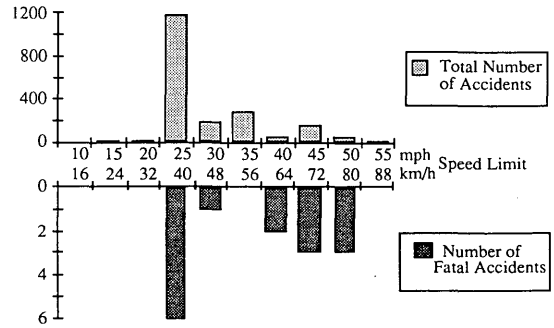

FIGURE 4 Speed limit on road where accident took place.

Accident Frequency and Speed Limit

A distinction must be made among frequency of accidents, rate of accidents, and severity of accidents. Figure 4 shows that the majority of accidents happen on roads with speed limits of 40 km/hr (25 mph) or less. This does not mean that roads with lower speed limits are less safe than others, but that the majority of biking takes place on urban streets with low speed limits. Consequently, to reduce the number of accidents, measures aimed at increasing the safety on these streets are necessary. However, the most serious accidents typically occur on roads with relatively high speed limits. Half the fatalities occurred on roads with a speed limit of 64 km/hr (40 mph) or higher.

Accident Severity and Speed Limit

Figure 5 shows the likelihood of a reported accident's ending up as a fatality. The "most likely ratio" is calculated as the recorded number of fatal accidents for a given speed limit divided by the recorded total number of accidents for that speed limit. The high

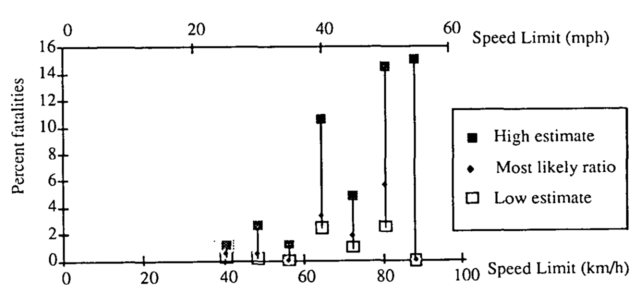

FIGURE 5 Number of fatal bicycle accidents per reported accident for different speed limits.

and low estimates are the maximum and minimum ratios that can reasonably be obtained, assuming that the observed numbers follow a Poisson distribution around true means. There is a 5 percent risk that the true ratio is lower than the low estimate, and a 5 percent risk that it is higher than the high estimate. As can be seen, the likelihood of a fatality is much higher for accidents on roads with speed limits above 56 km/hr (35 mph) than on those that have lower speed limits. The χ^2-test gives a statistically significant difference ($p < 0.1$ percent).

Furthermore, accidents may be less likely to be reported on low-speed roads since the bicyclist may not be injured at all. Therefore, the true ratio of fatalities to accidents in reality may increase even more with increased speed.

Vehicle Volume

Most accidents happening between intersections were reported on low- and medium-volume roads. Only 3 percent were recorded on roads with average annual daily traffic (AADT) above 25,000 and 45 percent where AADT was above 5,000; 16 percent happened on roads with AADT less than 500 and 37 percent with AADT less than 2,000. It may seem surprising that low volume is not a guarantee of safety on roadway sections. Bicycle counts have not been taken. This means that there can only be speculation as to the risk per cyclist on a busy road versus that on a residential street with very low vehicle volumes. European research reveals no strong correlation between the number of accidents per mile cycled and motor vehicle volume (*4,6*). These studies show that the risk—measured as bicycle accidents per mile ridden—may even decrease with increasing vehicle volume. At least four factors may help explain this paradox: (*a*) bicyclists become more careful when they ride on high-volume roads, (*b*) less skilled bicyclists do not attempt to ride on high-volume roads, (*c*) high volumes may keep motor vehicle speeds low, and (*d*) high-volume roads may have wide lanes and better overall design to accommodate motor vehicles and bicycles. It should be noted that intersection accidents are not included in this discussion.

One reason so many accidents happen on low-volume roads is that these typically are local access roads on which children are allowed to ride. The upper part of Figure 6 shows the relationship between the age of bicyclist involved and motor vehicle volume for accidents occurring away from intersections. This confirms that young children have most of their accidents on low-volume roads, whereas teenagers and adults have accidents on somewhat busier roads as well as on the ones with the lowest volumes. There is a very distinct peak around 15,000 to 20,000 vehicles a day for teenagers, indicating that this age group may have difficulties coping with such heavy flows (about one vehicle every other second during the peak hour). The reason that there are fewer accidents reported on roads with 20,000 vehicles per day and up is probably that there are not many roads in Maine with those traffic volumes.

A similar analysis including age of the injured bicyclist was made for intersection accidents (see lower part of Figure 6). Again the tendency for young bicyclists to be injured at low-volume intersections—where they are allowed to ride—may be seen, whereas teenagers and adults have more accidents at higher-volume intersections.

Width of Road

Most bicycle accidents between intersections happen on two-lane roads. Only 7 percent of them are reported on roads with more than two lanes. This does not show that multilane roads are safe, since most bicycling takes place on two-lane roads.

A question to ask is, "How much safer is a road with shoulders versus one lacking shoulders?" This question cannot be answered without access to bicycle counts. What can be determined is that half (51 percent) of all links with bicycle accidents lack shoulders completely, and 54 percent lack a shoulder on the right side. Only 13 percent of the roads had a right shoulder of 6 ft (1.8 m) or more.

Roadway Construction and Maintenance

In only 1 percent of the accidents was it noted that there was roadway construction going on. In less than one-fourth of a percent did the accidents take place in a maintenance area or utility work area.

Other Contributing Factors

Weather and Road Surface Conditions

Most accidents happen in clear weather on dry roads. Only 12 of the 2,059 accidents took place on icy or snow-covered roads. This,

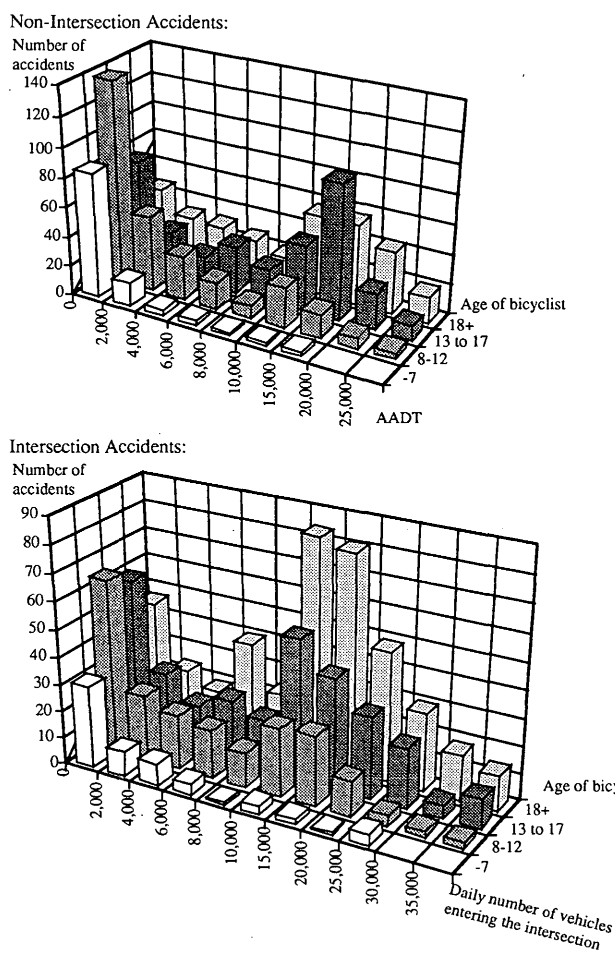

FIGURE 6 Bicycle accidents in Maine by age and vehicle volume.

of course, reflects the fact that very few bicyclists ride in bad weather or on snow-covered or icy roads. Six percent of the accidents happened during rainfall.

Light Conditions

Most accidents happen in daylight (83 percent) or at dawn or dusk (8 percent). Of those that happen when it is dark, over 80 percent happen on streets with street lights lit. The quality of this lighting may vary, however.

CONCLUSIONS AND RECOMMENDATIONS

The results show that a typical bicycle casualty in Maine is a 13-year-old boy riding his bicycle straight across a low-volume road and colliding with a four-door passenger car driven by a young male at around four o'clock on a sunny afternoon in early August.

Even though Maine is a fairly rural state, two out of three bicycle accidents are reported in urban areas. Nevertheless, the majority of the fatal accidents occurred in rural areas.

Fatalities are typically caused by head injuries. Increased use of helmets should therefore be a primary short-term safety goal.

One relationship clearly demonstrated is that the number of serious accidents increases significantly with higher speed limits.

According to the police reports, the vehicle driver involved in a bicycle accident has most commonly not violated any formal rule of the road. However, the driver may still have failed to detect the cyclist or to "use utmost care." The bicyclist commonly has violated a formal law, at least in the eyes of the police officer. There may be many reasons for this: lack of knowledge, youth or inexperience, and disrespect for regulations. Bicyclist training and information could influence a high percentage of the accidents (up to 80 percent). Increased enforcement could also reduce the accident number, but probably not as dramatically as education. Enforcement has to focus on relevant problems. For example, lack of nighttime equipment is not a major contributor to the accidents since less than 9 percent of the accidents happen when it is dark and only 1 percent of the accidents happen in darkness on streets lacking street lights or having the lights off. Teaching riders to observe traffic control devices, to yield the right-of-way, and always to ride on the right side of the road with the flow of the traffic is probably best achieved through a combination of education and enforcement. Not all violations can be eliminated with either of these methods. Everyone has at some time violated a highway code by mistake. It is human to miss a sign, even to run a red light once every few years. There will always be motorists and bicyclists making mistakes no matter how well trained they are and irrespective of how efficiently enforcement patrols work. Therefore, if the goal is the ultimate safety level, other measures have to be used as well, including engineering measures. Bicyclists are one of the most unprotected road-user categories, even if they wear helmets. Separated bike paths can be used to create a safer riding environment. Most fatal bicycle accidents are caused by collisions with automobiles. Separating cars and bicyclists also lets the biker breathe somewhat fresher air, which is another important aspect of public health. The question is how much can be spent in order to safeguard the small but growing number of bicyclists.

Realistically, total separation cannot be achieved, and many bicyclists may prefer the greater mobility offered on the existing road network. (Locally, for example, in Davis, California, the bicycle roads are spaced closer together than streets open to motorists, but this will remain the exception rather than the rule.) Mixed environments can, however, be made relatively safe. The data clearly demonstrate that the risk of fatality decreases with a lower speed limit. A German study (*7*) shows that the probability of death for a pedestrian hit by a car is closely related to the collision speed of the passenger car. It gave the following relationships between collision speed and death probability: 20 km/hr (12 mph) ≈ 10 percent, 30 km/hr (19 mph) ≈ 20 percent, 50 km/hr (31 mph) ≈ 60 percent, 80 km/hr (50 mph) ≈ 98 percent. The data in this study do not indicate that Maine bicyclists should have a survival rate very different from that of German pedestrians.

There is usually a correlation between actual speed and speed limit, but it is not always possible to get a desired level of speed through posted speed limits alone. Complementary measures may have to be used to make residential streets safer for all age groups, including young children. One solution is to rebuild local streets so that different traffic categories can relate to each other under conditions appropriate for the weakest in the chain—the playing child. This concept started in the Netherlands with the *Woonerf*. Here sidewalks are eliminated and the whole roadway becomes the domain of the resident. Car drivers always have to yield to playing children and if necessary get out of the car and ask the child to move in order to proceed. The roadway is "furnished" in such a way that the maximum vehicle speed cannot exceed a fast walking speed. This concept spread to Denmark [*Stillevej*, designed for 30 km/hr (20 mph) maximum speed, and *Opholds og Legeområder*, for 15 km/hr (10 mph)]; to the rest of Scandinavia; and to Germany (*Verkehrsberuhigung*), translation of which produced the British term "traffic calming." These measures have also been tried, for example, in the state of Washington. These concepts form a good basis for reducing the risks on residential streets. Stop signs are also very effective devices for reducing speed (*8*). Traffic signals, on the other hand, do not reduce top traveling speeds. This probably has contributed to the fact that 35 percent of all bicycle accidents at four-leg intersections occurred at signalized locations.

Outside residential and downtown areas, traffic calming can typically not be used, but separation can be used. To be effective, intersections have to be separated as well (by tunnels or overpasses). Where this is not feasible, reliance on selective improvements to accommodate bicycles on roads open to motor vehicles has been necessary. The data indicate that measures to improve safety for adult cyclists should focus on high-volume intersections, because on roadways between intersections, volume is of less importance to adults. Teenagers, however, should have access to a bicycle road network connecting high schools, malls, and so on, with residential areas excluding roads with volumes of more than 10,000 vehicles a day.

The fatal accidents analyzed here involved 12 males of varying age and 2 adult females. Both women lost their balance and fell onto the roadway in front of vehicles. The typical male accident involved a high degree of risk taking (e.g., riding at a high speed across a road from a blind driveway) rather than lack of skill. It is hard to generalize from such small numbers, but to reduce the number of similar accidents through education, the education should not focus on technical aspects of how to handle a bike but on a form of defensive driving—not to take risks when crossing a street, to assume that there will be a car coming and that the driver does not see you. How to reach bicyclists with this information is important. Children can be reached through school, and this is already being done in Maine. Eventually everybody could be reached this way, and it is hoped that the knowledge would stay with the person through old age. Nevertheless, could the process be speeded up by aiming campaigns toward adult bicyclists? Adult bicyclists are probably harder to influence because their habits are more set. Are television and radio commercials effective? Can adults effectively be reached when renewing their driver's licenses? Only in one case was it known that the bicyclist killed had a valid license. In at least two cases, the fatally injured bicyclist lacked a valid license (ages 19 and 22). One bicyclist had a police record including eight violations for operating motor vehicles without a valid license, failure to report an accident, and speeding. In four cases it was unknown whether the bicyclist had a license or not. In the remaining seven cases the bicyclist was below the age of 17.

A main conclusion of this study is that bicycle exposure data are lacking in the state of Maine. A risk analysis should typically be based on expected accident rates. The denominator for calculating this rate should be the number of road users or number of miles traveled. To estimate bicyclists' risk with respect to a given factor, it is necessary therefore to know the number of cyclists living in the area, the number passing the location, or the number of miles ridden along the section. Statewide bicycle counts are just now being initiated. This means that several essential risk estimates cannot yet be calculated. This analysis should be followed with a more comprehensive study once results from these bicycle counts are available.

During the writing of this paper, several serious accidents involving bicyclists occurred in the area. Educating motorists would probably have been the most efficient measure for avoiding these accidents. Reading police reports forces the conclusion that most often the bicycle rider is at fault, so teaching bicyclists to comply with the rules becomes the obvious first thought. Education and training probably should be directed at both bicyclists and motorists. Motorists need to be reminded that bicyclists have the legal right to operate on the public roadway and that they have essentially the same rights and responsibilities as other vehicle operators. Motorists should also be reminded to actively search for bicyclists in the traffic environment.

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Publication of this paper sponsored by Committee on Bicycling and Bicycle Facilities.

PART 2

Pedestrians and Pedestrian Facilities

Evaluation of Pedestrian Facilities: Beyond the Level-of-Service Concept

C. JOTIN KHISTY

For designing and evaluating pedestrian facilities, the 1985 *Highway Capacity Manual* (HCM) provides guidelines similar to those for vehicular flow, using the concept of level of service. It also recommends that additional environmental factors that contribute to the walking experience and therefore to the perceived level of service, such as comfort, convenience, safety, security, and attractiveness, also be considered. However, no guidelines are given on how to measure or use these environmental factors for designing and assessing pedestrian facilities. There is no question that environmental factors are of paramount importance for designing and assessing such facilities, because pedestrians, unlike motor vehicles, have practically no control over most of these factors. A practical method of assessing pedestrian facilities is described that takes into account several environmental factors observed by independent groups who are familiar with the situation being assessed. Assessment of the environmental factors is accomplished through suitable performance measures, and these in turn provide the operating characteristics and the qualitative level of service of the facility being assessed as perceived by its users. This qualitative level of service can then supplement the quantitative level of service of the facility on the basis of flow, speed, and density units, as described in the HCM. The methodology described can be most useful in monitoring and comparing the performance of such facilities as well as in allocating the budget for changes and improvements. A practical application of the methodology is described using seven performance measures: attractiveness, comfort, convenience, safety, security, system coherence, and system continuity. The methodology is quick, easy, and inexpensive to use.

Traffic standards for pedestrian facilities have been developed over the last 20 years by several researchers on the basis of empirical studies of pedestrian movement. These standards define flow relationships in terms of various speed levels and average personal space, classified into various levels of service, ranging from Level-of-Service (LOS) A to F, with LOS A representing the threshold of unimpeded free flow (considered the best) and F at critical density or breakdown of movement continuity (considered the worst). The level of service determined in this way can be considered as the quantitative one.

The LOS concept was first developed by traffic engineers for vehicular capacity studies connected with street and highway design. It is a powerful quantitative tool for planning, designing, and assessing transportation facilities serving vehicular movement. It was therefore not surprising that engineers and planners adopted the LOS concept for designing pedestrian facilities also. Pedestrian capacity analysis is a relatively new area of study, beginning with Fruin's Pedestrian Planning and Design in 1971 (*1*). In recent years the 1985 *Highway Capacity Manual* (HCM) has provided guidelines for designing walkways, crosswalks, and street corners using the LOS concept (*2*).

The HCM acknowledges that pedestrian facilities are far more complex to design as compared with vehicle facilities, although the LOS concept is used in both cases. Although the quantitative measures of flow, density, and speed affect such convenience factors as the ability to select walking speeds, bypass slower pedestrians, and avoid conflicts, the HCM makes it abundantly clear that additional environmental factors, such as comfort, convenience, safety, security, and the economy of the walking system, should be taken into account because these factors contribute to the walking experience and ultimately to the perceived level of service. However, no guidelines are given on how to measure or make use of these environmental factors in designing or assessing pedestrian facilities.

These environmental factors can have an important effect on a pedestrian's perception of the overall quality of the street environment. Whereas automobile drivers sitting comfortably in their vehicles have reasonable control over most of these factors mentioned, pedestrians, without the protection of the metal shell, have virtually no control. It is for this reason that the qualitative environmental factors appear to be as important as the quantitative flow, speed, and density factors in planning, designing, and evaluating pedestrian facilities. A practical method of taking into account environmental factors, and thus determining the qualitative level of service of a facility, is described on an individual link-by-link basis or at an overall systems level. Examples showing how the methodology is applied in a real-world situation are provided. It may be noted that it is not the intent of this paper to convey the notion that the qualitative level of service as described in this paper is a substitute for the quantitative LOS as explained in the HCM. On the contrary, both the quantitative and the qualitative levels of service clearly supplement each other.

COMPLEXITY OF ASSESSING PEDESTRIAN MOVEMENT

The deceptive simplicity of pedestrian movement on such facilities as streets, highways, malls, stairs, and ramps has led many reserchers to concentrate their attention almost exclusively on the flow-speed-density relationship for designing and evaluating pedestrian facilities. Several other researchers, mostly from the social sciences, have since identified major concerns with this practice of treating humans as vehicular units. Hill provides a comprehensive survey of the results of these investigations (*3*).

A particularly interesting conceptualization of pedestrian movement is presented by Goffman (*4*). He observes that vehicles using highways and streets are distinguished by the strength and thickness of their outer metal shells. Viewed in contrast, the pedestrian moving across and along streets is encased in a soft and exposed "shell," namely, his or her clothes and skin, and is thus amazingly vulnerable to injury and possible death. However, despite

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the fact that pedestrians are often forced to share the road with motor vehicles, they possess some characteristics that are truly unique. Goffman notes that "pedestrians can twist, duck, bend and turn sharply and therefore, unlike motorists, can safely count on being able to extricate themselves in the last few milliseconds before impending impact." Should two pedestrians collide, he continues, damage is not likely to be significant, whereas collision between a pedestrian and a car is most likely to result in instant death.

The bottom line is that the built environment can be considered to consist of interrelated geographic, social, and cultural components that afford certain behaviors in consistent ways. Indeed, there is an invitational quality about a well-designed pedestrian facility, the characteristics of which go far beyond the flow-speed-density measurements. Saarinen (*5*) suggests that some facilities that form part of the built environment, such as freeways and railroad tracks, are designed more for the successful functioning of vehicles than for people. In contrast, factors such as convenience and comfort are paramount when malls, sidewalks, elevators, stairs, and transit stations are designed. He labels the former facilities as "anthropozemic" and the latter "anthropophilic." In anthropozemic settings, people and the vehicles they use have to adapt to the built, sterile, and nonhuman conditions provided; in anthropophilic settings, the built environment has to be designed to adapt to the needs of human beings. Figure 1 supports the reason why the design and evaluation of pedestrian facilities cannot be performed in the same manner as that for freeways or pipelines (*6*).

METHODOLOGY

As has been noted, the level of service is the overall measure of all service characteristics that affect users of a system. The HCM provides guidelines for evaluating level of service, based primarily on performance elements, such as flow, speed, and density. In addition it is necessary, as pointed out before, that qualitative elements, such as attractiveness, comfort, convenience, security, and safety, be taken into account. The combined effects of these two categories of performance measures—the quantitative and the qualitative—contribute to the level of service of a particular facility.

An evaluation methodology is developed for the assessment of the qualitative elements of facilities used by pedestrians by independent observers familiar with the situation. These facilities include those used exclusively by pedestrians as well as those used jointly with other modes of transportation, that is, Regions 2 and 3 in Figure 1.

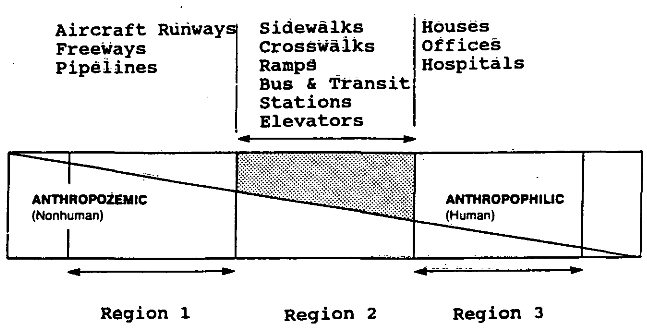

FIGURE 1 Anthropozemic and anthropophilic transportation facilities.

The basic input to the task of selecting potential performance measures (PMs) for assessing the environmental factors was derived from a literature review of traffic engineering and environmental psychology. Nearly 20 different PMs were extracted from this review and reduced by elmination (on the basis of duplication, relevance, and data availability) to 7. They are, in alphabetical order, attractiveness, comfort, convenience, safety, security, system coherence, and system continuity. The next two tasks were (*a*) to describe as accurately as possible what each PM represented and to measure them on a scale of A through F, with A representing the best and F the worst, and (*b*) to apply a weighting factor methodology that would rank order the perceived importance of the PMs for use in evaluation (*7*).

Performance Measures

A brief description of the seven PMs follows:

1. *Attractiveness*: This PM encompasses much more than aesthetic design. The PM goes far beyond the manifest or instrumental functions of safety, convenience, and comfort by considering latent functions, such as pleasure, delight, interest, and exploration.
2. *Comfort*: Such factors as weather protection, climate control, properly designed shelters, condition of walking surface, cleanliness of terminals, and provision of adequate seating arrangements can be considered to provide comfort. One could even include such factors as odor, ventilation, noise, vibration, and crowding.
3. *Convenience*: Walking distances connected with attributes such as pathway directness, grades, sidewalk ramp locations, directional signing, activity maps and directories, convenient connections between frequently used locations, and other features making walking easy and uncomplicated are qualities of convenience. Sidewalk obstructions and circuitous trip linkages are considered a source of inconvenience to pedestrians. Properly ramped curb cuts for the handicapped and tactile trails for the blind are considered assets.
4. *Safety*: The reduction of pedestrian-vehicle conflicts can be considered a basic factor promoting safety. Ease of movement in walking, even in vehicle-free areas such as malls, passageways, sidewalks, stairs, elevators, ramps, and escalators, is considered part of safety. Particularly in heavily trafficked street networks, the provision of properly designed control devices, providing adequate time and space separation from vehicular movement is an essential part of safety.
5. *Security*: The ability to provide pedestrian facilities that provide clear observation by the public and the police through unobstructed lines of sight, good lighting, absence of concealed areas, and television surveillance is considered a measure of good performance. The pedestrian should feel reasonably safe and secure, commensurate with the neighborhood and level of street activity prevailing.
6. *System Coherence*: Mental imagery and selectivity play a major role in perceiving and understanding the world of time and space. For instance, an able-bodied pedestrian using an unfamiliar street system would generally be looking impatiently for primary orientation and direction in reaching his or her destination rather

than admiring the aesthetics of the setting, particularly if it was getting dark and the street lighting was not adequate. There is a strong correlation between activity systems and the cognitive images people have of the physical environment. Distortion in imagery reflects and affects the perceptions people have of such things as the location of shops, parks, and other facilities. Even the perception of the distance of facilities is affected by such things as the geometry of paths. A path that is circuitous or full of junctions is perceived to be longer than one of the same length that is straight.

7. *System Continuity*: A well-designed pedestrian system may have all the attributes alluded to in the PMs mentioned earlier but lack an essential feature of continuity and connectivity. Continuity is particularly important for multimodal facilities connected to pedestrian paths that unify the system efficiently.

The next step was to prioritize the seven PMs and to assign weights to each. This was done by applying a weighting-factor methodology.

Weighting Factors

The constant-sum, paired-comparison method is a systematic approach for determining the relative importance of each of a large number of factors, using group consensus. Thus, not only is a ranking of factors by importance obtained, but also the relative importance or weight of each factor with respect to all other factors is found. As an example, Figure 2 shows a simple matrix that indicates all possible pair comparisons (A versus B, A versus C, A versus D, B versus A, and so on). Each respondent is asked to distribute a constant bundle of values (in this case, 10) between each pair of factors. If a respondent believes that Factor A is far more important than Factor B, a score of 10 for Factor A and a score of 0 for Factor B are noted in the cell (Row 1, Column 2). If, on the other hand, the respondent believes that Factor A is about equal to Factor C, the score would be 5 for A and 5 for C (Row 1, Column 3). The bottom left portion of the matrix is simply the mirror image of the top right portion.

The scores for the factors listed on the left side of the matrix are then summed for each row (e.g., the bottom portion of row A is 10 + 5 + 6 = 21). The sum of rows is taken (21 + 5 + 18 + 16 = 60) and used to normalize each of the row sums as shown in Figure 2. For a group response, the mean and standard deviations of the values may be determined to obtain the consensus or profile of the group. In this hypothetical case, Factors A, C, D, and B carry weights of 0.4, 0.35, 0.20, and 0.15, respectively, in descending order of importance. The mean and standard deviation of the group response can be plotted as shown in Figure 3, which provides a feel for the group's priorities.

APPLICATION OF METHODOLOGY

The Illinois Institute of Technology (IIT) campus was chosen as the setting for applying the methodology described in the previous section because the campus provides some interesting features. The 120-acre main campus is located in Chicago, about 3 mi south of the Downtown Loop, and is accessible by car and by public transportation (bus and train). The master plan of the main campus and the architecture of many of its 50 buildings were developed by Ludwig Mies van der Rohe, one of the century's most influential architects and city planners, and for 20 years the chairman of IIT's Department of Architecture. The bulk of the campus is located between 31st and 35th streets, running east to west, and between the Metra rail lines and Michigan Avenue, running north-south. South State Street, a four-lane divided highway running north to south, cuts the campus into two halves, with the parking lots located in the western half. The average daily traffic throughout the day is moderate except during the morning and evening peak hours. Six hundred survey forms were distributed to students, staff, and faculty during the spring and early summer of 1993 to apply the constant-sum, paired-comparison methodology, as described next.

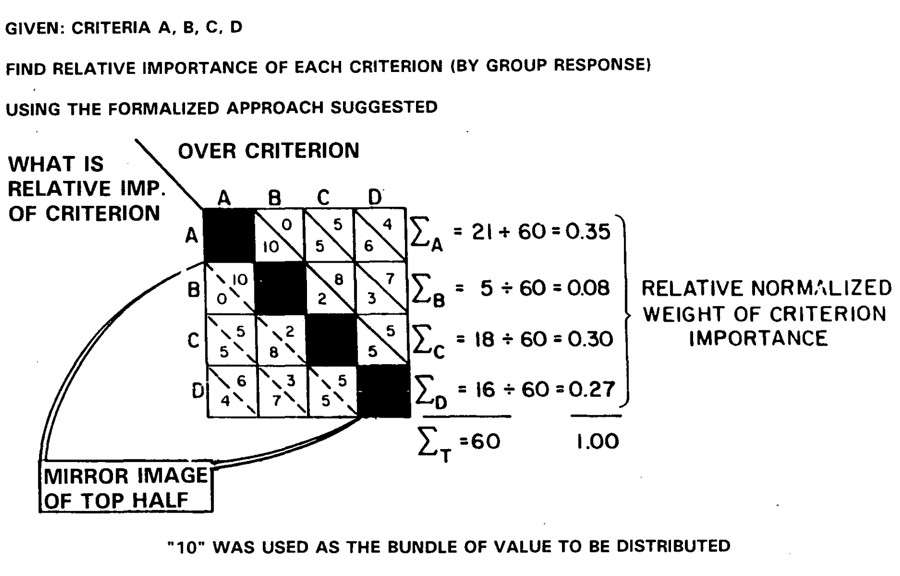

FIGURE 2 Sample calculation of constant-sum, paired-comparison method.

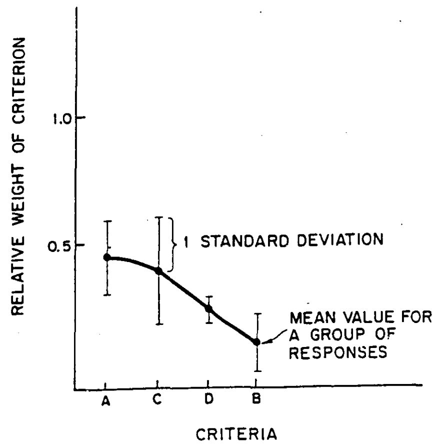

FIGURE 3 Conceptual plot of group of respondents.

RESULTS

Before applying the weighting-factor methodology, it was necessary to measure the seven PMs on a 5-point scale from LOS A = 5 (the best) to LOS F = 0 (the worst), as shown in Table 1. On the basis of a preliminary survey, this type of scaling and assignment of points not only coincided with the setup of having six levels of service as used in the HCM, but also seemed to be a pragmatic way of measuring the feeling of satisfaction or dissatisfaction expressed by the public while using the facility in question.

The application of the constant-sum, paired-comparison methodology to the seven selected PMs was taken up next and yielded the results shown in Table 2, which were based on responses from 320 valid survey forms received from the 600 distributed regular users of the IIT pedestrian system. An examination of the ranking and weighting indicated that the results were logical and consistent with the perceived values of the population. It is, of course, possible to do a more extensive survey on a broader systemwide basis and revise the weights and ranking as deemed necessary.

The results of the survey provided the level of service for 15 different routes and segments of routes on the IIT campus. For the purposes of this paper, however, the results for only two routes are given. The first results are for the path from the western half of the campus to the eastern half of the campus, where the parking lots are located. Although the security aspect of the lots is more than adequate (with the provision of police surveillance and well-lighted paths), users have to cross a four-lane divided street, with moderate traffic during most of the day, but with no pedestrian signals or markings. Particularly during inclement weather, the use of this route is unsatisfactory, because the vibration and intense noise of frequent trains on the elevated tracks just above the parking lots are most disconcerting. Also, the puddles of water on the street as well as in the parking lots are bad. The overall grand total score of 2.32 as shown in Table 3 truly reflects LOS D.

The second route results were for the sidewalks on the main campus, which are very well maintained and on which walking is a pleasure. Security may be a problem after dusk, but police surveillance is adequate for the most part. A total score of 4.35 as indicated in Table 4 shows that the level of service is better than B.

A summary of the procedure developed and applied is as follows:

Step 1: Choose a set of PMs with the help of a committee of people familiar with the site under investigation. It does not matter at this stage if the set is large; 7 to 10 is a reasonable number.

Step 2: Apply the constant-sum, paired-comparison method to determine the relative weight of each factor. For a group response, determine the size of the group by applying standard statistical methods. Determine the mean and standard deviation of the PMs.

TABLE 1 Measurement of PMs on 5-Point Scale

LOS A	greater or equal to	85% satisfied	= 5 points
LOS B	greater or equal to	60% satisfied	= 4 points
LOS C	greater or equal to	45% satisfied	= 3 points
LOS D	greater or equal to	30% satisfied	= 2 points
LOS E	greater or equal to	15% satisfied	= 1 point
LOS E	less than	15% satisfied	= 0 points

TABLE 2 Rank and Weight of PMs

Rank	Performance Measure	Mean	Std Dev	% Wt:
1	Security	0.354	0.120	35
2	Safety	0.241	0.108	24
3	Comfort	0.101	0.032	10
4	Convenience	0.092	0.049	9
5	Attractiveness	0.080	0.048	8
6	System Coherence	0.071	0.029	7
7	System Continuity	0.061	0.027	6
		1.000		100

TABLE 3 Route from IIT West Campus to Parking Lots on East Campus

Performance Measure	% Satisfied	LOS	Points	Wt	Total
Attractiveness	21	E	1	0.08	0.08
Comfort	22	E	1	0.10	0.10
Convenience	33	D	2	0.09	0.18
Safety	16	E	1	0.24	0.24
Security	61	B	4	0.35	0.35
System Coherence	42	D	2	0.07	0.14
System Continuity	48	C	3	0.06	0.18
		Grand total			2.32

The overall environmental LOS is slightly better than a D

Step 3: Examine the results of Step 2 and list candidate PMs by priority and weights. If necessary, reduce the number of PMs if any of the weights are too low in comparison with the ones with higher weights.

Step 4: Adopt a 5-point scale for the six levels of service.

Step 5: Choose routes (or segments of routes) that need to be evaluated, and administer a survey to persons who use the pedestrian system on a regular basis. On the basis of the percentage of respondents who are satisfied with the route (or segment of the route), (*a*) assign a level of service to each chosen PM, (*b*) assign a point value to each level of service (A = 5 through F = 0), (*c*) assign a weight to each PM from Step 3, (*d*) multiply the points by weights for each PM, (*e*) add the product of each PM to obtain a grand total, and (*f*) assign a level of service to this grand total.

USES, BENEFITS, AND CAVEATS

The evaluation of pedestrian facilities is now recognized as an important tool in improving the total transportation system. Used effectively, it can greatly enhance the efficiency and image of the system. Public involvement in selecting, priority ranking, and weighting PMs is a crucial part of the evaluation process, and therefore the potential uses and benefits of the methodology should be made known to those involved with the process.

There appear to be at least four primary applications of this methodology. First, the results can be used as a tool to guide decision makers in evaluating the quality of pedestrian facilities over and beyond the quantitative measures of flow, speed, and density, as elaborated in the HCM. Second, the results identify what can be considered an ideal route or benchmark with which other routes can be compared on the basis of either individual attributes or aggregate values. The third primary application is as a planning tool to develop future routes and overall perspectives for the system. The fourth application is for use in budgeting funds for route improvements. There are probably other uses as well.

The need for further refinement and verification of the research methodology described here is clearly indicated. The PMs must be used over a period of time to verify that they are methodologically appropriate and that the results they produce truly reflect the quality of pedestrian service being provided. The ranges of values proposed for the various measures must also be verified and refined, if needed.

It should be clearly understood that the level of service obtained by using PMs does not in any way invalidate the quantitative level of service calculated using the guidelines set forth in the HCM. In fact, the level of service obtained via the environmental factors and the PMs supplements the results obtained through the HCM.

TABLE 4 Sidewalks Anywhere on West Campus

Performance Measure	% satisfied	LOS	Points	Wt	Total
Attractiveness	83	B	4	0.08	0.32
Comfort	82	B	4	0.10	0.40
Convenience	95	A	5	0.09	0.45
Safety	90	A	5	0.24	1.20
Security	78	B	4	0.35	1.40
System Coherence	69	B	4	0.07	0.28
System Continuity	92	A	5	0.06	0.30

The overall total of 4.35 indicates that the LOS is better than a B

CONCLUSION

Major urban traffic generators produce considerable pedestrian activity and movement, and therefore an important factor is the planning, designing, operating, and evaluating of transportation systems. The HCM provides guidance in designing and evaluating pedestrian facilities based only on quantitative measures of pedestrian flow, walking speed, and flow density, resulting in six levels of service, similar to those for vehicular flow. However, it recommends that additional environmental factors that contribute to the walking experience, and therefore to the perceived level of service, be considered, but does not spell out a methodology of how to do so. This paper discusses the need to consider environmental factors over and beyond the quantitative measures of level of service provided by the HCM, and then sets out a methodology for evaluating pedestrian facilities. The IIT campus is used as an example of how the methodology is applied in a real-world situation.

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Publication of this paper sponsored by Committee on Pedestrians.

Pedestrian Speed-Flow-Density Relationships

MARK R. VIRKLER AND SATHISH ELAYADATH

Understanding the relationships among pedestrian speed, flow, and density is essential for improving the design and operation of pedestrian facilities. Seven established models relating speed to density for vehicular flow were tested against a set of pedestrian data. The seven models were Greenshields (single-regime linear), May's bell-shaped curve, Underwood's transposed exponential curve, Greenberg's modified exponential curve, Edie's discontinuous exponential form, two-regime linear, and three-regime linear. The evaluation procedure closely follows that developed by Drake, Schofer, and May in 1967. The study site was near the entrance to a pedestrian tunnel that caused a single, extensive queue. The walkway portion closest to the tunnel had a capacity equal to or slightly greater than the tunnel. Pedestrian demand at the location increased from near zero to over capacity and then returned to near zero. Flow parameters were derived from videotape. The performance of each model is described both by the results of statistical tests and by visual examination of the flow-density-speed curves. The three-regime linear model was not found to be statistically significant. Of the three one-regime models, the bell-shaped was judged to be superior to the Greenshields and Underwood models because of its better predictions of optimum density and optimum speed. Of the three two-regime linear models, the Edie was judged best on the basis of statistical tests and predictions of flow parameters. Since two distinct regimes were found, the Edie model was deemed to be the best model for this data set.

A variety of mathematical relationships were examined to describe the relationships among speed, flow, and density in vehicular traffic flow. Pedestrian flow has usually been described by linear relationships between speed and density (*1–6*). At least one researcher has examined a multiregime linear model (*7*). A better understanding of the pedestrian speed-flow-density relationships can be useful to those involved in the design and operation of pedestrian facilities.

This study examined various means to describe pedestrian speed-flow-density relationships. Seven models often used to describe vehicular flow were tested against a pedestrian data set. The procedure closely follows that of Drake et al. for highway flow (*8*). The performance of each model is described by statistical tests and visual examination of the flow-density-speed curves.

SITE SELECTION AND DATA COLLECTION

A site providing data over the widest ranges of speed and density was desired. The site also had to provide an elevated point for video camera placement. The most desirable available site was a pedestrian tunnel entrance in Columbia, Missouri. Significant pedestrian volumes pass through the tunnel after University of Missouri football games, resulting in a single, extensive queue.

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The 30-m-long tunnel has a width of 8.5 m. The paved walkway approach narrows before entering the tunnel. The walkway portion closest to the tunnel was judged to have a capacity equal to or slightly greater than that of the tunnel itself.

The data were collected after a warm 1992 Saturday afternoon football game. The pedestrians had spent over 3 hr watching a narrow defeat of the home team. Pedestrian demand at the location increased from near zero to over capacity and then returned to near zero. A video camera was placed to view a 12-m length of the walkway, which narrows from 14 m to 8.5 m before the tunnel. The average widths of the four 3-m sections were 8.5, 10, 12, and 13 m.

Data were collected during 18.25 min of significant flow. Samples of speed were collected (using a stopwatch and the video image) over four 3-m lengths during 15-sec intervals. The 15-sec time span was deemed long enough to avoid unusual problems with extremely low or high flow characteristics but short enough to avoid a high percentage of time periods with varying flow characteristics within the time period. The number of pedestrians within each 3-m length was determined at the midpoint of each interval. Time mean speed was virtually identical to space mean speed because of the low variability of speed within each interval. Flow rate was derived from the product of speed and density. Data characteristics include the following:

Parameter	*Low*	*Mean*	*High*
Density (ped./m^2)	0.16	1.61	3.12
Speed (m/min)	11.5	37	73
Flow (ped./min/m of width)	9	46	75

Since the calibrated flow relationships were to use density as the independent variable, one potential problem was that some ranges of density were much more frequently represented than others. As expected, the least frequent density ranges were those near the likely critical density (*4*). To avoid biasing the regression analysis, a random sampling procedure similar to that described by Drake et al. (*8*) was used to provide equal representation from all density ranges. This procedure resulted in 15 data points for each 0.537-ped./m^2 increment of density, or 90 data points from the original 292.

ALTERNATIVE HYPOTHESES

The seven hypotheses relating speed to density examined by Drake et al. (*8*) for vehicles are examined here for pedestrians. The models are thoroughly described by Drake et al. Additional descriptions are available elsewhere (*1–4,9,10*).

DISCUSSION OF STATISTICAL ANALYSIS TECHNIQUES

The speed-density hypotheses were analyzed to verify the significance of the models and the ability of each model to predict the flow parameters. The procedure employed by Drake et al. (*8*), with some modifications, was used to compare the models.

Regression Analysis and Statistics

Linear regression was used to calibrate the models. Of the seven speed-density models, three were linear models and four were nonlinear models. Nonlinear models were reduced to linear forms using a transformation upon density or speed.

Discontinuous models were developed by minimizing the sum of squares about the regression line for each regime. The composite statistics for discontinuous regression were calculated by integrating the results of the separate regressions. For example, the single r^2-value for a multiregime model was based upon the total sum of squared errors from the mean speed of the entire sample and the sum of the residual errors in speed estimates.

Testing of Multiregime Hypotheses

Quandt (*11,12*) has recommended a maximum likelihood technique for estimating parameters of a linear regression system obeying two separate regimes. Quandt's technique, with some extensions developed by Drake et al. (*8*), is used here.

Other Statistical Tests

The t-test was employed to identify nonzero slopes. Significance of the entire regression was based upon F-values for the ratio of regression mean square to residual mean square.

ANALYSIS OF RESULTS

Break-Point Analysis

Quandt's break-point analysis (*8,11,12*) was performed for the four discontinuous hypotheses. The three two-regime models were investigated for 11 break points. The likelihood functions for the Edie and Greenberg hypotheses showed only one local peak and indicated a break point at density 1.075 ped/m^2. The two-regime linear hypothesis showed three local peaks and indicated a break point of 1.881 ped/m^2.

The three-regime model required analysis of 54 combinations of break points. The optimal break points were 1.075 and 2.15 ped/m^2.

Tests for Distinctly Separate Regimes

Test results for distinctly separate regimes are given in Table 1. F-tests were employed to investigate the existence of multiregimes. In the three-regime linear model, the two higher-density lines did not appear to be statistically different at the 95 percent confidence level. All the other models (the three two-regime models) showed significant differences between regimes.

Tests for Nonzero Slope and Entire Regression

The t-test (Table 2) indicated that all slopes were different from zero at the 0.05 level of significance. However, at the 0.01 level, the free flow regime of the three-regime linear model and the free flow regime of the Edie model were not shown to have slopes different from zero. All models showed high significance for the entire regression (F-test in Table 2).

INTERPRETATION

Results of the statistical tests must be tempered with judgment based upon knowledge from previous studies and from the data of this study. The results of the regression analyses are shown in Table 2. Flow parameters for each calibrated model are in Table 3, along with the authors' judgment of the probable ranges indicated by the data. The field data are shown against the flow models in Figures 1 through 7.

TABLE 1 Results of F-test for Distinctly Separate Regimes

	Test Parameters		
Hypothesis	Test	Calculated F	F-critical (α=0.05)
Greenberg	1 on 2	14.01	1.73
	2 on 1	37.44	1.74
Edie	1 on 2	2.46	1.65
	2 on 1	34.44	1.74
2-regime linear	1 on 2	3658	1.73
	2 on 1	26.43	1.74
3-regime linear	1 on 2	2.662	1.90
	2 on 1	8.533	1.88
	2 on 3	[a]1.745	1.90
	3 on 2	15.36	1.91

[a]2nd and 3rd lines of the 3-regime model do not differ from one single line at α=0.05. In all other hypotheses, all tests reveal significant differences indicating that separate regimes exist.

TABLE 2 Regression Analysis Summary

Hypothesis	Equation	Regression Parameters r^2	S_e	^a^F-Test Value	^b^t value for non zero slope	Signif. Diff. between regimes
Greenshields	S=63.97-17.12D	0.84	7.0	453	21.3	N.A.
Bell shape	S=55.6e^(-0.162D^2)	0.84	6.9	473	26.2	N.A.
Underwood	S=75.17e^(-D/4.166)	0.79	8.0	323	23.6	N.A.
Greenberg	S=58	0.83	7.1	439	N.A.	
	[D<1.07]					YES
	S=36.78ln(4.32/D)				20.1	
	[D≥1.07]					
Edie	S=60.83e^(-D/4,166)	0.84	6.8	474	1.8	
	[D<1.07]					YES
	S=36.78ln(4.32/D)				21.1	
	[D≥1.07]					
2-regime	S=62.81-15.34D	0.84	6.8	478	7.0	
linear	[D<0.188]					YES
	S=50.37-12.15D				7.6	
	[D≥0.188]					
3-regime	S=60.91-11.94D	0.85	6.7	499	1.8	
linear	[D<1.07]					NO
	S=72.06-21.53D				6.8	
	[1.07≤D<2.15]					YES
	S=40.35-8.56D				4.4	
	[D≥2.15]					

^a^$F_{critical} = 6.97$ at $\alpha = 0.99$; $F_{critical} = 4.01$ at $\alpha = 0.95$

^b^$t_{critical} = 2.37$ at $\alpha = 0.99$; $t_{critical} = 1.66$ at $\alpha = 0.95$

Statistical Test Results

The results of the statistical tests can be summarized as follows.

1. All models satisfied the tests for significance of the entire regression.
2. All models satisfied tests for slopes different from zero at the 0.05 level of significance.
3. The three-regime linear model failed the test for three distinctly separate regimes.
4. The three two-regime models were each shown to identify separate regimes.
5. In each two-regime model there was a significant difference in standard error between the two regimes. The standard error was approximately 2.6 times larger in the free-flow regime than in the congested-flow regime.
6. The overall standard errors of the speed estimates ranged from 6.7 to 8.0 m/min. Excluding the Underwood model, the standard errors were in a narrow range from 6.7 to 7.1 m/min.
7. The r^2-values for the seven models ranged from 0.79 to 0.85. Excluding the Underwood model, the r^2-values were in a narrow range from 0.83 to 0.85.

Flow Parameter Results

A comparison of the model parameters with the field data and *Highway Capacity Manual* (HCM) parameters is presented below.

TABLE 3 Flow Parameter Summary

Hypothesis	Flow Parameters: Free flow speed, S_f (m/min)	Jam Density, D_j (ped/m^2)	Optimum Density, D_o (ped/m^2)	Optimum Speed, S_o (m/min)	Capacity (ped/m/min)
Data Set (subjective)	52-70	-	1.3-1.8	34-49	62-72
Greenshields	64	3.73	1.87	32	59
Bell shape	56	-	1.75	34	59
Underwood	54	-	1.89	28	52
Greenberg	54	4.32	1.59	37	59
Edie	61	4.32	1.59	37	59
2-regime linear	63	4.13	1.88	32	66
3-regime linear	61	4.71	1.68	37	62

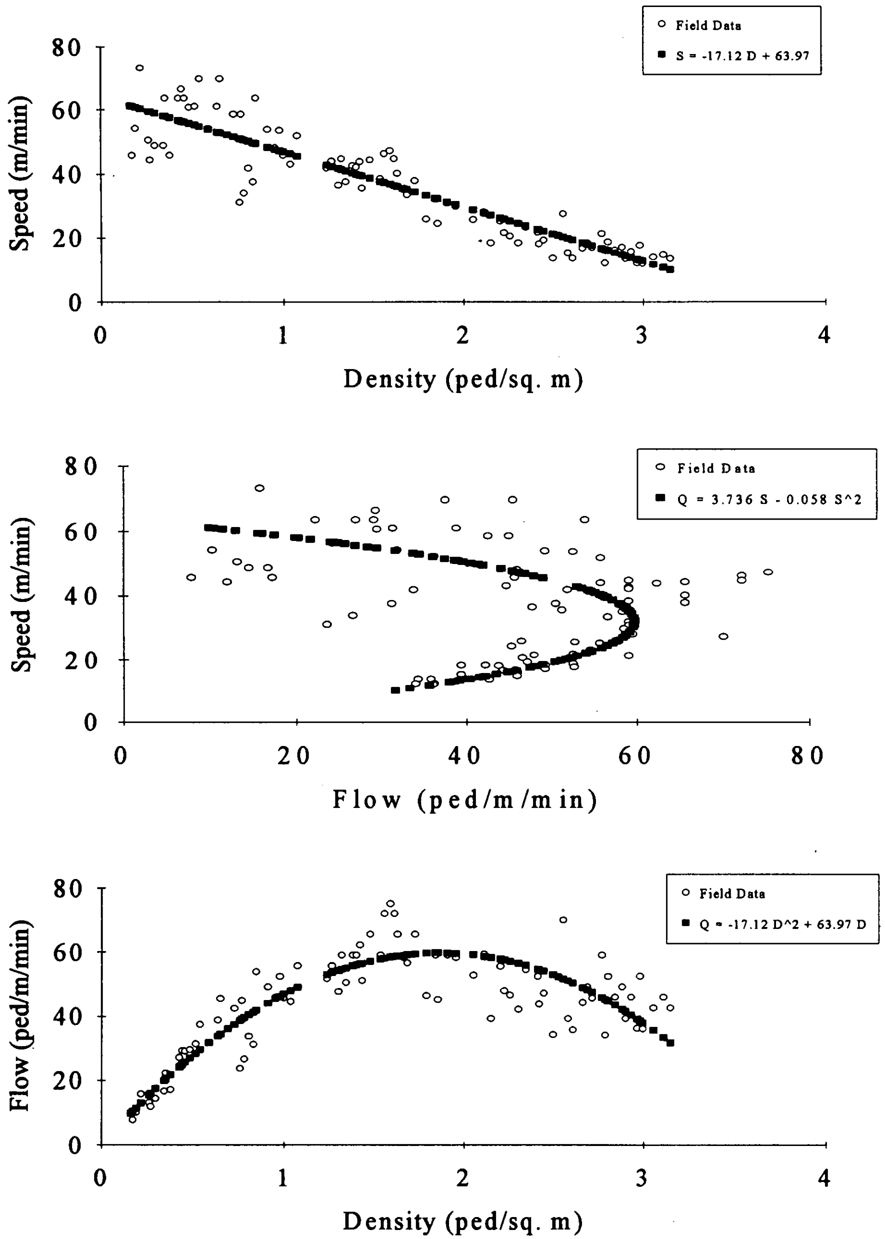

FIGURE 1 **Speed-density-flow plots for one-regime linear model.**

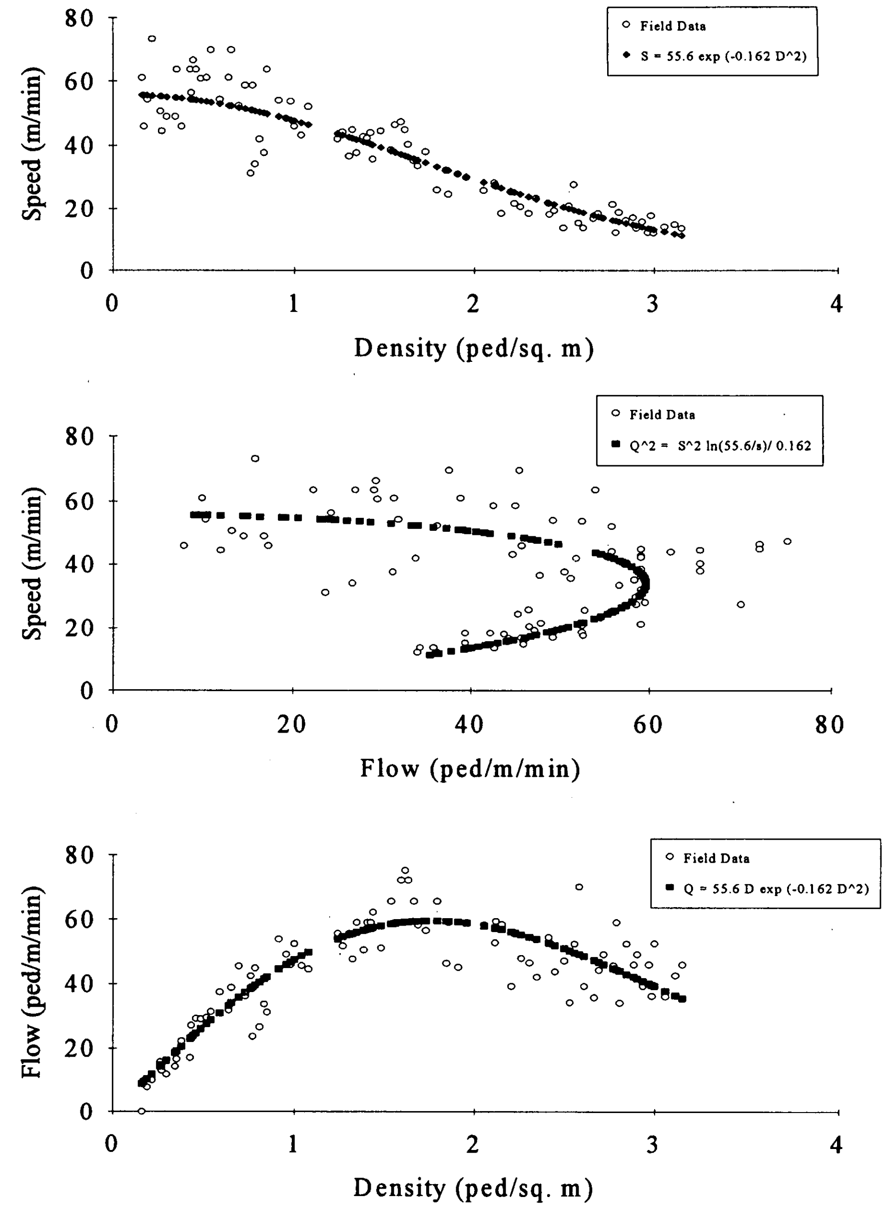

FIGURE 2 **Speed-density-flow plots for May's bell-shaped model.**

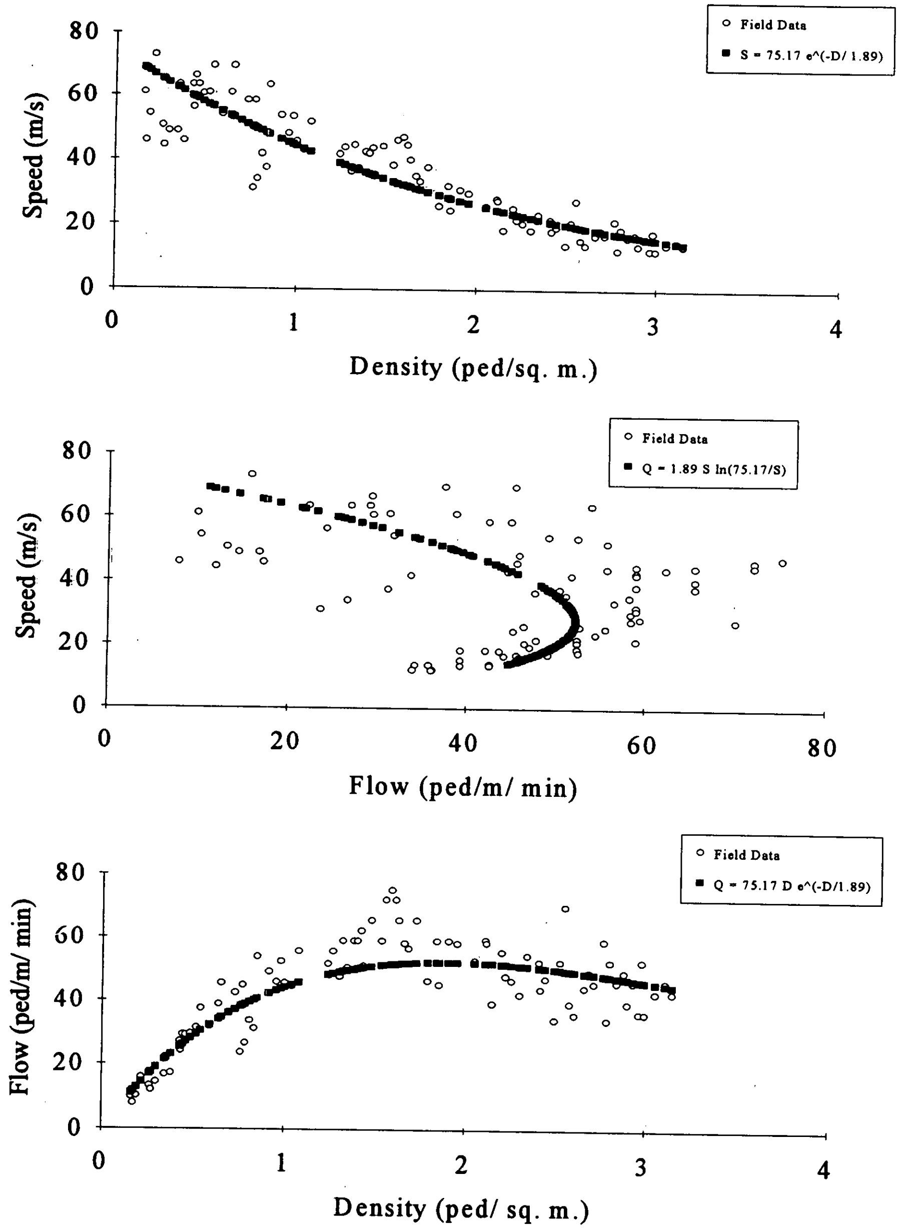

FIGURE 3 Speed-density-flow plots for Underwood model.

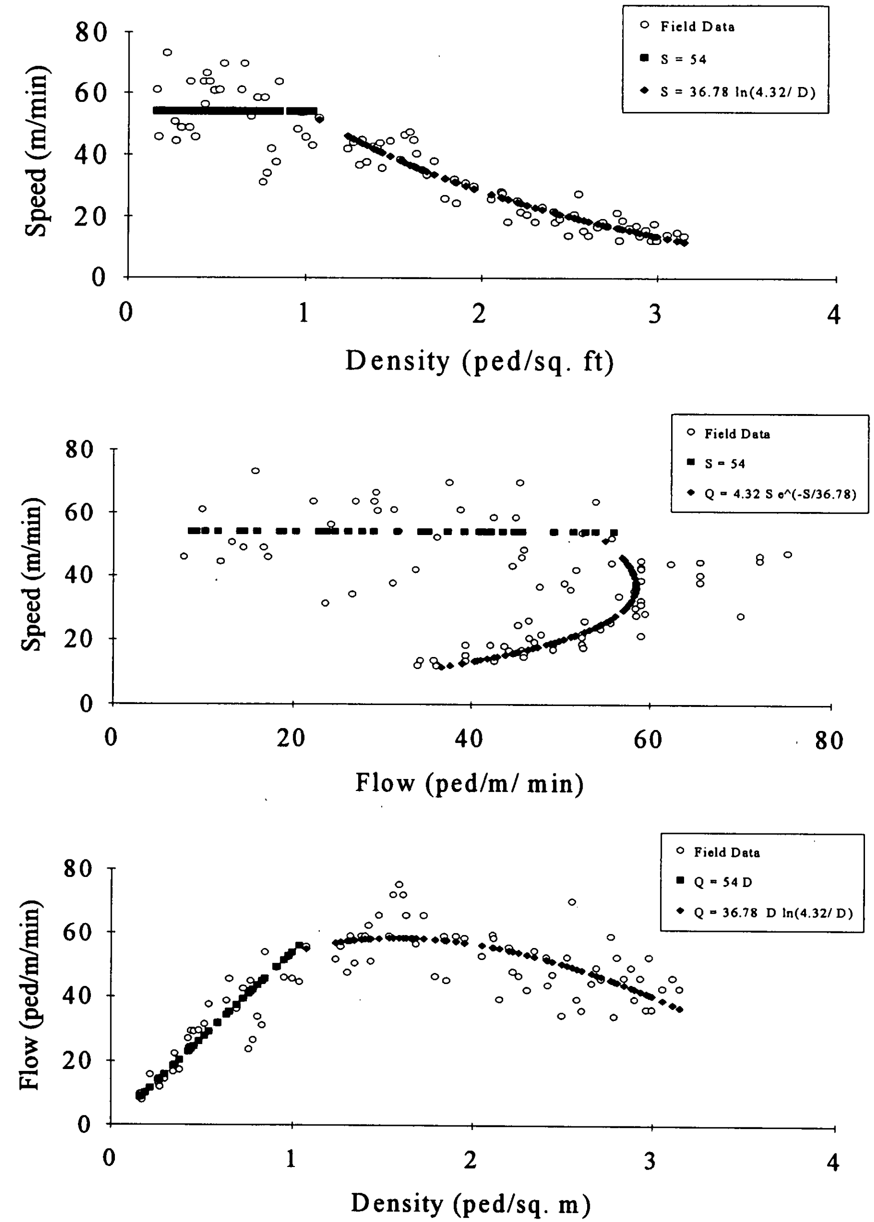

FIGURE 4 Speed-density-flow plots for Greenberg model.

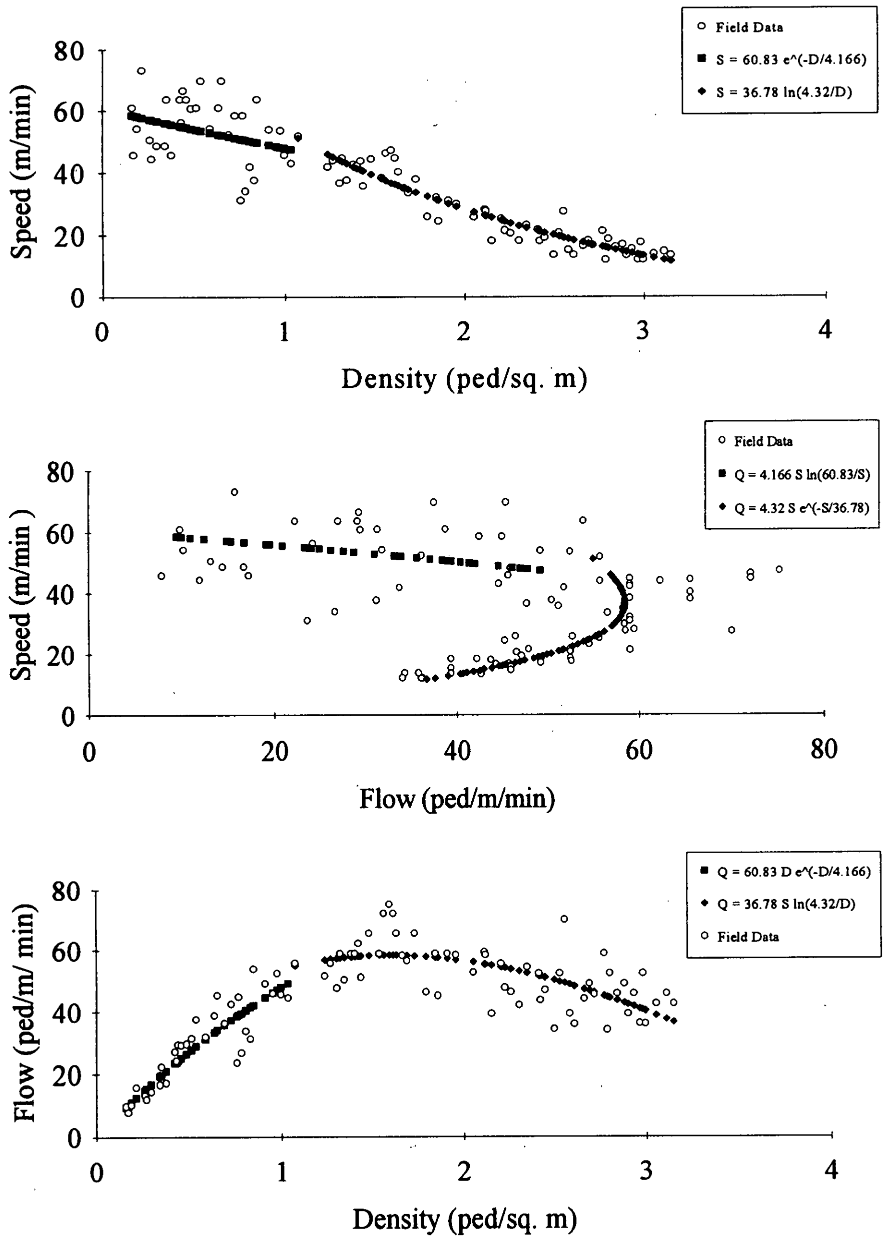

FIGURE 5 Speed-density-flow plots for Edie model.

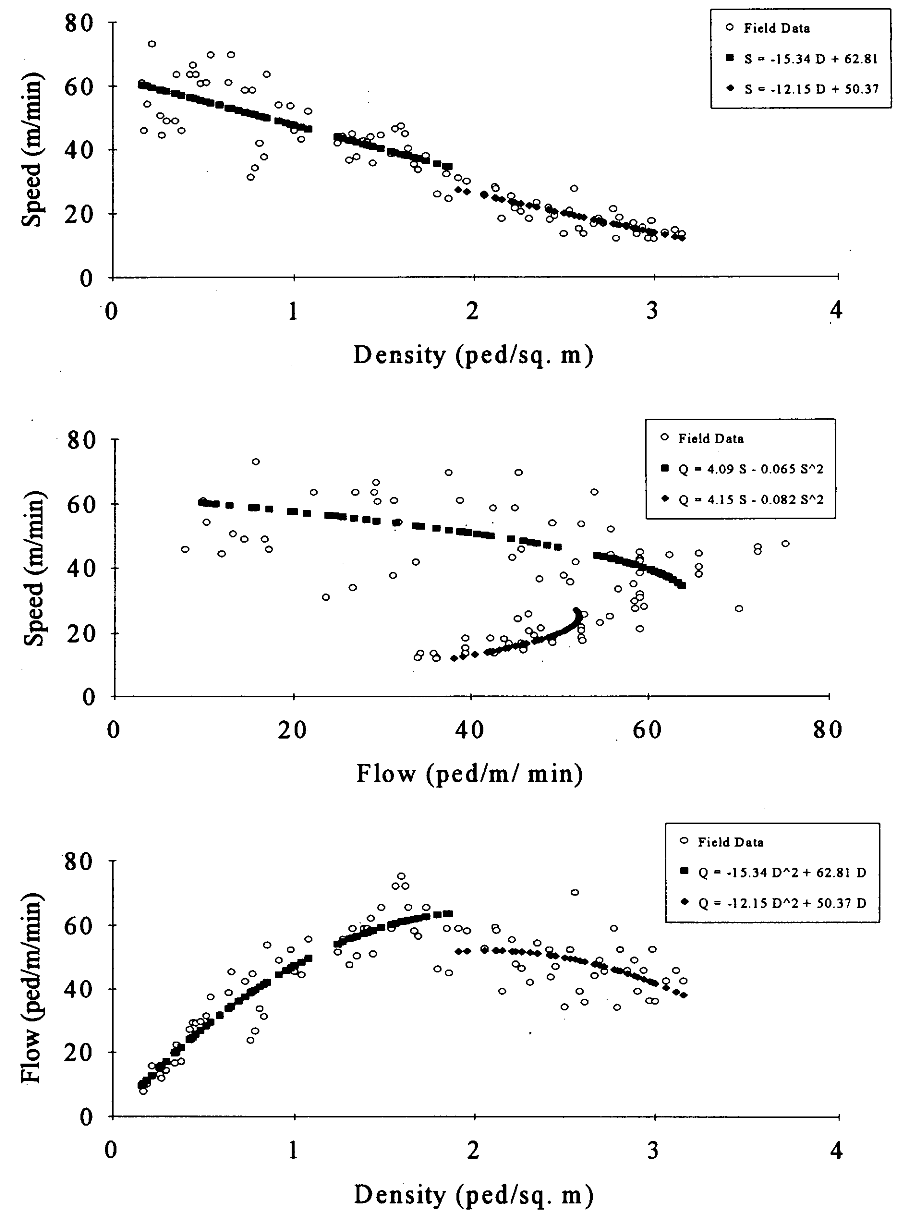

FIGURE 6 Speed-density-flow plots for two-regime linear model.

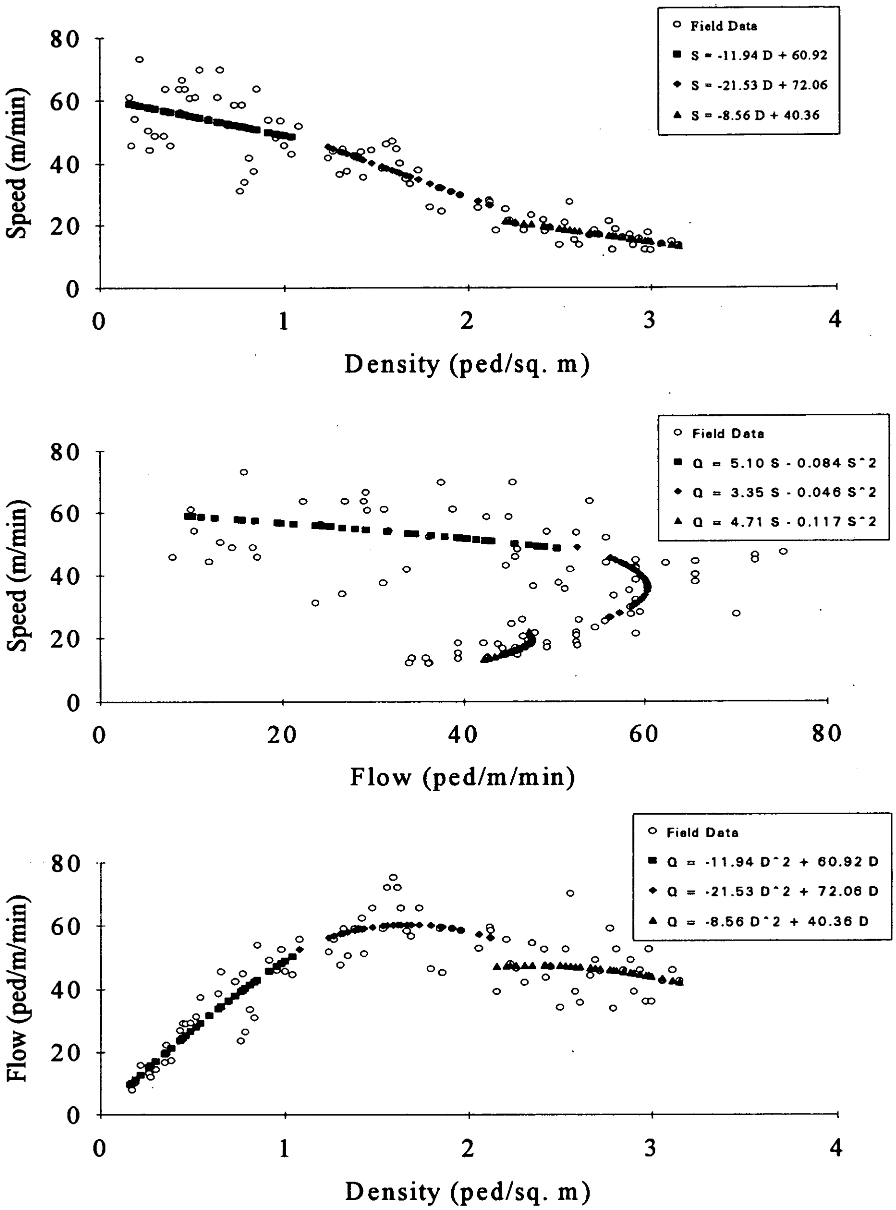

FIGURE 7 Speed-density-flow plots for three-regime linear model.

1. The two-regime and three-regime linear models gave fairly good estimates of maximum flow (66 and 62 ped/min/m, respectively) when compared with the field data. The Underwood model gave the lowest (and poorest) estimate (52 ped/min/m). The HCM (*1*) gives a capacity of 82 ped/min/m of walkway width.
2. Optimum densities predicted by the models ranged from 1.59 ped/m^2 to 1.89 ped/m^2. The data indicate an optimum density of about 1.3 to 1.8 ped/m^2. The HCM defines density at capacity as 1.8 ped/m^2.
3. The data indicate an optimum speed of around 35 to 50 m/min. The three-regime linear, Greenberg, and Edie models had optimum speeds within this range (37 m/min). All other models had lower optimum speeds.
4. The jam densities predicted by the models ranged from 3.73 to 4.32 ped/m^2. The highest recorded density was 3.149 ped/m^2, but the flow was not zero at this density.
5. The free-flow speeds predicted by the models (ranging from 54 to 64 m/min) appeared reasonable when compared with the data but appear low when compared with those of other studies (*1–7*). Perhaps sitting for over 3 hr on a warm, sunny day caused the pedestrians in this study to have relatively low speeds under free-flow conditions. The videotape also revealed that after the queue had dissipated, the pedestrians who approached the tunnel (i.e., the last to leave) seemed to walk at a slow pace for prevailing conditions. Perhaps these pedestrians were atypical of most pedestrians and biased the estimates of free-flow speed downward.

CONCLUSIONS

The three-regime linear model failed the test for significantly different equations for the free-flow and transitional-flow regimes.

The data do not support the theory that three separate regimes exist.

Of the three one-regime models, the Greenshields and May bell-shaped models had similar r^2-values and similar estimates of capacity. The Greenshields optimum density appeared to be high, whereas predicted optimum speed and capacity appeared to be low. May's bell-shaped curve provided better predictions of optimum density and optimum speed. Underwood's model had the worst r^2 and worst estimates of optimum density, optimum speed, and capacity. Of the three one-regime models, May's bell-shaped curve appears to be best for this data set.

The existence of two separate regimes was supported by the data. Significantly different curves apply to the two regimes, and the standard error is much larger in the free-flow regime than in the congested-flow regime. The three two-regime models had similar r^2-values. The two-regime linear model capacity estimate seemed reasonable, but its optimum density was too high and its optimum speed was too low. The Greenberg and Edie models gave slightly low estimates of capacity but provided good predictions of optimum density and optimum speed. An argument against the Greenberg model is that the data indicate a significantly negative slope for the range where the Greenberg model uses a constant speed. For the above reasons, the Edie model was judged to be best among the two-regime models.

Since the data were limited to one particular site, the results should not be viewed as universally applicable. However, the results indicate that further study is likely to lead to the conclusion that a multiregime (probably a two-regime) model is a better descriptor of flow on pedestrian facilities than the Greenshields one-regime linear model.

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Publication of this paper sponsored by Committee on Pedestrians.

Grade-Separated Pedestrian Circulation Systems

S. BANDARA, S. C. WIRASINGHE, D. GUROFSKY, AND P. CHAN

Grade-separated pedestrian networks, which are generally partial networks that serve as alternative systems to regular sidewalk networks, are analyzed. Indicators for selecting new grade-separated links for implementation, out of many available, are proposed. The proposals include measures of network connectivity (considering land use in, and separation of, origin-destination pairs) and network circuitry. A microcomputer program GSPCS has been developed to assist planners. Several examples are given based on the city of Calgary PLUS 15 elevated walkway system.

During the last 25 years, many cities have shown an interest in implementing grade-separated pedestrian circulation systems (bridge or tunnel networks) as alternative facilities for pedestrian circulation in downtown areas. The Calgary (Alberta) PLUS 15 walkway system, Minneapolis and St. Paul (Minnesota) Skyway system, Cincinnati (Ohio) and Des Moines (Iowa) Skywalk systems, and Houston Downtown Tunnel System are some examples.

The purpose of implementing these alternative pedestrian circulation systems changes from place to place. A few of the main objectives are to separate pedestrian traffic from vehicular traffic, to protect pedestrians from inclement weather, and to promote development such as an additional level of retail space (*1*). However, where the pedestrians are concerned, all of those objectives converge into a single goal: convenience.

There are concerns regarding the introduction of grade-separated pedestrian circulation systems (alternative networks) in downtown areas. Some argue that they may keep the pedestrian off the streets and eventually kill and sterilize the ground-level activities that reflect the liveliness of a city. Those who are in favor argue that pedestrian convenience outweighs the disadvantages (*2*) and that alternative networks can actually help to keep a downtown area alive, particularly in cities with severe climates. Other concerns are personal safety, particularly in tunnels, and the difficulty of way-finding indoors.

NEED FOR PLANNING TOOLS

The negative effects of alternative networks could be minimized if given careful consideration at the planning stage. The ideal is for an alternative network to have connectors between all the adjacent activity centers (blocks). However, topographical, land use, and financial constraints usually interfere with achieving that ideal condition. In such situations it is important to determine the most efficient network subject to constraints.

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At present very little information is available on planning and designing alternative circulation systems. Sound quantitative methods to estimate the origin-destination distribution (O-D matrix) and link flows of pedestrians are not readily available. Even with the availability of a methodology to estimate the O-D matrix and link flows, it is not easy to determine the best alternative network without the help of indicators to rank the different networks. Therefore, indicators that are used to evaluate the performance of an alternative network should be useful to planners.

OBJECTIVES

The aim of this study was to develop a methodology to evaluate a grade-separated pedestrian circulation network, so that different design alternatives can be compared at the planning stage, especially when links are added to an existing system. The main objectives are to develop indexes to evaluate the network in terms of connectivity and ease of pedestrian circulation. As an example, an idealized nine-block area is shown in Figure 1, with four existing links. Because of various constraints such as lack of a suitable connecting building, only four out of eight new links are feasible. Given that funds are available to build a fixed number of links (fewer than four), a question arises as to which one or ones should be built. A personal-computer-based tool that can undertake the above analysis should prove useful to planners in the decision-making process, which also takes into account a variety of other factors.

PLANNING PEDESTRIAN CIRCULATION SYSTEMS

Literature Review

Some studies have been done to estimate pedestrian trip generation, trip distribution, or trip assignment in downtown areas. However, specific studies on grade-separated pedestrian circulation systems are lacking in the literature. Bhalla and Pant (*3*) used regression analysis to estimate the link volumes in the Cincinnati Skywalk system. They showed that land use types have a significant impact on the link flows between blocks. Seneviratne and Morrall (*4*) identified the shortest route as the major criterion for pedestrian route choice in downtown Calgary. In general, the literature shows that land use type and distance between O-D pairs are the main parameters that govern pedestrian flow between different downtown blocks.

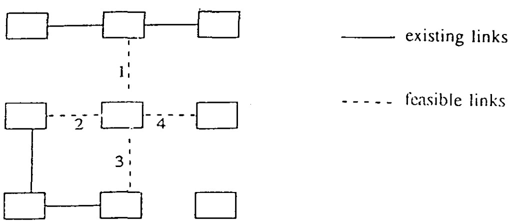

FIGURE 1 Idealized nine-block area.

Analytical Approach

In the absence of detailed information on pedestran behaviour and trip distribution, grade-separated pedestrian circulation networks can be evaluated in terms of the connectivity of the network and the ease of pedestrian circulation, as defined below. Connectivity of a network can be defined as the degree to which blocks are connected by a set of grade-separated links. Ease of pedestrian circulation depends on the directness of the alternative route network compared with the street-level shortest route, the availability of connections with the street level, and the ease of orientation (way-finding) in the network.

Measure of Connectivity

Connectivity Ratio (CR) The basic measure of connectivity of a network is the ratio between the number of links and the total possible links (CR). A link between blocks is possible in the PLUS 15 system if suitable buildings are available on both sides of the street separating the blocks. The connectivity ratio increases when links are added to the network. It can be calculated for individual subnetworks or for the entire system. When all the possible links are available, CR is equal to 1. However, the ratio does not take into account the location of a link. Thus, if a new link is added to the system, CR will be increased by the same amount irrespective of the location of the link. Further, CR does not reflect the attraction between O-D pairs and the spatial separation between them.

Weighted Connectivity Index (WCI) Total pedestrian flow between two blocks will essentially depend on the type and extent of land use in the two blocks and the separation between them. Given a measure to represent the intrinsic attractiveness between two land use types m and n (k_{mn}), one possible weighted connectivity index (WCI)—that is, a measure of how well the alternative network connects land uses between which there is likely to be travel—can be defined as follows:

$$WCI = \sum_{\substack{\text{for all}\\ i,j\\ i \neq j}} \left[\frac{\sum_{\substack{\text{for all}\\ m,n}} K_{mn} A_{mi} A_{nj}}{D_{ij}^2} \right]$$

where

K_{mn} = factor that represents the intrinsic attractiveness between land-use types m and n,
i,j = block pairs that are connected by the alternative network,
A_{mi} = floor area of land use type m at origin i,
A_{nj} = floor area of land use type n at destination j, and
D_{ij} = distance between origin i and destination j via the alternative network.

The WCI is a formulation of the gravity type. Connections that provide a route between land use types that are highly attracted to each other (e.g., shopping and parking) will increase WCI relatively more, as will higher amounts of land use. Routes between blocks that are far apart will increase WCI by relatively smaller amounts. The use of the function D_{ij}^2 is based on certain gravity-type models (*5*). The exponent 2 or the function itself can be changed (e.g., to an exponential form) if network-specific data are available.

The factor K_{mn} is defined here as the probability that a trip originating in land use type m will be destined for land use type n. Thus the product $K_{mn}A_{mi}A_{nj}$ is representative of the potential for trips of the m-n type from i to j. The summation over all m,n gives the potential for trips of all types from i to j. The division by D_{ij}^2 reflects the resistance caused by distance to trips between i and j on the alternative network. The ratio between the square brackets is a measure of the connectivity between an i,j pair weighted by the potential for trips and the resistance to trip making. The summation over all i,j provides a measure of weighted connectivity for the alternative network.

WCI can be calculated for the entire grade-separated circulation system or for a particular subnetwork. Higher values of the index indicate a higher connectivity. However, WCI can increase with the number of blocks in a particular subnetwork. Therefore, if different subnetworks are being compared, the number of blocks and the number of bridges (or tunnels) should also be taken into account along with the WCI value.

Ease of Circulation

The network efficiency will also depend on the relative ease of pedestrian circulation within the alternative network. Pedestrians usually like to take the shortest route between their origin and destination (*4*), and this is usually available at the ground level. If the grade-separated network requires additional walking and additional level changes, that will lead to lower network usage. The following two indexes can be used to evaluate the ease of pedestrian circulation.

Subnetwork Circuitry Coefficient (SNCC) The circuitry coefficient for a group of blocks that are connected by an alternative network (subnetwork) can be defined as the average of the ratio between the minimum street-level distance and the minimum distance via the alternative network for each pair of blocks:

$$SNCC = \frac{1}{n} \left[\sum_{\substack{\text{for all}\\ i,j\\ i \neq j}} \frac{SD_{ij}}{GD_{ij}} \right]$$

where

n = total number of O-D block pairs that belongs to a particular subnetwork:
i,j = origin block and destination block, respectively;

SD_{ij} = minimum distance between O-D pair i,j at street level; and

GD_{ij} = minimum distance between O-D pair i,j along grade-separated system.

For example, in the idealized six-block system in Figure 2, the use of the alternative network for travel from O to D will result in an additional two links of travel; the SNCC for that O-D pair is 3/5 or 0.6.

When all possible links between the blocks that belong to a subnetwork are available, the value of SNCC is 1. If additional walking is needed to use the grade-separated network, SNCC is less than 1.

System Circuitry Coefficient (SCC) In considering a group of blocks that may or may not be fully connected by an alternative network, the minimum distance traveled via the grade-separated network can be replaced by the minimum weighted distance traveled using the grade-separated network and the at-grade network. If different weights are introduced to represent walking at the street level and the grade-separated level, the minimum weighted distance between O-D pairs for the combined system can be calculated. Then SCC for individual subnetworks or for the entire system is defined as follows:

$$SCC = \frac{1}{n}\left[\sum_{\substack{\text{for all}\\ i,j\\ i \neq j}} \frac{SD_{ij}}{CD_{ij}}\right]$$

where n is the total number of O-D pairs that belongs to the subnetwork or the system, as the case may be, and CD_{ij} is the minimum weighted distance between the O-D pair i,j via a route combining ground level and grade-separated links, defined as

$$CD_{ij} = GD^c_{ij} + \delta_1 SD^c_{ij} + \delta_2 LC_{ij}$$

where SD^c_{ij} and GD^c_{ij} are the distances at the street and grade-separated levels for the combined route LC_{ij} is the additional number of level changes that are required because of the combined route. The coefficient δ_1 (≥ 1) is a penalty factor that represents the relative unattractiveness of the street travel (e.g., extra travel time because of pedestrian signals), and δ_2 is a penalty factor representing the grade-level distance equivalent to one level change.

Ignoring the $\delta_2 LC_{ij}$ term, it may be seen that the system SCC varies from $1/\delta_1$ to 1 for a 0 percent to a 100 percent linked system, respectively. Therefore, the closer the system SCC is to 1, the more likely the pedestrians will use the grade-separated network. If the $\delta_2 LC_{ij}$ term is taken into account, the system SCC values will be reduced and can never be 1.

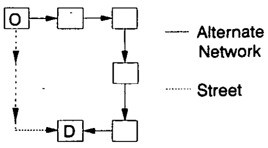

FIGURE 2 Idealized six-block area.

Further research is required to determine behaviorally validated values for δ_1 and δ_2.

COMPUTER PROGRAM GSPCS

The computer program GSPCS was developed to calculate CR, WCI, SNCC, and SCC for a given grade-separated pedestrian circulation system. The program is written in PASCAL and operates on IBM-compatible microcomputers. It is capable of handling any network (system) with maximum of 120 nodes and 30 subnetworks. The maximum number of links from a particular node is limited to four. At a particular node, up to five different land use types can be taken into account. However, most of these limitations can be changed with minor modifications to the GSPCS program.

Input for Program

The user can interactively enter the information that is required. The program first prompts for an input file name. If the input file entered already exists, the program will retrieve the input information. Otherwise it will prompt the user to advise whether to create a file under the given name. Then the user can update the input file or calculate the indexes if the input file already exists.

The input requirement for this program can be divided into two main categories: system related and user related. System-related information is entered on a block-by-block basis. The user should provide the floor areas belonging to different land use types, neighbors, and bridges for each block in the system. The user can add, edit, or delete individual blocks, neighbors, or bridges when updating the input file.

The user-related information is entered globally as factors K_{mn} to represent the attractiveness between different land use types and the disutility factor δ_1 to represent the disutility of street-level walking. The program as it is currently configured does not include the level change term $\delta_2 LC_{ij}$.

Calculations

When all the information has been entered, the user can request the program to calculate the different indexes that are used to evaluate the system performance. The program first calculates the minimum street level, grade-separated level, and combined (weighted) distances between each of the block pairs. A modified version of the well-known Dijkstra algorithm is used to determine the shortest path between all pairs of blocks (*6*) under the above three scenarios. Then the program identifies the nodes (blocks) belonging to different subnetworks. Finally, CR, WCI, SNCC, and SCC for each subnetwork and CR, WCI, and SCC for the entire system are calculated.

Output of Program

GSPCS gives an output on the screen after each calculation indicating the number of blocks, number of bridges, and CR, WCI, SNCC, and SCC for each subnetwork and for the entire system, as shown in Table 1.

TABLE 1 GSPCS Program Output

Subnetwork	No. of Blocks	No. of Bridges	CR	WCI	SNCC	SCC
1	14	14	0.875	55.090	0.876	0.899
2	20	19	0.731	378.382	0.766	0.856
3	7	6	0.750	87.567	0.870	0.909
4	8	8	1.000	228.189	0.975	0.975
Total	49	47	0.331	749.228		0.697

A user's manual for the program GSPCS (*7*) is available.

CASE STUDY 1

Calgary's PLUS 15 System

The Calgary PLUS 15 system is reputed to be the largest grade-separated pedestrian circulation system in the world. This system enables pedestrian circulation within the downtown area in walkways and on bridges that are approximately 15 ft above the street level. The PLUS 15 system currently consists of 50 bridges.

Application

System-Related Information

Study Area An area consisting of 79 blocks in downtown Calgary, as shown in Figure 3, is considered the study area. The PLUS 15 system had 47 bridges in 1989 distributed among four different subnetworks in the north, south, east, and west cores of downtown Calgary. The notations given in Figure 4 were used to identify individual blocks.

Floor Area Floor area measured in square meters was used to represent the various land uses on each block (*7*, Appendix B). There were five different land use types: office, residential, hotel and restaurant, parking, and other.

Neighbors and Bridges The blocks to the north, south, east, and west of a particular block are considered neighbors. It is assumed that no bridge will be built diagonally across an intersection. The distance between two adjacent blocks is considered to be uniform and equal to one distance unit, and it is assumed that the average walking distance of a pedestrian within a block at the origins or destinations is equal to one-half the block length. If the actual distances between the centroids of the blocks are available, they can be used at the input stage and the uniform block length assumption abandoned.

User-Related Information

Disutility Factor A value of 2 was arbitrarily selected to represent the disutility factor δ_1 associated with walking at the street level relative to walking at the PLUS 15 level when considering combined routes. One can alter this disutility factor globally by adjusting the GSPCS program. The factor δ_2 was set to zero because of lack of easily available information regarding facilities available for level changes.

Attractiveness Between Different Land Use Types The factor representing the intrinsic attractiveness between land use types m and n (K_{mn}) is defined as the probability that a randomly selected pedestrian will originate in an area of land use type m and will travel to an area of land use type n. Results of a PLUS 15 user survey (*8*) were used to determine the factors (K-values) for various land use pairs. This information was entered into a data file in matrix form so that it could be edited before use of the GSPCS program. The percentage values given in Table 2 were used for the subsequent calculations.

System Evaluation

First, the PLUS 15 system in 1989 consisting of 47 bridges, as shown in the Figure 4, was considered for the analysis. Table 3 shows the number of blocks and bridges belonging to each of the subnetworks and the entire system and the four performance indicators, namely, the connectivity ratio (CR), the weighted connectivity index (based on attractiveness between different land use types) (WCI), subnetwork circuity coefficient (SNCC), and system circuitry coefficient (SCC).

Then the best location for an additional link in the north core subnetwork was investigated. Seven alternatives were considered for the comparison. Because the total number of bridges does not change with the alternative, the new system CR value is uniform at 0.736 (an increase of 0.005 from the existing system). Table 4 shows how the subnetwork and the system performance indicators change with the different alternatives.

Discussion of 1989 System

From Table 3 it can be seen that the south core subnetwork has the best performance properties with respect to connectivity and circulation despite the lower WCI value. However, if WCI per bridge is taken into account, the south core subnetwork will rank 1 with respect to that indicator, too.

The low WCI value for the east core subnetwork is due to the low total floor area in that region and comparatively longer distances betweeen O-D pairs. The pedestrian counts carried out by the city of Calgary also show low system usage in this subnetwork (*8*).

Referring to Table 4, it can be seen that Link CR26-CR27 or Link CR15-CR16 would be the best alternative since they rank

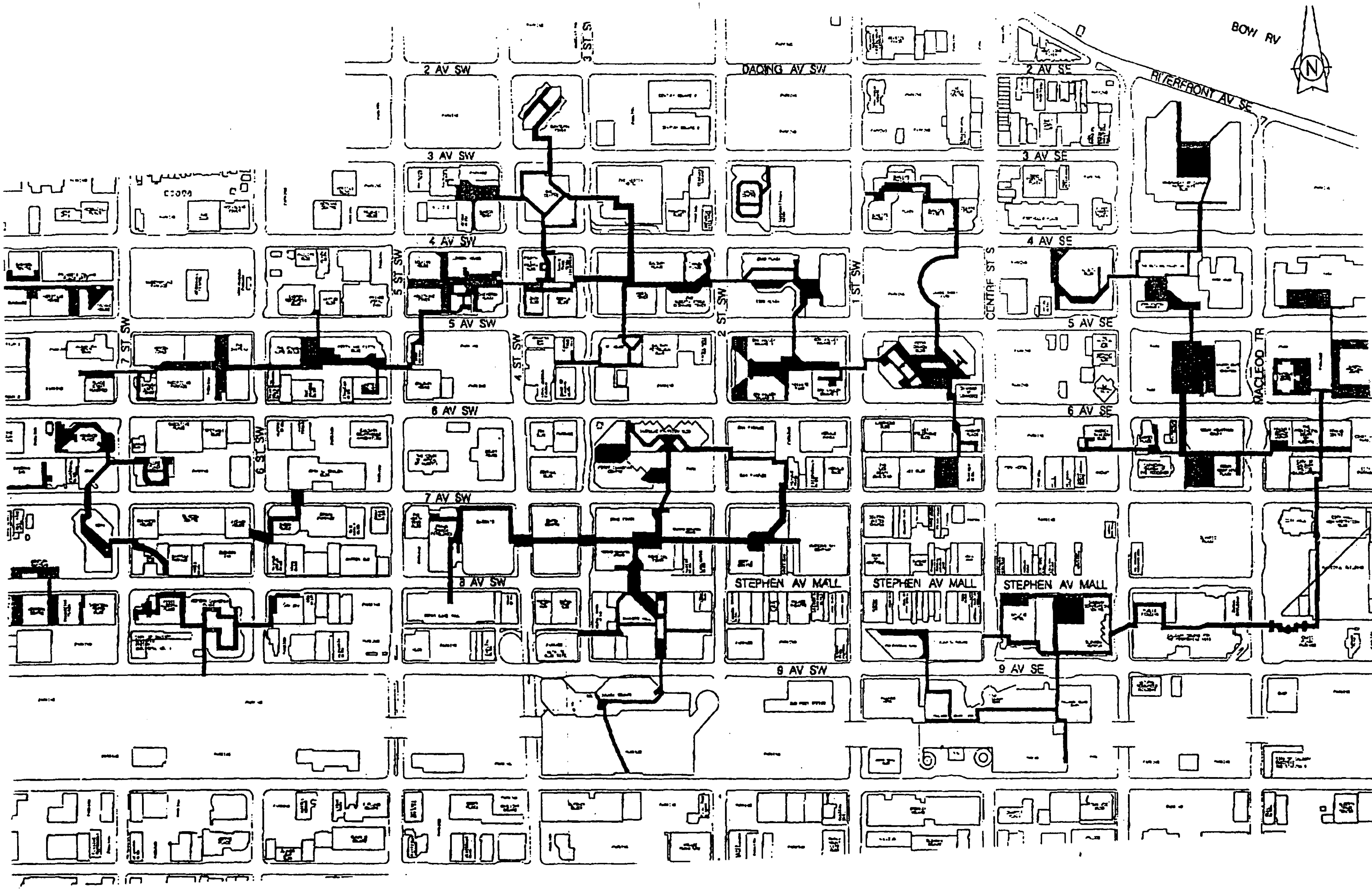

FIGURE 3 **PLUS 15 pedestrian walkway system, Calgary, Alberta, Canada.**

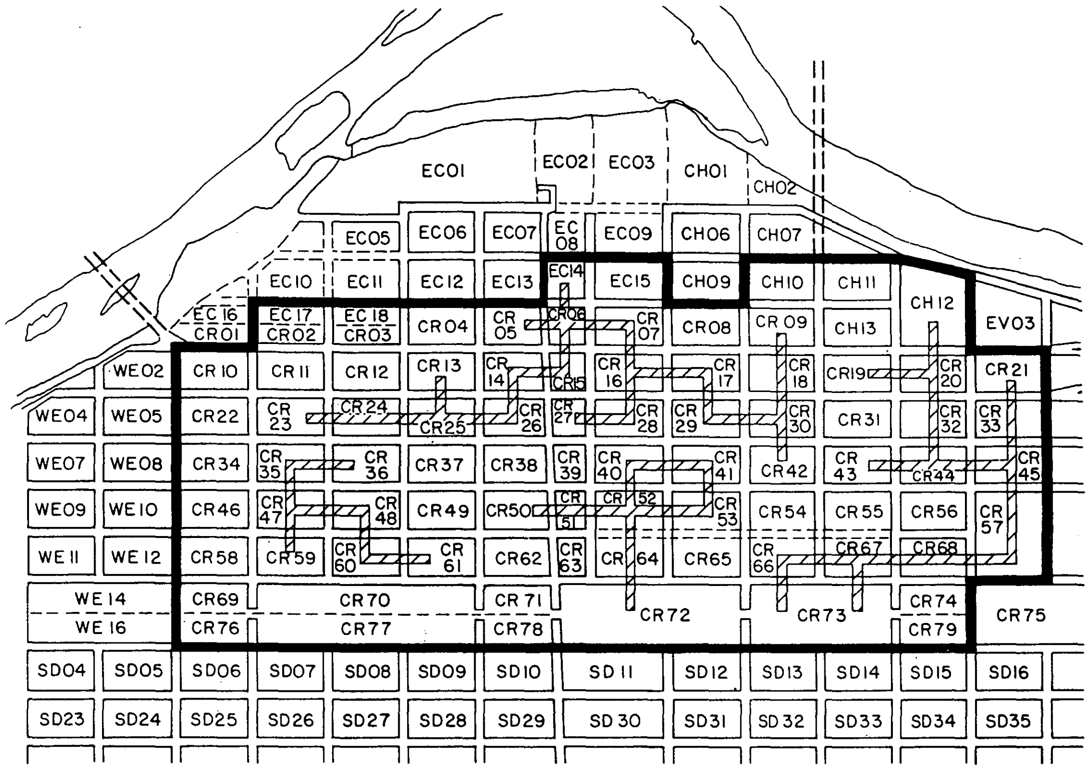

FIGURE 4 PLUS 15 network: 1989.

TABLE 2 K-Values

	Destination					
Origin	Office	Residential	Hotel	Parking	Other	Total
Office	10	1	14	4	16	45
Residential	1	0	0	1	1	3
Hotel	7	0	0	3	0	10
Parking	12	0	2	0	4	18
Other	10	1	2	3	8	24
Total	40	2	18	11	29	100

TABLE 3 Existing System

Subnetwork	No. of Blocks	No. of Bridges	CR	WCI	SNCC	SCC
East (1)	14	14	0.875	55	0.876	0.899
North (2)	20	19	0.731	378	0.766	0.856
West (3)	7	6	0.750	87	0.870	0.909
South (4)	8	8	1.000	228	0.975	0.975
Total	49	47	0.331	748		0.697

TABLE 4 North Core Subnetwork

			SCC	
Link	Subnetwork WCI	SNCC	Subnetwork	System
CR13-CR14	391	0.785	0.868	0.697
CR05-CR15	389	0.778	0.864	0.696
CR15-CR16	404	0.836	0.890	0.702
CR15-CR27	384	0.796	0.867	0.697
CR26-CR27	391	0.838	0.893	0.707
CR28-CR29	395	0.788	0.883	0.703
CR17-CR18	388	0.805	0.879	0.702

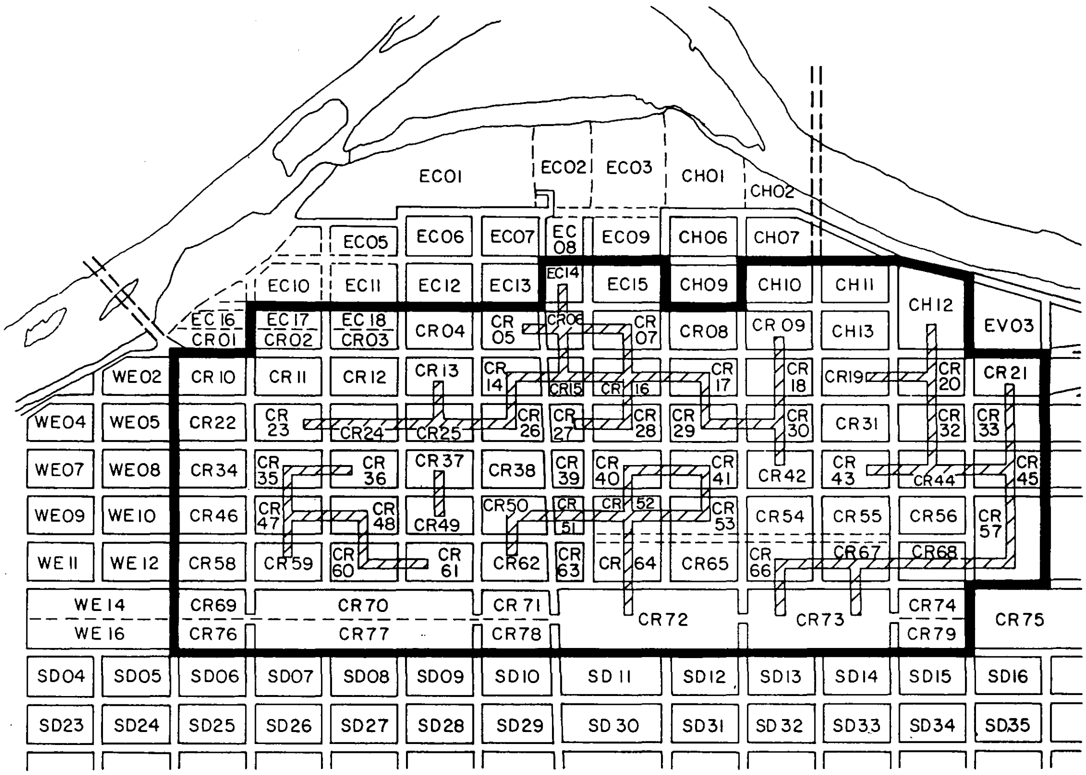

FIGURE 5 PLUS 15 network: 1993.

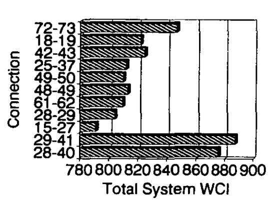

FIGURE 6 Different placements of additional link and effect on system WCI.

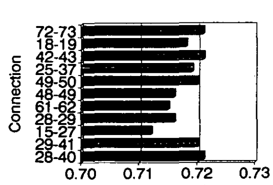

FIGURE 7 Different placements of additional link and effect on system SCC.

first or second according to the WCI and SCC criteria. Both these links are situated around the middle of the north core subnetwork and fill the gap in the east-west direction in which the subnetwork has developed.

CASE STUDY 2: ADDITIONAL LINK FOR CALGARY PLUS 15 SYSTEM

In 1993, Link CR15-CR16 and two others were in place, and there were 50 bridges distributed among four different subnetworks in the north, south, east, and west cores of downtown Calgary. The new PLUS 15 schematic is shown in Figure 5. The total system WCI is 786, and the SCC is 0.711.

To investigate the best location for an additional link for the entire PLUS 15 system, 14 alternative locations are considered for comparison. From Figures 6 and 7, it may be seen that Links CR29-CR41 and CR28-CR40 are the best alternatives. Both of these links will combine the north and south subnetworks into one large subnetwork. Link CR29-CR41 has a slightly higher WCI because it directly connects larger office areas. Link CR28-CR40 has a small edge in SCC because it is closer to the middle of the north and south subnetworks.

DISCUSSION OF RESULTS

Two indexes, WCI and the network circuity coefficient (NCC), were developed as indicators of the efficiency of alternative pedestrian networks. WCI is an indicator of the potential for travel between blocks via the alternative network given measures of land use in the blocks and separation between the blocks. NCC is an indicator of the portion of trips that may use the alternative network for the entire trip or a segment of a trip given the circuity of routes in that network relative to the street level.

It is worthwhile to note that the city of Calgary has added Link CR15-CR16 (Table 4), which was selected in the 1989 study on the basis of the indexes as a suitable addition to the PLUS 15 network.

The WCI could be improved by choosing a better function to describe the resistance to travel between two blocks. For example, an exponential travel-time function could be investigated, though a significant additional data collection effort would be needed to collect travel-time data.

A basic problem associated with having two indicators is the dilemma that occurs when they give different rankings of options. The possibility of combining the two indicators is worth consideration. An example is an indicator obtained by summing the product of WCI for a block pair and a function of NCC for that pair over all block pairs as an indicator of the propensity for travel in an alternative network.

The indexes proposed here can be used to evaluate the addition of k-links (instead of one link) to an alternative network. In such a case, the indicators are calculated for all possible partitions of k-links out of a feasible set of K-links, $K!/k!\ (K - k)!$.

A third index that has been suggested to the authors as worth considering is one that indicates the propensity for pedestrian-vehicle conflicts if the alternative network were not available.

In general, the indicators provide a low-cost microcomputer-based method for evaluating alternative pedestrian networks.

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Publication of this paper sponsored by Committee on Pedestrians.

Pedestrian Walking Speeds and Conflicts at Urban Median Locations

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Results are presented of an analysis of pedestrian walking speeds and conflicts for a project sponsored by the Federal Highway Administration. The project included analysis of urban and suburban medians located on unlimited-access arterials. Pedestrian walking times were measured in Atlanta, Phoenix, and Los Angeles–Pasadena on three types of arterial cross sections: raised median, two-way left turn (TWLT), and undivided. Pedestrian speeds were computed for three age categories of pedestrians. Statistical tests were applied to determine the effect on walking speeds of median type, crossing location (midblock versus signalized intersection), and pedestrian age. Pedestrian-vehicle conflict data and accident data were collected and conflict rates were calculated. Statistical tests were applied to determine the effect of crossing location, median type, and accident rate on conflict type. The results indicate that pedestrian walking speeds are a function of age and crossing location. The type of median did not affect pedestrian-vehicle conflicts. It was found that through and right-turn conflicts were related to the accident data.

Pedestrian accidents annually account for approximately 16 percent of total traffic fatalities in the United States, with 7,400 pedestrian fatalities occurring during 1990 (*1*). The pedestrian safety problem is largely an urban one. Each year nearly 60 percent of all pedestrian fatalities occur in urban areas. In some large urban areas 40 to 50 percent of those killed in traffic accidents are pedestrians (*2*).

Approximately 14 percent of the 1992 pedestrian fatalities consisted of children under age 15, and 22.8 percent were pedestrians over the age of 64 (*1*). The pedestrian problem has often been characterized as a problem "of the young, the old and the drunk." This characterization is misleading when considered in terms of pedestrian fatalities or involvement per 100,000 population. Since 1979, for example, pedestrian fatalities per 100,000 for those under age 14 have been lower than for pedestrians aged 14 to 64 and less than half the rate of adults 65 and older. Although the characterization may be misleading in some respects, it serves to demonstrate that certain segments of the pedestrian population are perceived as being overinvolved in accidents. This perception is based on the diverse physical and attitudinal characteristics of the pedestrian population.

One of the primary variables in pedestrian characteristics is walking speed. There is considerable variation in the walking speed of pedestrians depending upon their age and trip purpose. A study of free-flow walking speeds for 967 persons observed in two transportation terminals in New York City indicated that although 1.4 m/sec (4.5 ft/sec) was the observed average, 78 percent of the pedestrians normally walked more slowly than this (*3*). The median speed, considered to be more representative than the average, was 1.2 m/sec (4.0 ft/sec). The New York study stated that the normal average walking speed of 1.1 m/sec (3.6 ft/sec), observed in a laboratory study of healthy older men, was in the 25th percentile of the distribution. Studies of street crossing speeds display slightly different results because oncoming vehicles and impending signal change prompt nondisabled pedestrians to move faster. A time-lapse photography study of pedestrians in dense platoons crossing New York City streets indicated an average crosswalk walking speed of 1.0 m/sec (3.3 ft/sec) (*4*).

The *Manual on Uniform Traffic Control Devices* (MUTCD) indicates that normal walking speed can be assumed to be 1.2 m/sec (4 ft/sec) (*5*). The results of the New York study, however, indicate that if a walking speed of 1.2 m/sec (4 ft/sec) is used to determine the pedestrian clearance interval, 50 percent of pedestrians will have to walk faster than their normal walking speed to cross safely within the allocated green time. The Institute of Transportation Engineers (ITE) handbook suggests that a normal walking speed of 1.2 m/sec (4 ft/sec) is acceptable but speeds of 0.9 to 1 m/sec (3.0 to 3.25 ft/sec) may be more appropriate for slow walkers (*6*). The 1965 edition of the ITE handbook estimated that 35 percent of the pedestrians did not attain the 1.2-m/sec (4-ft/sec) rate (*7*). A recent study conducted in Florida at a location with a large number of elderly pedestrians determined that a walking speed of 0.8 m/sec (2.5 ft/sec) was appropriate for 87 percent of those pedestrians (*8*). In another study pedestrians aged 70 years or older were instructed to cross an intersection at fast, very fast, and normal speed. The results indicated that 60 percent of the older pedestrians considered a speed lower than 1.2 m/sec (4 ft/sec) as fast. Approximately 90 percent crossed at a speed lower than 1.2 m/sec (4 ft/sec), with 15 percent of the elderly sample walking at a rate less than 0.7 m/sec (2.3 ft/sec) (*9*).

The diversity of walking speeds presents a problem to traffic engineers in determining the minimum green time and appropriate clearance interval at signalized intersections. The *Traffic Control Devices Handbook*, which provides interpretation of the MUTCD, states: "Those having slower walking speeds have the moral and legal right to complete their crossing once they have lawfully entered the crossing" (*10*). The traffic engineer therefore has the task of selecting an appropriate walking speed and hence minimum green time while simultaneously providing the cycle splits required for progressive and efficient movement of vehicular traffic. The signal timing task involves decisions about the duration of the signal cycle, its phases, and the clearance interval with the goal of minimizing delay to vehicles. Pedestrian needs and vehicular needs, however, often conflict during the selection of optimal signal timing plans.

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TABLE 1 Pedestrian Observations by Age Group, Crossing Location, and Median Type

Age Group	Midblock		Signalized Intersection		Total
	TWLT	Undivided	TWLT	Undivided	
18 to 60	179	46	175	141	541
>60	20	3	24	20	67

Problems at signalized intersections are complicated by geometric design and vehicle movement paths. The majority of vehicular left-turn movements often takes place at the end of the green phase. At this time slower-moving pedestrians may still be in the roadway, partially fatigued, and concerned with arriving at the far curb line. The driver of the left-turning vehicle is concerned with oncoming traffic and may not be aware of pedestrians in the crosswalk into which the turn is being made. The result is an increased potential for pedestrian vehicle conflicts and subsequent accidents (*11*).

The differences in pedestrian walking speeds, vehicular travel distances, and vehicular signal timing needs are among the difficulties encountered by pedestrians in crossing roadways and by traffic engineers in producing optimal intersection signal timing plans. The magnitude of these problems increases as the vehicular volumes and roadway widths increase. Solutions to the problems include separating the paths of pedestrians and vehicles, narrowing the roadway cross section at intersections, and providing medians.

Medians are classifications of traffic control islands defined as areas between traffic lanes for control of vehicle movements or for pedestrian refuge. Medians can be designed to serve more than one purpose, including controlling or protecting vehicle crossover or other turning movements, providing a landscaped area, channelizing traffic, and providing pedestrian protection.

The results of an analysis of pedestrian walking speeds and conflicts for a project sponsored by the Federal Highway Administration are presented here. The project included analysis of urban and suburban medians located on unlimited-access arterials.

PEDESTRIAN OPERATION ANALYSIS

Walking Speeds

Pedestrian crossing behavior was obtained at selected intersections and midblock segments in Atlanta, Georgia; Phoenix, Arizona; and Los Angeles–Pasadena, California, using video cameras that had time-imaging capabilities to a hundredth of a second. The crossing times were extracted from the tapes, entered into a data base, and merged with the geometric data base. The width of the roadway from a developed geometric file and the crossing times were used to develop pedestrian walking speeds. Pedestrian age was estimated from the videotapes and grouped into three categories:

- Less than 18 years old,
- Aged 18 to 60, and
- Older than 60 years.

These categories identified age groups in which behavioral differences could be expected and reliability of age estimation is high.

The majority of pedestrian observations occurred in the central business district (CBD) or commercially developed suburban areas in which pedestrian activity was high. Because of the site collection criteria, the majority of observations were of pedestrians older than 17 years. Table 1 presents the number of pedestrian observations obtained by age group, crossing location, and median type. Efforts were concentrated on obtaining the walking speeds of pedestrians crossing two-way left-turn (TWLT) and undivided arterials since raised medians provide the opportunity for refuge.

Table 2 presents the mean walking speed, by age group, and *t*-test results to determine if there are statistically significant differences in pedestrian walking speeds by type of median and location. Pedestrians aged 18 to 60 exhibit a significantly higher walking speed at TWLT medians for both signalized intersections and midblock locations. Elderly pedestrians also exhibited higher walking speeds at TWLT signalized intersection locations, but the sample size of elderly pedestrian observations is too small for reliability. The increased walking speed for TWLT lanes may be due to the pedestrian perception of increased walking distance resulting from the presence of the TWLT lane.

TABLE 2 Test for Significance of Median Type on Pedestrian Walking Speed

Ho: Walking speed at midblock = walking speed at signalized intersection
Significance level of t-test = 0.05

Age	Midblock			Signalized Intersection		
	Mean Speed, m/sec		Prob > |t|	Mean Speed, m/sec		Prob > |t|
	TWLT	Undivided		TWLT	Undivided	
18 - 60	1.47	1.17	0.001*	1.46	1.19	0.001*
>60	1.18	--	--	1.30	0.63	0.001*

* Indicates significant difference in mean walking speeds.
1 m/sec = 3.3 ft/sec

Table 3 presents the mean walking speed by age group and *t*-test results to determine if there are significant differences in age group means by crossing location. The walking speed for the age group 18 to 60 is significantly higher than that of the over-60 age group for both signalized intersections and midblock locations. An analysis of the difference in walking speed between locations is presented in Table 4. Both age groups have significantly higher walking speeds at midblock locations than at signalized intersections. This may indicate that pedestrians feel protected at signalized intersections and do not feel the same urgency to cross as they do at midblock locations.

A summary of the number of pedestrians using raised and TWLT medians as refuge during the crossing maneuver is presented in Table 5. Over 18 percent of the observed pedestrians used the raised medians for refuge, whereas only 5 percent gained refuge from TWLT medians. A number of pedestrians were observed standing on the marks dividing the pavement during crossing of undivided roadways. The number of these observations was not, however, sufficiently large for meaningful analysis.

PEDESTRIAN CONFLICTS

Pedestrian conflict data were obtained by placing video cameras at areas with high pedestrian activity. Conflicts were taped for pedestrian crosswalks at signalized intersections and at midblock locations. The primary purposes of the conflict observations were to (*a*) determine if certain types of conflicts were indigenous to, or predominant at, particular median types; and (*b*) investigate if conflicts could be related with average daily traffic (ADT) to accident type.

The latter purpose was addressed in an effort to determine if use of the traffic conflict technique could be increased as a measure of safety by associating it with realistic data collection methods. Because of a number of factors, including the time required for data collection and its correlation to accident occurrence, traffic conflicts are not widely used. Obtaining accurate data on pedestrian conflicts and exposure is especially difficult since both pedestrian and vehicle counts are required. In addition, the conflicts are site specific and are not applicable to another location

TABLE 3 Test for Significance of Crossing Location on Walking Speed of Each Age Group

Ho: Walking speeds of (18-60) age group = walking speed of (>60) age group
Significance level of t-test = 0.05

Location	Mean Speed, m/sec		Test Results
	Age		
	18-60	>60	Prob > | t |
Midblock	1.41	1.19	0.002*
Signalized Intersection	1.35	1.03	0.001*

* Indicates significant difference in mean walking speeds.
1 m/sec = 3.3 ft/sec

TABLE 4 Test for Significance of Age on Pedestrian Crossing Speeds at Each Crossing Location

Ho: Walking speed at midblock = walking speed at signalized intersection
Significance level of t-test = 0.05

Age	Mean Speed, m/sec		Test Results
	Location		
	Midblock	Signalized Intersection	Prob > | t |
18 - 60	1.41	1.34	0.0176*
>60	1.19	0.99	0.0122*

* Indicates significant difference in mean walking speeds.
1 m/sec = 3.3 ft/sec

TABLE 5 Summary of Pedestrian Use of Medians for Refuge During Crossing Maneuver

Midblock	Raised	TWLT
Observations	164	591
Refuge	30	31
Percent	18.29	5.25

TABLE 6 Summary of Pedestrian Conflict Data Collection Activity

Area	Signalized Intersection			Midblock		
CBD	Raised	TWLT	Undivided	Raised	TWLT	Undivided
Conflicts	2	61	362	0	119	16
Hours	2.5	8.15	32.61	0	4	1.41
Locations	1	2	10	0	2	1
Suburban						
Conflicts	113	51	77	9	54	0
Hours	10	9.02	11.32	1.22	5.19	0
Locations	4	3	4	1	3	0

unless pedestrian and vehicle volumes are also available at the second location. The current technology in obtaining accurate pedestrian volume counts requires manual collection, which is time consuming and generally not performed by local agencies.

Pedestrian conflict data were obtained at 25 signalized intersections and midblock locations in both the CBD and suburban areas as summarized in Table 6. The majority of CBD observations were found at TWLT and undivided arterials because of the insufficient availability of raised medians in CBD areas.

Pedestrian-vehicle conflicts were categorized by the type of vehicle maneuver taking place at the time of the conflict. For example, a pedestrian stepping off the curb at the start of the green interval and incurring a conflict with a right-turning vehicle was classified as a right-turn conflict. Similarly, a pedestrian within the roadway at the start of the red interval and incurring a conflict with a through vehicle was categorized as a through conflict. This broad classification scheme had a number of advantages. First, it simplified the data collection task and removed judgment error prevalent with a large number of traffic conflict categories. Second, the scheme permitted comparisons of pedestrian conflict types with vehicle maneuvers from the accident data base on a site-specific basis. The conflict observations for signalized intersections are normalized by the total number of entering vehicles since conflicts were obtained from the four approaches simultaneously. Conflict observations for midblock locations are normalized by the ADT and the length of the effective visual field of the camera. Field measurements combined with the ability to view in both directions resulted in the use of a 0.16-km (1/10-mi) effective visual field.

Conflict rates at intersections were determined by assuming that the ADT of entering vehicle volumes was equally distributed throughout the 24-hr period. It is realized that the ADT is not equally distributed throughout the day and that it does not approximate the actual vehicles present during the conflict observations. The purpose in its use, as previously discussed, is to investigate the possible use of ADT as the base for conflict measures. This would facilitate use of the procedure by highway agencies. Conflict rates for midblock observations were obtained in a similar manner, with the exception that the effective visual field of the camera was used to obtain an estimate of miles. The equations used to obtain the conflict rates are presented below:

$$\text{Intersection conflict rate} = \frac{\text{Observed conflicts}}{\left(\frac{\text{ADT}}{24}\right)(\text{observation time})}$$

$$\text{Midblock conflict rate} = \frac{\text{Observed conflicts}}{\left(\frac{\text{ADT}}{24}\right)(\text{observation time})(\text{visual field})}$$

Table 7 presents the results of the statistical analysis to determine if differences existed in midblock and signalized intersection conflict rates between CBD and suburban areas. The purpose of this test was to determine if the increased pedestrian activity, typ-

TABLE 7 Statistical Difference in Pedestrian Conflict Rates Between CBD and Suburban Areas

Ho: Conflict rate at CBD = conflict rate at suburban
Significance level of t-test = 0.05

Location	Mean Rate		Prob > |t|	Significant Difference
	CBD	Suburban		
Midblock[1]	0.1920	0.0544	0.3118	no
Intersection[2]	0.0096	0.0068	0.5246	no

[1]Conflict rates for midblock locations in conflicts per vehicle-km.
[2]Conflict rates for intersections in conflicts per vehicle.
1 km = 0.62 mi

TABLE 8 Significant Difference in Type of Conflict Between Median Types

Ho: Conflict type raised = conflict type TWLT = conflict type undivided Significance level = 0.05						
Conflict Type	Mean Rate			Test Results		
	Raised	TWLT	Undiv	F	Prob > F	Significant
INTERSECTION[1]						
Right turn	0.0037	0.0026	0.0063	0.68	0.5153	no
Through	0.0014	0.0004	0.0010	0.0010	0.6676	no
Left turn	0.0021	0.0014	0.0014	0.0007	0.8417	no
MIDBLOCK[2]						
Through	0.0242	0.1396	0.3938	0.23	0.8038	no

[1]Intersection conflict rate in conflicts per vehicle.
[2]Midblock conflict rate in conflicts per vehicle-km.
1 km = 0.62 mi

ically found in CBD areas, could be used as a surrogate measure of pedestrian volume. The results of the test indicate that there were no significant differences between the conflict rates at CBD and suburban areas. The absence of a difference is probably more due to the project site-selection criteria (i.e., high pedestrian activity at both CBD and suburban locations) than to actual differences that may have existed by a random site-selection process.

Since there is no difference in the conflict rates between CBD and suburban locations, the conflicts were combined, retaining intersection and midblock stratification, for further analysis. Using analysis of variance (ANOVA), Table 8 summarizes the analysis to determine if there were significant differences in the type of conflict observed between median types at signalized intersections and midblock locations. Inspection of Table 8 indicates that there are no significant differences in the type of conflict observed between the different median types.

Pedestrian conflicts and pedestrian accidents at signalized intersections were analyzed to determine if there were statistically significant differences in vehicle maneuvers contributing to the conflict and accident rates between the median types. Only those pedestrian accidents that occurred at the same sites from which pedestrian conflict data were obtained were used in the analyses. Since the results of Table 8 indicated no statistical difference in conflict types between the different median types, an analysis was performed to determine if there were differences in vehicle maneuvers before vehicle-pedestrian accidents at the same locations used for the conflict analysis. The results of this analysis, presented in Table 9, indicate no significant difference in vehicle maneuvers between the different median types. The results of the vehicle-pedestrian conflict and accident analysis indicate, therefore, that the type of conflict and accident are not influenced by the type of median present.

The final step in the analysis of conflict data was to determine if there was a relationship between types of conflicts and types of accidents. A study by Migletz determined that a relationship did exist and developed a model to predict accidents on the basis of conflict observations (*12*). The relationship between conflict types and accident types for this project was determined by applying a paired-*t* analysis to the data of Table 9. Table 10 contains the site-specific rates for conflict and accident types observed at intersections. The analysis was not performed for midblock locations because of the difficulty in accurately locating the positions of accident occurrences. The results of the paired-*t* test, presented in Table 11, indicate rejection of the hypothesis, with 95 percent confidence, that mean conflict types and mean accident types are equal for left-turning vehicles. However, the data indicate a relationship between pedestrian conflicts and accidents for both through and right-turning types.

TABLE 9 Statistical Difference in Intersection Accident Maneuvers Between Median Types

Ho: Accident maneuver raised = accident maneuver TWLT = accident maneuver undivided Significance level = 0.05						
Conflict Type	Mean Rate[1]			F	Prob > F	Significant
	Raised	TWLT	Undivided			
Right turn	0	1.200	2.7115	0.67	0.5372	no
Through	5.2491	0	3.1608	0.86	0.4543	no
Left turn	0.5176	2.4002	9.1324	0.35	0.7134	no

[1]Accident rate per 100 million entering vehicles.

TABLE 10 Summary of Conflict Rates and Accident Rates by Vehicle Maneuver

Location No.	Conflict Rate (per 10^8 vehicles)			Accident Rate (per 10^8 vehicles)		
	LT	TH	RT	LT	TH	RT
1	1.4826	0.3955	0.9489	0	0	0
2	0.3053	0	0	0	8.4279	0
3	0	0.3053	0	0	8.4279	0
4	0	0.0435	0	0	4.1406	2.0703
5	0.2523	0.0505	0.1262	2.4002	0	4.8005
6	0.4634	0.0211	0.0211	0	0	0
7	2.6674	0.0363	1.4734	12.0142	0	0
8	1.9200	0.7200	0.2400	0	13.6986	54.7945
9	0.5031	0	0.0479	0	0	0
10	0.7682	0.1035	0.0205	0	0	0
11	0.8780	0	0.1244	4.2546	1.4182	0
12	0.0809	0	0	0	3.8479	0

TABLE 11 Paired Comparisons *t*-Test for Different Vehicle Maneuvers

Ho: (mean of conflict type) - (mean of accident type) = 0
Significance level = 0.05

Maneuver Type	t	Prob > |t|	Significant
Right	-1.85	0.0912	no
Through	2.13	0.0563	no
Left	-3.06	0.0108	yes

The analysis of conflicts and accidents indicates that there is no difference in the type of conflict observed among raised, TWLT, and undivided median types for either intersection or midblock locations. There is also no difference in the conflict rates observed between CBD and suburban environments. The absence of the difference between CBD and suburban locations may, however, have been due more to the selection of high-pedestrian-volume locations than to the environment. The data did indicate that there is a relationship between conflicts and accidents for through and right-turn types. This relationship should be verified by a larger study. If a definite relationship can be established, the use of ADT as a normalizing agent for conflicts and the use of conflict types to estimate accidents and develop countermeasures can be established.

CONCLUSIONS

The following conclusions on pedestrian walking speeds and conflicts are applicable to raised, TWLT, and undivided median arterials located in CBD and suburban environments. The conclusions are not applicable to rural environments or limited-access roadways.

- Pedestrians aged 18 to 60 years exhibit a significantly higher walking speed at TWLT medians for both signalized intersections and midblock locations (1.47 m/sec = 4.81 ft/sec, 1.46 m/sec = 4.79 ft/sec) than that exhibited at undivided median arterials (1.17 m/sec = 3.84 ft/sec, 1.19 m/sec = 3.90 ft/sec). Elderly pedestrians also exhibited higher walking speeds at TWLT signalized intersection locations, but the sample size of elderly pedestrian observations is too small for reliability. The increased walking speed for TWLT lanes may be due to the pedestrian perception of increased walking distance resulting from the presence of the TWLT lanes.
- The walking speed for the 18 to 60 age group is significantly higher than that of the over-60 age group for both signalized intersections and midblock locations. Both age groups have significantly higher walking speeds at midblock locations than at signalized intersections. This may indicate that pedestrians feel somewhat protected at signalized intersections and do not feel the same urgency to cross as they do at midblock locations.
- Pedestrian conflict data were obtained at 25 signalized intersections and midblock locations in both CBD and suburban areas. The majority of CBD observations were made at TWLT and undivided arterials because of the unavailability of raised medians

in CBD areas. Pedestrian-vehicle conflicts were categorized by the type of vehicle maneuver taking place at the time of the conflict.

- The analysis of conflicts and accidents indicates that there is no difference in the type of conflict observed among raised, TWLT, and undivided median types for either intersection or mid-block locations. There is also no difference in the conflict rates observed between CBD and suburban environments. The absence of the difference between CBD and suburban locations may, however, have been more due to the selection of high-pedestrian-volume locations than to the environment. The data did indicate that there is a relationship between conflicts and accidents for through and right-turn types. This relationship should be verified by a more comprehensive study. If a definite relationship can be established, the use of ADT as a normalizing agent for conflicts and the use of conflict types to estimate accidents and develop countermeasures can be established.

ACKNOWLEDGMENT

The partial results are presented of a project sponsored by the Federal Highway Administration of which Carol Tan was the COTR.

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Publication of this paper sponsored by Committee on Pedestrians.

PART 3

Older Drivers

Mature Driver Improvement Program in California

MARY K. JANKE

California's Mature Driver Improvement (MDI) Program offers insurance-premium reductions to older drivers completing an accredited driver-improvement course. Driving records of five cohorts (1988–1992) of course graduates and comparison drivers were analyzed. MDI subjects were volunteers; comparison subjects were sampled randomly from the automated driver file. Unadjusted 6-, 18-, and 30-month subsequent total crash rates of MDI and comparison drivers did not differ significantly between groups ($p < .10$, two-tailed) for any cohort or record length. Unadjusted fatal and injury crash rates showed significant differences in favor of the MDI group in the first two cohorts and a significant difference in favor of the comparison group in a later cohort. The unadjusted accident rates indicate no justification for offering insurance discounts to those completing the course after 1989. All between-group differences on unadjusted citation rates were significant, favoring the MDI group. Analyses of covariance showed, in two cohorts, significant differences favoring the comparison group on adjusted total crashes. In two cohorts there were significant differences on adjusted fatal and injury crashes, one favoring the MDI and one the comparison group. On citations all adjusted differences were significant, favoring the MDI group. Analyses of two cohorts' 6-month data using generalized two-stage least-squares regression indicated that program completion was associated with more total and fatal and injury crashes and fewer citations.

The Mature Driver Improvement (MDI) Program was established in California by legislation that went into effect on July 1, 1987. The intent of this legislation was to encourage older drivers (ages 55 and above) to update their driving-related knowledge by enrolling in a 400-min classroom driver improvement course. Upon completion of the course, participants would be entitled over the next 3 years to receive automobile insurance premium reductions. The amount of the discount was to be determined by the insurer on the basis of actuarial and loss experience data, and a discount could be denied to an individual whose record reflected certain types of violations or accidents.

The program has now been in effect for 6 years. The law establishing it mandated that the Department of Motor Vehicles (DMV) develop the course curriculum and accreditation procedures for schools wishing to teach the MDI course. It also required until very recently that DMV report yearly to the legislature, giving tabulations of accident and citation rates for course graduates and for drivers of similar age who had not taken the course. Five such reports have been published, and the present paper gives an overview of their findings. First, however, the course curriculum and its rationale will be discussed.

From California Vehicle Code (CVC), Section 1675, the course curriculum is to include, but not be limited to, the following:

California Department of Motor Vehicles, Research and Development Section, 2415 First Avenue, Sacramento, Calif. 95818.

1. How impairment of visual and audio perception affects driving performance and how to compensate for that impairment.
2. The effects of fatigue, medications, and alcohol, when experienced alone or in combination, on driving performance and precautionary measures to prevent or offset ill effects.
3. Updates on rules of the road and equipment including, but not limited to, safety belts and safe and efficient driving techniques under present-day road and traffic conditions.
4. How to plan travel time and select routes for safety and efficiency.
5. How to make crucial decisions in dangerous, hazardous, and unforeseen situations.

It was obvious to the DMV task force planning the curriculum that the problems of older drivers are very different from those of young drivers, "negligent operators" under California law, and the majority of persons taking a driver improvement course as part of the traffic violator school program for drivers who have been cited for a minor violation. The principal violation for the above groups is unsafe speed; older drivers, in addition to having a low violation rate relative to the driving population as a whole, are relatively unlikely to speed and relatively likely to incur right-of-way and sign-and-signal violations, particularly at intersections (*1*). More fundamentally, deliberate risk-taking and aggressiveness are not important factors in the behavior of older drivers; therefore a course curriculum aimed at this group should be very different from that aimed at young and "negligent" drivers.

From Janke (unpublished data), the following additional curriculum suggestions were listed:

- Older drivers should be reminded to receive periodic medical and vision examinations and to comply with their physicians' recommendations.
- They should be reminded to be even more careful than the average driver to leave a "space cushion" around their vehicles, giving them more time to react to evolving traffic situations.
- They should be encouraged to avoid (as they tend to do in any case) high-risk situations. As an example, they should avoid night driving, in which age-related declines in low-luminance acuity, contrast sensitivity, and tolerance of glare may pose a threat.
- They should be informed of traffic laws of which they may not be aware. For example, some older California drivers tend to expect passing drivers to be on their left and do not anticipate vehicles passing on their right.
- If they drive more slowly than surrounding traffic, they should be encouraged to stay to the right when possible, to mitigate the frustrations of other drivers. An exception (in addition to left turns) would be on California freeways, where the extreme right lane is a merging lane.

- They should be encouraged periodically to assess their own perceptual and psychomotor skills, in order to detect declines of aging and, if possible, compensate for them.

The curriculum as it finally evolved included as mandatory topic areas health and age-related physical changes as they affect driving performance, the effects on driving performance of medications and alcohol, rules of the road and defensive driving countermeasures, trip planning, and handling hazardous conditions. (The last topic included how to drive in fog, what to do when one's vehicle stalls, how to drive on slippery surfaces, and so forth.) Elective topic areas were also suggested, such as recreational vehicle safety and deciding when to stop driving. Course providers submit their lesson plans to DMV; these must follow the curriculum outline in order for the course to be accredited. MDI courses are monitored by the department, and in addition there has been a continuing series of legislatively mandated assessments of the subsequent driving records of course graduates.

With regard to assessment, the law had never required an evaluation of the course's traffic safety effect, asking only for comparative tabulations of the records of course graduates and of a comparison sample who had not taken the course. In fact, the program as established did not allow any definitive assessment of effect, since participation in the MDI program was voluntary, giving ample opportunity for self-selection bias to occur. To reduce the magnitude of such bias and add precision to the analysis, several covariates were used; their use will be described below.

Any traffic safety effect of such a course in terms of crash reduction was considered moot in light of a body of evidence, reviewed by Lund and Williams (*2*), suggesting no effect of defensive driving courses (DDCs) on crashes and only a slight effect (though in the desired direction) on violations. These authors noted that the general failure to show efficacy of DDCs against crashes is not because nothing was learned—on the contrary, the courses did seem to impart their intended knowledge. The difficulty, they believed, is that individual drivers taking such courses may have had little intention of changing their driving habits sufficiently to modify their accident risk. Drivers may take such a course for reasons extraneous to a concern for safety—because a court or employer has ordered them to or (relevant to the MDI program) to obtain an insurance discount. In the case of elderly drivers particularly, accidents are likely to be due to declining ability, probably not a factor that can be easily rectified by means of classroom instruction.

METHODOLOGY

The methodology of all five studies was essentially the same. For example, in the first study (*3*) the program graduate (MDI) group consisted of (all) drivers aged 55 or above who completed the MDI course between July 1, 1987, and June 30, 1988; later studies addressed successive yearly cohorts of first-time course graduates. Drivers who, at the time of selection, had never taken the course (the comparison group) were obtained by randomly sampling the department's automated driver file for drivers aged 55 or above and discarding any whose records showed that they had completed the program.

The date upon which an enrollee completed the course was considered to be his or her reference or "zero" date for determining prior and subsequent driving record. Drivers in the comparison group were randomly assigned the same reference dates as those in the MDI group, thus creating equivalent time windows within which to track the records of both groups.

In all five studies, 6-month post-course driving record variables for that year's cohort and follow-up driving record data for earlier cohorts (if any) were analyzed in two ways. In the first type of analysis, the groups were compared on unadjusted (raw) rates per time period of total accidents, fatal and injury (F/I) accidents combined, and total traffic citations, which appeared on the record as convictions, failures to appear in court or forfeit bail in connection with a citation (FTAs), or dismissals of a charge in consideration of attendance at a traffic violator school (TVSs).

Unadjusted accident and citation mean differences represented the net actuarial differences associated with MDI course completion. They were thus the differences in which insurers would be most interested, that is, those establishing whether a premium reduction was justified. Unadjusted rates were analyzed by means of one-way analyses of variance (ANOVAs) with treatment group as the sole factor.

In the second type of major analysis, covariate-adjusted rates on the same three dependent variables were analyzed in one-way analyses of covariance (ANCOVAs), again with treatment group as the sole factor. The covariates used were age, license class, gender, numbers of prior traffic accidents and citations, and ZIP code income, accident, and citation means (the latter being aggregated variables representing not individual subjects but their areas of residence). The alpha level used in all analyses was .10, two-tailed.

Stylos and Janke (*3*) analyzed 6-month subsequent driving record data for the first cohort of MDI drivers, who took the course in 1987–1988 (the 1988 cohort). In succeeding analyses (*4–7*), another year's worth of post-course data was added to the driving records of earlier cohorts and analyzed, along with the 6-month subsequent data for that year's cohort, in the manner described above. In the 1992 study, the 1988 cohort of Stylos and Janke (*3*) was dropped from the analysis after 30 months of follow-up, and in the 1993 study the 1989 cohort of Berube and Hagge (*4*) and the 1990 cohort of Foster (*5*) were dropped as well, after 30 months and 18 months of follow-up, respectively.

In follow-up analyses of previous MDI and comparison cohorts there was always some loss of subjects through attrition, and comparison group drivers who had taken the course within the preceding year were of course dropped. Therefore covariates were recalculated each year for use in the ANCOVAs. The same covariates were used in the follow-up analyses as had been used in the 6-month analyses, the only exception being elimination of the ZIP code income covariate from the 1993 analysis because it was based on outdated 1980 census figures and 1990 figures were not yet available.

In extracting driver records, a full 3-month buffer was added to the end of the period being monitored to ensure getting a complete, or almost complete, record of the time length indicated. Otherwise the actual driving record length would have been shorter than its nominal length, because of the time lag between occurrence of an accident or issuance of a citation and update of the incident on the automated driver file.

Although not all were included in reports to the legislature, some supplementary analyses of the data were conducted. Those that were included were Foster's (*5,6*) comparisons, by means of two-way ANOVA and ANCOVA, of previous study cohorts on their 6-month driving records. The factors were treatment group and year, and the analyses were done in order to determine whether the outcomes of the separate studies (the relative positions of the groups) varied significantly over time. The reason for making these comparisons only on the 6-month data was the expectation that training effects would be most likely to reveal themselves immediately following the course.

In supplementary analyses not included in the legislative reports, 6-month data from two cohorts, those of 1988 and 1991, were analyzed by means of a generalization of two-stage least-squares regression (*8*). Two-stage least squares is a technique used in econometrics (*9*); here the generalized version was applied because both assignment and outcome were (essentially) discrete. The rationale underlying use of this method was that in the MDI evaluations several important and potentially biasing variables were not measured, nor were they controlled through random assignment. Some of these variables were quantity and quality of risk exposure and the social responsibility and safety-related attitudes of the driver. Since some unmeasured or "latent" variables influenced both outcome and (self-) assignment to groups, the ordinary least squares (OLS) regression algorithm used by the ANCOVA computer program was not totally applicable; under such circumstances it commonly produces inconsistent (biased) estimators of treatment effects.

Two-stage least squares, an alternative procedure considered to be better under these circumstances, begins by developing two equations for each dependent variable, one representing assignment (treatment group) as a function of independent or exogenous variables and the other representing the outcome variable as a function of these exogenous variables (minus at least one "excluded variable"; see following paragraph) plus the assignment variable. This procedure allows the error terms in both equations to be correlated because of the presence of latent variables common to both. Similarly, the assignment variable itself is correlated, through its error term, with the error term in the outcome equation, again because of the latent variables affecting both assignment and outcome. In order to achieve consistent parameter estimates the error component must be eliminated from the assignment variable, and this is done by using predicted assignment rather than assignment per se in the outcome equation (*8*).

In addition, for the two-equation system to be identified (*10*)—meaning, in general, that no equation in a system is expressible as a linear combination of the remaining equations—at least one of the covariates from which assignment is predicted is chosen to be an excluded variable by virtue of its (relatively) high correlation with assignment and its (relatively) low correlation with outcome. The variable is designated as excluded because it enters into the outcome equation only through its contribution to predicted assignment; it is not included in the outcome equation in its own right. Results of the generalized two-stage least-squares procedure were compared with those of OLS analysis.

RESULTS

Prior Incident Rates

Table 1 shows 3-year prior rates per 100 drivers for total accidents, F/I accidents, and total citations. As shown, before taking the course, MDI subjects consistently evidenced a rate of traffic citations significantly lower than that of comparison subjects. In addition, where differences occurred on F/I accidents, the MDI group was either directionally or significantly superior to—that is, had a lower rate than—the comparison group. Total accidents, however, showed a different picture. In two cohorts the MDI group rate was significantly higher than the comparison rate, and in the remaining cohorts the MDI group was directionally though not significantly inferior.

Factors that may be related to these differences were the sex composition of the groups—the MDI group was predominantly (about 60 percent) women, the comparison group more than 50 percent men; the license class composition of the groups—though few commercial drivers were represented in either group, MDI subjects were even less likely than comparison subjects to hold heavy-vehicle operator licenses; and the groups' average ages—for each cohort, these were about 69 for the MDI group and 66 for the comparison group at the time they first took the course. These factors would be expected (arguably, in the case of age) to favor the MDI group in driving record comparisons (*11*). On the

TABLE 1 Three-Year Prior Driving Record of Treatment Groups Within Cohort

Cohort Group	Number	Rates per 100 drivers: Total Accidents	F/I Accidents	Citations
1988				
MDI	40,399	11.66	2.78*⁻	15.70*⁻
Comparison	75,064	11.33	2.97	23.40
1989				
MDI	45,520	12.04*+	2.97	15.79*⁻
Comparison	75,034	11.61	2.99	22.66
1990				
MDI	36,075	11.88	2.93	14.55*⁻
Comparison	65,620	11.67	2.93	21.78
1991				
MDI	38,719	11.80	2.83*⁻	15.51*⁻
Comparison	76,192	11.70	3.10	22.19
1992				
MDI	36,739	12.18*+	3.03	17.27*⁻
Comparison	75,082	11.28	3.03	22.64

Note: $*^{+}$ indicates a statistically significant ($p<.10$) difference; MDI rate greater than comparison rate.
$*^{-}$ indicates a statistically significant ($p<.10$) difference; MDI rate less than comparison rate.

other hand, MDI graduates were probably more likely to have vehicle insurance, by the nature of the course incentive, and therefore may have been more likely to report their property-damage-only (PDO) accidents to DMV. (Unlike PDO accidents, F/I accidents are generally reported by law enforcement, even if the involved driver does not report them.)

Unadjusted Subsequent Rates

Unadjusted subsequent rates per 100 drivers are shown in Table 2. As noted, these comparisons show actuarial differences, the ones an insurance company would find most interesting in deciding whether a group discount was justified. Across cohorts and time intervals (6 months, 18 months, and 30 months of follow-up) there were no significant differences on total accidents and no pervasive directional trend of obtained differences. On F/I accidents, there were significant differences in favor of the MDI group in the first two cohorts only; in later cohorts the only significant difference—in favor of the comparison group—appeared in the 6-month results for those taking the course in 1991. However, there were consistent significant differences across cohorts and time intervals in favor of the MDI group on citations.

Adjusted Subsequent Rates

The self-selected groups differed in many dimensions, some of which have been noted. To reduce bias and increase precision, incident rates were adjusted by means of the OLS algorithm for the covariates listed above in the Methodology section. Such adjustment, it was believed, would not enable strong inferences of cause-and-effect to be made in regard to the link between treatment and outcome but would make causal speculations more plausible than they would have otherwise been. Adjusted rates for the three dependent variables are shown in Table 3.

On total accidents, there were significant differences after adjustment only in two cohorts—1989 (at 30 months) and 1991 (at 18 months). These favored the comparison group. Two cohorts showed significant differences on F/I accidents, each difference occurring during the first 6 months after course completion. These differences were in opposite directions, that in the 1988 cohort favoring the MDI group and that in the 1991 cohort favoring the comparison group. Only on citations were there pervasive significant differences, in favor of the MDI group, in all cohorts and for all follow-up periods.

Analyses of Consistency of Study Results

In his 1991 report, Foster (*5*) compared the 1988, 1989, and 1990 cohorts on the 6-month criterion measures, seeking interactions between treatment group and year. His only significant finding was that for unadjusted F/I accidents there was evidence for a difference in study outcomes (p = .09) over the 3 years compared. This was attributed to the superior performance of the MDI group in the 1988 cohort. In Foster's (*6*) 1992 report, the 1988 cohort was dropped and the 1989, 1990, and 1991 study outcomes were compared. In that analysis he found no significant differences over time.

G2SLS Analysis Results

As mentioned above, 6-month data for two cohorts, those for 1988 and for 1991, were analyzed by means of generalized two-stage least-squares (G2SLS) regression (*8*). (The generalized method was used in place of two-stage least squares, or 2SLS, because assignment was dichotomous and outcome essentially so. Use of two-stage least squares, appropriate for continuous variables, would in this case have resulted in consistent estimators but incorrect standard errors of the estimators.)

For both cohorts, Exuzides and Peck (*8*) chose subject's age at reference date as the excluded variable because it had relatively high correlations (around .20) with assignment and relatively low correlations (ranging from .00002 to .05) with specific outcome

TABLE 2 Unadjusted Subsequent Accident and Citation Rates per 100 Drivers

Cohort Group	Total Accidents			Fatal/injury accidents			Citations		
	6 months	18 months	30 months	6 months	18 months	30 months	6 months	18 months	30 months
<u>1988</u>									
MDI	1.74	5.72	9.16	0.41*-	1.41*-	2.31*-	2.10*-	6.33*-	10.56*-
Comparison	1.86	5.53	9.36	0.51	1.56	2.54	3.21	9.53	15.66
<u>1989</u>									
MDI	1.94	5.70	9.58	0.52	1.40*-	2.33*-	2.03*-	6.08*-	10.47*-
Comparison	1.92	5.77	9.50	0.51	1.52	2.54	3.22	9.57	16.04
<u>1990</u>									
MDI	1.92	5.67	--	0.50	1.40	--	2.05*-	6.69*-	--
Comparison	1.94	5.64	--	0.52	1.53	--	3.38	10.25	--
<u>1991</u>									
MDI	1.88	5.42	--	0.53*+	1.31	--	2.39*-	6.69*-	--
Comparison	1.82	5.23	--	0.46	1.37	--	3.50	10.00	--
<u>1992</u>									
MDI	1.82	--	--	0.44	--	--	2.15*-	--	--
Comparison	1.84	--	--	0.51	--	--	3.23	--	--

<u>Note</u>: *+ indicates a statistically significant (p<.10) difference; MDI rate greater than comparison rate.
*- indicates a statistically significant (p<.10) difference; MDI rate less than comparison rate.

TABLE 3 Adjusted Subsequent Accident and Citation Rates per 100 Drivers

Cohort Group	Total Accidents			Fatal/injury accidents			Citations		
	6 months	18 months	30 months	6 months	18 months	30 months	6 months	18 months	30 months
1988									
MDI	1.79	5.73	9.42	0.42*-	1.47	2.38	2.52*-	7.43*-	12.37*-
Comparison	1.84	5.52	9.10	0.50	1.50	2.47	2.99	8.43	13.85
1989									
MDI	2.00	5.84	9.78*+	0.53	1.43	2.39	2.38*-	7.13*-	12.28*-
Comparison	1.86	5.63	9.30	0.50	1.49	2.48	2.86	8.52	14.24
1990									
MDI	1.94	5.78	--	0.51	1.42	--	2.45*-	7.93*-	--
Comparison	1.92	5.52	--	0.51	1.51	--	2.98	9.01	--
1991									
MDI	1.91	5.56*+	--	0.54*+	1.37	--	2.76*-	7.85*-	--
Comparison	1.78	5.09	--	0.45	1.31	--	3.13	8.84	--
1992									
MDI	1.86	--	--	0.46	--	--	2.48*-	--	--
Comparison	1.80	--	--	0.49	--	--	2.89	--	--

Note: *+ indicates a statistically significant ($p<.10$) difference; MDI rate greater than comparison rate.
*- indicates a statistically significant ($p<.10$) difference; MDI rate less than comparison rate.

variables. They also presented results using both ZIP code average income and age as excluded variables, but the correlation of income with assignment was very low (about .03 in each cohort), and its use together with age led to somewhat less interpretable results.

Table 4 shows, for the 1988 cohort's subsequent 6-month data on each dependent variable, treatment coefficients (effect sizes), their standard errors, and their t- and p-values for OLS and G2SLS.

A significant association between treatment and increased total accidents was shown by G2SLS. Although the treatment coefficient obtained using the OLS approach was in the opposite direction, it was far from significant. Both methods showed a significant association with F/I accidents, but the regression parameters had opposite signs. The OLS analysis showed the program to be associated with fewer F/I accidents, as described above, whereas the G2SLS analysis showed the reverse. On citations the findings were similar irrespective of method—a significant association with fewer citations.

It will be recalled that the ANCOVAs for the 1991 cohort showed significantly greater total and F/I accident rates for the MDI group at 18 months and 6 months, respectively, as well as significantly fewer citations in both follow-up periods. Application of the G2SLS methodology to the 6-month data gave the results shown in Table 5.

For total accidents, there was a highly significant positive association (i.e., increased accidents associated with course completion) according to the G2SLS analysis, but no association according to the OLS (ANCOVA) analysis, although the direction of both results was the same. For F/I accidents, both types of analy-

TABLE 4 1988 Cohort: 6-Month Data [adapted from Exuzides and Peck (8)]

Excluded variable	Age	
	OLS	G2SLS
Total accidents		
Treatment coefficient	-.00044	.0218
Standard error	.00084	.0039
t-value	-.519	5.52
p-value	.6036	<.0001
Fatal/injury accidents		
Treatment coefficient	-.00085	.0057
Standard error	.00044	.0021
t-value	-1.94	2.65
p-value	.0522	.0080
Total citations		
Treatment coefficient	-.0047	-.0109
Standard error	.0010	.0046
t-value	-4.57	-2.80
p-value	<.0001	.0173

TABLE 5 1991 Cohort: 6-Month Data [adapted from Exuzides and Peck (*8*)]

Excluded variable	Age	
	OLS	G2SLS
Total accidents		
Treatment coefficient	.00129	.0142
Standard error	.00083	.0035
t-value	1.55	4.12
p-value	.1205	<.0001
Fatal/injury accidents		
Treatment coefficient	.00102	.0035
Standard error	.00044	.0019
t-value	2.35	1.89
p-value	.0187	.0591
Total citations		
Treatment coefficient	-.0048	-.0220
Standard error	.0011	.0043
t-value	-4.43	-5.18
p-value	<.0001	<.0001

ses showed significant positive associations. The usual significant negative association with citations was apparent in both the OLS and G2SLS analyses.

DISCUSSION OF RESULTS

As seen above, the association of MDI course completion with citation reduction (relative to comparison drivers' performance) was pervasive throughout. It is true that MDI subjects also had significantly fewer citations in the 3 years before taking the course, but their superiority on this measure was shown on covariate-adjusted rates as well as unadjusted ones, suggesting that the program may reduce citations. On the other hand, Exuzides and Peck (*8*) wrote that this outcome should be regarded as questionable, noting the conflicting testimony of the accident data and also that the correlations of the excluded variable, age, with citations (magnitudes of .03 and .05 for the 1988 and 1991 cohorts, respectively) were large relative to the small size of the treatment effects. (Under the G2SLS model, these correlations optimally should have approached zero. In addition, the correlations of age with assignment were not high, being about .20.) Therefore, the authors concluded, the results could reflect a self-selection bias that was not removed by either the OLS or the G2SLS analysis. In fact, it is possible that there is no good candidate for an excluded variable in the MDI data, thwarting the attempt to minimize bias through a G2SLS analysis.

But if the program did in fact decrease citations, this would not necessarily be inconsistent with a failure to decrease accidents, as shown by the ANCOVA results in Table 3. Investigators (*12*) have often found educational programs to reduce traffic citations without reducing accidents. However, a significant increase in accidents with a decrease in citations may be an unprecedented finding, which, if real, is difficult to explain. Such an increase, in both total and F/I crashes, was shown in the subsequent 6-month data for both the 1988 and 1991 cohorts, using the G2SLS analytic method. The paradoxical nature of the results appears when it is considered that citations constitute the best predictor of crashes overall (*13*) and are often interpreted as an indicator of mileage or, in general, exposure to crash risk. More specifically, however, citations can be considered to index the amount of unlawful driving, which is not necessarily the same as the amount of driving per se.

The paradoxical outcome was found in the 2SGLS analysis; the ANCOVA results support it only to a limited extent. Citation rates of the MDI group, as seen above, were consistently significantly lower than those of the comparison group irrespective of analytic method. Using ANCOVA, on the total-accidents measure the MDI group was never found to have a significantly lower rate than the comparison group; directional trends, with one exception (the 6-month data for the 1988 cohort), favored the comparison group, and significant increases in accidents for MDI relative to comparison subjects were found in the 30-month data for the 1989 cohort and the 18-month data for the 1991 cohort. However, the picture was not as negative for F/I accidents, where the results might properly be described as mixed, being more favorable to the MDI group in the first two cohorts than in later ones. Where results of the two analytic methods are discrepant, there is reason to believe that the G2SLS analysis may be more valid; its purpose is to better control for latent (unmeasured) variables causing selection bias, and such uncontrolled bias—stemming in part, perhaps, from greater social responsibility and safety-consciousness among persons taking the course, especially when it first became available—may have accounted for the discrepant results. If it is accepted that the G2SLS analysis is in fact more valid, the paradoxical finding requires explanation.

Along these lines, and entering the realm of speculation, two factors may have been operative, either separately or (more likely) in combination. One of these is cause. Completing the course may have increased graduates' confidence in their driving abilities and caused them to drive more or in more challenging situations, exposing themselves to greater crash risk; at the same time it may have increased their knowledge of traffic laws and their motivation (possibly already high, considering the prior data) to obey these laws. Under this scenario it is conceivable that the course could increase exposure to accident risk but decrease citations—which, as mentioned, reflect not only exposure but law violation. Perhaps the crashes of MDI graduates were more often nonculpable than those of comparison subjects; these incidents might more likely have been mediated simply by inability to avoid dangerous situations caused by others, perhaps in part because of slowed responses due to aging or to other impairments of aging. Under this scenario, MDI graduates' accidents would not as likely (relative to comparison subjects') have been caused by explicit law violations, nor would these graduates have been so likely in general to violate laws and incur citations.

The second factor is uncorrected bias. This is the tentative explanation invoked by Exuzides and Peck (*8*), who suggested in particular that the finding of decreased traffic convictions was dubious. Even if this finding is accepted as valid, however, uncorrected bias could still have been operative. Under the bias scenario the favorable characteristics of MDI subjects—hypothesized to have been more socially responsible and safety-conscious, on the average, than comparison subjects—could have led to fewer citations and more consistent reporting of PDO accidents to the authorities, as California law requires. This would lead to an artifactual appearance of more total accidents for MDI subjects than would otherwise be the case, but would not imply any increase relative to the comparison group in F/I crashes. It will be recalled that the ANCOVA results were mixed on F/I accidents and more negative in the case of total accidents, consistent with the hypothesized greater preexisting propensity of MDI subjects to obey the law by reporting their PDO crashes.

These patterns existed in the prior data as well, and it seems entirely possible that in the ANCOVA analysis some residual uncorrected bias remained. Analysis of the 6-month data using a "better" statistical technique (G2SLS) did not alter conclusions regarding citations (in fact, effect sizes became larger), but changed a significant reduction in F/I crashes to a significant increase (1988 cohort) while confirming the ANCOVA analysis by finding a significant increase for the MDI relative to the comparison group in the 1991 cohort. G2SLS methodology also found previously undetected significant increases in total accidents for the MDI group relative to the comparison group in both cohorts. Even though the 1988 MDI group, who took the course when it was first offered, was the one hypothesized to be most "select" through inclusion of especially safety-conscious drivers, the significant F/I reversal for this cohort is particularly difficult to explain if reduction of the resulting bias favoring the MDI group was the only factor involved. If (again) it can be assumed that the G2SLS analysis using age as the excluded variable is more correct than the ANCOVA, then it seems that a causal factor, most likely increased risk exposure, may have led to increased accidents for MDI drivers, the finding emerging only after bias had been reduced more effectively.

The above has been highly speculative. Abandoning such speculation, at a minimum the conclusion to be drawn from this series of studies must be that course completion is not associated with a reduction in crashes. There was initially an actuarial justification for offering an insurance discount to course graduates, apart from any consideration of cause. However, no such justification has been shown for cohorts taking mature driver training for the first time after 1989.

It should be noted that the G2SLS analysis, though it is more mathematically correct and adds plausibility to causal inferences, does not in itself definitively show cause. It could do so only if all of the variables influencing both assignment and outcome were controlled, as would be the case in a large-sample randomized experiment; such was not the case here.

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Publication of this paper sponsored by Committee on Safety and Mobility of Older Drivers.

Effect of Age and Visual Impairment on Driving and Vision Performance

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The effects of age and visual impairment on driving and visual performance were investigated for a sample of 46 subjects including 10 young visually normal subjects, 18 elderly visually normal subjects, and 18 elderly subjects with early cataracts. Driving performance was assessed on a closed-road circuit for a series of driving tasks including peripheral awareness, maneuvering, reversing, reaction times, speed estimation, road position, and time to complete the course. Visual performance was assessed using disability glare tests, Pelli-Robson letter contrast sensitivity (CS), a measure of the useful field of view (UFOV), and simple and forced-choice reaction times. The results showed that group (young normals, elderly subjects with normal vision or with cataracts) had a significant effect ($p < 0.05$) on driving and vision. The cataract subjects had poorer driving performance ($p < 0.05$) than either the elderly or young normal subjects, and the elderly subjects had poorer driving performance ($p < 0.05$) than the young. Similarly, the visual performance of the elderly subjects (with or without cataracts) was significantly worse ($p < 0.05$) than that of the young subjects. The elderly subjects had higher disability glare, poorer letter CS, and reduced ability on the UFOV task. These findings indicate that elderly subjects have poorer driving performance than young subjects and those with cataracts have still more difficulties, even though the cataract subjects had visual acuity ≥ 6/12 and were therefore eligible to drive. These changes were reflected by reduced visual performance.

The community is aging. This new generation of elderly persons considers driving to be a right rather than a privilege and are likely to continue to drive well into old age, resulting in a significant increase in the number of elderly road users. This is important because elderly drivers have more traffic convictions and accidents per kilometer driven than any other age group (*1*) and are more often involved in accidents at intersections and when making right turns, failing to yield at Stop signs, and being inattentive, and are more frequently cited as being at fault (*2*).

A number of studies have investigated specific aspects of driving performance in older individuals, and these have suggested that elderly drivers have slower reaction times (*3*), less accurate platoon-car following (*3*) and poorer merging behavior at junctions (*4*) than do young drivers. However, there are a number of methodological problems associated with these studies. Most have been undertaken using laboratory simulations of driving or at isolated road sites that do not represent the complexity of the driving task. Other studies have derived self-reported information on elderly drivers by questionnaire-based measures and show that elderly drivers report problems with a number of driving tasks including lane changing, intersections, nighttime driving, unexpected appearance of other vehicles, and reading signs (*5,6*).

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Since driving is a highly visual task, it has been suggested that the increased accident rate of the elderly may arise in part from age-related changes in vision. With age the lens becomes yellow and less transparent, the pupil becomes smaller and loses its ability to dilate in dim light, and the integrity of the macular pigment and neural pathways is altered. These changes lead to decreased light sensitivity, increased glare sensitivity, reduced visual acuity, and prolonged dark adaptation. In addition, the incidence of visual impairment arising from eye disease increases significantly in elderly populations, with cataracts, macular degeneration, and glaucoma representing the leading causes of visual impairment (*7*).

Central visual acuity is the visual attribute most commonly screened for driving eligibility; however, the level of acuity and the frequency of testing varies from country to country and state to state. Though some studies support a relationship between vision and driving, there is no strong evidence to suggest that increased accident rates result from reduced vision. Indeed, only weak correlations have been shown between accident rates and either visual acuity (*8*) or visual fields (*9*), although other studies have reported a strong relationship between driving and visual field extent (*10,11*). The inconsistencies in these findings are likely to arise in part from differences in the methods employed, both in assessing driving performance and in measuring visual function. Council and Allen (*9*), for example, used a relatively crude technique to assess the visual fields, whereas Johnson and Keltner (*10*) used a perimeter that has been shown to be more accurate and reliable. Similarly, the measures employed to assess driving performance vary widely between studies. With the exception of studies such as that of Wood and Troutbeck (*11*), driving performance has been assessed by laboratory simulations or by self-reported or state-registered accident rates. Laboratory simulations may bear little relationship to on-road driving conditions and do not simulate the risks incurred in driving on road systems. Although accident rates are only a partial index of driving ability because many accidents remain unreported, the correlation between self-reported accident rates and state-registered accidents is poor (*12*).

Alternatively, it may be that the increase in elderly drivers will not compromise road safety, since aging drivers are believed to reduce their driving frequency. However, Jette and Branch (*13*) in a recent longitudinal study demonstrated that older drivers continue to drive as long as possible and resist change to their preferred mode of travel. Self-regulation could be more efficient if older drivers were made aware of which of their abilities were impaired relevant to driving. Owsley et al. (*12*) found that drivers who had been informed by their eye care specialist of significant eye health problems (such as cataracts or severe visual field loss) tended to avoid difficult driving situations. Thus being informed of visual impairment can be a persuasive means to achieve self-regulation, highlighting the need for studies to determine the effect of visual impairment on driving performance.

The overall aim of these ongoing studies is to test the hypothesis that age-related changes in visual function contribute to the alleged decrement in driving performance in elderly drivers. A unique methodological design was used to investigate this hypothesis, which incorporated assessment of driving performance under closed-road conditions rather than being derived indirectly from accident statistics. Vision was measured using functional tests that better reflect the normal visual environment than the simple letter tests currently employed by license testing centers.

SUBJECTS

Subjects were volunteers recruited through advertisement in a motoring magazine. All subjects were required to have distance visual acuity of 6/12 or better, to be in good health, and to be holders of a current driver's license.

In the study so far, 46 subjects have been tested, including 10 young subjects (mean age, 22.6 years; SD, 4.3 years) and 36 elderly subjects 18 of whom had normal vision (mean age, 67.7 years; SD, 3.3 years) and 18 of whom had a range of early cataracts (mean age, 68.6 years; SD, 4.2 years). Classification of the elderly subjects into either the visually normal or the cataract category was undertaken by a visual examination before the first session, in which a full case history was taken and ocular health assessed by biomicroscopy and ophthalmoscopy. Normal subjects had clear lenses by biomicroscopy and ophthalmoscopy and visual acuity $\geq$ 6/7.5. Cataract subjects had lens opacities as assessed by biomicroscopy and ophthalmoscopy and visual acuity $\geq$ 6/12.

Each subject was required to participate in two sessions on separate occasions, which included a driving assessment in the field and a visual function assessment in the laboratory. Written informed consent was obtained from each participant after the nature and purpose of the study had been fully explained, with the option to withdraw from the study at any time.

METHODS

Assessment of Driving Performance

Driving was assessed on a closed-circuit driving course that has been employed in previous studies of vision and driving (*11*). This circuit comprises a standard bitumen road surface including hills, bends, and straight stretches. The circuit was designed to permit the assessment of specific aspects of driving performance including those discussed in the following paragraphs.

Peripheral Awareness

As they drove around the circuit, subjects were required to report and identify any road signs or individuals seen. These included 19 standard road signs, 6 of which contained two extra pieces of information, which were changed between runs to minimize familiarity effects. Two individuals were also positioned at the roadside, and their location along the track was changed between runs. Peripheral awareness was given as an error score for the number of items of information not reported or identified.

Reaction Times

Two light-emitting diodes (LEDs) were located within the car, one positioned directly in front of the driver on the dashboard and the other at 30 degrees temporal to the left eye. The LEDs were linked to a timing mechanism connected to the brake pedal and a control box that the examiner operated. On illumination of the LED, the driver was required to lightly press the brake pedal as quickly as possible and the response time was recorded. Each LED was illuminated five times on average during each run, with the order and timing of LED presentation randomized and reaction time given as a mean value averaged throughout the course.

Speed Estimation

Subjects were instructed to drive at 60 km/hr (37 mph) along a straight flat stretch of the circuit while the view of the speedometer was obscured from the driver. The mean speed driven during that period was recorded. During the practice runs, the speedometer was visible to the drivers to familiarize them with the task and how the car performed when traveling at that speed.

Road Position

The road position of the car was recorded throughout each run by a video camera positioned within the car and directed backward. The resulting videotapes were analyzed by taking measurements of vehicle position relative to the markings at the edge of the road at three right turns, three left turns, and three straight stretches of the course. Five measurements were made at each location, giving a total of 45 measurements for each run.

Driving Time

The time to complete the course, excluding the maneuvering and reversing tasks, was recorded for each run.

Maneuvering

Subjects were required to drive through a series of cones positioned on a wide flat section of the course. A number of different arrangements of cones were tested to determine the optimum arrangement, whereby the level of difficulty was great enough to avoid a ceiling effect and could be easily reproduced from week to week of the study. Subjects were instructed to drive as quickly as possible through the maneuvering course without touching any of the cones. Each cone touched or knocked over was recorded by an examiner outside the car and given as an error score. The time taken to complete the maneuvering task was also recorded.

Reversing

Subjects were required to reverse into a standard parking bay as quickly and as accurately as possible. The distance from the outer edge of each of the tires to the inside border of the white lines delineating the parking bay was measured to calculate the straightness (expressed as an angle) and centrality of parking within the bay. The time taken to complete the reversing task was also recorded.

Research Vehicle

The car employed for these studies was instrumented to record its location and to assess various aspects of driving performance. Two LEDs were mounted within the car to provide the stimuli for the reaction time task and were linked to the brake pedal so an accurate measure of the time between illumination of the LED stimulus and braking could be made. A video camera was mounted in the back of the vehicle to record the road position of the vehicle along the driving course. The vehicle had automatic transmission and was selected in preference to a vehicle with manual control to increase the number of subjects eligible to participate in the study.

Procedures

Each subject was given several practice runs around the circuit (each circuit takes approximately 5 min to complete) until they were familiar with the car, the road circuit, and the driving tasks. This was followed by the recorded run, in which subjects were required to drive once around the circuit.

Assessment of Visual Performance

A battery of tests of visual function was employed, including a measure of functional fields, low contrast acuity, disability glare, and simple and forced-choice reaction times. All tests were undertaken binocularly, using the appropriate refractive correction for the working distance of the test.

Visual Acuity

Binocular visual acuity was measured using a high-contrast (90 percent) chart at the standard working distance of 6 m to give a measure of visual performance comparable with that used in driving test centers and to ensure that all subjects had binocular visual acuity ≥6/12.

Useful Field of View

A functional visual field test was included because studies have demonstrated significant correlations between functional visual field scores involving peripheral search within cluttered arrays and accident rates (*14,15*). A measure of the functional field known as the useful field of view (UFOV), as described by Sekuler and Ball (*16*), was employed that involved a computer-generated task to measure central and peripheral information processing. Targets consisted of cartoon faces that subtended 4 degrees by 3.5 degrees and were presented centrally and at one of 24 peripheral locations along 8 radial directions at eccentricities of 8, 17, or 26 degrees for a duration of 90 msec. The central task provided a stimulus for fixation as well as creating various levels of central demand. The peripheral component measured localization of targets when they were presented against an empty field (for the low level of difficulty) or within a distractor array (for the high level of difficulty). The distractor stimuli consisted of outline boxes of the same size and luminance as the targets. Subjects were required to detect the central targets and at the same time determine the location of the peripherally presented targets, making the task a divided attention search, which also tested the ability of the subject to recognize relevant targets within a cluttered array.

Pelli-Robson Letter Contrast Sensitivity

A test of letter contrast sensitivity (CS) was included because it has been suggested that such tests better reflect the visual environment, which includes low- as well as high-contrast detail (*17*). Letter sensitivity was measured using the Pelli-Robson letter CS chart as described by Pelli et al. (*18*), in which letter size remains constant but contrast decreases from the top left to bottom right of the chart in 0.15 log unit steps. Sensitivity was measured at the recommended luminance of 85 cd/m^2 and at a working distance of 1 m (*18*). Subjects were instructed to identify the letters starting with the high-contrast letters in the top left-hand corner and working down the chart until all the letters in a given triplet had been incorrectly identified. Subjects were encouraged to look at each line of letters for 20 to 30 sec and were forced to guess when they were unsure because scoring depended on a forced-choice paradigm.

Disability Glare

A test of disability glare was included because it is well established that tests of glare sensitivity more accurately reflect the functional decrement suffered by patients with cataracts than do visual acuity measures (*19*). An index of disability glare was derived by taking the difference in visual acuity measured for the low-contrast chart under no-glare and glare conditions using the Berkeley glare test (*20*). This test consisted of a reduced low-contrast Bailey-Lovie letter chart (Weber's contrast = 18 percent) mounted on a triangular opaque panel in the center of an opal Plexiglas panel at the medium glare setting (750 cd/m^2). Visual acuity was measured at 1 m with and without the glare source. Alternative charts were used to reduce the subject's familiarity with the letters, and an adaptation period was provided between glare conditions to ensure that no carry-on effect occurred from one condition to another. Responses were scored as a Visual Acuity Rating (VAR) in which VAR = 100 was equivalent to 6/6 visual acuity, with credit being given for each letter seen correctly (one point for each letter seen correctly).

Reaction Times

A laboratory test of reaction times was included since a general slowing of information processing has been reported as part of the normal aging process (*21*). Simple and forced-choice reaction times were measured using a computer-generated technique. A series of eight boxes (the stimuli) were generated on the computer screen with a response panel on the keyboard composed of eight buttons, each corresponding to one of the stimulus boxes. On initiation of the program, one of the boxes was illuminated at a randomly timed interval. For the simple reaction time task, the subject was required to press any response button when the stimulus boxes were illuminated. For the forced-choice task, subjects were required to press the response button corresponding to the illuminated stimulus box. For both the simple and the forced-choice tasks, the reaction time was recorded in milliseconds by a simple timer device; for the forced-choice task, an error rate was also recorded. Subjects were given a number of practice trials before the experimental run to familiarize them with the task. The results were given as the mean of 50 trials.

RESULTS

Driving Performance

A multivariate analysis of variance (MANOVA) performed with Genstat demonstrated a significant difference between groups even when the 10 driving measures were taken into account ($F_{20,56}$ = 2.47; $p < 0.001$). A multiple correlation of the driving measures showed that the driving variables included in the MANOVA were not highly correlated (the highest correlation was $r = 0.41$ between central and peripheral reaction times). The results of individual ANOVAs for each of the driving measures are given in Table 1 and show significant differences ($p < 0.05$) between groups for driving time, maneuvering time, maneuvering errors, peripheral reaction times, and speed estimation.

Post hoc analysis using *t*-tests demonstrated that the driving performance of the cataract subjects was significantly worse ($p < 0.05$) than that of the young and elderly visually normal subjects for driving time, maneuvering time, and peripheral reaction times. The elderly visually normal subjects were significantly worse ($p < 0.05$) than the young subjects for peripheral reaction times, maneuvering errors, and speed estimation; the results for peripheral reaction times are shown in Figure 1.

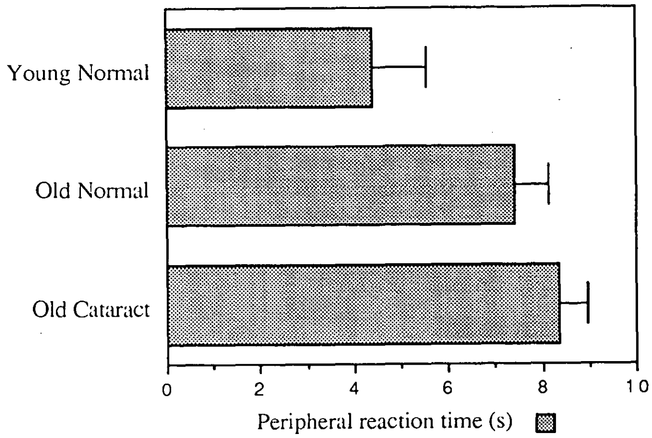

FIGURE 1 Histogram representing group mean results for peripheral driving reaction time for young normal subjects, elderly normal subjects, and elderly cataract subjects.

Visual Performance

A MANOVA performed with Genstat demonstrated that there was a significant difference in visual performance between groups even when the nine measures were taken into account ($F_{18,58}$ = 7.85; $p < 0.001$). A multiple correlation analysis of the visual performance measures demonstrated that none were significantly correlated (the highest correlation was between the central and peripheral UFOV errors for the low demand condition, where r = 0.51). The results of individual ANOVAs for each of the visual measures are given in Table 2 and demonstrate significant differences ($p < 0.05$) between groups for disability glare, Pelli-Robson letter CS, simple reaction times, and peripheral UFOV scores for the low and high levels of demand.

Post hoc analysis using *t*-tests demonstrated that the visual performance of the cataract subjects was significantly worse ($p < 0.05$) than that of both the young and the elderly visually normal subjects for simple reaction times, Pelli-Robson letter CS, and disability glare. Performance of the elderly visually normal subjects was also significantly worse than that of the young subjects for the high demand UFOV test, disability glare test, and Pelli-Robson letter CS.

DISCUSSION OF RESULTS

The study demonstrated that the elderly subjects had poorer driving performance as assessed on a closed-circuit driving course compared with the young subjects, and the elderly subjects with early cataracts had poorer driving performance than those who

TABLE 1 Results of ANOVA for Driving Performance (DF = 2,37 in all cases)

Driving Task	F statistic
Driving Time	4.68
Maneuvering Time	4.09
Maneuvering errors	3.66
Reversing Time	3.07
Reversing Errors	1.00
Peripheral Reaction Time	4.73
Central Reaction Time	0.01
Speed Estimation	4.24
Peripheral Awareness Errors	1.50
Road Position	1.23

TABLE 2 Results of ANOVA for Vision Performance (DF = 2,37 in all cases)

Visual Task	F statistic
Disability Glare	5.70
Pelli-Robson Letter CS	45.49
Simple reaction time	4.48
Forced choice reaction time	1.80
(Percent correct)	1.79
UFOV foveal low demand	0.93
UFOV peripheral low demand	4.56
UFOV foveal high demand	2.30
UFOV peripheral high demand	19.95

were visually normal, even though the cataract subjects had visual acuity ≥ 6/12 and were therefore eligible to drive.

Peripheral reaction times, driving times, and maneuvering times were significantly worse for the cataract subjects compared with the visually normal young and elderly subjects. The cataract subjects also had higher disability glare scores, reduced Pelli-Robson letter CS, and poorer peripheral performance on the UFOV for the high demand condition. When the young and elderly visually normal subjects were compared, it was found that peripheral reaction times, maneuvering errors, and speed estimation were worse for the older drivers, who also had higher disability glare scores, reduced Pelli-Robson letter CS, and poorer peripheral performance on the UFOV for the high demand condition.

Driving Performance

The finding of increased peripheral reaction times for the elderly subjects compared with the young subjects is in accord with studies that have reported a general slowing of information processing speed (*21*) and increased reaction times (*3*) as part of the aging process. These changes may contribute to the reduction in driving performance reported with age. This hypothesis is supported by the study by Wolffelaar et al. (*4*), who looked at the merging behavior of older drivers and demonstrated that speed of judgment in a traffic merging task was significantly related to reaction times measured in the laboratory, and also concurs with Cooper (*22*), who found that older drivers most commonly reported that their major driving fault was not stopping at red lights or Stop signs.

The elderly subjects with cataracts also had longer driving times compared with the young and elderly visually normal subjects. This has significant implications for traffic flow and may indicate that drivers with cataracts should avoid peak-hour traffic in which maintenance of a given traffic speed is necessary for constant traffic flow. The elderly subjects with cataracts also took longer to complete the maneuvering task, although they did not make significantly more errors than the other groups.

These results have important implications for road safety, since all elderly people have some degree of lens opacity as part of the aging process. Nevertheless, lens opacities must be relatively advanced to reduce visual acuity below the level required for driving because in driving test centers, vision is measured using high-contrast letters that do not reflect the decrement in visual function experienced by cataract patients. These results are supported by the fact that having cataracts is given as one of the reasons that the elderly self-regulate their driving and surrender their driving license (*5*). It is also possible that the changes in performance of older drivers demonstrated in this study may represent an underestimate of that seen in the driving population as a whole, because the subjects who participated were volunteers recruited via advertisement in a motoring magazine and thus were likely to have a greater interest in and awareness of driving.

It should be noted that the results of this study may only be applied to driving on a closed-road circuit free of other vehicles. These conditions were selected in the interests of safety because the effects of visual impairment on driving performance were not known. It is acknowledged that driving in the presence of other road users is a far more complex task than that involved in the study. However, the number of signs and their information content were relatively high, and the reaction time task was included to increase the degree of information processing for the driving task in an attempt to compensate for the lack of other vehicles on the road.

Visual Performance

The finding that disability glare scores and Pelli-Robson letter CS were significantly worse for the old compared with the young subjects and that the scores for the elderly subjects with cataracts were worse than those of the visually normal elderly subjects is in agreement with previous studies (*23*). The disability glare results indicate that older individuals, regardless of whether they have lens opacities that are categorized as cataracts or not, have a greater sensitivity to light scatter than do younger individuals. The results for the Pelli-Robson letter CS chart suggest that the older subjects have more problems in detecting low-contrast images. These results are supported by the fact that some of the most common complaints of the elderly in general, particularly those with cataracts, are having poor vision for nighttime driving and being almost blinded by sunlight (*22,24*).

The findings of the laboratory reaction time tests were in general agreement with those recorded for subjects when driving, although the differences were not as pronounced when measured in the laboratory and were only significant for the simple and not the forced-choice task. This lack of difference likely reflects the fact that elderly persons have greater difficulties with divided-attention tasks such as the driving task in this study, where they were required to undertake a number of tasks as well as to respond to the reaction time stimulus, whereas in the laboratory the reaction time test was a relatively simple task and therefore not representative of a real-world situation.

For the UFOV test, the older subjects had more problems when they were required to locate a target within a cluttered array, which is in agreement with the findings of Sekuler and Ball (*16*). These results are also in accord the finding that the age-related decline in the extent of the UFOV, demonstrated both in the presence of distractors (*25,26*) and with secondary central tasks (*27*), reflects the problems experienced by older adults with visual distractors in real-life situations, such as locating a familiar face in a crowd or trying to read a sign surrounded by other street signs (*28*).

These effects are important, because they highlight areas in which elderly drivers have difficulty and emphasize the significance of the impact of visual impairment (particularly cataracts) on driving performance. The importance of these differences will become more evident over the next few decades as the driving population ages.

Implications for Performance of Road System

The driving performance of older drivers is becoming a more important issue. Goebel (*29*) indicated that the elderly have a greater chance of a collision compared with younger drivers and that their performance should influence road design standards and road safety programs. Other studies and papers have concentrated on the ability of elderly drivers to read signs, given that contrast is an important factor (*30*). The general gist is that larger signs are needed; however, since many signs are not read, the question of more strategically placed signs would seem to be more important.

TABLE 3 Calculated Extra Stopping Distance Traveled by Elderly Drivers with Cataracts Compared with Young Drivers

	Extra distance travelled by the elderly	
Speed (km/h)	metres	equivalent car lengths
40	43	6
50	54	8
60	65	9
70	76	11
80	87	12

The conclusions from this study are that the elderly have more difficulty finding information from a cluttered view than do young drivers. Furthermore, drivers with cataracts find it still more difficult. In Australia, the location of traffic control signs, such as Stop and Yield signs, is specified in the standards, and they are generally in a conspicuous position and reinforced by road geometry. These signs are not considered a problem for the elderly. Information signs, however, are not as well controlled and often have to compete with advertising signs. Drivers are expected to locate the sign, read the message, and act on the information within a few car lengths. This is a difficult task for any driver, let alone the elderly or those with cataracts. Sign arrangements are often cluttered. It is thus expected that elderly drivers would find it more difficult to find the correct road.

The time required to see a stimulus in the periphery was 8.3 sec for the elderly subjects with cataracts, 7.4 sec for the elderly subjects who were visually normal, and 4.4 sec for the young drivers; this is an increase of 3.9 sec of travel time for the elderly subjects with cataracts. The distance traveled as a result of this increase in reaction time is shown in Table 3. These distances might mean the difference between seeing or not seeing a child or another car at an intersection. From this example, it can be seen that the elderly driver is at risk or puts other road users at risk. In practice, the elderly generally drive much slower and the effective risk is lessened.

One of the main problems for the elderly driver is that driving performance changes gradually; thus, drivers may not be able to detect a significant degradation in their performance until an incident occurs or until they are advised. It is highly unlikely that any change in the visual performance of elderly drivers other than a gross one would be detected with the current system because vision is measured using high-contrast letter charts at the driver testing center and the doctor's office (during medical checkups). The indication is that testing using low-contrast letter charts such as the Pelli-Robson chart and functional field measures would be more appropriate, because these would highlight any changes in vision due to age and the formation of cataracts. On the basis of these results, patients could be advised of their increased risk and situations to avoid, such as late afternoon with the sun on the horizon, peak traffic, and night driving.

Future Work

The results from this study provide a basis for further investigations, which will include larger numbers of subjects, both those with visual impairment and those who are visually normal. It is proposed that these studies will be undertaken both on closed roads and on public roads under daylight and nighttime conditions.

CONCLUSIONS

Elderly subjects (either with normal vision or with cataracts) had significantly worse performance for many of the aspects of driving assessed on a closed-circuit driving course than the young visually normal subjects. This was despite the fact that all of the elderly subjects had visual acuity ≥ 6/12 and were therefore eligible to drive. The elderly subjects also had higher disability glare scores, reduced Pelli-Robson letter CS, and poorer peripheral performance on the UFOV for the high level of demand compared with the young subjects.

ACKNOWLEDGMENT

The authors gratefully acknowledge the cooperation of the Queensland Department of Transport and the Queensland Police in providing the Mt. Cotton Complex for the driving studies in the field.

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Publication of this paper sponsored by Committee on Safety and Mobility of Older Drivers.

Effects of Aging on Older Drivers' Travel Characteristics

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This study focuses on the changes in driving characteristics of older drivers. A statewide survey of older drivers combined with focus group meetings was conducted. A total of 664 older drivers responded to a mail survey. Data were analyzed at three levels. First, the responses of all drivers to a certain question were investigated. Next, the data were divided into four age groups: 66 to 68, 69 to 72, 73 to 76, and 77 and more years of age. Finally, the differences in gender were examined. The survey results indicated that 70 percent of older drivers used their cars at least 5 days a week, and a higher proportion of male drivers than female drivers drove 7 days a week. The majority of older drivers did most of their driving in a town or a city, and as age increased, urban road use increased and highway use decreased. Nearly half of older drivers drove less than they did 10 years ago, and they drove fewer miles as their age increased. The majority drove frequently in off-peak hours, and age is a factor in deciding when to drive during a day. The older drivers recognized significant changes in their driving capabilities.

The American population is aging rapidly, and an increase in the percentage of older drivers using the highways and streets is expected. In 1990, 12.6 percent (31 million) of the population in the United States was 65 years old and over (*1*). This percentage is projected to increase to 21.1 (64 million) in 2030 (*2*). A growing proportion of the elderly live in the suburbs. For example, in Illinois, census data from 1970 and 1990 show that the number of persons over 65 in the central areas and the fringes inside the urbanized areas increased by 13 and 88 percent, respectively (*1,3*). Another trend is the increasing proportion of the elderly who drive automobiles. For those who live in the low-density suburbs, the automobile is the dominant mode of mobility (*2*). The number of licensed drivers 65 years and over in the United States has increased more than 50 percent since 1969 (*4*).

These trends indicate that the travel characteristics of older drivers should be understood and that their driving needs should be considered in the design and operation of highways and streets. It has been found that, in general, visual and cognitive performance on driving-related tasks diminishes with age. Many highway design assumptions used today, however, are based on the performance characteristics of a younger population (*2*) and provide less margin of safety in driving to the elderly.

It is known that travel characteristics of older people are different from those of younger people. For example, the elderly drive fewer miles than do others, and, on average, men drive more annual miles than women (*2,5*). The elderly tend to drive when conditions are the safest. For example, they drive less frequently at night than do those under 65. Research has found that the most difficult driving conditions are headlight glare, followed by night driving, driving when tired or upset or in rain and fog, peak-hour driving, long-distance driving, and driving in snow, sleet, and slush (*6*).

Little research, however, has been directed at a detailed analysis of travel characteristics of older drivers. Understanding travel characteristics of the elderly is essential for responding to their mobility and traffic safety needs. A study was conducted for the Illinois Department of Transportation (IDOT) to analyze the travel characteristics of older drivers in Illinois and to determine their needs and concerns in driving. A statewide survey of older drivers accompanied by focus group meetings was conducted in order to gain more insight on their travel characteristics and to better comprehend travel behavior and needs of the elderly. The travel characteristics of older drivers (those over 65) in Illinois are discussed in this paper.

STUDY APPROACH

A statewide survey of older drivers was conducted in Illinois to determine travel characteristics and driving changes occurring with aging. A total of 664 senior drivers responded to a mail survey. The survey also sought the older drivers' comments and suggestions concerning improvements that they would like implemented in Illinois highways and streets.

In addition, focus group meetings were conducted to examine their needs and concerns in a more detailed approach than the one provided by the survey. Older drivers from rural and urban areas participated in these meetings. The findings about older driver travel characteristics from the survey and the focus group meetings are presented. Statistical analyses were performed to study the survey results.

Data Collection

A mail survey was conducted of a statistically random sample of Illinois residents over 65 years old who had valid Illinois driver's licenses. Older drivers who renewed their driver's licenses in 1990 (the year before the survey) were identified with the help of the Illinois Secretary of State's Office. Renewal criteria for a driver's license in Illinois (effective in 1989) are as follows: vision test only for ages 69 to 74 every 4 years, written or road test or both for ages 75 to 80 every 4 years, written or road test or both for ages 81 to 86 every 2 years, and written or road test or both for age 87 and older annually. Also, vision tests are required for all

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in the 75+ group. Since this stepped-expiration scheduling was not in effect long enough to cover all older drivers at the time of the survey, it is not known what the driver's license renewal rate is for older drivers over 65 years. From this population of older drivers, 850 were randomly selected as the sample control group. The questionnaire was mailed to them and they were asked to fill out the survey form and return it in the prepaid envelope enclosed. For those who did not respond to the first mailing, follow-up letters and questionnaires were sent.

Nearly 78 percent of the recipients (664 drivers) returned the completely filled-in questionnaires. The age distributions of male and female participants were very similar, indicating that similar proportions were selected from both sexes in a given age category. A very large number of respondents (about 85 percent) were 75 years old or younger. Only a few drivers were 90 years or older.

Data Analysis

For a given question, data were analyzed at three levels. First, the responses of all drivers to the questions were examined. Second, the data were categorized by the age of the respondents. Given the sample size, four age categories were used: 66 to 68, 69 to 72, 73 to 76, and 77 and older. Third, the differences among responses from male and female drivers were examined. If statistically significant differences existed between male and female drivers, these two gender categories were investigated by dividing them into the four age groups.

Different statistical tests were used, based on the distribution characteristics of the responses for each question as well as on the number of groups to be compared. For instance, if a question displayed continuous features, a general linear model (GLM) for the analysis of variance (ANOVA) was applied (7). Duncan's multiple range tests were used if the ANOVA showed significant differences. Similarly, *t*-tests were performed when two groups were compared for continuous features. The remaining statistical analyses, where the responses were discrete and comparisons were made, were conducted on the basis of χ^2 test results. Table 1 is a summary of χ^2 goodness-of-fit tests of gender and age groups. All statistical tests were performed with a 95 percent level of confidence.

Focus Group Studies

In addition to the statewide survey, focus group studies were carried out. One focus group meeting was conducted in the Chicago metropolitan area and three others in the Champaign-Urbana area. The purpose of these focus groups was to probe in depth senior drivers' feelings about driving and highway design. In essence, this part of the study was designed to supplement the survey data and provide further insights into the driving behavior of the older population.

The number of participants varied from 5 to 12 a meeting. All of the participants were senior drivers. The discussions were taped, reviewed, and analyzed after the meetings. A content analysis was performed on the recordings for the urban and rural groups. A total of 18 participants were interviewed in three different meetings in the Champaign-Urbana area. There were 6 male and 12 female participants from different income levels, who were still driving.

SURVEY FINDINGS

Travel Frequency

The survey results indicated that older drivers used their cars on a regular basis. Seventy percent drove at least 5 days a week and

TABLE 1 Summary of χ^2 Goodness-of-Fit Tests

Items		Degree of Freedom	χ^2-value	Probability for $\geq\chi^2$ Value	Interpretation (With 95% Confidence Level)
Trip frequency	Gender	7	31.657	0.000	Significant
	Age	21	40.868	0.006	Significant
Road type	Gender	3	3.073	0.381	Not Significant
	Age	9	15.626	0.075	Not Significant
Trip recency for most recent trip	Gender	3	18.370	0.000	Significant
	Age	9	6.531	0.686	Not Significant
Trip purpose for most recent trip	Gender	6	19.905	0.003	Significant
	Age	18	37.297	0.005	Significant
Conditions avoided	Gender	2	1.836	0.399	Not Significant
	Age	6	22.450	0.001	Significant
Driving difficulty	Gender	2	3.211	0.201	Not Significant
	Age	6	5.326	0.503	Not Significant

42 percent used their cars daily. As the age of older drivers increased, the frequency of daily driving decreased and the frequency of 2 or 3 days of driving a week increased. Figure 1 shows the distribution of travel frequency for different age groups. The ANOVA showed that a statistically significant difference existed among the four age groups. Duncan's multiple range test with a 95 percent confidence level showed that driving frequency for the oldest group (77+) was significantly different from those of the other three age groups (66 to 76). Driving frequency for the oldest group was 4.4 days a week, but for the other three age groups it was 5.7 days a week.

A higher proportion of male drivers than female drivers, 50 percent compared with 32 percent, drove 7 days a week. Conversely, more female drivers used cars fewer days a week as compared with male drivers. The distribution was significantly different using a χ^2 test with a 95 percent confidence level. Furthermore, a *t*-test showed that the average travel frequency of men (5.8 days a week) was significantly higher than that of women (5.0 days a week).

For each age group the average number of days driven was computed. For all drivers combined, the average frequency for the 77+ group (4.4 days a week) was significantly lower than those of the other three groups (5.4 to 5.7 days a week), using Duncan's multiple range test with a 95 percent confidence level. The other three groups did not have significantly different frequencies. The data were divided into male and female categories, and similar tests were run. A significant difference in average travel frequency was found for male, but not for female, drivers. The 66- to 76-year-old male drivers drove more frequently (5.7 to 6.3 days a week) than the 77+ male group (4.7 days a week).

Detailed analyses were performed separately for male, female, and total drivers because the gender difference was significant. For these analyses trip frequencies of 3 days or less were combined in one group. Thus a total of five trip frequency groups was obtained. For each gender category and each trip frequency group, a one-way χ^2 test was performed to determine if the observed frequencies were significantly different from the expected frequencies for that age group. A total of 15 (5 trip frequency groups and 3 gender categories) χ^2 tests were run, and the results are summarized in Figure 2. The results show that only for frequencies of 3 days or less and 7 days, the distributions of drivers in the four age groups were significantly different for male and total drivers. It should be noted that male drivers were the main reason for total drivers to have significantly different distributions among the four age groups.

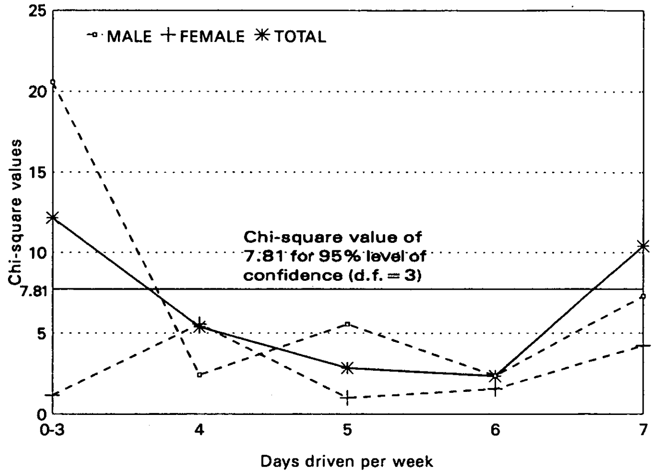

FIGURE 2 Summary of χ^2 goodness-of-fit tests for trip frequency distributions among age groups.

More detailed analyses were performed for the 3-days-or-less and 7-day trip frequency groups. For these two groups the observed number of drivers in each age category was compared with the expected number, and the deviations are shown in Figure 3, which shows that the youngest senior group is overrepresented in the 7-day trip frequency group and the oldest senior group is overrepresented in the 3-day-or-less trip frequency group.

Road Type

The majority of older drivers (75 percent) did most of their driving in a town or a city, but 16 percent use highways. As the age of

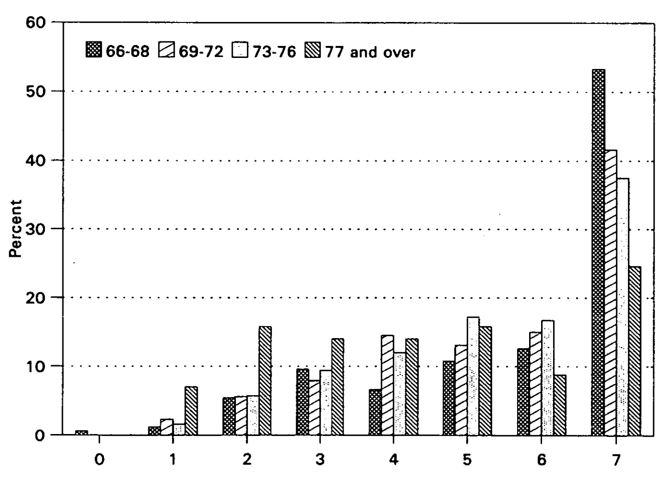

FIGURE 1 Number of days per week that older drivers use cars.

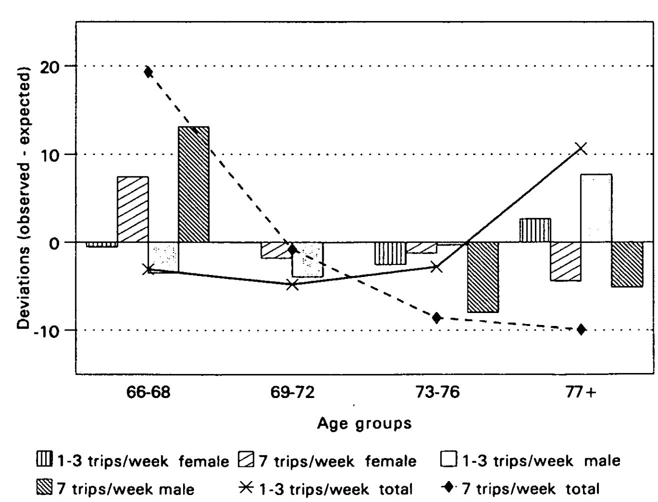

FIGURE 3 Deviations from expected values of average weekly days driven versus age group.

the respondents increased, urban road use increased and highway use decreased. For example, 23 percent of the 66- to 68-year age group use highways compared with 7 percent in the 77+ age group, and 66 percent of the same age group compared with 78 percent of the 77+ age group drive on urban roads. This trend was statistically significant with a 92 percent confidence level.

Trip Recency

Male and female drivers were asked about the two most recent trips they had made. Nearly 69 and 19 percent, respectively, responded that their most recent driving took place that day or the day before, and 12 percent of the respondents said that their last trips occurred two or more days before. This trend was true for all age groups, with a slight (but not significant) decrease for the 77+ age group. More male drivers than female drivers drove that day. This confirms the findings on trip frequency that indicated that men drove more often than women.

About 14 percent of the respondents said that their second most recent trip had been made that day, 49 percent said that it had been the day before, and 20 percent said that it had been two days before. Trip frequency showed a shift from "today or yesterday" to "two or more days ago," as is expected to happen with the age increase. Statistically significant differences were found when comparing all four age groups. Also, a significant difference in gender was found. More men than women drove that day or the day before for the second most recent trip.

The frequency of driving indicates that some of the older drivers drove two or more times in one day. This finding about trip frequency is important in the determination of vehicle miles traveled (VMT) by older drivers. Those who drove a car more than once in a given day were identified, and this proportion was determined to be approximately 15 percent.

Trip Purpose

The predominant trip purpose for the most recent trip was grocery and personal shopping (45 percent), followed by personal business (15 percent) and recreational or social trips (12 percent). A relatively small percentage (8 percent) reported going to work as the main driving reason, 6 percent reported medical or dental appointments, and 7 percent reported more than one purpose.

The frequency of work and recreational and social trips decreased, whereas that of grocery and shopping and multipurpose trips increased as the age of drivers went up (Figure 4). The χ^2 tests indicated a statistical difference among the four age groups with regard to trip purpose. The purpose of trips within the four age groups varied significantly, without showing, however, a specific age-related trend. In addition, a significant difference was observed in the comparison between the youngest and oldest age groups, since the work and recreational and social trips significantly decreased with age.

The distributions of trip purposes for male and female drivers were also different. More female drivers responded that their main trip purpose was grocery and shopping. Conversely, more male drivers than female drivers reported medical and dental and recreational and social as their main trips. Age group analyses for different gender categories did not show any significant trends besides the results already mentioned.

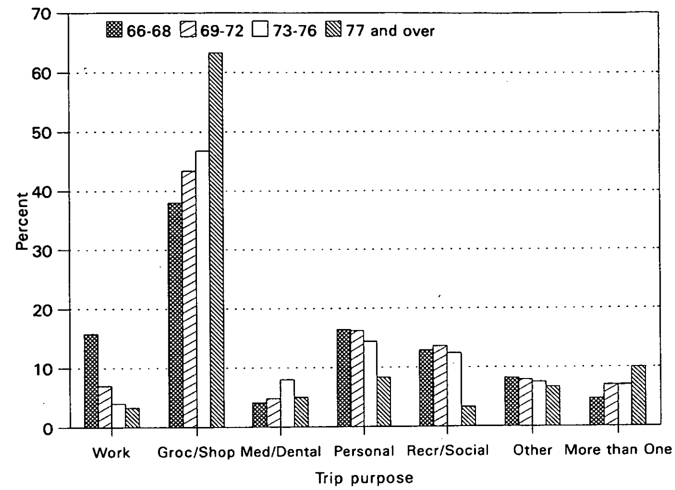

FIGURE 4 Purpose of most recent trip.

For the second most recent trip, the predominant purpose was still grocery and shopping (29 percent), followed by recreational and social (22 percent), personal business (17 percent), and medical and dental (10 percent). However, compared with the results for the most recent trip, the proportion of recreational and social and medical and dental trips increased, whereas that of grocery and shopping trips decreased. For the second most recent trip, 7 percent of the elderly drove to work, and 4 percent drove because of multipurpose trips.

The χ^2 analysis did not show any statistically significant difference among the four age groups in terms of trip purposes for the second most recent trip. However, a *t*-test between the oldest and the youngest groups showed significant differences with a 95 percent confidence level. Gender difference was not significant.

Trip length of grocery and personal shopping (9.1 mi) was significantly different from the others (ranging from 11.3 to 13.7 mi) for the most recent trip.

Trip Length

The mean of a sample of observations is the most widely used and often the most precise indicator for inferential purposes for distributions with a central tendency (*8*). However, the mean lies far from the bulk of observations in extremely skewed distributions, in which the mean is influenced by extreme values in the sample. Trip length distributions are very skewed and show no central tendency. Consequently, in skewed distributions the mean is drawn toward the elongated tail that is the median or mode. When the mean and median differ greatly, the median is usually the most meaningful measure of central tendency for descriptive purposes (*8*). However, the median does not provide the average values one may need for analyzing a distribution, such as the average VMT.

An approach based on systematic deletion of extremely large trip lengths was used to compute average trip length, which was based on the remaining data. In Figure 5, 100 percent indicates that all of the trip length data was used, and 80 percent indicates that 20 percent of the extremely large trip length data was not used in finding the average values. Figure 5 shows the change in

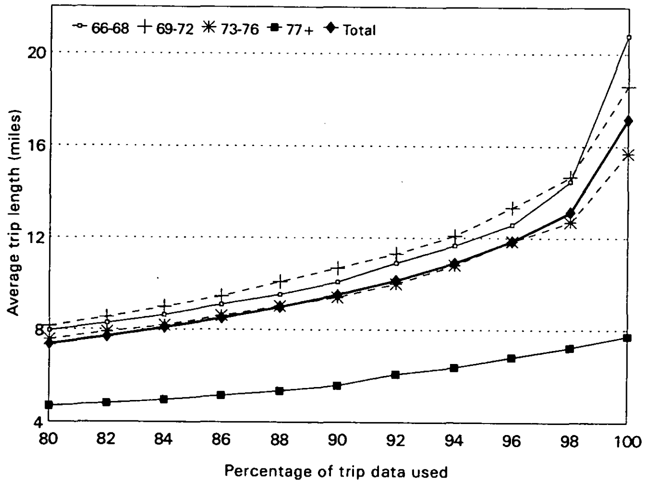

FIGURE 5 Average trip length versus percentage of trip data used.

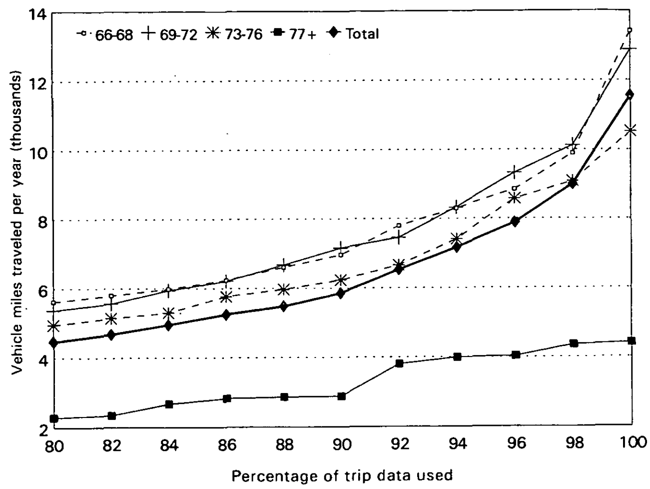

FIGURE 6 Average VMT per year versus percentage of trip data used.

the average trip length when up to 20 percent of the extremely large values observed was deleted from the total sample size. As Figure 5 shows, the average trip length reduces very rapidly when the first 5 percent of the data was deleted, continuing to decrease almost constantly thereafter. It should be noted that the average trip length for the 77+ age group was far less than those of the other three groups. The average trip length when 95 percent of the data was used turned out to be 11.4 mi (Figure 5). Nationwide data for 1983 indicated that among the elderly (65 years and over), average local daily person-miles of travel in privately owned vehicles were 13.4 mi for men and 9.0 mi for women (*9*).

Vehicle Miles Traveled

The survey did not directly ask older drivers to estimate the average VMT per year because the estimated VMT tends to be less precise. Figure 6 shows the change in VMT versus the percentage of trip data used. Instead, it was attempted to calculate VMT on the basis of trip length and trip frequency data from this survey. Vehicle miles driven (VMD) for each of the two most recent trips and for the average of those trips was computed for each individual driver from the following equation:

VMD (each driver) = (trip length)(2)(days driven)(TRIP)(52)

where

- Trip length = one-way trip length driven by a driver, miles (there were three trip length values: most recent trip, second most recent trip, and average of the two trip lengths);
- Days driven = number of days drivers drove a car per week; and
- TRIP = number of time drivers drove in one day (1 if they drove once and 2 if they drove more than once).

The factor 2 was applied to make it a round trip, and the factor 52 to convert it to miles driven per year. Then the average VMT for all participants was calculated from the following equation:

VMT = Σ (VMD by each driver)/(total sample size)

The average VMT was computed as a function of the percentage of trip length data used. As discussed above, 100 percent indicates that all of the trip length data was used to compute the VMT. Similarly, 80 percent trip length data used indicates that the 20 percent of extremely long trips was not included.

From the questionnaire, it was not possible to determine the number of drivers who use their cars more than twice a day. However, it was possible to determine the number of drivers who drove exactly twice a day. To find daily trip frequency, the number of drivers who drove twice on the same day was computed. The number of drivers who responded that they had driven twice that day or the day before was determined. It was found that about 15 percent of the total participants drove at least twice in one day. The number of drivers who may have driven twice two days or more before the day of the survey was very small. Thus, it was assumed that this group did not make two or more trips in one day. The average VMT per year was 7,522 mi in this study when 95 percent of the data was used (Figure 6).

Drivers were also asked to compare the number of miles driven now and 10 years ago. Nearly half responded that they drive less now than they did 10 years ago. However, 37 percent drive the same amount and 14 percent said that they drive more now. There was no significant difference between male and female drivers, but the difference among the four age groups was significant. The respondents affirmed that they drove fewer miles as their age increased. The average ages of the above three categories were 72.6 (for the fewer-miles-driven group), 71.3 (for the same-miles-driven group), and 70.3 years (for the more-miles-driven group).

The average trip lengths (most recent trip) were 9.3 for the fewer-miles-driven, 12.2 for the same-miles-driven, and 14.9 for the more-miles-driven groups. The trip length differences among these groups were statistically significant. Furthermore, VMT (based on the most recent trip) for the three groups were 5699, 8404, and 13,131 mi, respectively. The VMT for the senior drivers in the more-miles-driven group was significantly higher than that for the same-miles-driven group, which in turn was significantly higher than that for the fewer-miles-driven group. Therefore, the group who had a higher VMT had also a higher trip length as well as higher trip frequency.

Travel Time

The majority of older drivers (87 percent) drove frequently in off-peak hours. However, over half of them (56 percent) also drove in the afternoon peak period (3:00 to 6:00 p.m.), over one-fourth drove in the morning peak period (6:00 to 9:00 a.m.) or during the evening and at night (6:00 to 12:00 p.m.), but less than 1 percent drove after midnight. It was also noted that some study participants had driven in more than one time period, so the percentages do not sum to 100.

Age was a factor in deciding when to drive during a day. In general, as the age of drivers increased, they drove more in off-peak hours and less during the morning or at night (Figure 7). Statistical analyses have shown that all age groups presented significant differences within the same driving period.

More women drove in the off-peak hours (9:00 a.m. to 3:00 p.m.) as compared with men, and such a difference was found statistically significant.

Conditions Avoided

The elderly drove when conditions were the safest. The most-often-mentioned condition in which older drivers purposely avoid driving was ice and snow, followed by peak hours, night, and rain. Only 3 percent avoided driving on the weekends. About 11 percent replied that they did not purposely avoid any of the aforementioned conditions. More male drivers avoided peak-hour traffic and more female drivers avoided the ice and snow and evening and night driving. As their age increased, they avoided peak-hour traffic, ice and snow, and night driving conditions (Figure 8).

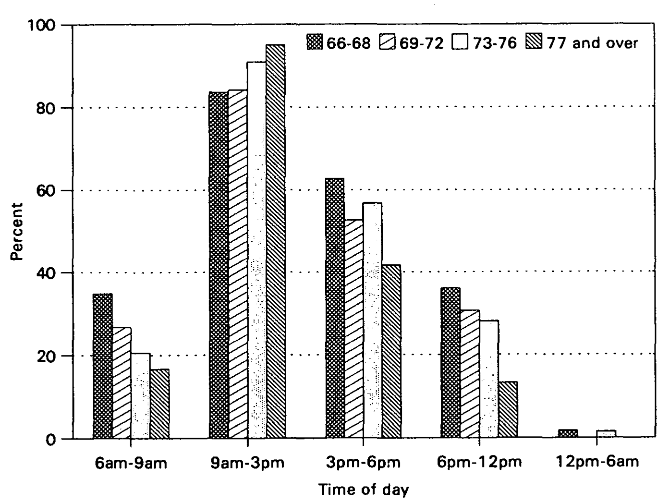

FIGURE 7 Road conditions avoided by older drivers.

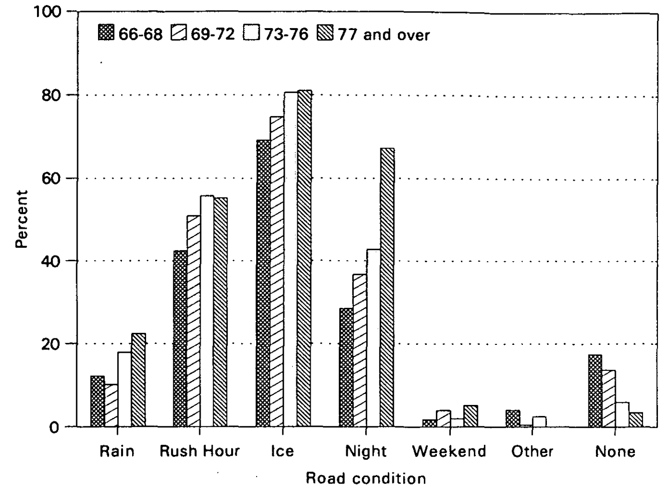

FIGURE 8 Avoided road conditions by older drivers.

Driving Difficulty

Participants were asked to take everything into consideration and compare driving difficulty now and 10 years ago. About 63 percent replied that the difficulty is about the same, and 26 percent said that it has become more difficult now. On the other hand, 11 percent reported that driving now has become less difficult.

The differences between genders or among age groups were not statistically significant. This results supports the theory that chronological age alone may not be a good predicator of physical, mental, or social competence (*2*). Driving difficulty varied from one person to another within the same age group. The average ages of three categories of driving difficulty were 72.0 (more-difficulty group), 71.8 (same-difficulty group), and 71.2 (less-difficulty group).

There are two interesting findings about the perception of overall driving difficulty among the respondents. First, differences in trip frequency, trip length, and VMT for the drivers in the three difficulty groups (more-, same-, and less-difficulty groups) were not statistically significant. Thus, trip frequency, trip length, and VMT are not based on the perceived overall driving difficulty. Second, when participants were asked detailed questions about driving difficulty—for example, about nighttime driving or left turns at intersections—they recognized that they are having increased difficulty. Hence, they did not realize driving difficulty when an overall question was asked, but they did when specific questions were asked. They may have had to drive in more complex driving conditions (e.g., work trips) when they were younger, but now they have more freedom to select less complex driving conditions (less crowded road and off-peak hours).

FOCUS GROUP FINDINGS

Focus group meetings were conducted for both the Chicago metropolitan area and the Champaign-Urbana area in Illinois.

Nighttime driving was avoided by most elderly participants, but a small number liked it because of less traffic and higher driving speeds. Nighttime driving in town was not a problem when there were few surrounding lights, but participants avoided nighttime highway driving.

The two groups, urban and rural, had significant differences in their responses. As it might be expected, the urban group was more concerned about traveling in high-volume traffic and more on urban arterials than on freeways. In general, their trips were shorter than those of the rural group, but the driving environments were more complex. The rural group tended to avoid peak-hour travel and the more complex driving environments. The rural group also tended to be more concerned about driving at night than the urban group. A greater proportion of the comments of the urban group was focused on driver behavior in traffic, mainly other drivers. Thus, much of their concerns were related to speed, weaving behavior, drunk driving, and police enforcement.

Both groups were concerned with managing in complex traffic environments. Rural drivers generally avoided such situations—for example, driving during off-peak hours, taking alternate routes, or avoiding certain areas. Urban drivers, for whom such avoidance was less possible, tended to focus on external control of other drivers for their benefit and safety.

In general, the older drivers in both groups have adapted their driving behavior to the basic sensory, cognitive, and motor changes they have experienced. They were aware of some of the changes but appeared to have adapted without conscious awareness. The urban group as a whole was less aware of changes in capacity than the rural group. Older drivers in the urban group were also more competitive in their approach to driving than the rural group and saw their problems in driving more nearly due to the behavior of others rather than to themselves. However, it was clear from the analysis that significant decrements in driving performance had occurred. There were significant differences in attitude toward driving between the two groups. The rural drivers perceived driving as a necessity, a cost to be paid. For the urban group driving had a personal and social significance, what appeared to be a means of staying involved, or "young." This was especially obvious among the male members of the urban group.

In summary, the results of both the survey and the focus group meetings suggested that the older drivers recognized significant changes in their driving capabilities. The responses to these changes can be categorized in three ways: compensatory behavior, self-imposed restrictions on driving, and increased anxiety levels. Older drivers select routes, for example, that are of lower complexity and avoid unpredictabilities. Similarly, night driving is significantly more difficult for older drivers, so they avoid driving at night, especially in unfamiliar areas. Many of these drivers exhibit higher levels of anxiety about driving itself, as well as sharing the roadway with other drivers. They frequently see themselves at a disadvantage in dealing with younger drivers in traffic and unable to keep up. All these factors condition older drivers and constrain the timing and place of the trips they will make. Since almost all these drivers are out of the labor force, all their travel is for personal trips as well as being discretionary. Consequently, they are free to adapt their trip making to their perceived limitations. For example, they do not need to drive cars in the morning peak hour unless they go to work or are on urgent business. It is interesting to note that the focus groups suggested that the elderly find this kind of adaptive behavior quite acceptable.

CONCLUSIONS

A statewide survey of Illinois older drivers (66 years and over) who had valid driver's licenses was conducted. The survey results indicated that older drivers used their cars on a regular basis. About 70 percent used their cars at least 5 days a week and 42 percent used their cars daily. Frequency of daily driving decreased and driving of 2 or 3 days a week increased as age increased. Driving frequencies were 4.4 and 5.7 days a week for the oldest group (77+) and the other three groups (66 to 76), respectively. This decrease was mainly due to the reduction in driving frequency with age for male drivers.

The majority of older drivers did most of their driving in a town or a city, and as age increased, urban road use increased and highway use decreased.

The predominant trip purpose was grocery and personal shopping. The frequency of work and recreational and social trips decreased, whereas that of grocery and shopping and multipurpose trips increased as age increased. Trip purposes for male and female drivers were different. More female drivers responded that their main trip purpose was grocery and shopping, whereas more male drivers reported their main trip purposes to be medical and dental and recreational and social.

The average trip length was 11.4 mi, and the average VMT per year was 7,522 mi when 5 percent of the extremely large trip length data was deleted. Nearly half of the older drivers drove less than they did 10 years ago, and statistical analysis showed that they drove fewer miles as their age increased.

Age was also a factor in deciding when to drive during a day. In general, as the age of drivers increased, they drove more in off-peak hours and less during the morning or at night. Conditions under which older drivers purposely avoided driving are ice and snow, followed by peak hours, night, and rain.

When asked what the overall driving difficulty was compared with 10 years ago, most participants (74 percent) replied that it was about the same or less. However, when they were asked detailed questions about driving difficulty (e.g., nighttime driving or left turns at intersections), they recognized the increasing difficulty they had. The results of both the survey and the focus group meetings suggested that older drivers recognized significant changes in their driving capabilities. Their responses to these changes can be categorized in three ways: compensatory behavior, self-imposed restrictions on driving, and increased anxiety levels.

Finally, the focus groups suggested that the elderly see driving not only as a necessity but also as a routine that they regard as a measure of their own freedom of action.

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Publication of this paper sponsored by Committee on Safety and Mobility of Older Drivers.