Title

Selecting Bicycle Commuting Routes Using GIS

Authors

Huang, Yuanlin
Ye, Gordon

Peer reviewed

SELECTING BICYCLE COMMUTING ROUTES USING GIS

Yuanlin Huang
Gordon Ye

This study develops a procedure for using a geographic information system (GIS) to select bicycle routes in a city. The procedure includes: developing the required database, finding the most desirable route between each origin-destination pair, and identifying the best bicycle routes in a city. The study shows that GIS is a powerful tool for developing a database from various readily available sources; that it can conveniently integrate quantitative analysis, data manipulation, and visualization in one operating environment; and that GIS is uniquely capable of performing spatial analyses that are critical to the selection of bicycle routes.

Introduction

Concerns about increasing traffic congestion and deteriorating air quality have led to a search for alternatives to automobile use in American cities. The bicycle has received growing interest as one of these alternatives because it is emission free, energy efficient, and relatively inexpensive. In response to this interest, many communities and local agencies are now involved in planning bicycle transportation systems. This study grows out of a project to plan such a system for the city of Berkeley, California.

The city of Berkeley has designated many bicycle routes along its streets. However, past bicycle facility planning was mostly geared toward providing recreational opportunities through cycling rather than promoting cycling as an alternative to driving. In response to the increasing popularity of bicycle commuting, the City decided to take a serious look at designating bicycle routes to serve the commuting needs of residents. Toward this end, our study seeks to provide a systematic evaluation of potential bicycle routes in the city in order to determine each one's desirability and potential level of use for bicycle commuting. Routes can then be selected so as to maximize the benefits accruing to bicycle commuters while minimizing the costs of maintenance. With a well-defined system of routes, limited available funding can be used to improve signing, marking, and pavements; and to inform cyclists of the route system most efficiently.

Discussions regarding the planning of bicycle facilities are not new (Hamill and Wise 1974; MAUDEP 1977). And the federal government has recently sponsored demonstration projects and passed legislation granting funds for bicycle facilities (NBWS 1994).[1] Despite the general attention, however, there have been few systematic studies of bicycle planning, whether directed at route selection or at design and safety criteria. Among the few, Replogle (1984) found that bicycles are particularly efficient for short trips and for access to and from public transportation. Several others have shown that cyclists are highly sensitive to motor traffic, particularly truck traffic (Berryhill, et al. 1977; Hamill and Wise 1974; Hudson, et al. 1982). An average daily traffic below 1200 vehicles is most desirable. This sensitivity is at least partially due to the emissions from motor vehicles, which bicyclists are forced to breathe in a highly concentrated form.

Daniel Smith was one of the first to study design and safety criteria for bicycle facilities. In a Department of Transportation user manual, he recommended focusing on grades, stopping sight distance, lane width, and horizontal and vertical curvature when selecting bicycle routes (Smith 1975). The acceptability of grades was determined by considering the amount of work of which the typical cyclist is capable. Lane width was divided into two components: a basic width and a "shy" distance separating the lane from adjacent boundary obstructions. The basic width for "A" level service is 50 inches, for example, and the shy distance with parked vehicles along the road is 14.5 inches. Thus, the suggested width for an "A" level route is 64.5 inches, which is comparable to the 6 feet width recommended by today's design manuals (AASHTO Task Force 1991; CalTrans 1993).

Others have studied the actual safety of bicycle travel. Plotkin and Komornick (1984) studied motor vehicle-bicycle accidents in the Boston metropolitan area. They found that the accidents occurring with the highest frequency were those involving a motorist turning right or left at an intersection and hitting a bicyclist coming from behind or from the opposite leg of the intersection. Wachtel and Lewiston (1994) studied the same subject in the city of Palo Alto, California. They found that bicyclists riding on a sidewalk or dedicated bicycle path incur greater risk than those on the roadway, most likely because of blind conflicts at intersections. Both of these studies found that intersections are the least safe locations for bicyclists due to auto cross traffic.

The most comprehensive study of the process of bicycle planning is one based on experiences in Europe, Australia, and the United States, in which the authors emphasize the subjective nature of bicycle facility planning (Hudson, et al. 1982). The aim of planning for cyclists is not

to provide a physical product, such as a cycletrack, they say, but rather to ensure safe and efficient travel by bicycle. The process of selecting bicycle routes usually begins with the development of a list of criteria (such as safety, continuity, directness, and grade) that are to be employed in the route selection process. Then, considering the trade-offs between these criteria, a planner uses his/her best judgment to select bicycle routes. Hudson, et al. found no quantitative analyses or systematic weighting of criteria within existing bicycle planning processes.

Geographic information systems (GIS) technology provides an excellent opportunity to computerize the process of bicycle route selection. Bicycle route planning is quite different from traditional transportation planning because of the criteria mentioned above. In particular, bicyclists are more sensitive to the slope (or grade) and the surface quality of a route than are automobile drivers. As noted, they are also especially sensitive to the level of automobile traffic on· a route. Thus, bicycle route planning requires more data layers than traditional transportation planning. These data layers can be very costly to construct by traditional means, but GIS can easily integrate digital information which is already available from government or other institutional sources, thus greatly reducing the cost of data assembly. Furthermore, GIS can perform unique spatial operations, such as terrain modeling and network analysis, which are crucial to bicycle route planning; and its network analysis data model and path-finding algorithms make it a straight-forward way to implement sophisticated cycling models that incorporate crossing traffic, turn penalties, slope, and other more standard transportation factors.

To date, although there have been many studies on transportation planning and operations using GIS, none has applied GIS in the planning and selection of bicycle routes. Current GIS applications in transportation planning focus on its mapping function; and current GIS applications in vehicle routing focus on implementing mathematical algorithms. Critical factors to cycling – such as grade and crossing traffic – have not been touched upon, nor have the GIS capabilities of integrating inexpensive ancillary data been well explored.

The purpose of this study is to develop a procedure for selecting bicycle routes using GIS, and to apply it to the city of Berkeley. Of the few previous studies mentioned above, those on the process of bicycle route planning serve as ·a general framework for our study; and the design and safety studies provide very useful information on the importance of specific criteria critical to cyclists. The procedure we have developed considers these specific criteria and exploits the unique spatial analysis capability of GIS. Our experience in the city of

Berkeley shows that such a procedure is implementable. We believe that this procedure, and our experience in general, will be helpful to transportation planning professionals in selecting bicycle routes and in using GIS.
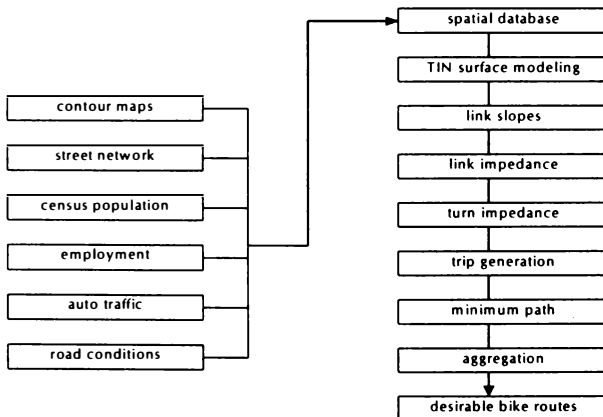
Procedure

Taking the results of previous studies into consideration, we chose the following criteria to determine the desirability of a bicycle route:

- Travel Time
- Auto Traffic
- Grade
- Road Surface Conditions

Travel Time accounts for many factors, including distance and intersection delay. Auto Traffic accounts for both traffic conflicts and air pollution, because roads with heavy auto traffic are heavily polluted. Grade is a direct measure of the steepness of a road. Road Surface Conditions includes both the smoothness of the pavement and the width of the road.

Figure 1

Flow Chart of the Procedure

Employing the above criteria, we developed a procedure for selecting bicycle routes using GIS (see Figure 1). The procedure can

be divided into two stages: (1) the development of a spatially referenced database; and (2) spatial analyses of bicycle routes. The spatial analyses stage can be divided into three components: trip routing using a path-finding algorithm, modeling trip generation with a gravity model, and summarizing trip frequency by network link.

Database Development

As with any GIS application, a database must be developed before any spatial analysis can be done. The data included in our database are terrain, street network, population, employment, auto traffic, and road surface conditions. Population and employment data will be used for gravity-model based trip generation, while the other data layers will be used for trip routing. Most of the data were already in electronic format prior to this project, so we were able to simply retrieve and convert them into our Arc/Info system.[2]

Street network data were available from the U.S. Census TIGER file. Streets and other linear features are represented as arc segments in the TIGER file. Non-street arc segments (such as border lines) were removed, leaving the street network of Berkeley in a spatial data file. Each arc in that file is associated with a specific street block by census coding; and it is attached to information including, among other things, street name, address ranges, and census tract number.

Figure 2

Topographic relief of the city of Berkeley
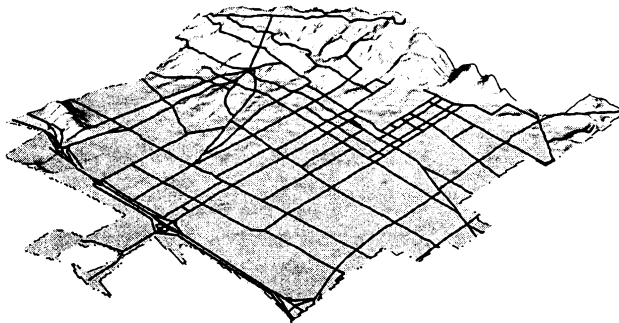
NOTE: Vertical scale exaggerated by a factor of 2

Terrain data were obtained from U.S.G.S. 7.5 minute quad sheets of the Berkeley area. Although we digitized contour lines from the quad sheets, terrain data are also available in digital form directly from U.S.G.S.[3] As seen from the perspective view in Figure 2, the elevation of Berkeley increases from the west and south to the east and north. Specifically, the west side of the city, which borders the San Francisco Bay, is at sea level, and the east and north sides of the city are very hilly.

Figure 3

Daily Auto Traffic Volume

1000 - 4000
4000 - 10000
10000 - 25000
25000 - 60000
> 60000

Scale: 0   1/2   1 mile

N

Data on auto traffic volume for major streets were available from the city of Berkeley in map form (24 hour traffic counts taken in 1987). The data were associated with corresponding streets by manual editing

80

using Arcedit.[4] Figure 3 shows auto traffic on highways and major streets in Berkeley. The north-south bound roadway with the heaviest auto traffic is I-80. The east-west bound roadway with the heaviest auto traffic is University Avenue, which connects the freeway interchange and the University of California campus.

Figure 4

Census tract population density
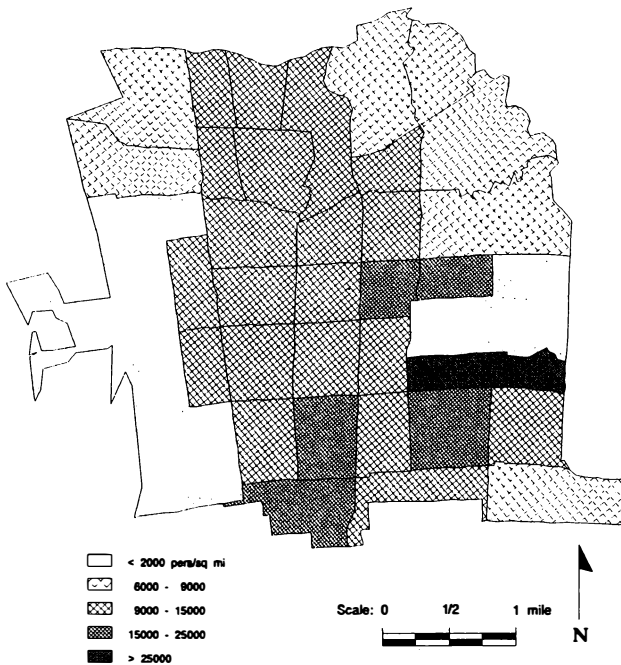
Data on road surface conditions were provided by the city of Berkeley in a Lotus format database file. The Lotus file was converted and read into the Arc/Info system. The city's data identify street segments by the names of the cross streets at the ends of the block. In contrast, our street network data identify street segments by address

ranges. Therefore, a special computer program was written to match Berkeley's road surface conditions data with our street network.

Tract-level population data were available from U.S. Census data files. A population density map of Berkeley is shown in Figure 4, from which we see that south Berkeley is more densely populated than west and north Berkeley.

Figure 5

Location of Employment

Employment data by street address were also available from the city of Berkeley.[5]   The address information was matched with TIGER address ranges using the address geocoding capabilities of ArcView,[6] in order to locate the employment centers on the street network.

Figure 5 maps the size and location of employment centers on the street network. It shows that most of the employment is located in the west and the center of the city.

Spatial Analyses

The most desirable bicycle routes can be found by a series of spatial analyses, using the database created. This process involves path finding, trip generation, and summarizing trip frequency. To prepare for path finding, roadway impedance must be defined, and origin-destination pairs must be generated.

Figure 6

Street Slope

major traffic streets
〜 3 - 6 %
〜 6 - 12 %
〜 > 12 %

Scale: 0   1/2   1 mile

N
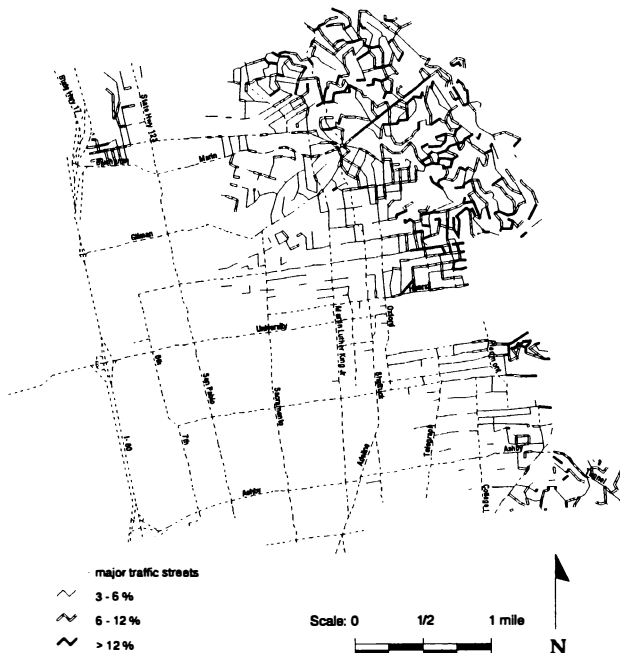
Characteristics of Roadways
1. Link Slope

Cyclists are much more sensitive to slope than are motorists. Conventional slope calculations in Arc/Info, however, give only surface slope calculated for the direction of the steepest descent; they do not take into account the direction of streets. Therefore, we calculated the slope of each street block using the elevations of the street block ends.

First, we converted the contour map into a Triangular Irregular Network (TIN) surface. Then we interpolated the elevation of all street intersections in Berkeley from the TIN surface. Link slope was then calculated from the elevation of the starting and ending intersections of each block:

$$S_{ab} = \frac{h_b - h_a}{l_{ab}}$$

Where S_{ab} is the slope between starting point a and ending point b, h_a is the elevation at point a, h_b is the elevation at point b, and l_{ab} is the distance between point a and point b. Figure 6 shows the slope of all streets in Berkeley.

2. Link Impedance

For auto travel, impedance is usually treated as the time it takes to traverse the length of a roadway segment. For bicycle travel, we take into account three other factors, namely auto traffic, link slope, and surface conditions.

For each street segment or link, we define a "forward impedance" and a "backward impedance," indicating the impedance of traveling from point a to point b and from point b to point a, respectively:

$$I_{ab} = \frac{l_{ab}}{v} * f^t_{ab} * f^s_{ab} * f^c_{ab}$$

$$I_{ba} = \frac{l_{ab}}{v} * f^t_{ba} * f^s_{ba} * f^c_{ba}$$

Where:

I_{ab} – the impedance of a link from point a to point b. The subscripts a and b indicate direction (e.g., I_{ab} indicates the impedance from a to b and I_{ba} indicates the impedance from b to a.) For a one-way street, a negative value is assigned to prohibit modeling travel in the wrong direction.

l_{ab} – the length of the link.

84

v – the speed of bicycles under ideal conditions; we chose 15 mph.

f'_{ab} – the auto traffic factor. Auto traffic generally increases the impedance of cycling. For very light auto traffic, the value of f'_{ab} is 1; as auto traffic approaches the roadway capacity, the value of f'_{ab} increases rapidly. Considering findings in Berryhill, et al. (1977), we set the value of f'_{ab} at 2 when auto traffic reaches the roadway's capacity.

f^s_{ab} – the link slope factor. Uphill slope increases the impedance. Moderate downhill slope decreases the impedance, but overly steep downhill slope will adversely impact cycling. We divide the slope range into riding range and bicycle-walking range. Within the riding range, cyclists can ride either uphill or downhill, albeit at different speeds. If the slope is beyond the riding range, cyclists must walk their bicycles. The basic criteria for determining the riding range are: (1) the amount of work a cyclist is capable of doing, and (2) the power of a bicycle's brakes. Considering the findings in Smith (1975), we chose values for f^s_{ab} ranging from 5 to 0.4 for riding speeds between 3 to 35 mph, and equal to 7.5 for walking speed (2 mph).

f^c_{ab} – the road surface conditions factor. Here, we reference only usable street width because information on pavement quality was not available for all streets. Streets with bicycle lanes are assigned values of 0.5 or less. If a street with no bicycle lanes is nevertheless wide enough for a bicycle to share the lane with autos, it is assigned a value of 1; otherwise, it is assigned a value greater than 1.

3. Turn Impedance

Turn impedance is defined as the extra time it takes to travel through an intersection in the desired turn direction. This time varies with the direction of the turn and the auto traffic, particularly crossing auto traffic, at the intersection. We express the turn impedance as:

$$I'_{ij} = ln(t_{ab} + t_{cd}) * f'_{ij}$$

Where:

I'_{ij} – the impedance of a turn from leg i to leg j

t_{ab}, t_{cd} – auto traffic on the parallel street and auto traffic on the cross street

f_{ij}' – cross factor. This is the ratio of cross traffic to total traffic at an intersection. Right turns take the minimum value (f_{ij}' = 0), because no auto traffic is crossed. Left turns take the maximum value (f_{ij}' = 1), because all auto traffic is crossed. For straight movements (no turns) the value of f_{ij}' is between 0 and 1, because only the cross street auto traffic is crossed.

For simplicity of calculation, all U-turns are prohibited.

Trip Origins and Destinations

We assume that the origins and destinations of bicycle commuting trips are population and employment centers, respectively. To represent population centers, we use census tract centroids and associate with each the aggregate population of the tract. We represent employment centers as point locations and associate with each the total employment at all workplaces clustered within a 1-2 block radius. This reduces the number of destinations, and therefore reduces the computational intensity of the path-finding analysis conducted later. Both population and employment centers were associated with nodes in the street network within Arc/Info. The 36 population centers and 29 employment centers combine for a total of 1044 origin-destination (O-D) pairs.

Most Desirable Routes for Individual O-D Pairs

Since impedance is undesirable, the minimum impedance path between each O-D pair represents the most desirable route for cyclists riding from the origin to the destination. The minimum impedance paths are found by the network analysis functions within Arc/Info. In order to simulate both home-to-work trips and work-to-home trips, minimum impedance paths going in both directions were generated. Often the forward and return paths for an O-D pair trace different routes; their difference can be substantial when the population center is located in the hills, so that work-bound trips are downhill while home-bound trips are uphill.

Gravity Model-Based Trip Generation

The potential bicycle trip volume between each O-D pair is simulated by a doubly-constrained gravity model. According to the model, the number of trips is: (1) inversely proportional to the total impedance between the origin (the population center) and the destination (the employment center); and (2) directly proportional to the population in the origin and the number of employees at the destination. The relationship can be expressed as:

$$T_{ij} = A_i B_j \frac{P_i \cdot E_j}{I_{ij}^\gamma}$$

Where:

T_{ij} – number of trips from location i to location j

P_i – population at location i

E_j – employment at location j

I_{ij} – impedance between location i and location j

γ – a parameter with its value between 1 and 2

A_i – a scaling parameter to keep the total number of bicycle trips from location i equal to the number of cyclists living in i

B_j – a scaling parameter to keep the total number of bicycle trips to location j equal to the number of cyclists working in location j

Figure 7

Simulated bicycle trip frequency, assuming 3,000 bicycle commuting trips within Berkeley

major traffic streets

∿ 45 - 75

∿ 75 - 135

∿ > 135

Scale: 0   1/2   1 mile

N
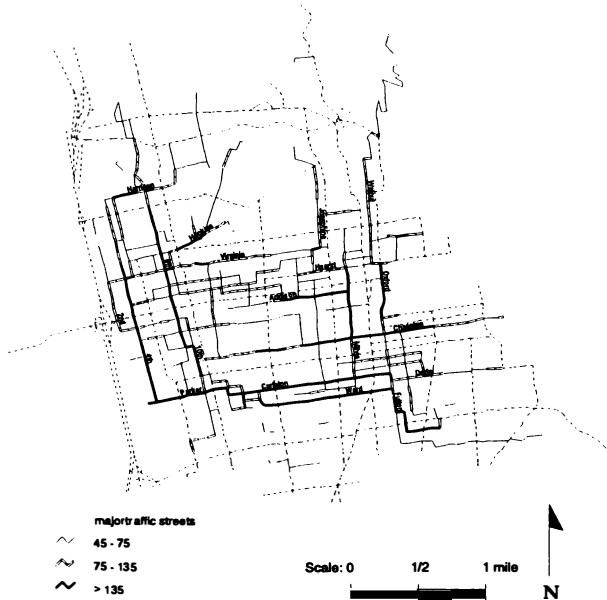
The network analysis module of Arc/Info has the capability to calculate T_{ij} according to the foregoing gravity model.

Aggregation

If we assume that each cyclist has an equal voting power, the most desirable bicycle routes for all cyclists in Berkeley should be the most heavily traveled routes. These can be identified by aggregating the minimum impedance paths for all O-D pairs. The output of this analysis is presented in Figure 7, a map of minimum impedance routes with trip frequency indicated by line thickness, assuming there are 3,000 daily bicycle commuting trips in Berkeley (2 trips for each cyclist). Bicycle routes with less than 45 commuting trips per day are not shown. All routes shown in Figure 7 are among the more desirable bicycle routes for Berkeley; thicker lines represent more desirable routes.

Conclusions

This study develops a procedure for using GIS to select bicycle routes in a city. The procedure includes developing a database, finding the most desirable route between each origin-destination pair, and aggregating those results to identify the most desirable routes in the city.

Implementation of this procedure for the city of Berkeley shows that GIS is a very effective tool for selection of bicycle routes. GIS is powerful at integrating data from various readily available sources. It is also effective in capturing specific spatial features crucial to cycling – a task that is difficult without GIS. In addition, the mapping and dynamic visualization functions of GIS are extremely effective at both communicating intermediate results to analysts, and at communicating final results to citizens or clients.

There are several caveats to the results reported above. First, this study considered only commuting trips. To develop a general purpose bicycle route system, one would need to include trips for other purposes, such as recreation and shopping, in the analyses. Second, this study considered only trips whose origin and destination points are both within the city boundaries of Berkeley. It does not, therefore, serve the needs of inter-city bicycle commuters, including Berkeley residents who work elsewhere or Berkeley employees who live elsewhere. Third, the results from this study should be used with caution because of the lack of employment data from the University of California campus. Nevertheless, the procedure developed here should be helpful to other transportation professionals considering the use of GIS technology for bicycle route planning.

NOTES

1. Intermodal Surface Transportation Efficiency Act of 1991.
2. Arc/Info is a GIS software package created by Environmental Systems Research Institute.
3. Digital Line Graph (DLG) hypsography layer, or Digital Elevation Model (DEM).
4. A component of Arc/Info, primarily for the purpose of editing line features of spatially referenced data.
5. Unfortunately, the employment of the University of California campus was not available; the University of California is the biggest employer in Berkeley.
6. GIS software developed by Environmental Systems Research Institute, primarily for managing and displaying spatially referenced data.

REFERENCES

American Association of State Highway and Transportation Officials, Task Force on Geometric Design (AASHTO Task Force). 1991. *Guide for the development of bicycle facilities*. Washington, D.C.: AASHTO.

Berryhill, James, Curtis Yates, and Mary Meletiou. 1977. *Planning for statewide bicycle routes: the North Carolina experience*. Atlanta, GA: U.S. Bureau of Outdoor Recreation, Southeast Regional Office.

California Department of Transportation (CalTrans). 1993. Bikeway planning and design. In *Highway design manual*, Chapter 1000, 1000-16. Sacramento, CA: California Department of Transportation.

Hamill, James, and Peter Wise. 1974. *Planning for the bicycle as a form of transportation*. Washington, D.C.: Pan-Technology Consulting Corporation.

Hudson, Mike, et al. *Bicycle planning: policy and practice*. 1982. London, UK: Architectural Press.

Metropolitan Association of Urban Designers and Environmental Planners (MAUDEP). 1977. *Bicycle and pedestrian facilities*. New York City, NY: MAUDEP.

National Bicycling and Walking Study (NBWS). 1994. *Integrating bicycle and pedestrian considerations into state and local transportation planning, design and operations*. Washington, D.C.: Federal Highway Administration.

Plotkin, Wendy, and Anthony Komornick, Jr. 1984. Bicycle-motor vehicle accidents in the Boston metropolitan region. *Transportation Research Record* 959: 62-73.

Replogle, Michael. 1984. Role of bicycles in public transportation access. *Transportation Research Record* 959: 55-62.

Smith, Daniel. 1975. *Safety and locational criteria for bicycle facilities: User manual volume II: Design and safety criteria.* Washington, D.C.: U.S. Department of Transportation.

Wachtel, Alan, and Diana Lewiston. 1994. Risk factors for bicycle-motor vehicle collisions at intersections. *ITE Journal* 64(9): 30-35.