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SAFETY AND LOCATION CRITERIA FOR BICYCLE FACILITIES

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Final Report

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16. Abstract

The purpose of the Safety and Locational Criteria for Bicycle Facilities research project is to improve the quality and consistency of bicycle facility planning and design. This report is a compendium of all research activities undertaken during the program. User oriented versions of research findings are presented in two companion manuals. Volume I deals with design, focusing on the process and details of laying out the physical features of bikeway facilities. Volume II deals with locational criteria for bicycle facilities and the process of systematic planning for bicycle facilities in a community. These user volumes expand upon an earlier interim product of the program, the FHWA report "Bikeways -- State-of-the Art -- 1974." However, most of the information in that report remains relevant.

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Dr. Melvin Ramey and Dr. William Adams led the University of California, Davis efforts on the project and, assisted by John Seabury, undertook research leading to development of grade evaluation criteria. Under direction of Dr. Ramey, Rock Miller was responsible for basic research and initial documentation on bikeway level of service and width criteria upon which recommendations on these subjects are based and Dr. Thomas Ferrara was responsible for research and initial documentation on intersection control warrants. Under the direction of Dr. Adams, Dr. Anthony DeLucia undertook studies of effects of air pollutants on bicyclist performance.

Donna Lott and Dr. Dale Lott of Bicycle Research Associates conducted studies of bike-motor vehicle accidents, bicyclist-motorist operations at intersections and case studies of bicycle usage and ongoing bikeway planning programs.

Many persons outside the project staffs of FHWA and the contractor contributed technical information and personal insights. Special thanks is due Mr. Dave Pelz, City of Davis Public Works Director, who facilitated several of the observations and experiments undertaken in the course of this research.

CHAPTER 1

INTRODUCTION

ABOUT THIS REPORT

Bicycle facility planning and design as a field of interest is in its infancy. Major facilities for the use of bicycles have been constructed in this country only in recent years, and as a result, little quantified data exists upon which planning and design of such facilities can be based. As a result, planning to date has been done largely on the basis of subjective judgment rather than detailed evaluation of well defined criteria and characteristics.

In order to improve the quality and consistency of bicycle facility planning and design, the Federal Highway Administration in 1973 initiated a program of research in bicycle facility planning and design. This effort has included both extensive study of experience on existing bicycle facilities and new research. Its objective has been to develop methods and guidelines for planning and design of safe and effective bikeway facilities.

This research report is one of four documents produced as principal products of the FHWA program. User-oriented versions of the research findings are presented in two companion user manuals. Volume I deals with design, focusing on the process and details of laying out the physical features of bikeway facilities. Volume II deals with locational criteria for bicycle facilities and the process of systematic planning for bicycle facilities in a community. These user volumes expand upon an earlier interim product of the program, the FHWA report "Bikeways -- State-of-the-Art -- 1974." However, most of the information in that report remains relevant.

This final report completes the program's documentation by presenting a compendium of the study activities undertaken in connection with the project. It is intended to identify to FHWA and other interested researchers those bicycle facility related items which appear to warrant action in policy and research areas, to emphasize major findings of this work program, to document supportive research and to demonstrate fulfillment of contractual work scope.

STRUCTURE OF THIS REPORT

This report is intended to document all research carried out in the course of the project. As such, the report is organized in parallel to tasks defined in the contractual scope of work.

Chapter 1 presents a summary of key findings of the research. It also includes a section on definitions of user, trip and facility types which are referenced throughout the report. The remaining four chapters correspond to the program's major tasks. Chapter 2 presents a summary of the assessment of existing bicycle facility provisions. Chapter 3 details technical studies of factors affecting safety and operations under continuous flow conditions. Chapter 4 describes evaluations of bicycle operations and safety at intersections. In Chapter 5, criteria for locating and planning bicycle facilities are discussed.

SUMMARY OF KEY FINDINGS

- BICYCLISTS PERCEIVE SIGNIFICANT BENEFITS FROM BIKE LANES.

  Surveys of bicyclist perceptions indicate that most cyclists believe streets with bike lanes are far safer than they would be without the lanes. On the average, cyclists feel that bike lanes decrease safety hazard to nearly half what it would be were no bike lanes present on the street. Belief in the relative safety of bike lanes was expressed in a great variety of street situations from commodious suburban streets with wide lanes and no auto parking to auto-impacted urban streets with narrow bike lanes and parked cars. Some sophisticated bicyclists perceive little benefit from bike lanes, being satisfied to depend upon their own riding skills and judgement in traffic.

- BIKE LANES HAVE POSITIVE IMPACT ON TRAFFIC FLOW CHARACTERISTICS.

  Presence of lane delineation lines normalizes the incidence of extremely close passes and wide avoidance swerves by motor vehicles.

- BIKE LANES ARE SIGNIFICANTLY MORE EFFECTIVE IN REDUCING BIKE-MOTOR VEHICLE COLLISIONS THAN PREVIOUSLY BELIEVED.

  Recent accident studies have provided data base on accident causal factors and some direct evidence on the effectiveness of bike lanes in reducing collision incidence. These studies show that overtaking and sideswipe collisions occur far more frequently than bike lane critics alleged. Studies indicate that bike lanes are effective in reducing the incidence of a number of other bike-motor vehicle collision types.

- BICYCLES AND MOTOR VEHICLES SHOULD NOT BE MIXED IN A SINGLE TRAFFIC STREAM EXCEPT ON STREETS WHERE COMPATIBILITY CAN BE ACHIEVED.

  Research has shown that motor vehicles on streets with 25 MPH speed limits will exceed 90 percent of bicyclists in speed. The high incompatibility restricts the number of locations where mixing should be considered. Locations where conditions satisfactory for mixing may occur include streets where motor vehicle speeds are constrained, on long downgrades, on approaches to intersections and on lightly traveled streets.

- BIDIRECTIONAL FACILITIES ARE STRONGLY DISCOURAGED.

  Accident data reveal that riding against traffic is a primary cause of bicycle-motor vehicle accidents. Studies have shown that single direction facilities are most effective from a safety standpoint.

- INCONVENIENT OR INDIRECT ROUTING IS THE PRIMARY REASON GIVEN FOR NON-USE OF A BICYCLE FACILITY.

  Bicycle facilities must connect logical bicycle trip origins with their destination conveniently and directly. Facilities which fail to provide convenient and direct service will simply not be used unless they afford significant recreational benefits.

- NO SINGLE "DESIGN CYCLIST" CAN BE IDENTIFIED AS A BASIS FOR DESIGN.

  There is a tremendous range of bicyclist physiological capabilities, bicycling judgment and skill, and trip purposes. Hence, the planner should consider the full range of cyclist types expected to use a facility or, in response to specific planning policy, may tailor the design to the needs and capabilities of a specific user group.

- SIX LEVELS OF SERVICE FOR BICYCLE OPERATION CAN BE DEFINED.

  These service levels are related to similar levels defined in the Highway Capacity Manual and describe a quality of bicycle flow. Specific speed, volumes, and densities have been ascribed to these service levels.

- SPECIFIC BICYCLE FACILITY WIDTH CRITERIA CAN BE ESTABLISHED.

  Research has established minimum bicycle separation distances which can be used to define lane widths. The recommendations in Chapter 3 of this report should replace the multitude of conflicting width specifications which have been promulgated previously by various authorities.

- EQUATIONS FOR SIGHT AND STOPPING DISTANCE FOR BICYCLE DESIGN HAVE BEEN PREPARED.

  These equations are of particular use in facility design -- particularly locations where bicycles interface with high speed traffic.

- DIRECT CONSIDERATION OF BICYCLE TRAFFIC VOLUMES IN WARRANTS FOR TRAFFIC CONTROL DEVICES APPEARS APPROPRIATE.

  Research undertaken in this program included a major effort to evaluate the role of bicycles in traffic control warrants and the user manuals include specific warrants based upon the findings of this research. Additional research and testing in this area appears desirable.

- FIFTEEN CRITERIA MEASURES HAVE BEEN IDENTIFIED WHICH SHOULD BE CONSIDERED IN THE BIKEWAY LOCATION PLANNING PROCESS.

  Principal user-related criteria include potential use, basic width, connectivity, safety, grades, and barriers. Secondary user-related criteria include attractiveness of the bicycling environment, imageability, air quality, surface quality, and truck traffic intensity. Non-user-related criteria include cost and funding, competing use and security. All of these criteria must be considered, to varying degrees, depending on site circumstances and policy objectives. It is particularly important that user travel needs be kept uppermost in weighing the constraints of conflicting criteria categories.

- DESIGN AND LOCATION TECHNIQUES AND CRITERIA SHOULD BE WIDELY DISSEMINATED TO PLANNERS AND TECHNICIANS ACTIVE IN THE FIELD.

  The infant state-of-the-art has resulted in many local agencies doing their own "pioneering" with the result that many mistakes have been duplicated and little standardization has taken place in location, design, and graphics. Dissemination of material in this manual and future research efforts, similar to that enjoyed by the Uniform Manual on Traffic Control Devices and the Highway Capacity Manual, will greatly aid professionals in this field.

DEFINITIONS

In the documentation of research in this and following chapters, frequent references will be made to cyclist and facility types that are generally well understood by persons active in this field. For purposes of orientation, these characteristics are summarized in the following paragraphs.

Trip and User Characteristics

There are two functional types of bikeway users, and their differing characteristics will influence the use and emphasis of the location and design criteria. The principal division of user types is between utilitarian and recreational bicyclists. Utilitarian bicyclists use the bicycle for transportation on some purposeful trip which they are making -- to school, to work, to shop, etc. For recreational bicyclists, the act of riding and the enjoyment of it is the total purpose of the trip. Utilitarian bicyclists tend to be sensitive to the functional service qualities of the bikeway. They are willing to trade off amenity and, to some extent, safety in order to get where they wish to go and to maximize the efficiency of their effort in propelling themselves there. By contrast, recreational bicyclists tend to place higher value on amenity and safety qualities.

The differences between these two types of bicycling activity have been well documented in the literature and are generally well understood by facilities planners, but there are a number of factors which have been frequently overlooked. The first is that differences between utilitarian and recreational bicyclists are not necessarily differences of personal traits but rather a function of differences in the type of activity engaged in. While there are numbers of persons who use a bicycle solely for recreation or solely for utility purposes, there are equally large numbers of persons who ride a bicycle for both types of activities. Thus, except in unusual circumstances, it is not the specific traits of the population which dictate whether utilitarian-oriented or recreationally-oriented locational and design variables should be emphasized in considering bikeway alternatives within a corridor. Rather, it is the inherent character and siting of the corridor which dictate whether it will be most predominantly used by individuals on utilitarian, recreational or both types of trips and, therefore, what kind of values to emphasize in tradeoffs among locational criteria.

A second major point is that whether a facility serves predominantly utilitarian, recreational or both types of bicycle trips, there is a tremendous individual variation in the types of persons engaged in these bicycling pursuits. For instance, there is a tremendous range of bicyclist skill and experience. At one end of the spectrum are extremely young bicyclists having limited experience in traffic judgment, incomplete knowledge of or respect for the rules of the road, and incompletely developed motor skills relevant to controlling a bicycle, who may well be riding a bicycle too big for them. At the other end of the spectrum are highly sophisticated bicyclist often riding bicycles specially designed for their physical needs and uses, highly developed physical and judgmental skills essential to effective riding in traffic, and a strong confidence in these skills and willingness to use them. Falling in between are large numbers of cyclists with varying degrees of skill and experience and varying degrees of willingness to rely upon that skill and experience in traffic situations.

Another type of variance among cyclists, irrespective of their trip purpose, is in their physiological work capability. The typical sophisticated bicyclist is capable of aerobic work efforts some 50 percent higher than the casual cycling population and nearly 100 percent greater than post-coronary patients who are also members of the potential cycling population. This wide range of user characteristics and traits leads to one of the key findings of this report:

> NO SINGLE "DESIGN CYCLIST" CAN BE IDENTIFIED AS A BASIS FOR PHYSICAL DESIGN.

As a result, the emphasis placed on certain design qualities will depend upon the anticipated mix of user types. Alternatively, planning objectives in providing the facility may dictate design for a specific user group.

Bicycle Facility Characteristics

Two bicycle facility classifications are referenced in this report. The first classifies bikeways by the degree of exclusiveness accorded to bicycles as defined in the pathbreaking Bikeway Planning Criteria and Guidelines report. (ITTE, 1972)

Class I

A completely separated right-of-way designated for the exclusive use of bicycles. Crossflows by pedestrians and motorists are minimized.

Class II

A restricted right-of-way designated for the exclusive or semi-exclusive use of bicycles. Through travel by motor vehicles or pedestrians is not allowed. However, vehicle parking may be allowed. Cross flows by motorists to gain access to driveways or parking facilities, is allowed; pedestrian cross flows, to gain access to parked vehicles, bus stops or associated land use is allowed.

Class III

A shared right-of-way designated as such by signs placed on vertical posts or stenciled on the pavement. Any bikeway which shares its through-traffic right-of-way with either moving motor vehicles or pedestrians is considered a Class III bikeway.

The second classification system refers to physical characteristics of facilities depending on design. This classification will overlap the first to a certain extent.

Independent Paths

Bikeway corridors in their own rights-of-way are usually desirable and attractive facilities. They may function as Class I or Class III bikeways depending on the level of pedestrian activity on them. Such facilities may be recreational in character or locational circumstances of the right-of-way may make them attractive for utilitarian travel as well.

Bike Lanes

The concept of on-street bike lanes includes a broad range of design treatments. Typically lanes operating in the same direction as motor vehicle traffic are provided on each side of the street although other variations are in general use. Following are the principal bike lane configurations:

Type A: Bike lanes are placed between the parking shoulder and the motor vehicle travel lane.

Type B: Curbside bike lanes are provided along streets where no parking is permitted or where parking has been removed to provide space for the bike lane.

Type C: Offset centerline treatments are a combination of Types A and B involving prohibition of parking on one side of the street, asymmetric location of the traffic directional "centerline", and provision of bike lanes of the Type A configuration on one side and the Type B configuration on the other.

Protected Lanes

Protected lanes are a major variant of the on-street bike lane concept. They differ in that they provide a positive physical separation between bicycles and motor vehicles rather than a simple marking delineation. Lanes protected by visually delineated buffer areas or plastic pylons fall somewhere between common bike lane and the protected lane concept, but are similar in operation to the common stripe delineated on-street lane.

Bike Routes

Signing a street or system of streets and ways as a "Bike Route" has been a first step in many jurisdictions' attempts to provide bicycle facilities. Properly used, the signed bike route is an effective tool to designate specific linkages within the framework of a bikeway plan where provision of more advanced treatments is not possible. They are also useful in guiding bicyclists to streets having characteristics inherently attractive to bicyclists. This guidance is of particular value to the first-time or infrequent users who are unfamiliar with route alignment such as recreational riders.

CHAPTER 2

CURRENT PRACTICES AND PERCEPTIONS

INTRODUCTION

An initial activity in this project was a review of the state of then-current design practice with respect to bicycle facilities. This review included investigations in the following topic areas:

- Physical design treatments employed on bicycle facilities.
- Design specifications used in the various types of physical treatments.
- Signs and pavement markings and other bikeway graphics.
- Accident data base relevant to understanding the bicycle safety problem and for evaluating the safety effectiveness of bicycle facility provisions.
- Measurements of rider satisfaction with and observational analysis of functional effectiveness of existing physical facilities.

The results of this investigation have been published as a separate report (De Leuw, Cather, Bikeways -- State of the Art -- 1974, FHWA-RD-74-56, Department of Transportation, Federal Highway Administration). This material is basically self-supporting and will not be further documented or repeated in this document. This chapter will emphasize material on two topics, bicyclists' perceptions and bicycle-motor vehicle accident data, which have been developed further since the previous document was published.

Summary

The material in this chapter is divided into two sections. The first deals with cyclists' perceptions of different types of bikeway facilities and attempts to define cyclists' levels of satisfaction with these facilities. The second section summarizes relevant information on bicycle-motor vehicle accidents and introduces a technique for predicting accident reduction due to provision of bicycle facilities.

CYCLIST PERCEPTIONS OF EXISTING FACILITIES

Purpose and Scope

Bicycle facility planning is a profession in its infancy. As such, there is a wide variety of techniques as well as facilities which have been developed in recent years. In order to assess the degree to which these techniques and facilities are serving the target population, a portion of this study involved assessment of user opinions. Forty-nine sites in various parts of the country were established as a representative sample, and cyclists were interviewed and asked to rate facilities for safety, satisfaction of bike lane treatment, and suitability of sidewalk bikeways, facility width and surface materials. Information on reasons for non-use of parallel facilities has also been surveyed. This information is of considerable value in assessing the current state-of-the-art and indicating direction for further planning and research.

The major finding is that bicycle facilities are used and approved by the majority of users. The details of the research will indicate which types are favored and for what reasons.

One parenthetical comment is in order relative to the findings described below. The survey technique used was a standard one involving random sampling of the facility users. The results derived may differ markedly from the opinions voiced by cyclists petitioning or opposing governmental action in this field. This dichotomy is due to the fact that vocally active cyclists often tend to be sophisticated and organized, often as part of a club. The sophisticated cyclist must be recognized as an extremely capable person, both in physical ability and cycling techniques; as such, his needs for facilities will differ markedly from the broad range of users of typical facilities. In responding to the needs of cyclists as a class, it is important to realize that the most vocal element is not necessarily representative of the general cycling population. The findings of this research can be used to place the opinions of sophisticated cyclists in a larger and more representative perspective. It should further be noted that findings reflect the views of current bicycle facility users and inferences on the ability of facilities to attract potential bicyclists cannot be drawn on the basis of these data.

Methodology

Bicyclists riding on urban, suburban and interurban bikeways were randomly selected and interviewed at 49 roadside sites in 21 areas across the United States. Forty-nine percent of the respondents were on bikeways in the western states, 18 percent in the midwest and 33 percent on the East Coast. Sampling sites were selected in the following locations:

California

Berkeley
Isla Vista
Marin County
Palo Alto
Sacramento
San Francisco
Santa Barbara
Sausalito

Colorado

Denver
Greeley
Fort Collins
Littleton

Florida

Gainesville
Miami

Illinois

Chicago

Massachusetts

Boston

Michigan

Ann Arbor

New York

New York City

Oregon

Eugene

Virginia

Alexandria

Washington, D.C.

Fifteen respondents were contacted at 51 percent of the locations; ten to fifteen respondents at 35 percent of locations, and six to nine at 14 percent of the locations. Typical interviews lasted ten minutes, but a few lasted as long as half an hour.

Sampling sites were selected under four types of conditions -- Class I, Class II and Class III bikeways and on streets with no designated bicycle facilities. "No facility" sampling locations were selected on streets that paralleled signed bike routes or bike lane streets one or two blocks away.

Sample Characteristics

To estimate characteristics of the bicyclist population from which the survey sample was drawn, systematic observations and counts of cyclists were made at 21 of the 49 sampling locations. The cyclists' age, sex, bicycle type (i.e., ten-speed or three-speed) and size of cycling group were recorded. A total of 852 observations was made. None of these locations were school routes, i.e., being used by only one age group such as elementary school children or college students, so that the figures reflect a rough cross section of cyclists on the four kinds of utility and recreational urban bike routes -- signed routes, on-street bike lanes, sidewalk bikepaths and independent bikeways. School children are represented here only to the extent that they rode their bikes for mainly non-school purposes on the routes sampled. Table 1 presents a summary of bicyclist characteristics as observed at survey sites.

Two thirds of the riders were male and most were over 17, riding by themselves, and using a five- or ten-speed bike. If bikeways of recreational character are examined separately, the proportion of women rises to 41 percent, and the number of cyclists riding alone falls to 45 percent. Conversely, on utility bikeways the proportion of males rises to 77 percent, and 90 percent of the cyclists ride alone. The kind of bicycles used does not vary significantly across recreational and utility bikeways, and the age distribution is essentially the same for both types of facilities. Note that these figures represent only riders using bikeways. They do not represent the total population of cyclists since, among other reasons, most cities do not have bikeways, and therefore, most riding is done on regular city streets.

Indices on the types of cyclists interviewed in this survey are useful in interpreting survey results, as well as being of some independent

Table 1
CHARACTERISTICS OF RIDERS OBSERVED AT SAMPLE SITES

Category			Percentage of Cyclists
SEX:	M		66
	F		34
AGE:	Less than 13		10
	13 - 17		12
	18 - 22		36
	23 - 49		35
	50 and over		7
SIZE OF CYCLING GROUP:			
	1 cyclist		65
	2 cyclists:	same sex	12
		different sex	12
	Non-family group larger than 2		7
	Family		4
BICYCLE TYPE:			
	1 speed		7
	3 speed		31
	5 or 10 speed		60
	other (adult tricycle, tandem bike, or hi-rise)		3

interest. As measured by age, sex, and frequency and major purpose of their bike riding, the type of cyclist interviewed varied little across bikeway types, with the exception of separated bikeways in parks. Cyclists interviewed in parks rode less often and did less utility riding than other cyclists. Overall, 75 percent of the interviewed cyclists rode their bikes almost every day, most often for recreation or commuting as indicated in Tables 2 and 3. Age of survey respondents is shown in Table 4.

Table 2
FREQUENCY OF BIKE RIDING IN GOOD WEATHER

	Everyday or 5 Times/Week	3 or 4 Times/Week	1 or 2 Times/Week	Less Often
Sidewalk Bikeways	87%	8%	4%	1%
Bike Lanes	82%	9%	7%	2%
Separated Bikeways				
In Parks	34%	17%	22%	27%
Not In Parks	91%	6%	2%	1%
Signed Routes	79%	8%	13%	0%
All Bikeways	75%	10%	9%	6%

Table 3
MAJOR PURPOSE OF BIKE RIDING

	Pleasure or Exercise	Shopping or Errands	Commuting to Work or Social	Other
Sidewalk Bikeways	32%	8%	46%	14%
Bike Lanes	26%	7%	65%	2%
Class I				
In Parks	85%	1%	12%	2%
Not In Parks	24%	0%	63%	13%
Class III	31%	7%	52%	10%
All Bikeways	38%	4%	52%	6%

Table 4
AGE OF SURVEY RESPONDENTS

	Less Than 13	13 - 17	18 - 22	23 - 49	50 or Over
Sidewalk Bikeways	14%	28%	31%	21%	6%
Bike Lanes	17%	15%	35%	29%	4%
Signed Routes	12%	18%	31%	36%	3%
Separated Bikeways	4%	11%	42%	38%	5%
All Bikeways	11%	16%	37%	31%	5%

Findings

Safety

Bicycle facilities are perceived by users as being much safer than streets with no facilities. Separated bicycle facilities are perceived as being much safer than mixed-use facilities.

Survey questions relative to bikeway safety can be summarized in the three tables that follow. Table 5 indicates safety ratings of four types of bikeways. The survey asked users to rate the relative safety of the bikeway they were using. Overall differences between bikeway types are statistically reliable ($\chi^2 = 13.07$, $P<.01$). The table indicates the degree to which separated bikeways are valued over those with less protection.

Cyclists were also asked to rate (on the same ten point safety scale) the street they were on, supposing there were no bikeway on it. In the case of separated paths and sidewalk bikeways, where the bikeway was removed from the street, the adjacent street was rated. (In all cases, there was a street within sight of the Class I bikeways which many cyclists reported riding on before the bikeway was built.) A comparison of these street ratings with the bikeway ratings is shown in Table 6.

Table 7 indicates the degree to which bikeways are perceived to provide protection from cars, a major element of bicycle safety.

In summary, cyclists perceive bikeways as having very positive safety value. The greater the physical separation that is provided, the greater the perceived level of safety.

Table 5
SAFETY RATINGS AT FOUR TYPES OF BIKEWAYS

(1 = Very Safe, 10 = Very Dangerous)

	Separated (Class I)	Sidewalk (Class III)	Bike Lanes (Class II)	Signed Routes (Class III)
Median Safety Rating	2.80	3.13	3.87	5.10

Table 6
SAFETY RATINGS OF BIKEWAYS VS. UNIMPROVED STREETS

(1 = Very Safe, 10 = Very Dangerous)

	Separated (Class I)	Sidewalk (Class III)	Bike Lanes (Class II)	Signed Routes (Class III)
Mean Safety Rating of Bikeway	3.0	3.1	4.0	5.3
Mean Safety Rating of Street Without Bikeway	8.8	7.9	7.3	6.3

Table 7
RATINGS OF PROTECTION FROM CARS AFFORDED BY THE BIKEWAY

	Good	OK	Poor
Separated Bikeways	72%	19%	9%
Sidewalk Bikeways:			
Cars in the Street	70%	24%	6%
Cars in Driveways	19%	39%	42%
Bike Lanes	32%	39%	29%
Signed Routes	17%	24%	59%

Bike Lane Ratings

Bike lanes with no adjacent parking are perceived as significantly safer than lanes with adjacent parking.

A special survey to test perceived differences between two types of bike lane design -- with or without adjacent parking -- was conducted at two sites where the two designs occurred on opposite sides of a street. These sites were chosen to eliminate as many extraneous variables as possible. Table 8 shows these ratings.

Cyclists comments on the difference between the two types of design were considerably stronger than the ratings indicate. Most (86 percent) cyclists in the lanes with parking rated the lanes without parking as safer. Although the number of interviews is not large enough to allow generalization of these results, they do conform to a priori expectations.

Table 8
COMPARATIVE SAFETY RATINGS
TYPE A VS. TYPE B LANES (1 = Very Safe; 10 = Very Dangerous)

	Berkeley CA (4 foot lanes)	Isla Vista CA (4.5 foot lanes)	Combined Rating
Type A (With Parking)	4.95	4.08	4.51
Type B (No Parking)	3.39	3.28	3.33

Sidewalk Bikeway Ratings

Overall, sidewalk bikeways are perceived as less safe than on-street bike lanes. Commuting cyclists tend to disapprove of sidewalk bikeways; recreational users approve of them in comparison to on-street bikeways.

Sidewalks have received considerable attention as potential candidates for bikeways; yet some cyclists tend to disapprove of their use. Interviews with bicyclists at sidewalk bikeway locations indicate that bicyclist willingness to use a sidewalk bikeway is closely related to purpose of the bike trip. Commute riders indicated general dissatisfaction with sidewalk bikeways. Recreational riders, in contrast, were generally satisfied with the level of service provided since the alternative was usually a busy city street, the use of which would have detracted from a quiet, enjoyable ride. These differences are most marked where sidewalk facilities are poor, particularly on converted narrow pedestrian walks. The commute cyclist appears much more sensitive to sidewalk bikeway problems -- intersection conflicts with cars, poorly constructed ramps, pedestrian conflicts, bumpy pavement and driveway conflicts.

Palo Alto, California, which had extensive facilities of both sidewalk and on-street varieties provided an ideal site for evaluating cyclists' perceptions of sidewalk bikeways. Although cyclists there gave sidewalk bikeways a fairly good safety rating, they generally felt on-street lanes were safer. Table 9 presents mean safety ratings (scale 1 - 10, 1 = Very Safe, 10 = Very Dangerous) indicated by cyclists directly comparing bike lanes and sidewalks in Palo Alto. Rating differences as indicated on Table 9 are statistically significant.

Table 9
COMPARATIVE SAFETY RATINGS
SIDEWALK FACILITIES VS. ON-STREET LANES

Type	Mean Rating
Sidewalk Facilities	3.4
On-Street Lanes	2.5

In a second test, cyclists riding in on-street lanes were asked to rate as a bicycle facility the sidewalk adjacent to the street they were on. Interview sites were carefully chosen so that the quality of the sidewalk at the site was equal to or better than those designated as bikeways elsewhere in the city.

Again, as indicated on Table 10, Palo Alto cyclists perceived the sidewalk bikeways to be less safe than on-street lanes but a substantial improvement over no provision of designated bike facilities. Nearly 75 percent of the respondents felt sidewalk bikeways were more dangerous than the on-street lane they were on; slightly over 20 percent felt sidewalks were less dangerous.

Actual rating values of the sidewalks in Table 10 are deceptive. Since the cyclist was asked to rate first the on-street bike lane, then the condition of "no designated facility", if the respondent felt the sidewalk fell somewhere in between, the safety rating value placed on this was somewhat pegged by the prior responses. This probably accounts for the fact that the ratings for sidewalks as per Table 10 were higher (worse) than ratings of actual sidewalk bikeways (Table 9). Yet the controlled comparison data still

Table 10
MEAN SAFETY RATINGS

(1 = Very Safe, 10 = Very Dangerous)

Facility	Location 1	Location 2
On-Street Lane	3.0	2.1
Sidewalk Bikeway	5.0	4.5
No Designated Facility	7.1	6.6

validly shows a marked preference for on-street lanes over sidewalk facilities. Not only is there a significant difference among the ratings given the three possible situations, but the difference between sidewalk and on-street lane ratings is statistically significant.

Bicyclists also appeared to be using the rating to describe more than safety perception in evaluating sidewalk bikeways. Convenience factors such as stopping for pedestrians or negotiating curb ramps seem to be taken into account by most cyclists. The utility-recreational dichotomy is strongly reflected in issues of convenience as indicated by interview subjects' comments: Cyclists whose use of the bicycle was for utility transportation rather than recreational purposes complained that a satisfactory travel speed could not be maintained on the sidewalks. They said their progress was slowed by such things as overhanging tree branches, untrimmed bushes and vines on front lawns, pedestrians, and badly tilted and cracking sidewalks.

Cyclists indicated that their progress at intersections was impeded by steeply ramped curbs which cyclists, especially ten-speed riders, described as giving them flats or bending their rims while they were trying to maintain a good traveling speed. Offset ramps designed to retard cyclists' entry to the crosswalk area also drew considerable adverse comment from commute cyclists. Commute riders maintained that autos were not expecting bikes to enter an intersection from sidewalks at commute speed, and that having to slow down to look out for cars in intersections and driveways made the sidewalk inconvenient for travel.

Recreational riders, on the other hand, often commented on how dangerous the adjoining street was for cyclists, and that they appreciated the option of having a direct route to their destinations without all the danger and bother of riding on arterial streets. Female children tended to show more acceptance of the sidewalks than adults or boys, although they also frequently mentioned problems of parked cars protruding from driveways and the danger of being struck by cars backing out of them.

Non-Use of Facilities

Out-of-direction travel is the most frequent reason why cyclists will not use a parallel bicycle facility.

In order to contrast perceptions of cyclists who were not using bikeways with those using them, a sample of 190 cyclists riding on urban streets was interviewed. Two types of sampling locations were chosen: Five locations were on quiet residential streets and six were on arterial streets. Ten of the eleven sites were within two blocks of parallel streets with bike lanes and one site was on a street paralleled by a signed bike route two blocks away.

Table 11 documents the surveys on arterial streets where a bike lane was present on a parallel residential street. Since some cyclists gave more than one reason for non-use, the total exceeds 100 percent.

Table 11
ARTERIAL STREETS SURVEYS*
REASONS FOR NON-USE OF BIKEWAY

Reason For Non-Use	Percentage
Out-of-Direction Travel	52
Unaware of Bike Route	27
Too Many Stop Signs	10
Not Easily Accessible	10
Route Stopped Before Destination	8
Poor Maintenance	8
Undesirable or Inappropriate	3

*Number surveyed = 92

Table 12 documents surveys on residential streets where a bike lane was present on a parallel arterial street. Again, some respondents provided more than one reason for non-use.

These tables indicate that a distance as small as two blocks may be unacceptable to some cyclists for out-of-direction travel. They also indicate that arterial facilities are more likely to be perceived as bike routes than residential streets. Finally, they illustrate the conflict between the directness of travel that an arterial provides and the competition with automobiles that cyclists must face on arterials.

Table 12
RESIDENTIAL STREET SURVEY
REASONS FOR NON-USE OF BIKEWAY

Reason for Non-Use	Percentage
Out-of-Direction Travel	50
Too Much Traffic	43
Drivers Ignore Bike Lanes	4
Poor Maintenance	4
Not Easily Accessible	4
Unaware of Bike Route	3

Width

To satisfy user desires, separated bike paths should be at least eight feet wide; bike lanes should be at least five feet wide.

Cyclists were interviewed to determine their preferences for bicycle facility width. The results of this survey are shown in Table 13. It should be noted that if a bike lane or separated path has a shoulder in good condition, the formal width of the facility will not be viewed as critically. Following from this research, details on techniques proposed for evaluating this and other lateral conditions were developed. These are described in Chapter 3 of this report.

Surface Materials

Cyclists greatly prefer asphalt to gravel surfaces.

Surface materials of the bikeway at interview locations was either asphalt, concrete or gravel. Separated bikeways were either asphalt or gravel, and the gravel surfaces* generally received poor ratings as compared to asphalt. Survey results shown in Table 14 reflect cyclist reactions to various pavement treatments on bikeways in northern Virginia and the Washington, D.C. area.

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*Most gravel paths consisted of four to six inches of coarse aggregate topped by two inches of fine screenings, usually bluestone.

Table 13
WIDTH RATINGS OF BIKE LANES AND SEPARATED PATHS

Separated Paths (Class I)

Width:	Less Than 8 Feet	8 - 9 Feet	More Than 9 Feet
Good	24%	70%	80%
OK	48%	26%	16%
Poor	28%	4%	4%

Bike Lanes (Class II)

Width:	Less Than 5 Feet	5 - 6 Feet	More Than 6 Feet
Good	41%	67%	85%
OK	38%	29%	10%
Poor	21%	3%	4%

Table 14
RATINGS OF SURFACE MATERIAL AT SEPARATED BIKEWAYS

	Good	OK	Poor
Asphalt	81%	15%	4%
Gravel	33%	50%	17%

Recreational riders showed a much greater tolerance for the gravel paths than did commuters. Commuters complained that gravel paths were not designed for commuting speeds, and that dust from the path coated bicycle derailleurs necessitating more frequent maintenance. Both groups noted, however, that gravel was unsuitable on grades or where there was any cross drainage, since the gravel surface tended to erode and leave a "washboard" surface that was dangerous to ride on. Cyclists often pointed out that any coarse aggregate on the surface of the path made balancing difficult and slowed their progress.

Where there was a choice between a conventional concrete sidewalk or an asphalt path, cyclists choose the asphalt. Expansion joints in the sidewalks were a frequent source of complaint from ten-speed riders. Respondents also expressed the feeling that an asphalt path would be recognized by both pedestrians and motorists as a bikeway.

Conclusions and Implications

The basic conclusion to be drawn from the study of cyclists' perceptions is that cyclists perceive substantial value in designated bicycle facilities, and appear to have marked preference for facilities in the higher classifications (I and II). The findings of these surveys have been incorporated into the User Manual on facility design criteria, and have shown that the survey method is a useful tool in assessing user satisfaction with facility design and location. As the recommendations contained in the two manuals are implemented, it would seem appropriate that continuing surveys of this type be conducted to verify that users are satisfied by the new techniques as anticipated from this study.

BICYCLE ACCIDENTS

Purpose and Scope

The number of bicycle accidents in the United States cannot be easily quantified, since many are of a minor nature and are never officially recorded. Yet data from a 1972 accident survey by the National Safety Council suggested that annually there are 1,000,000 bicyclist injuries requiring professional medical treatment, 100,000 motor vehicle-bicycle accidents, and 1,100 fatalities (Chlapecka, 1974). A number of studies have determined a system of causal classification and have analyzed bicycle-motor vehicle accidents* by this system. Other studies have evaluated fault for such accidents.

A summary of these studies follows. While these studies provide an excellent description of accident causality, little research has been directed toward predicting what effect bicycle facilities have on accident experience. This is because bicycle accidents are fortunately infrequent enough that it is difficult to obtain data on a statistically significant number of accidents under before bicycle facilities/after bicycle facilities conditions. In the course of this study, evaluation of accident reports from the City of Davis, California was undertaken to gain insight on this point. The results of this research should be used with caution due to the unique characteristics of that city and

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*Hereafter, the term "accident" will refer to accidents between bicycles and motor vehicles unless stated otherwise.

the fact that the data is from only one location. However, further research may prove the technique developed to be valid as further bicycle facilities come into use and more data sources appear.

Summary of Previous Studies

The pioneering work in this field was done by Cross (1974) using data from Santa Barbara, California between January, 1971 and December, 1973. It was found that 91.4 percent of the 384 accidents analyzed could be categorized into one of ten generic accident types, each referenced by specific motorist and cyclist movements. Table 15 defines the categories and accident percentages in each.

Table 15
BICYCLE-MOTOR VEHICLE ACCIDENTS IN SANTA BARBARA, CALIFORNIA
1971 - 1973

Type	Percentage
A - Cyclist Exited Driveway Into Motorist's Path	8.59
B - Motorist Exited Driveway Into Cyclist's Path	5.73
C - Cyclist Failed to Stop/Yield at Controlled Intersection	8.33
D - Cyclist Made Improper Left Turn	11.20
E - Cyclist Rode on Wrong Side of Street	14.23
F - Motorist Collided With Rear of Cyclist	4.17
G - Motorist Failed to Stop/Yield at Controlled Intersection	7.81
H - Motorist Made Improper Left Turn	12.76
I - Motorist Made Improper Right Turn	11.20
J - Motorist Opened Car Door Into Cyclist's Path	7.29

Two other studies have attempted to identify responsibility for bicycle-motor vehicle accidents. Williams (1974) used a sample of 888 accidents in Maryland between October 1, 1971 and September 30, 1972. He concluded that accident responsibility is largely a function of age, as shown in Figure 1.

A study in Eugene Oregon (De Leuw, Cather, 1974) also assessed accident responsibility. Table 16 indicates responsibility of accidents in Oregon in 1973 and in Eugene for the period 1972 - 1973. The two studies differ in responsibility summed over all age groups: Maryland data indicated bicyclists were responsible for 78 percent of the accidents studied;

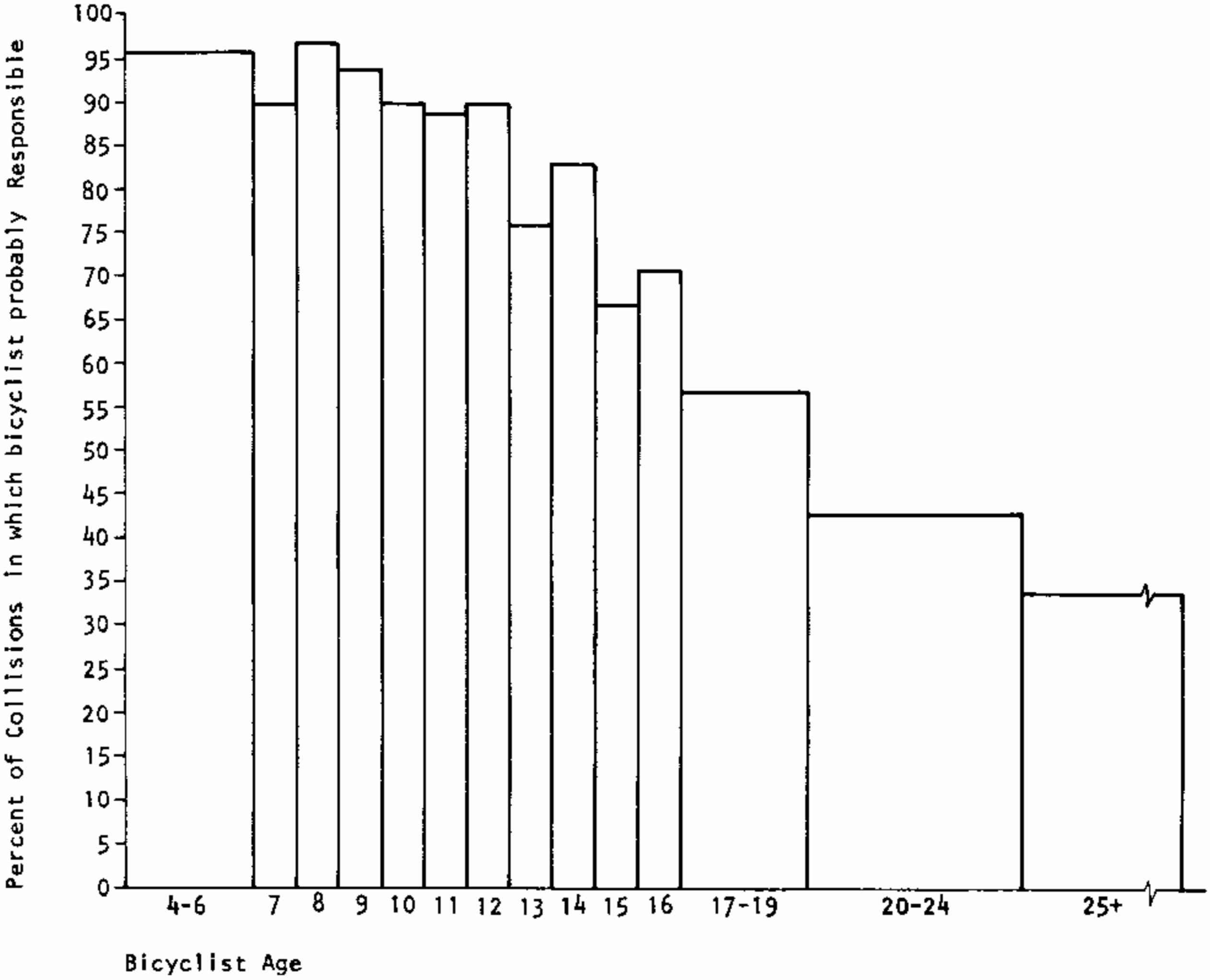

Figure 1
DISTRIBUTION OF BICYCLE-MOTOR VEHICLE COLLISIONS IN
WHICH THE BICYCLIST WAS PROBABLY RESPONSIBLE, BY BICYCLIST AGE
MARYLAND, OCTOBER 1, 1971 - SEPTEMBER 30, 1972

in Oregon in 1973, 66 percent were attributed to cyclists; in Eugene, only 51 percent of the accidents could be blamed on cyclists.

Table 16
AGES OF CYCLISTS MAKING ERRORS IN BICYCLE ACCIDENTS

Age Group	Oregon 1973 Accidents Number	Oregon 1973 Accidents Percent in Study	Eugene 1972-73 Accidents Number	Eugene 1972-73 Accidents Percent in Study
Under 6	10	2.4	0	0.0
6 - 12	134	32.1	11	13.1
13 - 17	100	24.0	11	13.1
18 - 30	28	6.7	18	21.4
31 - 65	2	0.5	0	0.0
Over 65	2	0.5	0	0.0
Unknown	-	-	3	3.6
TOTAL	276	66.2	43	51.2

Findings and Methods

> Almost all types of accidents related to facility type seem to occur less frequently on streets with bike lanes than on streets without such provisions.

The previous work in this field has defined techniques and provided estimates of accident causality and fault at a fairly gross level of detail. The categorization system of Cross, however, provides a starting point for developing a technique for predicting the degree of accident reduction which bicycle facilities can provide.

The technique to be described is based on data from Davis, California. In the course of research, this was the only location found to provide sufficient data on locations with and without bike lanes to allow analysis. Davis is unique in at least two areas: 1) it is a university town with a large number of college-age riders, and 2) the local traffic code specifically requires right turning motorists to avoid encroaching on bike lanes and, though not specified in code, in practice motorists generally yield to through bikes when turning. These unique conditions, plus the fact that this is but one sample, suggest caution in using the results of this analysis.

Policy records on bike-motor vehicle collisions reported in Davis from 1970 through 1974 were evaluated. Of 177 total collisions, 145 were deemed suitable for categorization according to the Cross system. Table 17 shows the accident data according to sex, age, and presence or absence of bike lanes. Table 18 shows the data by percentage of total accidents and compares Davis and Santa Barbara data.

Tables 17 and 18 show accident percentages; they do not illustrate accident rates. Thus, it is not possible to compare these percentages to assess relative frequency of accidents on streets with and without bike lanes. Since rates are extremely difficult to develop given the lack of knowledge of operating mileage or some such standard for comparison, the technique proposed involves defining certain accidents as "neutral", certain others as "non-neutral" and using neutral accidents as a basis of comparison.

Neutral accidents are defined as those in which the presence of bike lanes is not a relevant factor. By the Cross classification, Types C, G, and H (cyclist failed to stop/yield at controlled intersection, motorist failed to stop/yield at controlled intersection, and motorist made improper left turn), can be considered as neutral accidents. The technique presumes that the ratio of neutral to non-neutral accidents is relatively constant at all locations. Thus, the ratio of neutral accidents at locations without bike lanes to neutral accidents at locations with bike lanes can be used as a weighting factor to allow comparison of non-neutral accidents.

In Davis this "without/with" ratio for neutral accidents is .71. This ratio, multiplied by the percentages in Table 18, provides the percentages of accidents at bike lanes in Table 19, and these can be compared directly to locations without bike lanes as shown.

Table 19 indicates that expectation of non-neutral accident types is lower on streets with bike lanes for all but one non-neutral accident type. These expectations are intuitively reasonable. For instance, considering Accident Type A (cyclist exits driveway into path of motorist), for every 7.89 accidents which occur on streets without bike lanes, only 1.03 would be expected if bike lanes were provided. This is a reasonable expectation as the bike lane shifts motor vehicles away from the right side of the road (where the bicyclist is entering) and provides the bicyclist with guidance for turning onto the roadway without conflicting with motor vehicles' paths.

Bike lanes do appear to increase expectation of one type of accident -- Type D (cyclist improper left turn) which appears about twice as likely on streets with bike lanes as on streets without (some 10.29 accidents on streets with bike lanes for each 5.26 on streets without bike lanes). Table 20 presents a detailed breakdown of accidents of this type. It appears that when bike lanes are provided, cyclists tend to avail themselves of the bike lane almost all the way to the intersection and then make a left turn from the right side of the road, bringing them to con-

Table 17
DAVIS BIKE-AUTO ACCIDENTS (BY AGE, SEX AND BIKE LANE PROVISIONS)

Accident Type	NO BIKE LANES									BIKE LANES PRESENT									Total
	0-11		12-17		18-24		25+		Sub-Total	0-11		12-17		18-24		25+		Sub-Total	
	M	F	M	F	M	F	M	F		M	F	M	F	M	F	M	F		
A - Cyclist Exited Driveway Into Motorist Path	3	0	1	0	0	2	0	0	6	0	1	0	0	0	0	0	0	1	7
B - Motorist Exited Driveway Into Cyclist Path	0	0	1	0	1	1	0	0	3	0	0	1	0	0	1	0	0	2	5
C - Cyclist Failed To Stop/Yield At Controlled Intersection	1	0	2	0	1	2	0	0	6	2	0	2	1	2	0	0	1	8	14
D - Cyclist Made Improper Left Turn	2	0	0	1	1	0	0	0	4	3	1	1	0	0	1	2	2	10	14
E - Cyclist Rode On Wrong Side Of Street	2	1	2	1	3	5	0	0	14	1	0	1	1	0	2	0	0	5	19
F - Motorist Collided With Rear Of Cyclist	1	0	1	1	1	2	0	0	6	0	0	0	0	0	1	0	0	1	7
G - Motorist Failed To Stop/Yield At Controlled Intersection	0	0	2	0	5	3	2	1	13	1	0	0	2	4	1	5	2	15	28
H - Motorist Made Improper Left Turn	0	0	2	0	3	3	2	1	11	2	0	3	0	3	3	5	3	19	30
I - Motorist Made Improper Right Turn	0	1	1	0	5	3	0	0	10	0	1	0	0	3	2	2	0	8	18
J - Motorist Opened Car Door Into Cyclist's Path	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTALS	9	2	12	3	20	21	4	2	73	9	3	8	4	12	11	14	8	69	142

*Davis bike-auto accident types during the years 1970 through 1974 on and off bike lanes by age and sex.

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

Table 18
ACCIDENT DISTRIBUTION COMPARISON

Accident Type	Santa Barbara (No Bike Lanes)	Davis (No Bike Lanes*)	Davis (With Bike Lanes*)	Total
A	8.59	7.89	1.45	3.95
B	5.73	3.95	2.90	2.82
C	8.33	7.89	11.59	7.91
D	11.20	5.26	14.49	7.91
E	14.32	18.42	7.25	10.73
F	4.17	7.89	1.45	3.95
G	7.81	19.74	20.29	16.38
H	12.75	15.79	28.99	18.08
I	11.20	13.16	11.59	10.17
J	7.29	0.00	0.00	0.00
Other	8.60	-	-	18.08
Total	99.99	99.99	100.00	99.99

*Percentages in these columns reflect percent of total accidents which could be classified. Accident percentages in subsequent tables are also based upon total accidents which could be classified.

Table 19
COMPARATIVE ACCIDENT EXPECTATIONS, Non-Neutral Accidents

Accident Type	With Bike Lanes	Without Bike Lanes
A	1.03	7.89
B	2.06	3.95
D	10.29	5.26
E	5.15	18.42
F	1.03	7.89
I	8.23	13.16
Total	27.79	56.57

Table 20
LEFT TURN ACCIDENTS, BICYCLIST FAULT
Davis and Santa Barbara

	Santa Barbara	Davis Without Bike Lanes	Davis With Bike Lanes
Cyclist Hit Oncoming Motorist	26%	25%	0%
Cyclist Hit From Behind Crossing In Front of Motorist at Intersection	16%	25%	60%
Cyclist Turned Into Path Of Motorist	58%	50%	40%

flict with motor vehicles traveling on the same intersection approach.*

Two important implications of this work should not be overlooked. First, there is clear evidence that bike lanes reduce the likelihood of several types of accidents in addition to the sideswipe/rear end collision, contrary to the assertions of bike lane critics. In addition to the overtaking accident, the above analysis demonstrates that bike lanes tend to reduce the following types of accidents:

- Cyclist exiting driveway or alley into motorists' path (Type A).
- Motorist exiting driveway or alley into cyclists' path (Type B).
- Cyclist riding on wrong side of street (Type E).
- Motorist opening car door into cyclist's path (Type J).

In addition, there is evidence that the sideswipe/overtaking collision occurs with significantly greater frequency than some critics have alleged. Bike lane critics concede that bike lanes do protect against such accidents. Table 21 presents overtaking accident percentages from the two studies discussed above as well as some additional studies. It shows substantially greater bicyclist involvement in this type of accident than the "less than one percent" figure sometimes cited.

Table 21
OVERTAKING/SIDESWIPE ACCIDENTS

Study Area	Percent Sideswipe and Rear-End
Davis, California	4.0
Eugene, Oregon	9.5
Maryland, Statewide*	6.0
Oregon, Statewide	13.0
Santa Barbara, California	4.2

*Rear-end accidents only; sideswipe not included.

Conclusions and Implications

The research described in the preceding paragraphs provides the first indication that bicycle lanes reduce accidents. However, the case study is specific and unique. As more bicycle facilities are created in the

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*Subsequent sections in this report and in User Manual Volume II suggest methods of reducing this accident exposure.

future, it would appear appropriate to compare sites with and without bike lanes at other locations in the country. Such research will be valuable both in enlarging knowledge of bike lane effectiveness and allowing better quantification of potential accident reduction.

Clearly additional research is required in the field of accident causality. Previous work has been able to classify accidents and assess fault, but insufficient research has been done in defining causality in sufficient detail to allow cause/effect relationships and effective accident prevention techniques to be developed. Given the large number of bicycle accidents noted in the introductory paragraphs of this section, such research would appear to be of vital import.

CHAPTER 3

SAFETY AND OPERATING PARAMETERS ON LINEAR BICYCLE FACILITIES

INTRODUCTION

Safety and operations of bicycle facilities can be clearly separated into two categories: Conditions at intersections, and conditions along the remaining linear portions of the bikeways. Chapter 4 will describe the results of research aimed at identifying criteria for use of recommended intersection treatments. This chapter will describe several studies which dealt with the non-intersection problems. Studies included evaluation of:

- Effects of vehicle speed differentials and maneuverability on mixing.
- Operating space and lateral separation requirements and implications on capacity.
- Implications of bike lane presence or absence on bike-motor vehicle lateral separation.
- Effects of sight distance requirements and braking capabilities.
- Evaluations of user perceived safety in mixed use and designated space situations.
- Consequences of bicycles traveling with or against traffic.
- Feasibility of separating modes by striping or physical barriers.
- Feasibility of bicyclist use of highway shoulders on rural and urban expressways and arteries.

The sections which follow will document research done in each of these areas. The results of these studies have been directly applied in presenting recommendations in the User Manuals on Design and Location of Bicycle Facilities.

SPEEDS AND MIXING

Purpose and Scope

As part of a research project oriented toward defining the need and standards for separated bicycle facilities, it is necessary to identify situations where bicycles, motor vehicles, and/or pedestrians can share a common path and situations where separation is desirable. Toward this end, research has been directed toward the analysis of speeds of these three travel modes in an attempt to determine if conditions occur where speed ranges are relatively equal. This section documents research on speed and maneuverability of bicycles as they relate to pedestrians and automobiles.

Methodology

Bicycle speeds were measured using hand-held radar units on three types of facilities in Sacramento, California:

- Class I (separated path) -- recreation oriented
- Class I -- utilitarian oriented separated path
- Class II (bike lane)

Auto speeds were measured on uncongested suburban and downtown streets with signed speed limits of 25 MPH.

Findings

> Bicycles and motor vehicles are not compatible except on surface streets where motor vehicle speeds are constrained, on long downgrades, and on lightly traveled streets.

Figure 2 presents cyclist speed distributions on various types of facilities on level terrain. Table 22 indicates mean velocities, standard deviations and number of observations corresponding to the velocity distributions presented in Figure 2. Speed distributions are relatively stable on level terrain with the 85th percentile speed approximately 15 MPH and very few cyclists traveling in excess of 20 MPH. The implication is that

Table 22
MEAN BICYCLE VELOCITIES AND STANDARD DEVIATION ON LEVEL TERRAIN

		Mean Velocity	Standard Deviation	No. of Samples
Class I	Recreation	11.00	2.89	182
Class I	Utility	11.82	1.78	136
Class II	General Use	12.50	2.33	103

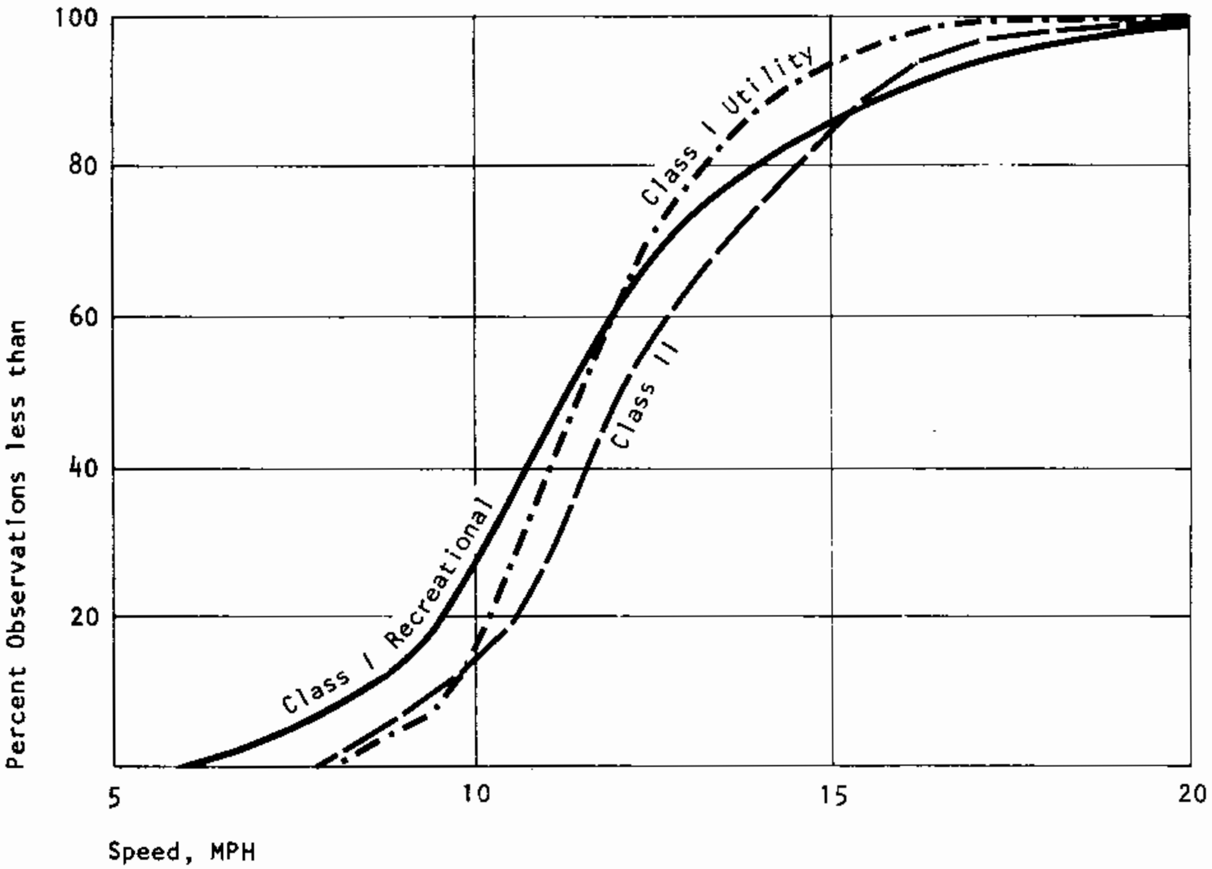


Figure 2
BICYCLIST SPEED DISTRIBUTION

bikeways can be designed to accommodate the full range of bicyclist travel speed desires without imposing stringent requirements for sight distance, curvature and other design parameters. On upgrades and downgrades, cyclist speed distribution profiles change significantly with cyclist speeds falling to just above walking speed (4 to 6 MPH on steep upgrades) and reaching well above 30 MPH on long downgrades.

Statistically significant differences in velocities among age-sex groupings were found in the level facilities observations as indicated on Table 23. However, these statistically significant differences in mean velocity were at most on the order of 2 MPH -- not sufficiently different to affect design parameters.

Figure 3 presents a comparison of typical motor vehicle and bicycle speed distributions on separated paths. The figure shows that 90 percent of all bicyclists travel slower than virtually all motorists under free flow conditions and that the average bicyclist travels only half as fast as the average motorist.

One finding presented in User Manual Volume II relative to design is of sufficient import to be reemphasized here. The recommendation of 10 MPH as a bikeway design speed in many early planning guides is inadequate. Between 80 and 90 percent of all cyclists would prefer to select speeds above that level. Normally a 20 MPH design speed would comfortably accommodate most bicyclists. However, provision should be made for the possibility of significantly higher speeds on downgrades and lower speeds on upgrades.

Additional analysis unreported in the user manuals relates to the differential between bicyclist and pedestrian walking speeds. Typical free flow pedestrian speeds range between a low of some 1.65 MPH to a high of some 5.35 MPH with normal walking rates in the 2.45 to 3.1 MPH range (John J. Fruin, Pedestrian Planning and Design, MAUDEP, 1971). This distribution falls significantly below the entire level path bicyclist distribution. This provides rationale for the general recommendation that any bicyclist-pedestrian shared facilities include comfortable passing space.

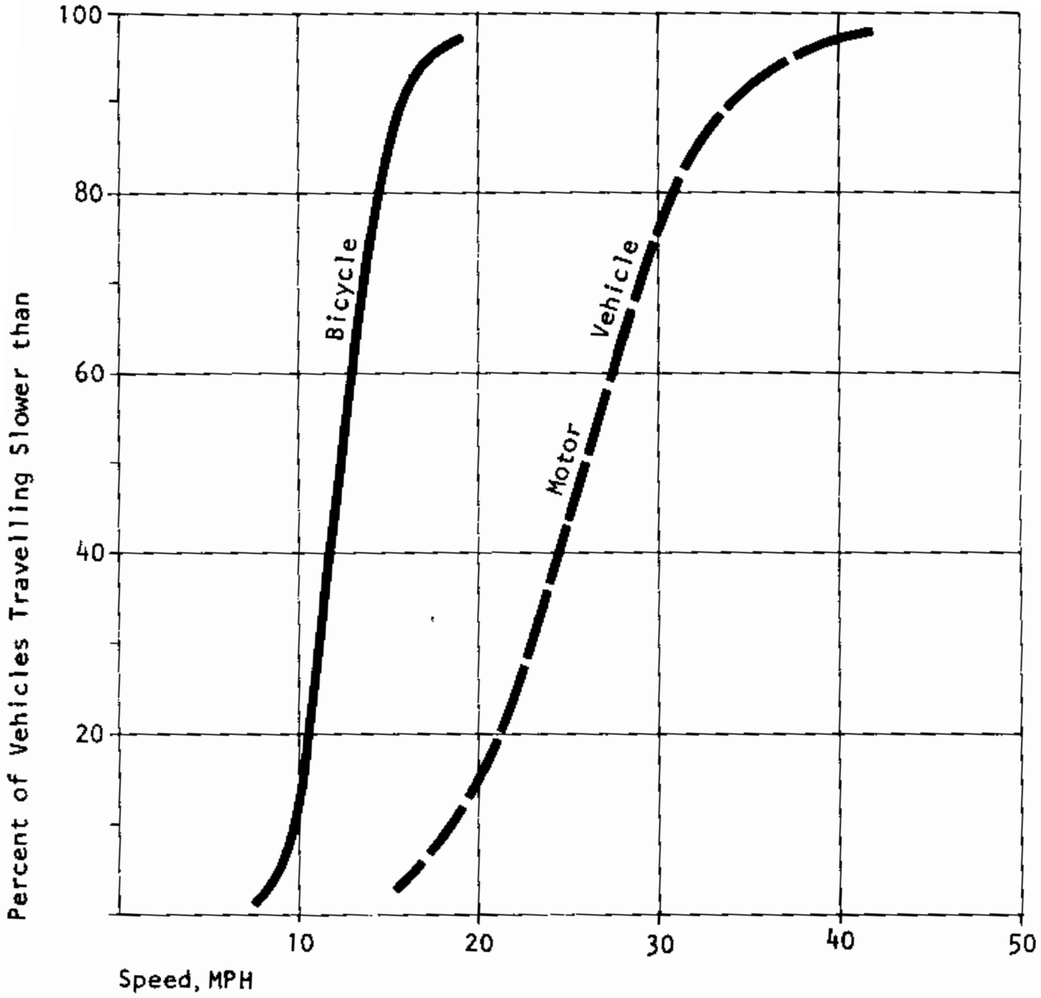
To briefly summarize findings with respect to the effects of maneuverability on feasibility of mixing, behavioral tendencies related to the predictability of human decisions to make maneuvers are far more significant than differences in inherent maneuverability capabilities. These behavioral tendencies can be affected by physical facility provision as well as by education and training. More significant than maneuverability may be bicyclist behavior induced by desire to maintain momentum. Conflicts which result from this can also be reduced by physical provisions.

Apart from speed, inherent maneuverability characteristics of bicycles and motor vehicles are not so different as to make the vehicles incompatible. Conflicts between the two which involve unusual and unpredictable maneuvers are generally not a function of differences in maneuverability capabilities -- turning radius capability, stopping distance,

Table 23
MEAN SPEED VARIATION BY AGE AND SEX

Sex		Age					
		All	0 - 10	11 - 20	21 - 30	31 - 50	51+
Males	# Observations	11	12	38	27	32	2
	Mean Velocity	12.6	11.18	13.69	13.00	11.62	11.17
	Standard Deviation	2.99	2.43	3.0	3.70	1.65	2.8
	t Statistic	5.8	- 0.3	- 5.5	- 2.9	- 2.2	- 0.09
	Significance*	Yes	No	Yes	Yes	Yes	
Females	# Observations	6	3	24	14	21	0
	Mean Velocity	10.7	9.0	11.37	10.43	10.28	-
	Standard Deviation	1.56	1.77	1.34	1.36	1.62	-
	t Statistic	1.43	1.41	- 1.35	1.56	2.03	-
	Significance*	No	No	No	No	Yes	-
All	# Observations		15	62	41	53	2
	Mean Velocity	11.00	10.8	12.79	12.1	11.09	11
	Standard Deviation	2.39	2.4	2.73	3.38	1.77	2.8
	t Statistic	-	0.23	- 5.1	- 2.2	- 0.30	- 0.07
	Significance*	-	No	Yes	Yes	No	No

*All t statistics are with respect to the total set of observations -- data in the lower lefthand cell. Significance is at the 90 percent level corresponding to a t statistic of 1.65.



Midblock Speeds

Bike Speeds on Level Ground

Motor Vehicle Speeds Typical of 25 mph Speed Zone

Figure 3
COMPARATIVE SPEED PROFILES
Bicycles and Motor Vehicles

Source: De Leuw, Cather & Company

acceleration rate, straight line tracking. They are the result of abnormal and unpredictable operator choice and behavior rather than a characteristic of the vehicles.

Maneuverability relationships of bicyclists to pedestrians are somewhat different. Pedestrian capabilities for lateral and reverse changes of direction and stopping are radically different from bicycle and motor vehicle capabilities. But what causes problems in bicyclist-pedestrian mixed use situations is not that pedestrians have significantly greater maneuverability characteristics but that they use these with such frequency and unpredictability.

A hypothesis which can be drawn from this is that if behavior and choice can be normalized and lent predictability by physical facility provision, conflicts which involve exercise of maneuverability capabilities will tend to be minimized.

One difference between bicycle and pedestrian maneuverability has import in sidewalk bikeway problems at intersections. A pedestrian entering a crosswalk and confronted by a motorist who fails to yield can quickly stop or back up. Once a bicyclist is committed to enter the crosswalk, he thereafter has little opportunity to avoid a collision by stopping and no opportunity to back up. The bicyclist's only resources are evasive action by turning or accelerating. This is another of the reasons why sidewalks are less safety effective for bicyclists than for pedestrians.

More significant than maneuverability in conflicts between bicycles and motor vehicles are conflicts resulting from source of motive power and the behavior it may induce. Because bikes are propelled by human effort there is a very natural and strong desire to maintain momentum. This desire leads to a number of facets of operating behavior which bring bicyclists to conflict with motor vehicles.

Conclusions

The research on speed and maneuverability indicates that mixed flows are generally undesirable; the following are circumstances under which mixed flows may be acceptable:

- On surface streets in urban centers where traffic conditions constrain motor vehicle speeds resulting in considerable overlap of bicyclist and motor vehicle speed distributions.
- On long downgrades where bicyclist speeds are significantly above those typical on the level.
- At and on the approaches to intersections where motor vehicle speed is depressed preparatory to stops, turning movements and intersection-related decisions.

- On lightly traveled streets on which encounters between bicyclists and motor vehicles are infrequent and on which motorists can be expected to tolerate brief delay until bicyclists can be safely passed.

OPERATING SPACE

Purpose

The basic purpose of this portion of the research effort was to clearly define bicycle facility width requirements based on user satisfaction and safety criteria. Toward this end, level of service criteria, similar to those found in the Highway Capacity Manual, were developed to reflect the variation in flow and density conditions that might occur. The resultant width requirements are directly related to six defined service levels.*

The basic need for this type of research is due to the wide variety of bike facility standards that have been produced by many agencies throughout the country. Table 24 illustrates some of these existing standards. The intent of this research is to scientifically determine a sound set of width standards.

Summary of Findings

Table 32 shows the essential results of this research: A table of minimum bicycle widths based on level of service. In evaluating width for any design situation, these widths should be used as a starting point. Complete evaluation of width requirements requires calculation of bikeway capacity as explained below and provision of extra marginal space based on conditions at the boundaries of the facilities.

Methodology

To determine level of service and velocity-density-volume relationships, unwitting bicyclists were observed on level paths which carried heavy bicycle traffic in a single direction (both unidirectional paths and bidirectional facilities with peak traffic in a single direction). Data collection sites were selected on facilities where there were no boundary conditions (curbs, fences, posts, trees, etc.) such that users might maintain an extraordinary shy distance from the pavement edge. Data were collected at a number of free path locations of varying widths. For each data entry, the number of bikes passing a point per unit time were measured along with the mean velocity of the individual platoon of bicyclists. Capacity and service level determination was based on these data.

To determine naturally selected lane widths, naturally selected bicyclist separation distributions were measured for a limited population of rider

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*Reference 1, Chapter 3 provides full details of this research.

Table 24
VARIOUS CURRENT BIKEWAY WIDTH STANDARDS

CLASS I WIDTH DIMENSIONS

ITTE	1 lane	3.3 ft.		
	2 lanes	5.3 ft.		
	3 lanes	8.5 ft.		
Oregon	Bidirectional	8 ft.	(min)	
	Unidirectional	6 ft.	(min)	
	Bridge Section	12 ft.	(between guardrails)	
Desimone, V.	Bidirectional	6.5 ft.		
	Unidirectional	3.3 ft.	(minimum per lane)	
California	Bidirectional	8 ft.		
	Unidirectional	5 ft.		
	Add 4 additional feet for high volume or velocity			
AASHTO	1 lane	3.5 ft.	(min)	4.0 ft. desirable
	2 lanes	7.0 ft.	(min)	8.0 ft. desirable
	3 lanes	10.5 ft.	(min)	12.5 ft. desirable
Germany	1 lane	3.3 ft.	(= 1 meter)	
Japan	2 lanes	5.3 ft.		
Sweden	3 lanes	8.5 ft.		
India	Lateral clearance to barriers 0.8 ft.			

CLASS II WIDTH DIMENSIONS

UCLA-ITTE	4.1 ft.
	7.5 ft. to allow for passing
	------ these values are for streets without parking -----
Oregon	6.0 ft. desirable
Desimone	5.0 ft. (8-10 ft. parking lane)
California	5.0 ft. (8 foot parking lane)
	5.0 ft. (to raised curb, no auto parking)
	4.0 ft. (without raised curb, no auto parking)
	8.0 ft. (freeway shoulder, only if necessary)
AASHTO	4.5 ft. (between two raised curbs)
	4.0 ft. (adjacent to curb, no auto parking)
	5.5 ft. (adjacent to parked cars)

RECOMMENDED LATERAL CLEARANCES FROM EDGE OF BIKEWAY TO BARRIER

Germany	0.8 ft. to any barrier, except:
	2.3 ft. to curb dropoff if bikeway is on a sidewalk
Canada	1.0 ft. to any barrier, except:
	1.5 ft. to curb dropoff if bikeway is on a sidewalk
Netherlands	1.6 ft. to any barrier
India	1.8 ft. to any barrier
USSR	1.3 ft. to any barrier
Finland	0.8 ft. to a sloped dropoff (embankment with less than 2:1 slope)

pairs and selected lane width was estimated as equal to the separation distance measured from center of bicycle to center of bicycle. In each measurement, one cyclist was a member of the research team who acted as a stooge, riding in a straight line irrespective of the position of the other cyclist. The second cyclist was a volunteer subject instructed to ride as close to the other bicyclist as they might normally under everyday operating conditions. Thus, the separation distance reflected the riding space desires of the volunteer subject.

Measurement of separation distance was done in the following fashion: A plastic bottle filled with water was attached to the diagonal bar on the front of each bicycle frame. A small aquarium hose value was permanently mounted to the underside of the water bottle so that, when opened, water would slowly drain from the bottle to the ground directly beneath the bicycle. In this way the water left a temporary record of the exact lateral position of the bicycle in the form of droplets. At the conclusion of each ride, the distance between the two water trails was measured periodically over at least a fifty foot stretch, much longer if the test was run at high velocity. Separation distance measurements were made at points spaced between five and seven feet apart along the tracks. The exact locations for measurements changed with each trial so that the subjects did not know where they were being measured until after the trial. These measurements produced a log of the two cyclists' relative positions, showing the instantaneous spacing and the amount of wavering. Velocity of the pair of cyclists was determined using hand-held radar. For each run by each rider pair, mean separation was calculated and used as a single velocity-separation data point. The relationship between velocity and separation was then determined by linear regression on mean data for all runs.

Findings relevant to operating space are presented in the following pages under these headings:

- Level of Service
- Speed-Volume-Density-Capacity Relationships
- Determination of Minimum Width
- Boundary Conditions
- Effect of Swerve Maneuvers on Width

Level of Service

> Six levels of service can be defined for bicycle operation, as shown in Table 25.

These levels of service have been defined by use of volume-density and volume-velocity relationships shown in Figures 4 and 5 and described in the following section.

Table 25
BICYCLE SERVICE LEVEL DEFINITIONS

Service Level	Definition
Level A:	Free flow with low volumes and full choice of velocity and lateral lane position. Average velocity usually above 11 MPH.
Level B:	Stable flow with significant volumes and slight slowing of average stream velocity (10.5 to 11 MPH), but there is still a reasonably wide range of velocities present.
Level C:	Flow is still stable, but speeds are markedly depressed. Maneuverability is restricted and velocity is largely determined by stream/velocity rather than choice. Average velocity is in the 9.5 to 10.5 MPH range.
Level D:	Flow speed is greatly depressed and maneuverability is highly restricted. Velocity is in the 8 to 9.5 MPH range.
Level E:	Flow speed is tremendously reduced. Maintaining balance may become a factor. Velocity is in the 6 to 8 MPH range.
Level F:	Traffic may be stop and go. Flow is very unsteady. Velocity is unpredictable.

Speed-Volume-Density-Capacity Relationships

> Speed on unrestricted paths can be directly related to volume and density measurements. Capacity is defined from maximum volume observed by these measurements.

Figure 4 shows observed data on speed and density. These data have been used to develop a least-squares curve as follows:

$$V = 12.3 - 251/M$$

Where:

V = platoon velocity, MPH

M = path area per bicycle (density), ft^2

For this equation,

Standard errors = (.89)(20)

R^2 = 0.61

Standard error of estimate = 0.9

Density can be related to capacity through the following set of equations:

$$M = \frac{VW}{Q}$$

Where:

M = density module or path area per bicycle (sq. ft.)

V = platoon velocity (ft. per second)

W = path width (ft.)

Q = bicycle flow (bicycles per second)

Since:

$$\text{Volume} = \frac{Q}{W}$$

and

$$\text{Capacity} = \text{Volume}_{max} = \frac{Q_{max}}{W} = \left(\frac{V}{M}\right)_{max}$$

Substitution of the derived relationship between velocity and density provides the following capacity-density relationship (velocity units converted to feet per second).

$$\text{Capacity} = \left(\frac{V}{M}\right)_{max} = \left(\frac{18.04}{M} - \frac{368}{M^2}\right)_{max}$$

Figure 5 presents a plot of the above expression for various values of M. Maximum volume or capacity is reached at a density module of approximately 40 square feet. At this point:

Capacity = .22 bicycles/foot/second

Velocity = 6.1 MPH = 9.0 feet/second

M = 41 square feet

Figure 6 presents an alternate expression of this relationship, showing capacity as a function of velocity.

Volume to capacity ratios and density modules corresponding to these levels of service are summarized on Table 26. Bike volume-capacity ratios to level of service relationships are compared to similar relationships for motor vehicles and pedestrians on Table 27.

Table 26
LEVEL OF SERVICE PARAMETERS

Level of Service Class	Volume/Capacity	Density Module(ft^2)
A	.33	200
B	.50	140
C	.75	85
D	.90	60
E	1.00	43
F	variable	--

Table 27
LEVEL OF SERVICE - MODAL PARAMETER COMPARISON

	Volume-to-Capacity Ratio		
Service Level	Bicycle	Auto	Pedestrian
A	.33	.30	.28
B	.50	.40	.50
C	.75	.60	.75
D	.90	.80	.90
E	1.00	1.00	1.00
F	variable	variable	variable

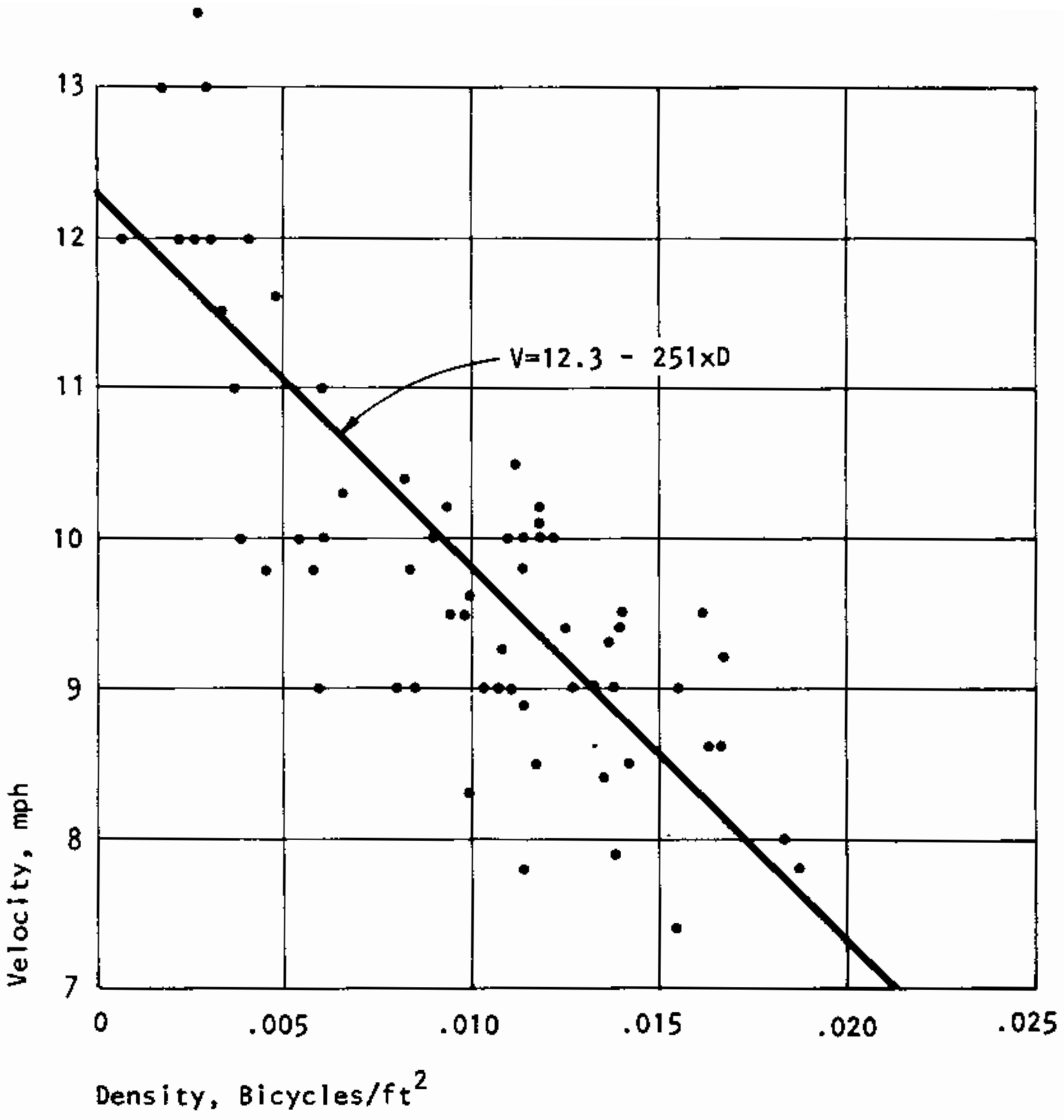

Figure 4
VELOCITY - DENSITY RELATIONSHIP

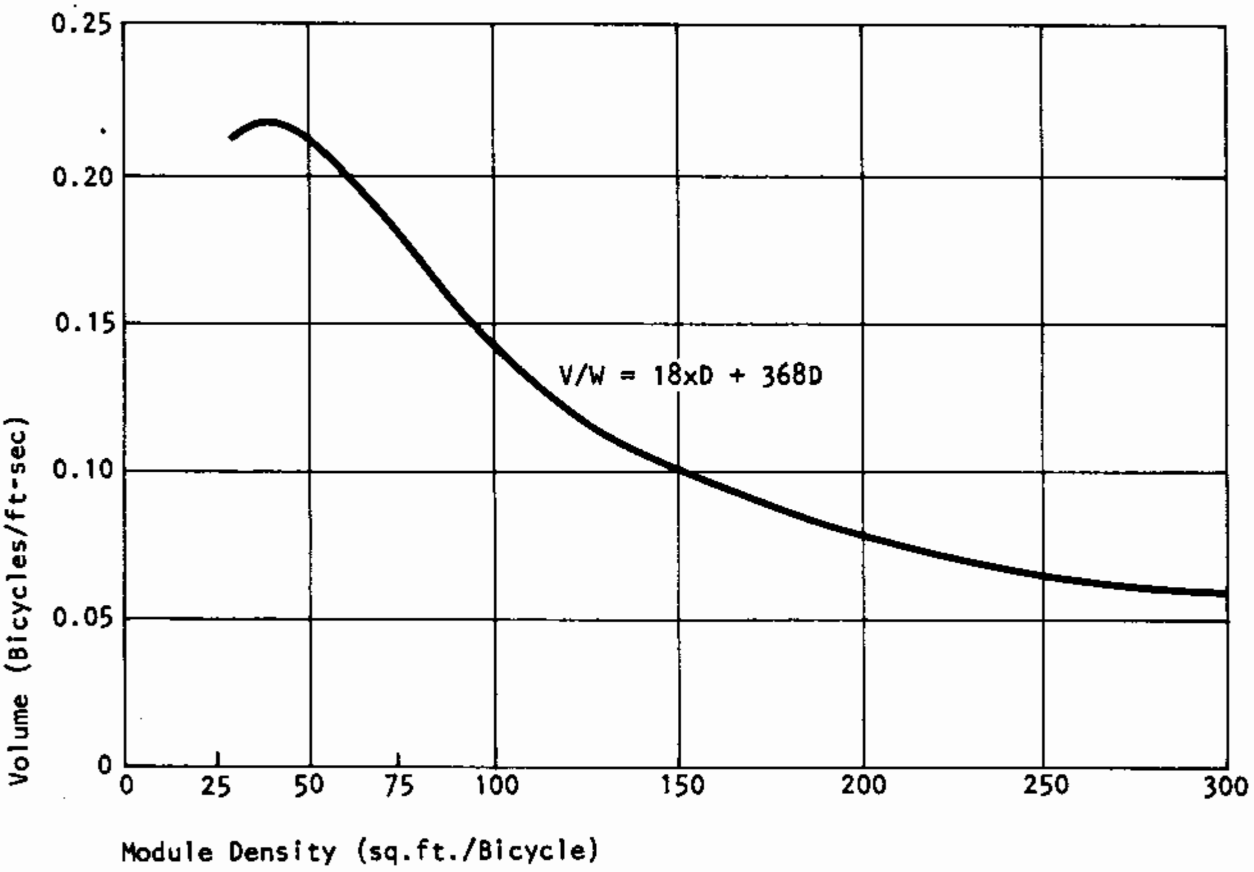

Figure 5
VOLUME - DENSITY RELATIONSHIP

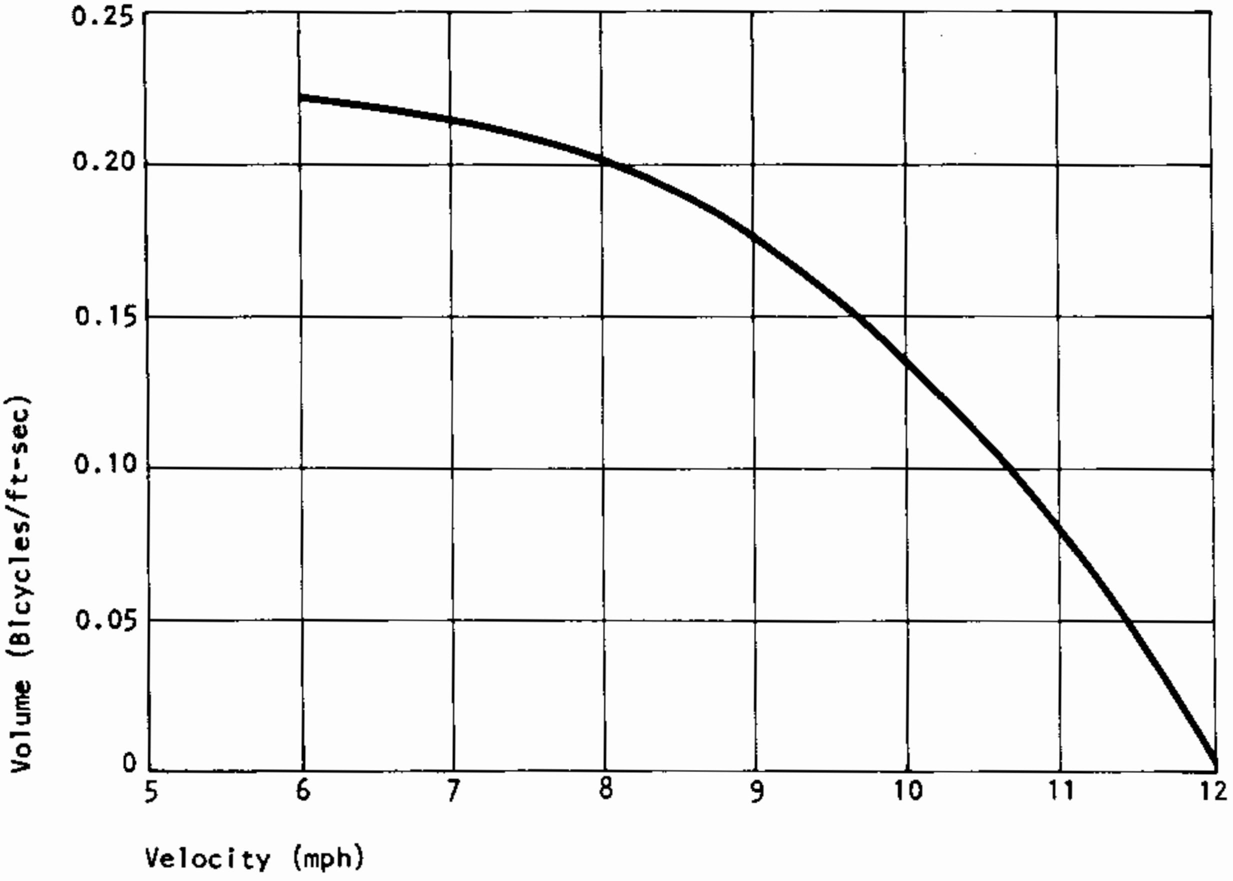

Figure 6
VOLUME - VELOCITY RELATIONSHIP

Determination of Minimum Width

> Minimum width is related to level of service by comparing satisfaction with naturally occurring bicycle separation distances to satisfaction with defined service level.

The above findings related to level of service enable determination of demand-related facility width requirements. Levels of user satisfaction corresponding to the previously defined levels of service can be established by determining the percent of the persons in the naturally occurring free-flow velocity distribution (presented on Figure 1) who would be satisfied by the maximum speed achievable under each level of service. Resultant level of satisfaction ranges are presented on Table 28.

Table 28
PERCENT USER SATISFACTION BY SERVICE LEVEL

Service Level	Velocity	Percent User Satisfaction Range
A	11.0	100 - 88
B	10.5	88 - 74
C	9.5	74 - 58
D	8.2	58 - 24
E	6.1	24 - 6
F	-	6 - 0

If the percentages of satisfaction for each level of service as indicated on Table 28 are applied to facility width, width dimensions corresponding to the various levels of service can be defined. The procedure for estimating these widths is to relate naturally occurring bicycle separation widths at various speeds to the percent of cyclists satisfied at each increment of width.

Data from the test of velocity and separation was aggregated by velocity and analyzed with mean separation distances computed for all trials at each velocity. Table 29 presents analysis of separation data for both unweighted results and data weighted by number of trials per velocity point.

Table 29
BICYCLE SEPARATION AS RELATED TO BICYCLE VELOCITY

	Aggregated	Disaggregated
Separation (Inches)	32.0 + .79 x velocity(MPH)	30.1 + .91 x velocity(MPH)
R^2	0.67	0.63
Standard Error	3.80	3.40

In order to determine percent satisfaction at various widths, the disaggregated separation equation given on Table 29 was utilized. It was assumed that at any given velocity, the distribution of selected separation widths about the value given in that equation was normal with standard deviation equal to the standard error of estimate. The distribution of separation distances, D, expected in a large sample of bicyclists traveling at velocity, V, is given by the equation:

$$D = 30.1 + .91V + RN$$

where RN is a random normal with mean equal to zero and standard deviation equal to 7.02. From this relationship the probable proportion of bicyclists traveling at velocity, V, with a separation distance, d, less than D can be calculated based upon the standard normal distribution.

$$P\ (d<D) = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{d} \exp(-\tfrac{1}{2}(\frac{t-D}{7.02})^2\ dt$$

To determine the probable proportion of bicyclists satisfied with a separation distance less than D, irrespective of velocity, each probability at a given velocity must be weighted by the probability of traveling at that velocity. Such probabilities or "velocity weights" expressed in percentages are given on Table 30 for three facility types.

Table 30
VELOCITY WEIGHTS

Velocity	Weights (P(v))		
MPH	Utility Class I	Utility Class II	Recreation Class I
6	0	0	1
7	0	0	1
8	1.5	1	5
9	3	5	6
10	20	6	12
11	25	11	15
12	21	27	25
13	13	12	8
14	8	12	6
15	5	12	7
16	2	11	6
17	1.5	2	4
18	0	1	2
19	0	0	1
20 or more	0	0	3

Using these percentages, the probable proportion of bicyclists requiring a separation distance, d, less than the available width, D, (that is, satisfied with D) can be calculated from:

$$P(d<D) = \sum_{v=6}^{20} P(d<D/v)\ P(v)$$

The probable proportion of bicyclists whose separation distance requirements were less than an entire range were computed to produce Figure 7 which indicates the correspondence of level of satisfaction to level of service as per Table 28.*

Table 31 presents level of service widths for the various facility types as drawn from Figure 7. Since the range of width differences among the three facility types analyzed was so minimal, these were condensed to the single set of width minimums presented on Table 32. It should be noted that the ability to pass slower cyclists is implicit in the definition of Levels of Service A and B. For these levels to be achieved, the facility must provide at least two travel lanes or be twice the minimum widths indicated on Table 32. Table 32 forms the basis for width recommendations presented in User Manual Volume II.

Table 31
LANE WIDTH - SERVICE LEVEL BY FACILITY TYPE

Service Level	Recreational Class I	Utility Class I	Class II
A	50.0 inches	49.5 inches	50.5 inches
B	46.5	46.0	47.0
C	43.0	42.5	43.5
D	36.0	36.0	37.0
E	30.0	30.0	30.5
F	<30.0	<30.0	<30.5

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*Similar analysis was performed using the observed separation data as a verification. This data was not originally used as it was feared that inadequate numbers of data points existed at some velocities. However, the results using field data did not differ significantly from the findings with synthetic data.

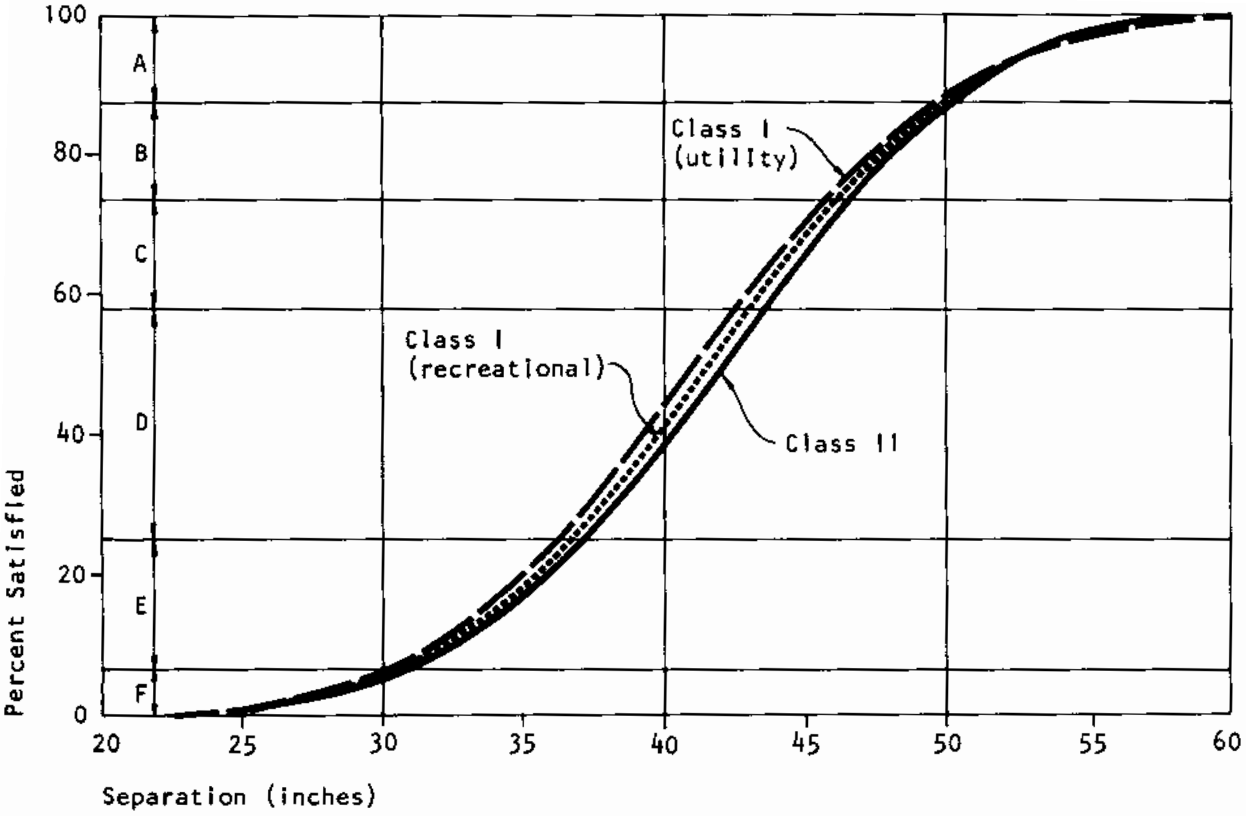

Figure 7
WIDTH - SATISFACTION RELATIONSHIP

Table 32*
LANE WIDTH - SERVICE LEVEL

Service Level	Minimum Width (inches)
A	50* (100)
B	47* (94)
C	43
D	36
E	30
F	--

Correspondence between level of service and capacity was given on Table 21. This relationship is brought together with the width-level of service relationship given on Figure 7 to generate the width-volume-level of service relationship presented on Figure 8.

Boundary Conditions

> Boundary conditions (fences, trees, slopes, etc.) should be considered in bicycle facility design. Specific width adjustments have been developed for various lateral obstructions.

Width specifications presented on Table 32 and Figure 8 correspond to "free path" situations. The fact that conditions other than free path boundaries reduce the effective width of a bicycle facility is apparent from casual observation. In order to estimate the loss of effective bikeway width or shy distance from boundary conditions, observations were made of bicyclist reactions to common types of bikeway edge conditions -- fixed obstacles such as rows of parked cars, fences, curbs and gutters and intermittent obstacles such as trees, utility poles and the like. Then distributions of cyclists' positions on bikeways with non-free path boundaries were compared to cyclists' position distributions on free paths as indicated on Figure 9 to derive the shy distance or reduction in effective width due to the boundary. Shy distances were computed for several types of common boundary conditions. These are presented on Table 33.

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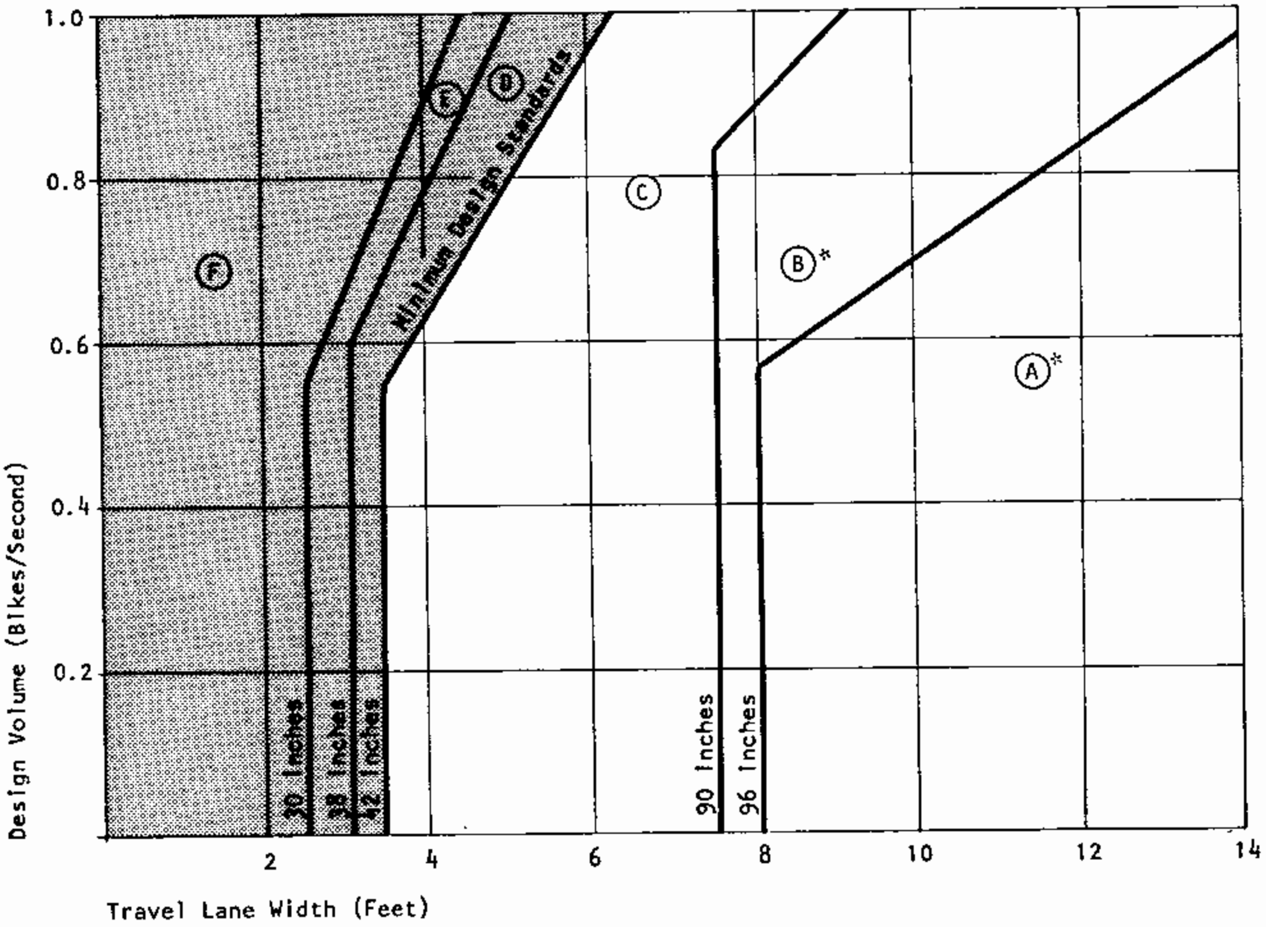
*Table 32 gives single lane width minimums. For Level of Service A or B conditions to actually be achieved, width for multi-lane operations must be provided.

To determine appropriate design width, boundary condition adjustments given on Table 33 must be applied to the free path width value for the selected level of service as given on Table 32. For instance, to provide Level of Service C conditions on a path bounded on one side by a fence at pavement edge and on the other by grass level with the pavement surface, a minimum paved width of 54 inches would be required (43 inch Level of Service C free path width plus 12 inch continuous lateral obstruction boundary adjustment for the fence plus zero boundary adjustment for the grass). Alternately a paved width of 43 inches could be provided with its nearest edge offset some 12 inches from the fence.



Ⓓ Level of Service

* Double lane widths required as minimum condition to achieve levels of service A and B.

Figure 8
WIDTH - CAPACITY - LEVEL OF SERVICE RELATIONSHIP ON FREE PATHS

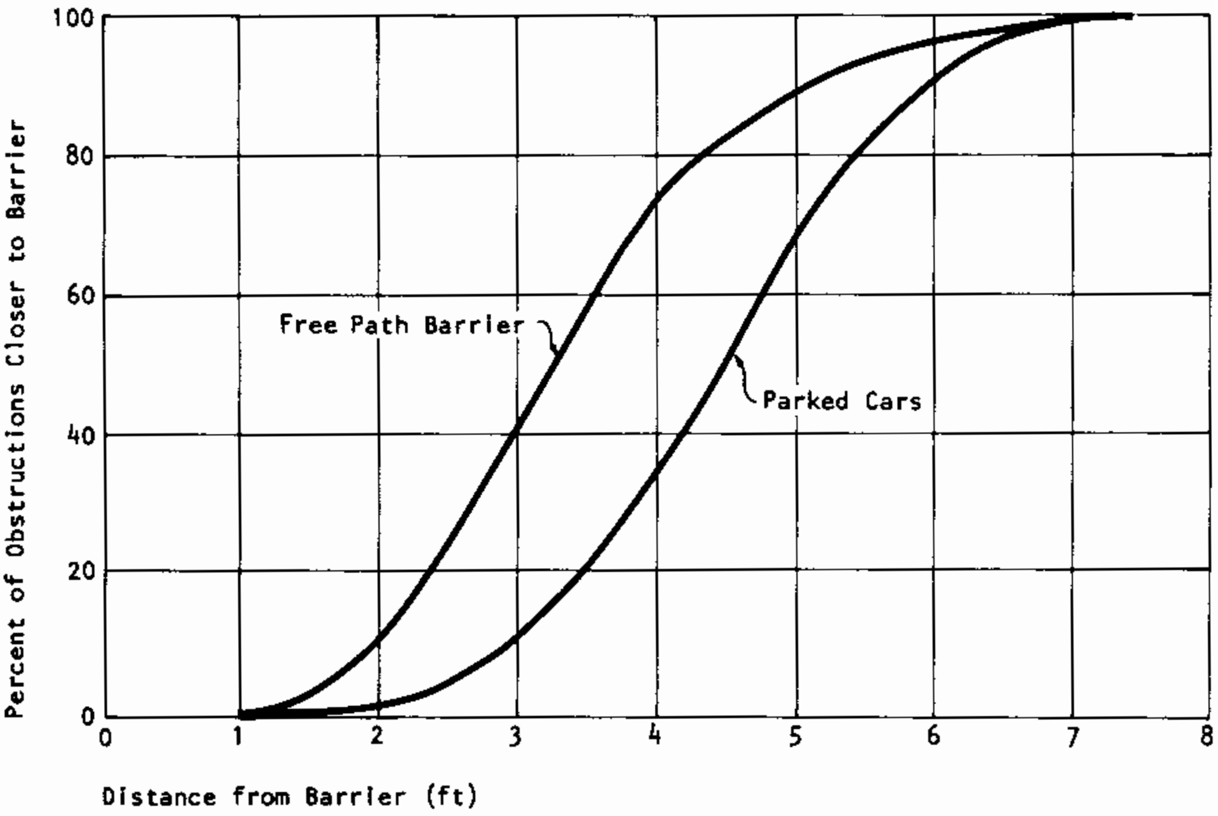


Figure 9
TYPICAL BARRIER COMPARISON

Table 33
LANE ADJUSTMENT DISTANCES

Boundary Condition	Shy Distance*
Free path	0
Parked vehicle	+14.5 inches
Lane line	- 9.5 inches
Continuous lateral obstruction (walls, fences)	+12.0 inches
Intermittent lateral obstruction (poles, trees)	+18.0 inches
Curb/Gutter	+12.0 inches, or width of gutter if unridable

Effect of Swerve Maneuvers on Width

> Maneuvering for the purpose of avoiding instantaneous objects such as opening car doors should not affect bicycle facility width design.

An additional element of this research was the assessment of bicyclist swerve maneuvers in avoidance of dynamic obstacles (such as suddenly opening doors of parked cars) and the implication of these on bikeway width requirements.

Subject bicyclists riding on a bike lane temporarily delineated for purposes of the experiment suddenly were confronted by a simulated car door opening**and their avoidance swerve trajectories measured using the water droplet technique described previously. Cyclist approach velocity was simulataneously measured. The simulated door openings were initiated when the cyclists reached pre-selected points on their approach. Cyclist passes on which simulated car door openings were made were selected randomly to minimize cyclist anticipation of such an event. Simulations were made of a partial and full door opening and their impacts on cyclist swerve assessed.

At simulations of a door opening which projected to the bicyclists' line of travel, subjects swerved 3.6 feet to the left of that projection. On

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*Positive values in Table 33 correspond to conditions which decrease effective path width and should be added to the free path width corresponding to the selected level of service. Negative values indicale conditions which increase effective width. However, these values should not necessarily be deducted from the selected free path width.

**A simulation was used rather than use of an actual car door opening as this was judged to be too hazardous for experimentation with human subjects. Natural occurrence of this type event in the field is too infrequent to permit direct observational study of the phenomena.

simulations of a door opening projecting 1.5 feet to the left of cyclists' line of travel, cyclists swerved 2.75 feet beyond the door projection. These swerve distances were consistent for reaction times within the emergency swerve range. That is, where successful emergency swerves can be made, the deflection trajectory is more dependent on the obstruction projection than cyclist speed or available reaction time.

Interpreting swerve findings in terms of a cyclist riding in the center of a five foot wide bike lane, a partial door opening projecting to the cyclists' line of travel (roughly a half opening on most car doors) would cause the cyclist to swerve about one foot out of the bike lane. An opening projecting about 1.5 feet beyond the same original cyclist line of travel (equivalent to a full extension of the largest car doors) would cause the cyclist to swerve some 1.75 feet out of the bike lane. Since these measurements are made to the center or track of the bicycle, the bicycle would project onto the roadway an additional foot over the values given above. Hence, 7 and 7.75 foot wide bike lanes would be necessary to enable bicyclists to avoid suddenly opening car doors without swerving out of the bikeway.

Bike lanes of such widths are impractical in most areas. Moreover, at lane widths less than the above values for avoidance swerves (six feet for instance) it would be possible for cyclists to position themselves such that their line of travel would not be obstructed by virtually any opening parked car door. Hence the avoidance swerve parameter is not a primary criteria for bike lane dimensioning.

EFFECTS ON DRIVER AND BICYCLIST BEHAVIOR

Purpose and Scope

Prior to this study original research on the effects of bike lane presence and width on motor vehicle traffic characteristics was very limited. R. Jilla (1974) documented a reduction in mean vehicular speed and a lateral displacement of the motor vehicle when a motorist passes a bicyclist in a bike lane. But still unclear were the relationships of these effects to specific lane width requirements and the question of whether provision of a bike lane significantly improves the situation.

The present study attempts to assess the extent to which driver and bicyclist behavior is affected by the provision of a bicycle lane. Observations were made at a variety of roads both with and without bike lanes, roads having different speeds, widths and number of travel lanes. These observations make possible an analysis of bike and auto positioning as functions of speed, lane width, the presence of the other vehicle, and the presence or absence of a bike lane.*

Findings are discussed in four following sections: Bicycle positioning, lane width versus separation, motor vehicle speed, and wind versus separation.

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*Reference 7 of Chapter 3 provides complete details of this research.

Methodology

Cars and bikes were observed traveling on a variety of urban streets (both with and without bike lanes) in the Sacramento, California area. At each sampling location, cars passing a cyclist comprised half the filmed observations (car-pass-bike condition), and cars traveling with no cyclist present comprised the other half (car-alone condition). Cyclist placement without cars present was also noted. In addition to car and bike positioning and separation distance, the incidence of cars crossing the center line when passing a bike was noted for all sampling locations. Incidence of cars crossing bike lanes was so rare, it was not tabulated.

All sampling was done at midblock during afternoon peak hours. Observations which showed nearby cars in opposing or adjacent vehicular lanes were discarded, although in the busy four-lane sampling locations, frames with cars visible in adjacent lanes were used as long as they were not directly adjacent. Observations with two or more cyclists riding in a platoon or in a bike-pass-bike condition were also not included; nor were frames used which showed vehicles larger than pickup trucks or small campers.

Half the observation sites had bike lanes and half did not. All bike lane streets were clearly marked by standard bikeway signs, lanestriping, and sometimes additional pavement stencils. Of the streets without bike lanes, none were edge lined.

Streets were selected in 25, 35 or 40, and 55 MPH speed limit categories. When actual travel speeds seemed to differ from those posted, auto speeds were measured with portable radar from an inconspicuous roadside point.

An attempt was made to include a variety of road widths with the other experimental factors. However because of the discrete values of widths due to county and city standards for residential and arterial streets, ability to obtain data on experimental continuum of roadway widths was limited.

Because of the limited bicycle traffic at most observation sites, a stooge cyclist was employed. Data was gathered at 20 observation sites using the stooge cyclist, ten with bike lanes, ten without them. At three of these sites*, it was possible to make observations before and after installation of bike lanes. At another six sites bicycle traffic was sufficient for observations to be made using unwitting bicyclists rather than the stooge.

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*Saverine Drive in Sacramento, California; Chiles Road and "F" Street, both in Davis, California.

Placement data was collected using a Bolex H16 Reflex-5 single framed, usually operated from a concealed position. Photographic data was transferred to magnetic tape using a digitizing table and analyzed on a Burroughs 6700 computer. Pilot studies showed that street width could be estimated to within four percent from the film using the known lane width as a scale and to within six percent using the rear wheel of a ten-speed bicycle (27") as the scaling device. Pilot studies also indicated the standard deviation of separation distance on six streets was 15.5 inches. Given this, sample size was determined to be 26 observations for a 95 percent confidence limit and 44 for a 99 percent confidence limit. Observations for 95 percent confidence limit were obtained at 18 of the 20 stooge cyclist sampling sites and observations for 99 percent confidence limit were obtained on one site.

Following are specific measurements taken in the observations and subsequent analysis:

- Position of bicyclist.
- Position of motor vehicles with and without bicyclists present.
- Displacement of motor vehicle due to bicycle presence -- the difference between the two motor vehicle position measurements above.
- Separation distance between bicyclist and motor vehicle.
- Centerline violations by the motor vehicle.

These measurements were correlated with other data such as speed limit, lane width and number of lanes, presence or absence of bike lanes and a measure related to lane width denoted as "Available Travel Space" (ATS). This is defined as the space theoretically available for lateral motor vehicle movement while passing a bike -- the distance between the bicyclist and the centerline of the roadway. In the case of multi-lane streets, the outside lane stripe is substituted for the centerline in defining ATS.

Bicycle Position

> When passed by autos, bicyclists tend to vary their position less when on bike lanes than on streets without bike lanes.

In the original research design, expectation was that cyclist stooge positioning would vary only two or three inches from a preset chalk line which the stooge was instructed to follow as closely as possible. The stooge was an experienced male cyclist in his early 20s who, until the data was reduced, believed he had followed the preset track consistently on each run. Film analyses revealed that the expected variation was actually the lowest stooge variation attainable. On streets with bike lanes, where chalk marks were set 2'4" inside the bike lane, actual mean stooge positioning varied from -4 to +8 inches from that figure. On streets without bike lanes, however, the variation from the chalk line was higher.

Stooge placement, ideally 4'2" or 11'0" from the curb (with a seven foot differential allowed for parked cars) almost always erred on the minus side. That is, the stooge cyclist's position when being passed by a motor vehicle ranged from only two inches too far in the street to as much as 1'8" too far toward the curb. The standard deviation (S) of stooge position was also larger on streets without bike lanes. On bike lane streets S ranged from two to five inches; on streets without bike lanes the range was from three to eleven inches. Table 34 summarizes operational stooge positioning and its standard deviation for observations at each observation site.

Table 34
OPERATIONAL STOOGE POSITIONING

Bike Lane Streets			Streets Without Bike Lanes		
Street	Mean Distance Inside Bike Lane*	Standard Deviation	Street	Mean Distance From Parked Cars or Curb**	Standard Deviation
"K" Street	2'4"	3"	Freeport	3'11"	3"
Morse-1	2'5"	2"	Bell	3'	8"
Morse-2	2'2"	4"	Elk Grove	3'9"	9"
Marconi	2'	5"	Folsom	2'8"	11"
Amer. Ri.	3'	3"	Jacob	2'6"	4"
Watt	2'2"	3"	Road 99	4'4"	4"
Sunset	2'3"	2"	14th St.	2'10"	8"

*Ideal = 2'4"
**Ideal = 4'2"

This variation from the desired placement was handled by recognizing its effect on available travel space for motor vehicles (ATS). The ATS figures used throughout this paper show the distance between the center line of the street (or outside lane stripe on four-lane streets) and the actual mean stooge position, not the position marked by the chalk line.

Stooge placement in the before and after case studies of bikeway installation appears in Table 35. On Saverine Drive and Chiles Road, the mean placements in the before and after conditions differed by a negligible two and three inches, respectively. However, on "F" Street, there was a

1'1" difference, a difference large enough to be important in evaluating "F" Street results.

Table 35
OPERATIONAL STOOGE POSITIONING IN THREE BEFORE-AND-AFTER CASE STUDIES

Street	Before Bike Lane Mean Distance from Eventual Bike Lane	After Bike Lane Mean Distance from Bike Lane
Saverine	4'7"	4'5"
Chiles	3'	2'9"
"F" Street	3'4"	2'3"

The above tables on operational stooge placement show that the stooge cyclist was measurably less able to follow a preset path on streets without bike lanes than on streets with bike lanes. It is possible that intermittent chalk marks (placed about ten feet apart) were somewhat inadequate as path markers without the added point of reference provided by a bike lane. But the variation on streets without bike lanes was not random; the cyclist nearly always strayed in the direction away from passing vehicles under these conditions. That is, passing autos appeared to have a stronger effect on cyclist position when no bike lane was provided even though the cyclist was an experienced rider attempting to maintain a constant lateral position regardless of traffic.

Street Width Versus Separation

> Bike lanes tend to reduce hazardous close passes and avoidance swerves by autos. To achieve a negligible level of centerline crossing by cars avoiding bicycles, however, a 13-foot auto lane is required even with a bikeway.

Mean separation distance, S.D., between the stooge cyclist and passing motor vehicles shows a strong positive relationship to available travel space (ATS) on streets having a range of signed speed limits from 25 MPH to 55 MPH. Tables 36 and 37 detail available travel space and separation distance values observed. The following regression relationships between separation distance and available travel space were estimated:

With Bike Lanes $\quad \text{S.D.} = .66\ \text{ATS} - 2.07$

$r = .95$

Table 36
SEPARATION DISTANCE (MEAN AND S), ATS, AND SPEED LIMITS ON TEN STREETS WITH BIKE LANES

Street	Avail. Travel Space (ATS)	(S.D.) Mean Separation Distance	Separation Distance Standard Deviation	Speed Limit MPH	Cross Section of Half Street			
					2nd Vehicle Lane	Right Hand Vehicle Lane	Bike Lane	Parking or Shoulder
Morse at Berkshire	12'10"	6' 4"	10"	25	-	10'6"	5'	4'
"K"	12'10"	6' 6"	11"	25	-	10'6"	6'	7'
Morse at Mayfair	14'5"	7'10"	10"	25	-	11'6"	5'	-
"F"	13'7"	7'	11"	25	-	11'4"	5'10"	8'
Saverine	19'5"	10'11"	13"	25	-	15'	6'	-
American River	20'8"	11'	27"	25	-	16'6"	7'	8'
Marconi	12'9"	5' 7"	9"	40	10'6"	10'6"	5'	-
Chiles	15'1"	7' 1"	11"	40	-	12'	6'	8'
Sunset	14'6"	8' 3"	13"	40	-	12'	5'	-
Watt	17'5"	10' 1"	24"	55	12'6"	15'	6'6"	-

Table 37
SEPARATION DISTANCE (MEAN AND S), ATS, AND SPEED LIMITS ON TEN STREETS WITHOUT BIKE LANES

Location	Street	Avail. Travel Space (ATS)	(S.D.) Mean Separation Distance	Separation Distance Standard Deviation	Speed Limit MPH	Cross Section of Half Street		
						2nd Vehicle Lane	Right Hand Vehicle Lane	Parking or Shoulder
1	Jacob	13'11"	8' 6"	20"	25	-	14'6"	7'
2	14th	14' 2"	6'11"	15"	25	-	17'	7'
4	"F"	14' 8"	7' 5"	21"	25	-	25'2"	-
5	Saverine	19' 7"	10' 9"	18"	25	-	21'	-
8	Chiles	15'	7'	11"	40	-	25'3"	-
3	Bell	17'	8' 8"	16"	40	-	20'	-
6	Freeport	18' 3"	9' 8"	13"	40	14'	20'	-
7	Elk Grove	13' 3"	7' 3"	11"	55	-	17'	-
9	Folsom	15' 4"	8' 5"	27"	55	12	17'	-
10	Road 99	15' 6"	10' 5"	14"	55	-	20'	-

Without Bike Lanes $S.D. = .52\ ATS + 23$

$r = .75$

The overall regression for streets with and without bike lanes is:

$$S.D. = .6\ ATS - 1.14$$

$$r = .88$$

Analysis of these regressions indicates that the area which describes the 99 percent confidence interval for S.D. values about the regression curve for streets with bike lanes always overlaps S.D. values for streets without bike lanes. In other words, the two regression lines are so close that a very tight confidence interval around one overlaps values described by the other. An implication to be drawn is that the relationship between ATS and separation distance on bike lane streets and streets without bike lanes are essentially the same, although the strength of the linear relationship is much higher in the case of streets with bike lanes.

Variability of motor vehicle position as reflected in standard deviations (S) of separation distances was generally smaller on streets with bike lanes than on streets without them for streets in the 25 MPH operating speed range. As indicated on Table 38, five of six bike lane streets in the 25 MPH category show smaller values of S than streets without bike lanes. This finding was in spite of overlapping ATSs between bike lane and no bike lane streets. The one high bike lane score in this category was on a street 61 feet wide, which although originally built for four lanes, had only two travel lanes and two 7-foot bike lanes. The unusually large ATS in this case appears to have the effect of encouraging greater driver variability.

Two before and after case studies which appear on Table 38 (sites 4 and 8 in both columns) both show a drop in standard deviation of separation distance as a result of provision of bike lanes. The reduction in standard deviation at Savarine Drive just missed statistical reliability at the .05 level ($F_{25,25} = 1.92$); the "F" Street decrease is highly reliable ($F_{43,43} = 3.65$, $p<.01$).

In the 40 MPH speed category, the four lane street without bike lanes had a reliably larger standard deviation of separation distance than the four lane street with them ($F_{25,25} = 2.09$, $p<.05$); however, the street width disparity (a wider street allowing more variation in separation distances) could easily account for this. This highest standard deviation in this speed category is on a street with no bike lanes. The before and after case in this category (location number 8) showed no change in standard deviation in separation distance.

A comparison of the two four lane streets in the 55 MPH group shows a higher standard deviation of separation distance for the street with no bike lane, in spite of its being a narrow street with consequent lower

Table 38
VARIABILITY IN SEPARATION DISTANCE BY SPEED CATEGORY

	WITH BIKE LANES			WITHOUT BIKE LANES		
Speed Range MPH	Index[1] #	Standard Deviation of Separation Distance	ATS	Index[2] #	Standard Deviation of Separation Distance	ATS
25	1	10	12.8	1	20	13.9
	2	11	12.8	2	15	14.2
	3	10	14.4	-	-	-
	4[3]	11	13.6	4[3]	21	14.7
	5[4]	13	19.4	5[4]	18	19.6
	6	27	20.7	-	-	-
35	7[5]	5	12.7	3	16	17
to	8[6]	11	15.1	8[6]	11	15
40	9[5]	13	14.5	6	13	18.3
55	10[5]	24	12.4	7	11	13.3
	-	-	-	9[5]	27	15.3
	-	-	-	10	14	15.5

[1] Corresponds to numbers of streets on Table 36.

[2] Corresponds to numbers of streets on Table 37.

[3] "F" Street before and after case.

[4] Saverine before and after case.

[5] Four lane street.

[6] Chiles before and after case.

ATS. However, two streets without bike lanes in this category show standard deviations of separation distance as low as most streets with bike lanes in the lower speed groups. Analysis of incidence of centerline violation* showed an increase in violations on streets with lesser ATS and streets with bike lanes showing a strong though not unanimous ten-

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*A centerline violition was recorded if a motor vehicle's left rear tire touched or crossed the centerline.

dency to exhibit fewer violations. Incidence of centerline violations was virtually nonexistent on streets where ATS exceeded 15.5 feet but rose significantly for lesser values of available travel space with centerline violation incidence rates of over 30 percent of all passes measured on one street. No specific correlation of speed to ATS and centerline violation rate was evidenced in the data which is summarized on Figure 10.

Observations of motor vehicle positions with no bicycles present is roughly related to travel lane width as indicated on Table 39. On streets without bike lanes, no relationship between car-alone distance from the centerline and lane width was evidenced as indicated on the table.

Motor vehicle displacement caused by presence of a bicycle is defined as the difference between the mean car-alone position and the mean motor vehicle position in the car-pass-bike condition. Figure 11 shows motor vehicle displacement values for streets with and without bike lanes. While the data is insufficient to develop any direct relationships between displacement, lane width and presence or absence of bike lanes, it is clear that lower displacements are likely to result where bike lanes are provided. Displacements due to bicyclist presence on streets without bike lanes ranged from .33 to 6.33 feet while streets with bike lanes had a displacement range of from .67 to 2.75 feet. Half the streets without bike lanes had mean displacements higher than any of the streets with bike lanes despite overlapping values of ATS.

As already noted, measurements of flow conditions before and after bike lane provision was conducted on Saverine Drive in Sacramento, Chiles Road in Davis, and "F" Street, also in Davis, California. Following is specific discussion of work at those locations.

Mean separation distance did not change appreciably with the installation of bike lanes on the two streets with ATS of 15 feet and 19'7" (Chiles and Saverine respectively). On "F" Street, where the ATS was smaller, mean separation distance decreased five inches with installation of bike lanes. However, this appears due to the eleven inch differential in stooge placement in the before and after conditions, a differential which decreased ATS. In any case, the five inch difference is not statistically reliable ($t = 1.58$; $p<.2$). Table 40 indicates changes in separation distance relationships.

Variability in separation distance dropped on two of the three streets. On the third street the standard deviation of separation distance remained the same as indicated on Table 41. The two streets where standard deviation of separation distance dropped after bike lanes were installed (drops of five and ten inches) were 25 MPH streets; the no-change street had a speed limit of 40 MPH.

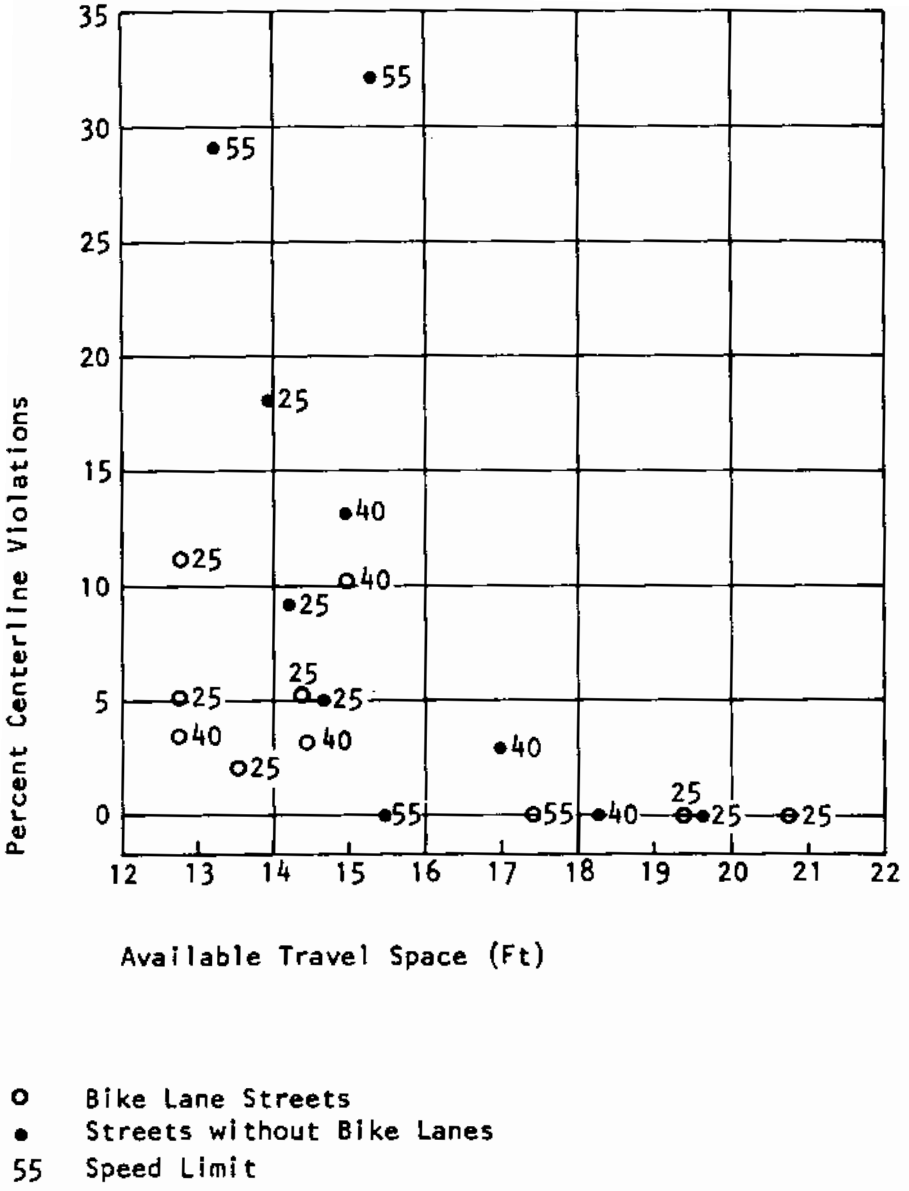


Figure 10
CENTERLINE VIOLATIONS

Table 39
MEAN MOTOR VEHICLE POSITION - NO BICYCLES PRESENT

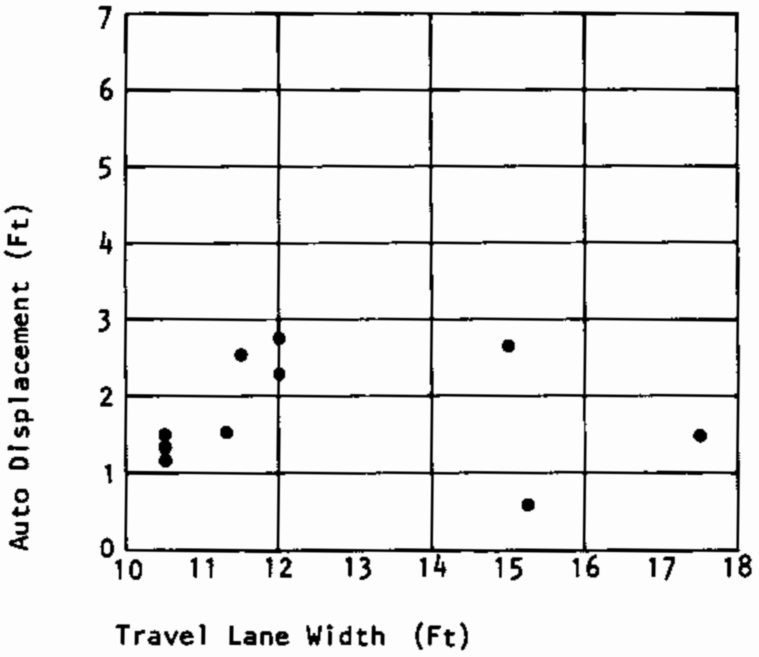
Streets With Bike Lanes

Street	ATS	Motor Vehicle Travel Lane Width	Car-Alone Distance from Bike Lane
"K" Street	12'10"	10'6"	2' 8"
Morse	12'10"	10'6"	2'10"
Marconi	12' 9"	10'6"	2' 3"
"F" Street	13' 7"	11'4"	3' 1"
Morse	14' 5"	11'6"	2' 8"
Sunset	14' 6"	12'	3' 2"
Chiles	15' 1"	12'	2' 7"
Saverine	19' 5"	15'	3'11"
Watt	17' 5"	15'3"	7' 3"
American River	20' 8"	17'6"	6' 8"

Streets Without Bike Lanes

Street	ATS	Travel Lane Width (Excluding Parking)	Car-Alone Distance from Centerline
Jacob	13'11"	16'6"	8' 5"
14th	14' 2"	17'	7' 7"
Elk Grove	13' 3"	17'	9' 3"
Folsom	15' 4"	17'	8' 6"
Chiles	15'	18'	9'10"
"F"	14' 8"	18'6"	9'
Road 99	15' 6"	20'	11' 7"
Bell	17'	20'	10' 1"
Freeport	18' 3"	22'	9' 4"
Saverine	19' 7"	23'	12' 4"

STREETS WITH BIKE LANES
Displacement Range = 8" to 2'-9"



STREETS WITHOUT BIKE LANES
Displacement Range = 4" to 6'-4"

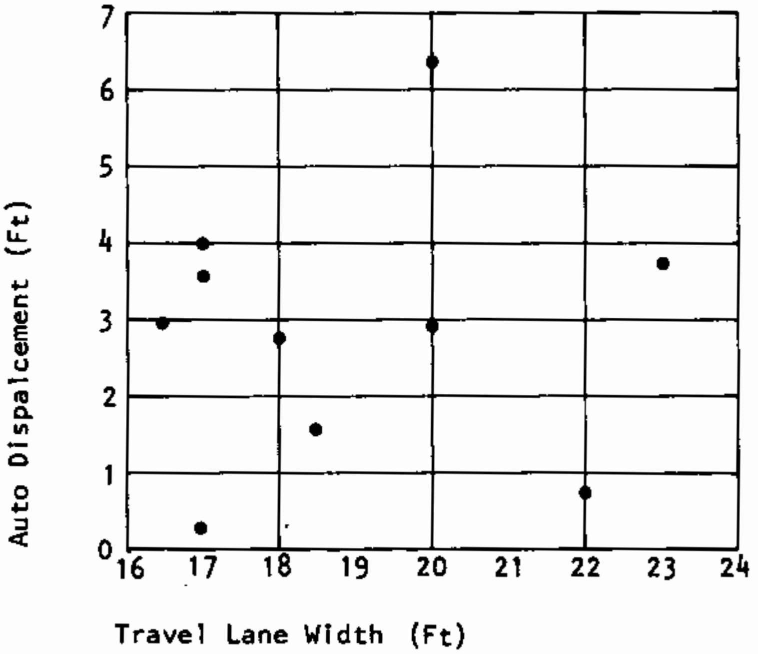


Figure 11
MOTOR VEHICLE DISPLACEMENTS
DUE TO BICYCLIST PRESENCE

Table 40
SEPARATION DISTANCE BEFORE AND AFTER BIKE LANES

Street	Without Bike Lanes Mean Separation Distance	ATS	With Bike Lanes Mean Separation Distance	ATS
Chiles	7'	15'	7' 1"	15'1"
Saverine	10'9"	19'7"	10'11"	19'5"
"F"	7'5"	14'8"	7'	13'7"

Table 41
STANDARD DEVIATION OF SEPARATION DISTANCE BEFORE AND AFTER BIKE LANES

Street	Speed Limit	Before Bike Lanes	After Bike Lanes
Saverine	25	18"	13"
"F" Street	25	21"	11"
Chiles	35	11"	11"

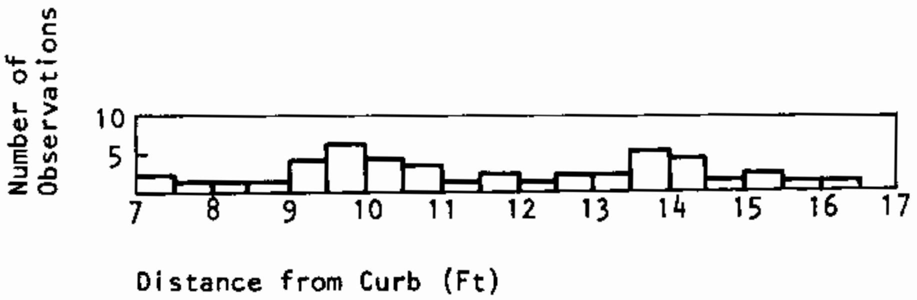
The incidence of cars crossing the centerline while passing the stooge cyclist fell slightly with the addition of bike lanes on the streets with lower ATS. On Chiles Road (ATS 15', 35 MPH), centerline violation fell from 13 to ten percent; and on "F" Street (25 MPH), from five to two percent. The "F" Street decrease was in spite of the previously noted decrease in ATS with bike lanes installed due to differential stooge positioning. On Saverine (25 MPH, average ATS 19'6"), there was no change in centerline violations with the installation of bike lanes: Cars had never crossed the centerline before installation and did not do so afterward.

Auto displacement decreased on the two wider streets with the addition of bike lanes, but did not change on "F" Street as indicated on Table 42. Hence, motor vehicles travel in a more normal path when bike lanes are provided than when they encounter bicyclists without bike lanes.

On "F" Street in Davis, the large number of normal cyclist users of the street made possible measurement of a bike alone position. Analysis of before and after observation indicates that bicyclist position was altered considerably by provision of the bike lane. Figure 12 shows the distribution of bicyclist positions before and after bike lane provision. The mean bike position shifted more than one foot toward the curb and the standard deviation of bike position decreased by 16 inches. Whereas bicyclists had traveled anywhere from seven to 16 feet from the curb before bike lanes, the range was eight to 12.5 feet after bike lanes were installed.

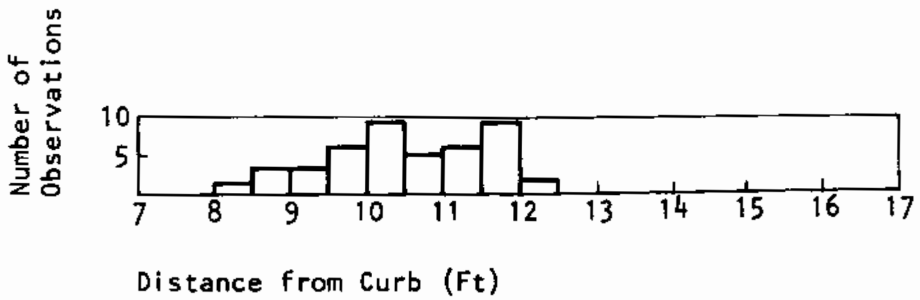
WITHOUT BIKE LANE

Mean = 11'-7"
Standard Deviation = 2'-5"
n = 44



WITH BIKE LANE*

Mean = 10'-8"
Standard Deviation = 1'-1"
n = 44



*Bike lane delineated between 8' and 13'8" from curb.

Figure 12
BICYCLIST POSITION COMPARISON

Table 42
AUTO DISPLACEMENT ON THREE STREETS BEFORE AND AFTER BIKE LANES

Street	Auto Displacement Before Bike Lanes	After Bike Lanes
Chiles	2'9"	2'4"
Saverine	3'9"	2'8"
"F"	1'7"	1'7"

On six streets in Davis, California where heavy bicycle traffic allowed sampling of normal cyclists, data similar to that with the stooge cyclist was obtained. Five of these streets sampled had bike lanes. Only one Davis street without bike lanes was found having sufficient bike traffic for efficient sampling. All streets had 25 MPH speed limits. Although data involving normal cyclists was insufficient to prepare as extensive analyses as with the stooge cyclists, overall findings on streets where normal cyclists were observed lends credence to findings based on stooge cyclist data.

Separation distance on these streets was closely related to travel lane width, with higher separation found on streets with wider travel lanes as indicated on Table 43. The exception to this was 8th Street at "B", where bicyclists riding unusually close to the bike lane stripe made the separation distance smaller than usual. A rough dropoff to the gutter at the roadway edge was the probable explanation for bike position here.

Specific correlation of separation distance to available travel space ATS could not be made since there was a wide distribution of bicycle placements in addition to the car placement variable. Despite this, findings parallel those with stooge cyclists.

As indicated on Table 44, both motor vehicles and bicyclists are displaced in the passing situation. Mean car displacement was larger than mean bike displacement at all sampling locations, but not disproportionately so considering the relative sizes of the bike lanes and travel lanes. Although both bikes and cars are displaced in the passing situation, the degrees of displacement of the bike and auto are not particularly related on the streets with bike lanes. On the street with no bike lane, bike and car lateral placements were only weakly correlated (r = .47). Overall the responsiveness of bikes and cars to each others lateral placement was very small. If any effect occurred at all, it was in the direction one would naturally expect: The further toward the curb the cyclist rode, the further toward the curb the auto was driven (or vice versa). There is no implied direction in the effect.

Table 43
SEPARATION DISTANCE, CAR POSITIONING, AND BIKE POSITION - NORMAL CYCLISTS

Location	CAR-PASS-BIKE Mean Separation Distance	CAR ALONE Mean Distance of Car From: Bike Lane	Centerline	BIKE ALONE Mean Distance of Bike From: Bike Lane	Centerline	STREET CROSS SECTION Motor Vehicle Lane	Bike Lane	Parking/ Shoulder
8th at "L"	94"	25"	105"	39"	169"	10'10"	5'	8'
3rd at "D"	96"	33"	104"	34"	171"	11' 5"	5'8"	8'
Anderson	106"	51"	87"	40"	178"	11' 6"	6'2"	8'
8th at "B"	96"	46"	94"	26"	166"	11' 8"	4'9"	-
"L" Street	113"	45"	99"	42"	186"	12'	6'	8'
1st Street	87"	-	122"	-	156"	13' 5"	-	8'

Table 44
MEAN BIKE AND AUTO DISPLACEMENT ON SIX STREETS*
DAVIS, CALIFORNIA

Street	Auto Displacement	Bike Displacement	Travel Lane Width (Excludes Parking)	Bike Lane Width (Excludes Parking)
"L"	21"	5"	12'	6'
8th at "B"	18"	6"	11'8"	4'9"
Anderson	10"	5"	11'6"	6'2"
3rd	18"	11"	11'5"	5'8"
8th at "L"	17"	14"	10'10"	5'
1st (No Bike Lane)	46"	5"	14'6"	-

*Displacement is calculated by subtracting the mean distance from the bike lane (or centerline) in the car-pass-bike condition from the same distance in the vehicle alone condition.

Motor Vehicle Speed

> Results on effects of bike lanes on motor vehicle speed were inconclusive.

Auto speeds were recorded before and after bike lanes were installed on "F" Street, both in a car-pass-bike condition (stooge rider) and for cars alone. Mean speeds in all four conditions appear on Table 45. Both with and without the presence of a cyclist, mean speeds increased slightly with the addition of bike lanes. However, only the increase in the bike present condition was statistically reliable ($t = 2.26$; $p<.05$) and neither of the speed changes is meaningful functionally.

Table 45
MEAN AUTO SPEEDS BEFORE AND AFTER BIKE LANES (n = 69)

	Without Bike Lane	With Bike Lane
Bike Present	25.34 MPH	26.6 MPH
No Bike Present	27.09 MPH	27.73 MPH

In summary, speed data collected in the before and after bike lane implementation cases did not indicate a significant effect of lane provision on motor vehicle speed. However, because of the limited observation sites, it is likely that this finding reflects other circumstances of the location which control speed such as upstream and downstream intersection proximity or enforcement conditions rather than a lack of effect of the bike lanes.

Wind Versus Separation

> Moderate headwinds tend to result in significantly increased swerving of bicycles.

On two Davis Streets with bike lanes, sampling was repeated on windy days to measure any effect on cyclists due to wind. A cup anemometer was used to sample wind speeds at intervals of three minutes. In both cases, cyclists were heading directly into a north wind, and mean wind speeds were 9 and 15 MPH with gusts to 26 and 28 MPH. Bikes in the car-pass-bike condition in the 15 MPH example moved a foot further towards parked cars on the windy day, separation distance increased seven inches, and the standard deviation of bike positioning in this condition increased eight inches on the windy day as opposed to the calm day. In the 9 MPH example, neither the mean bike placement nor the separation distance in the car-pass-bike condition changed due to wind as indicated on Table 46.

Table 46
BIKE POSITIONING AND SEPARATION DISTANCE ON WINDY VERSUS CALM DAYS

Street	Mean Wind Speed (MPH)	NO WIND Mean Distance of Bikes from Bike Lane (s) CAR-PASS-BIKE	NO WIND Separation Distance (s)	WIND Mean Distance of Bikes from Bike Lane (s) CAR-PASS-BIKE	WIND Separation Distance (s)
"L"	9	47" (17")	113" (14")	47" (17")	111" (25")
Anderson	15	45" (11")	106" (13")	57" (11")	113" (20")

The standard deviations of separation distances increased on windy days on both streets, and in the 15 MPH wind condition the increase in separation distance itself is statistically reliable.

Conclusions and Implications

Bike lanes have definite effect on bicyclist position on the roadway. Significant normalizing of observed cyclist position was demonstrated in the before and after data. Similarly, the effects of lane presence or absence on the stooge cyclist's ability to maintain position while being passed by traffic may be indicative of the sense of security bike lanes afford cyclists although observations of many more subjects would be necessary before a conclusive finding in this vein could be made.

When bike lanes are provided, motor vehicles tend to maintain more linear tracking paths -- displacement from normal motor vehicle path while passing a bicyclist is less when bike lanes are provided. Apparently as a result of the foregoing, bike lanes tend to normalize separation distances between bikes and passing motor vehicles. Although mean separation distances for comparable traveled way widths are quite similar with and without bike lanes, the variance in separation distance is significantly less when bike lanes are provided. The implication of this is that bike lanes tend to reduce the hazardous close passes and wide avoidance swerves.

Bike lanes tend to reduce center line violations by passing motor vehicles, probably a result of normalization of passing distance. Although this tendency is observed, the data indicate that in order to reduce centerline violations by motor vehicles passing bicycles to a negligible level, provision of an "available travel width" in excess of 15.5 feet is necessary. This roughly corresponds to an 18 foot outside travel lane with no bike lane designation or a 13 foot motor vehicle lane plus five foot bike lane. Such dimensions for motor vehicle lanes are well above those commonly employed in current practice and difficult to achieve in most surface street situations.

Due to variance in cyclist ability to maintain position which results at wind velocities commonly experienced while riding, provision of bike lane widths above basic minimums appears desirable when available space permits.

SIGHT DISTANCE, BRAKING, AND TURN RADIUS

Purpose

Research in this area is directly applicable to design of bikeway facilities.

Methodology and Findings

> Procedures for determining sight distance, braking, and turn radius for bicycle facilities are similar to procedures for determining these characteristics for highways. Research determined several design coefficients to be used in standard highway formulas.

Stopping distance is given by the formula:

$$S = 1.47\ TV + V^2/30\ (F \pm G)$$

Where:

S = stopping distance in feet

T = perception/reaction time (usually 2.5 seconds)

V = initial speed in MPH

F = coefficient of friction (.25)

G = grade, ft/ft

This is the standard highway engineering formula for stopping distance. The extremely low coefficient of friction (.25) is suggested to account for the ineffectiveness of bicycle brakes in wet conditions and to provide a conservative allowance for stopping distance.

This stopping distance relationship enables computation of sight distance on cresting vertical curves using the standard highway engineering method of computation as given below.

$$L = 2S \quad \frac{200\ (\sqrt{h_1} + \sqrt{h_2})^2}{A} \qquad \text{when } S > L$$

or

$$L = \frac{AS^2}{100\ (\sqrt{h_1} - \sqrt{h_2})^2} \qquad \text{when } S < L$$

Where:

S = stopping sight distance

A = algebraic difference in grade

h_1 = 4½ feet = eye height of cyclist

h_2 = 0.0 feet = height of object

L = minimum vertical curve length

The only difference from standard highway engineering procedure relates to the object height. A zero object height is used (as opposed to a height representative of some raised obstacle) because of the numerous hazards to bicycle travel which exist at pavement level -- broken glass, unsafe drainage grates, potholes, etc.

Methodology for computation of sight distance and sight clearance areas on horizontal curves is given by the standard highway engineering formula.

$$M = R\ (1 - \cos \frac{28.65S}{R})$$

Where:

R = radius of curvature

S = safe stopping distance along lane centerline (arc distance)

M = obstruction offset from lane centerline

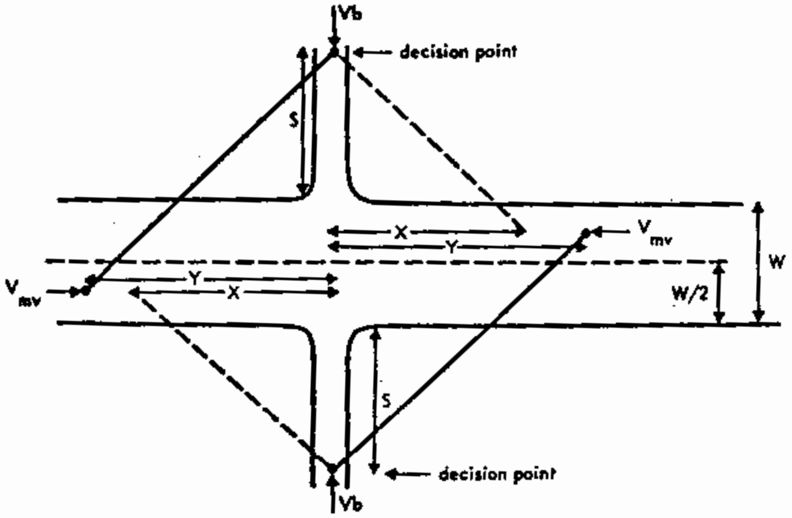
Use of this formula is particularly critical in design of independent paths which are to be used bidirectionally. Here the problem is stopping before striking a converging bicyclist, not a fixed obstruction. Hence, the value of S substituted into the above equation should be twice the required stopping distance at the facility's design speed.

Methodology for determining sight clearance triangles at bikeway crossings is shown on Figure 13. This is also an adaptation of common highway engineering practice to bikeway design. Sight clearance areas should be defined to provide guidance for planting policies and location of other sight obstructions. When the bicycle facility is on-street, the greater sight distance requirements of motor vehicles will normally insure adequate sight clearance zones at intersections. However, these should always be checked when designing bikeways to assure proper lines of sight from the bicyclists' typical position on the roadway.

Empirical studies of turning radius requirements were conducted. A limited number of adult cyclists, riding a standard sized ten speed bicycle made unbraked (coasting) 180 degree turns at various speeds under instructions to turn as sharply as they felt comfortable. Turning approach speed was measured at turn initiation. Full turning trajectory was recorded in polar coordinates about a point on the line perpendicular to the original trajectory which served as the demarcation line for initiation of turns. Turning trajectories were traced using the water droplet technique described previously.

Analysis of this data indicates that turning radius of bicyclists can be given by the formula:

$$R = 1.528V + 2.2$$



Time for full intersection clearance from the "stop-go" decision point is given by:

$$\frac{S + W + 6}{Vb} = t_1$$

Where S = Stopping Distance (including perception and reaction time) at design

W = Width of crossing

Vb= Actual bikeway typical approach speed (rather than design speed)

Time for near side lane(s) clearance is given by:

$$\frac{S + W/2 + 6}{Vb} = t_2$$

A crossing cyclist at the "decision point" must be able to see any vehicle which would threaten conflict in the crossing within time t_1 or t_2. Thus, the cyclist at the decision point must be able to see approaching vehicles at the following distances:

<u>near side</u> $x = t_2 V_{mv} = \frac{V_{mv}}{Vb} (S + W/2 + 6)$

<u>far side</u> $y = t_1 V_{mv} = \frac{V_{mv}}{Vb} (S + W + 6)$

Projections between the "stop-go" decision points and the points given by x and y define the sight clearance areas.

Figure 13
INTERSECTION SIGHT CLEARANCES

Where:

V = design speed in MPH

R = curve radius in feet

This equation gives significantly sharper turning radius for bicycles at any given speed than does the adaptation of the standard highway engineering equation for curvature shown on Figure 14. This is partially due to the deceleration (due to air and rolling resistance) of the coasting bicyclist during the turn. The standard highway engineering computation assumes maintenance of constant speed around the curves. It is believed that the empirically derived relationship is more realistic in this regard as cyclists do coast (hence decelerate somewhat) on turns where radius of curvature is limited.

Differences between the empirical and highway engineering curvature equations also presumably reflect effects of inward inclination and steering angle which may be significant factors in turning capabilities of single-tracked short wheelbase vehicles not accounted for in the highway engineering solution.

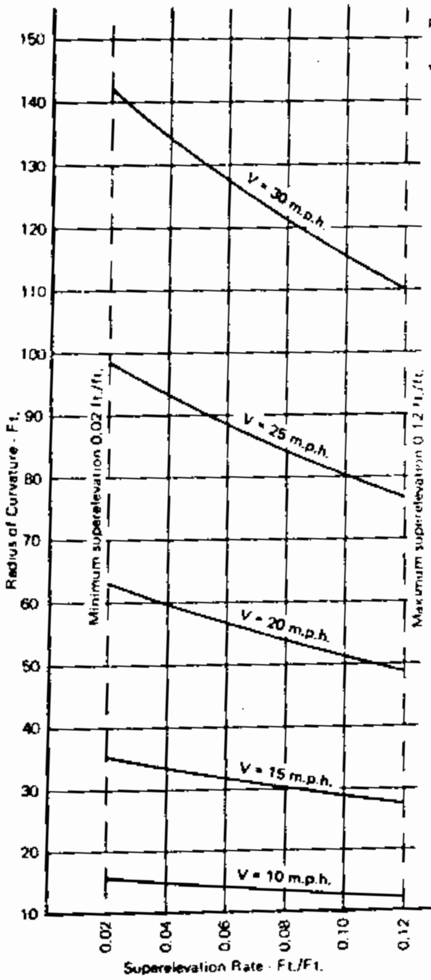
Extremely limited empirical data was collected at speeds in excess of 25 MPH due to the difficulty of achieving higher speeds on the test site. For this reason and due to the desire to provide an additional margin of safety at higher speeds, application of the more conservative (higher) turning radius values given by the standard highway engineering equation is recommended where speeds are anticipated to exceed 25 MPH.

Curve widening is recommended at short radius (less than 100 foot) curves on two way bikeways. This is to compensate for increased lane width occupancy due to bicyclists leaning to the inside of a turn. Methodology for curve widening presented on Figure 15 is drawn from State of Oregon procedures. Maximum widening is limited to four feet.

USER SATISFACTION

Purpose

User satisfaction has been analyzed to establish the state-of-the-art and to allow evaluation of current and proposed design techniques. Efforts were made to evaluate user perception of safety in mixed use and designated space conditions using two forms of measurement -- interview responses and physiological indicators of stress. The interview approach, conducted in connection with measurements of other user perceptions of the functional qualities of bicycle facilities provided significant data on user comfort and safety in relation to type of bicycle facility provided or lack of bicycle facilities. These findings have been presented in Chapter 2 of this report. As indicated in



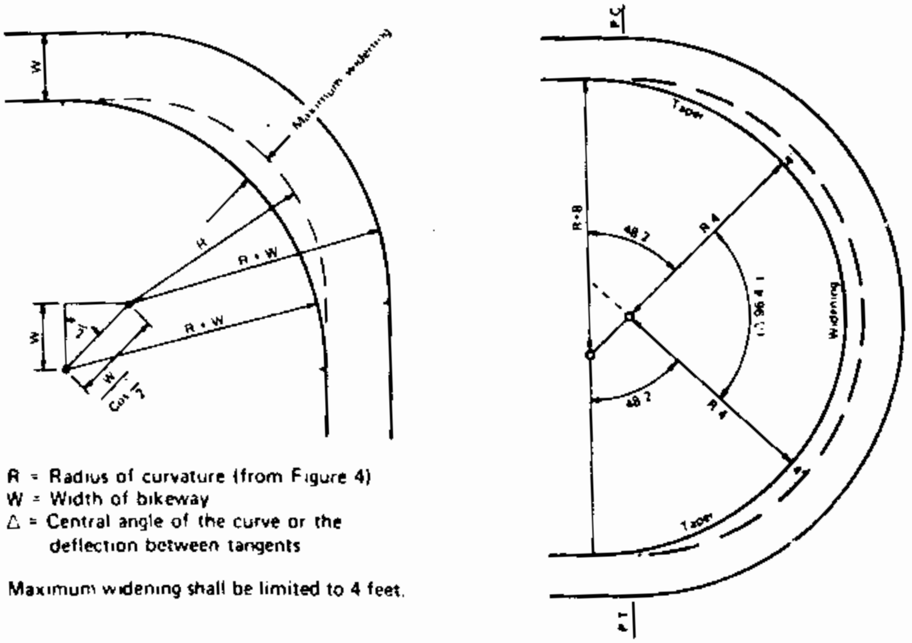
plot of $\frac{V^2}{gR} = \frac{\tan\theta + f}{1 - f\tan\theta}$

where V = velocity, ft./sec.
g = acceleration due to gravity, ft./sec.²
R = radius of curvature, ft.
f = coefficient of friction on dry pavement - 0.4
tan θ = superelevation rate, ft./ft.

Curvature shall be based on a normal design speed of 20 m.p.h. Within limits shown, either the radius or the superelevation may be varied to fit individual situations. The dependent variable may be selected from the adjacent chart.

Figure 14
STANDARD SUPERELEVATION FOR BIKEWAYS

Source: State of Oregon



R = Radius of curvature (from Figure 4)
W = Width of bikeway
Δ = Central angle of the curve or the deflection between tangents

Maximum widening shall be limited to 4 feet.

When widening reaches 4 ft. (Δ > 96.4°), that width shall be carried on a radius of R-4 through the central portion of the curve (Δ-96.4°) as shown on the right.

Figure 15
CURVE WIDENING

Source: State of Oregon

the extensive analysis presented in that chapter, bicyclists perceive significant safety benefit from bicycle facilities in comparison to mixed use situations.

Methodology and Findings

Unique characteristics of bicycle travel made efforts to analyze bicyclist stress under operating conditions unsuccessful. Further research in this area is warranted.

Attempts were made to measure heart rate as an indicator of physiological stress in relation to type or absence of bicycle facility provision and events in traffic; these attempts proved disappointing. Measurements of heart rate were selected for a number of reasons. Principal among these are its objectivity and suitability for telemetering over a distance which makes it suitable for use with a mobile subject. Moreover, variations of heart rate as a function of both psychological and physiological stress are well documented for a number of activities such as driving an automobile (Simonson et al, 1968), piloting aircraft (Smith, 1967), climbing (Zenz and Berg, 1966), parachuting (Shane, 1968), anticipation of shock (Jenks and Deane, 1963), and mental arithmetic problems (Defayolle, 1966, and Johnson and Campos, 1967). Peake and Leonard (1971) successfully used heart rate as an indicator of differences in anxiety among blind persons walking unaided in a sidewalk situation versus being guided over the same course by a sighted person. This study closely paralleled the intended use of heart rate as a measure of stress on various bicycle facility types. However, a number of problems were encountered when attempts in devising satisfactory operating procedures for relating heart rate measurements of bicyclists in traffic to the circumstances of riding.

The basic problem is that an observation vehicle is needed to follow the bicyclist subject and make a record of traffic events in traffic which can be correlated with the heart rate record. Such an observation vehicle itself has an impact on traffic and tends to screen the subject from incidents which would ordinarily occur in normal exposure to traffic. In the study of blind persons described above, the test course was a limited walkway segment on which events could be controlled and which could be observed from a fixed position. Hence problems cited above were not encountered. But it appears unlikely that measurements of bicyclists in actual traffic situations can be adequately measured from a fixed position; it appears infeasible to attempt to simulate such conditions on a controlled course.

A second problem is obtaining similar incidents or exposures of the subject to similar traffic conditions with and without bike lanes on streets requiring the same level of exercise stress. A third problem is controlling the pace of the subject so that exercise stress actually experienced on different streets will be similar, while at the same time avoiding screening the subject from normal exposure to traffic.

It is believed that if the above problems were overcome this approach could yield meaningful information on relative levels of user anxiety while riding various facilities and hence give a measure of user satisfaction of various facility types. However, it was not possible to devise satisfactory procedures for experimental measurements during this project. Fortunately, the results of surveys of user perceptions of safety qualities on various type bikeways described previously provide sufficiently conclusive information that findings based upon physiological measures of stress would generally be redundant.

BIDIRECTIONAL TRAVEL

Purpose

The purpose of this research was to determine the frequency and safety of bicycles riding against traffic and to determine if bidirectional bikeways could be a recommended practice.

Methodology

Examination of the consequences of riding against traffic included evaluations of accident studies, assessment of the implications of motorists' habitual traffic scanning patterns at intersections and other points of conflict and examination of implications of increased rate of closure on sight distance relationships. Implications of travel against traffic on signs and markings were also examined.

Findings

Bidirectional facilities are strongly discouraged as a general recommendation.

Accident studies consistently show that riding against traffic is a significant direct causal factor in bike-motor vehicle collisions or a primary identifiable critical behavior antecedent to the collision. Evidence from accident studies indicates that wrong way riding is a causal element in ten to fifteen percent of all bike-motor vehicle collisions. Attempts were made to identify why against traffic riding is such a significant accident causal factor. Portions of this investigation relate to intersections, a subject reported on in Chapter 4. Findings related to bidirectional operations are presented here.

Most motor vehicle operators have expectations that all vehicles in the traffic stream will conform to the rules of the road, particularly the most basic of them -- the "keep right" rule of operation. This expectation affects motorists' traffic scanning patterns at intersections, driveways and other points of conflict or decision. Bicyclists traveling against traffic may never be seen by motorists at conflict points simply because motorists do not expect and hence never look for contra flow vehicles. Observations of motorist' traffic scanning patterns at intersections were conducted to the extent necessary to confirm the above hypothesis. However, detailed studies to make specific quantified measurements of head and eye movements and scan times were not undertaken.

Another potentially important factor is the implications of increased rate of closure for sight and stopping distance. Motor vehicle sight distances on horizontal and vertical curves are normally designed to enable safe stops before reaching a fixed object. But when that object (a bicycle traveling contra flow) is moving toward the motor vehicle, existing sight distance, if close to design minimum, will no longer be adequate. (On independent path facilities which are used bidirectionally, care must be taken to provide adequate sight distance for converging bicyclists on horizontal and vertical curves.)

Certain types of collisions involving contra flow bicyclists stem from combinations of inadequate sight distance and conflict with motorist expectation. For instance, when a motorist initiates a right turn, he is not likely to be expecting or looking for a vehicle moving toward him in the lane into which he is turning. Moreover sight distance is likely restricted. So any brief glance the motorist might direct toward the bicyclist might be frustrated by sight distance obstructions until the motorist has completed the turn and is in a head-on relationship with the cyclist.

Traffic signs and markings are not placed with contra flow vehicles in mind. A cyclist traveling against traffic may not see a STOP or YIELD sign or a visor shielded or optically programmed traffic signal positioned on the other side of the street. The cyclist may assume that because these devices are not positioned for his benefit, they simply don't apply to bicyclists. The hazard involved in this is quite obvious.

Under certain conditions, bidirectional operations on one side of the street may not involve any of the above potential hazardous conflict situations -- no intersections or driveways, no sight distance restrictions, no traffic control devices. Here a bidirectional facility might not be hazardous. However, a potentially hazardous situation occurs when such a facility ends. Bicyclists may be forced to make awkward transition movements to place themselves on the proper side of the street or may continue riding against traffic in an area where this is no longer safe.

For all of the above reasons, bidirectional facilities are strongly discouraged as a general recommendation.

Specific studies have also been made on the tendency toward bidirectional or contra flow riding on bicycle facilities normally intended for single directional use.

Well marked on-street bike lanes have been shown to significantly decrease contra flow riding in a Santa Clara County, California study (South Bay

Transportation Officials Association, October 1972). In that study before and after counts indicated a 21 percent decrease in contra flow riding over a period in which total bike traffic increased by 50 percent. In other words, contra flow riding dropped from 25 to 13 percent of total bicycle activity on the street as a result of provision of well demarcated bike lanes.

Similar counts of contra flow riding were made in Davis, California prior to and after implemenation of bike lanes on a major street. The counts showed a net reduction in wrong way riding after implementation of bike lanes. Some 2.6 percent of all pre-bike lane bike travel was contra flow and only 1.3 percent of post-bike lane traffic was contra flow.

The 1.3 percent contra flow riding reflects a rather typical rate of contra flow riding on Davis streets with bike lanes as indicated by counts on other bike lane streets. However, streets with protected lanes show a quite different pattern. There a contra flow usage rate on the order of eight percent was measured. Further observation showed that the protected lane made it difficult for cyclists to get into or out of the proper directional lane at mid-block when their trip origin or destination was on the opposite side of the street. So they did the most convenient thing which was to ride the wrong way. The fact that protected lanes are physically separated from motor vehicle traffic at mid-block may decrease cyclists' sense of responsibility to operate according to the vehicle code and reinforce their tendency to ride in the manner most convenient to them.

Effects of other types of bikeway facilities on contra flow riding tendencies were noted in connection with other research activities over the course of the study. For instance, the bikeway system in one community studied in connection with measurements of user perceptions included a number of bidirectional on-street lanes. It appeared that the riding behavior induced or sanctioned by these facilities was carried over by cyclists to any street on which they rode. Even on streets without bicycle facilities in this community, casual observation indicated contra flow riding was nearly as prevalent as riding in the proper direction. In another city, directional commuter bike lanes were provided to the CBD by removing parking in peak periods on a pair of one way streets, the parking bans and bike lane being functional in the inbound direction during morning commute period and in the outbound direction in the evening. In discussion of experience on these facilities, a city official argued that these lanes demonstrated that bike lanes were ineffective in central area situations and caused wrong way riding. But it is quite clear that the problem is not one of bike lane ineffectiveness but of poor planning -- there were numbers of bicyclists who wished to travel in the opposite direction of peak commuter flow. Because of the temporal arrangement of the parking bans, the lane in the direction they wished to travel was not operational at the time they wished to use it. So some bicyclists did what they perceived to be the next best thing and rode contra flow in the bike lane which was functioning. In a sense, then, the bike lanes induced wrong way riding. But this occurred only because of the failure to provide adequate facilities for desired bicycle travel in both directions -- not because of some inherent property of bike lanes.

The experience points up the need to maintain functional bike lanes throughout the day. Lanes in effect for brief durations and only in peak travel directions are inherently problematic.

HIGHWAY SHOULDER USAGE

Purpose

The purpose of this research phase was to determine safety factors associated with bicycle usage on high speed rural and urban expressways.

Analysis involved investigations in the following areas:

- Assessment of the effects on bicyclists of aerodynamic disturbances generated by large vehicles passing at high speed.
- Assessment of the exposure of cyclists to conflict with motor vehicles at high speed interchanges.
- Evaluation of the adequacy of highway shoulders for continuously providing basic bicycle operating width and adequacy of pavement quality in that area.
- Comparisons of the safety and quality of highway shoulder use to alternative surface streets.
- Investigation of experience in areas where shoulder use on higher class facilities is permitted and experiences of bicyclists who use such facilities.

Methodology

Investigation in this area consisted of field observation of bicycle-truck interaction and informal interviews with cyclists. Attempts to quantify a threshold of adverse aerodynamic effect of trucks on cyclists did not prove successful.

Findings are presented below under three topics: Aerodynamics of Trucks, Bicyclist Crossings at Interchanges, and Continuity of Shoulders.

Aerodynamics of Trucks

> At normal speeds on local streets, trucks are not of concern in bikeway design. Cyclists have expressed concern only when truck speeds exceed 50 MPH.

Figure 16 presents estimates of aerodynamic disturbance induced forces on bicyclists in relation to separation distance from the passing heavy vehicle (Beauvais, 1970). Other research (Roland, Calspan) on bicycle stability has demonstrated that a bicycle will remain stable when subjected to a lateral force impulse somewhat above the maximal levels indicated on Figure 16. While this would seem to indicate that aerodynamic disturbances due to trucks and other large vehicles should not be a problem, findings are not so conclusive. For as a large vehicle passes a bicycle, the initial force reverses direction so that the bicyclist is first pushed away from the passing vehicle, then suddenly pulled toward it. No technical data is available which would enable determination of threshold levels of truck speed and separation distance at which bicyclist stability would become a concern under such a pattern of lateral force reversal. The problem of aerodynamic disturbances posing serious concern has only been noted by bicyclists passed at close quarters by large vehicles traveling at freeway or expressway speeds (50 to 70+ MPH).

Bicyclist Crossings at Interchanges

> Direct bicyclist movements across exit ramps from the point of exit taper initiation to the gore are generally not feasible.

Bicyclists cannot safely gauge whether overtaking motorists will exit and conflict with the bicyclist while crossing the ramp. Cyclists must be able to gauge whether overtaking vehicles up to about three-tenths of a mile behind intend to exit. At this distance many motorists have not yet begun to slow or signal; frequently clear lines of sight do not exist over this distance. Only in the case where bicyclists can see that there are no overtaking vehicles within three-tenths of a mile would direct "taper initiation to gore" crossings be safe. Because of the potential for misjudgments of distance and the serious potential consequences of high speed accidents or avoidance maneuvers, taper to gore crossings should be generally discouraged.

By executing right angle crossings of high speed exit ramps, time of bicyclist exposure to conflicting traffic is minimized. Hence, the distance within which bicyclists must detect potentially conflicting vehicles is decreased. To execute safe crossings of single lane ramps under right angle crossing conditions, bicyclists must be able to

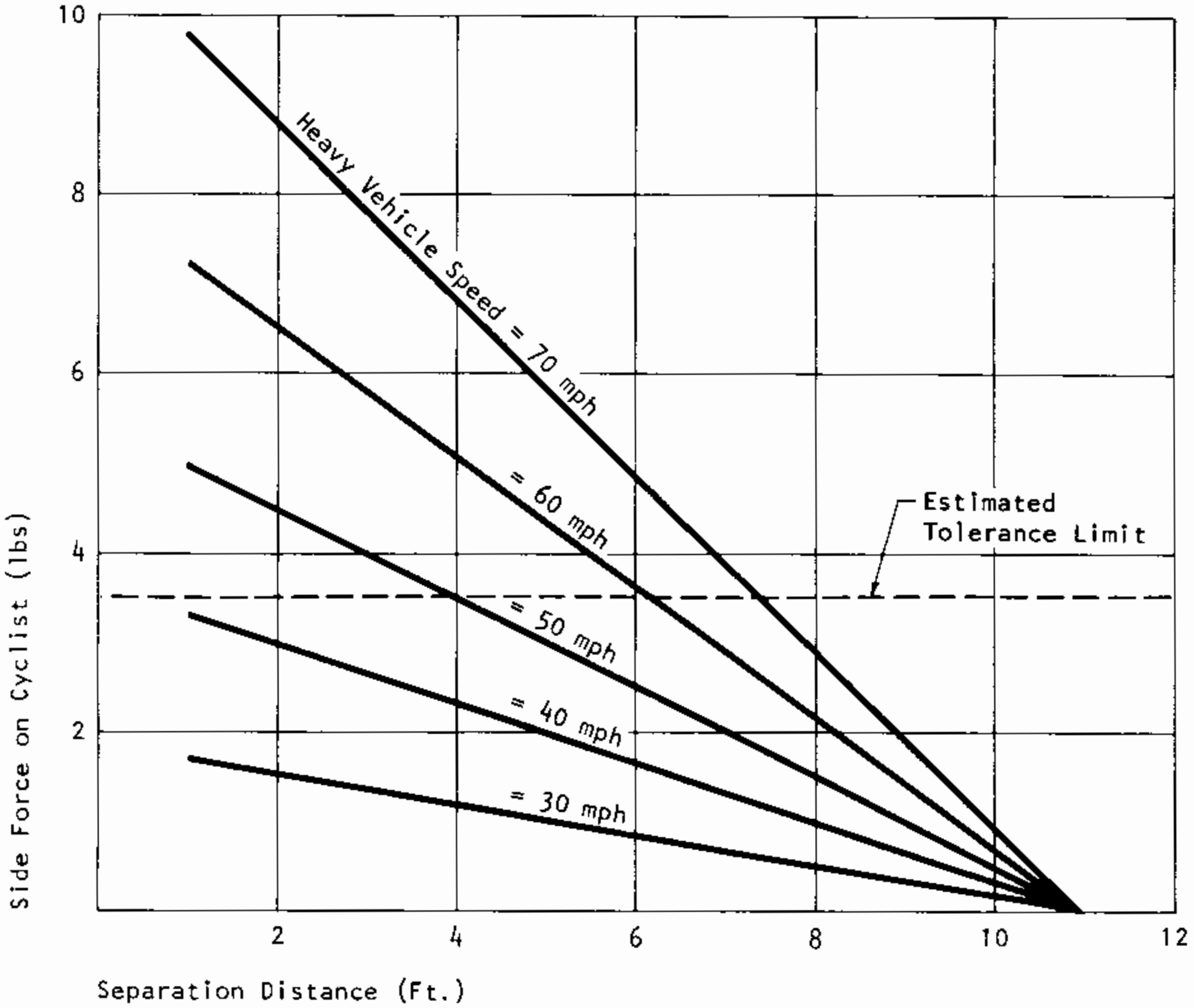


Figure 16
HEAVY VEHICLE INDUCED AERODYNAMIC DISTURBANCES:
Lateral Force on Bicyclists

detect exiting intent of motor vehicles at least 900 feet in advance of the crossing. This can normally be done provided <u>sufficient sight distance exists</u>.

Given that judgments of safe gaps can be made in this situation, the next question is whether safe gaps exist and occur frequently enough that cyclists will not attempt to accept unsafe gaps. If the above sight distance requirement is met, the likelihood of safe gaps can be estimated using procedures similar to those used in estimating warrants for control of isolated bikeway crossings of roadways as discussed in Chapter 4 of this report.

Simulations of gaps under exit ramp approach speeds and control conditions have not been made. But judging from simulations done for independent path crossings, it is estimated that safe gaps would not occur at acceptable frequency at peak hour ramp volumes above 400 to 500 vehicles per hour. On multi-lane exit ramps, it is recommended that grade separations be provided or crossings be made at points where motor vehicle traffic is stopped.

Crossings of entry ramps need only be considered if crossings of exit ramps prove feasible. Because of motor vehicles' lower and accelerating speed on entry ramps, sight distance requirements range from slightly over 100 to less than 600 feet depending upon actual ramp width to be crossed and ramp design speed. If adequate sight distance is available, similar ramp volume levels to those indicated above are estimated to indicate upper limits of likelihood of sufficiently frequent safe gaps for crossing.

Where at-grade crossings of freeway entry or exit ramps prove infeasible, it remains possible to provide for bicyclist grade separated crossings of the ramps or to mandate cyclist exit on the off ramp, crossing of the surface street intersection at the ramp termination and re-entry via the on ramp. These options should always be employed in the case of multi-lane entry and exit ramps. Grade separations should always be employed where it is necessary that bicyclists cross freeway-to-freeway interchange ramps.

Continuity of Shoulders

> Continuous shoulders providing adequate riding width of acceptable riding surface quality should be available if bicycle travel is to be considered on a high speed highway.

Where inadequate or unridable shoulder exists over long sections, this condition should be corrected or the highway should not be considered suitable as a bikeway. Where shoulders are inadequate for short stretches, such as on minor structures, where temporarily occupied by disabled vehicles, debris and the like, individual assessments of acceptability can be made. This involves estimating the time a bicyclist would require to safely clear the constrained area, comparing this to the likelihood of existence of such a gap in traffic within a brief waiting tolerance period (15 to 30 seconds delay tolerance might be assumed) and estimating the sight distance properties for each fixed site of shoulder constraint. Numbers of fixed and likely frequency of temporary shoulder obstructions should also be taken into account. Other factors which should be taken into account include air and noise pollution. Discussion of these criteria is presented in Chapter 5.

Use of Alternate Routes

> Use of high speed facilities should be considered only where alternate routes do not exist.

Any determination regarding location of a bicycle facility (or decision to permit bicyclist use of a highway) must ultimately consider not just the facility in question but its quality in relation to alternatives available. If the alternative to use of a freeway shoulder in an area of light traffic is a rural surface roadway with no shoulders, minimal width travel lanes, poor sight distances and used by high speed traffic, the freeway shoulder might be judged safer for bicyclist use than the surface roadway. In California, freeway shoulder use is permitted when no acceptable surface routes exist. In several rural counties in that state blanket judgment has been made that freeway shoulders are inherently safer for bicylists than parallel surface roadways.

Conclusions and Implications

The discourse on freeway shoulder use presented herein is in more detail than other study topics because this subject has not been formally addressed in the user manual documentation. The reason for this is as follows.

Ultimately the safety of any bicycle facility on any street or highway is in large measure determined by the degree to which cyclists conform to rules of behavior predictably and exercise prudent judgment in traffic. But this is of paramount importance on high speed, high traffic volume facilities where any deviance or error in judgment has high probability of creating a conflict. In the absence of some form of bicyclist licensing, there is no method of insuring the riding skill, judgment and behavioral stability of bicylists who might use a freeway or expressway shoulder. And even if users were limited to those of higher skill and judgment levels, the rule of behavior essential to safe operation on a high speed roadway -- that the bicyclist adopt a yielding posture toward motor vehicles in any conflict situation -- runs counter to the prevalent viewpoint and behavior of many sophisticated bicyclists.

Such bicyclists assert that in all cases bicyclists have rights (and responsibilities) equal to any motor vehicle. Given this premise, the logical extension is that in potential conflict situations such as at a shoulder obstruction or interchange crossing, if the bicyclist establishes position in a travel lane, overtaking vehicles will be bound to defer. This approach is directly opposite to what is judged as necessary behavior and rule of operation for safety on high speed facilities.

The sections which preceded suggested rationale for evaluating the objective aspects of shoulder use feasibility on high speed facilities. However, the critical element appears to be cyclist behavior. Beyond conjecture, there is little basis for evaluating the adequacy of cyclist behavior for use of high speed facilities at this time. For this reason no general recommendations regarding the use of high speed roadway shoulders have been made. It is recommended that experience in areas where bicycling on high speed roadway shoulders is permitted be monitored for a period of time before general policies regarding shoulder usage are articulated.

PHYSICAL BARRIER AND STRIPE SEPARATION FEASIBILITY

Findings and Conclusions

> On the basis of the foregoing research and observations of existing facility performance, separation of bicycles and motor vehicles by striping is assessed to be feasible and effective.

Observations of performance on facilities with stripe separation of bike and pedestrian travel areas indicates that this treatment at times does provide some desired separation of the two modes. However, the treatment is far less effective than on-street striping as bicyclists and pedestrians casually disregard lane designations on sidewalks and independent paths when it suits them. Application of this treatment seems most appropriate in areas shared by large numbers of bicyclists and pedestrians rather than as a matter of routine on all facilities shared by bicyclists and pedestrians.

Additional evaluations were made of the feasibility of separating bicyclist and motor vehicle flows by physical barriers. Discussion of "protected lanes" in User Manual Volume I provides a rather complete summary of problems associated with this type of lane separation. Another problem identified in observation of existing protected lane treatments was bicyclist and motorist vandalism of the more nominal forms of barrier delineation such as plastic pylons. Finally, as per the foregoing section, provision of protected lanes appears to increase bicyclist tendency to use facilities bidirectionally, an obviously undesirable result.

For these reasons, User Manual Volume II includes a general recommendation against employment of physical barriers to separate and delineate on-street bike lanes.

CHAPTER 4

SAFETY AND OPERATIONS AT INTERSECTIONS

INTRODUCTION

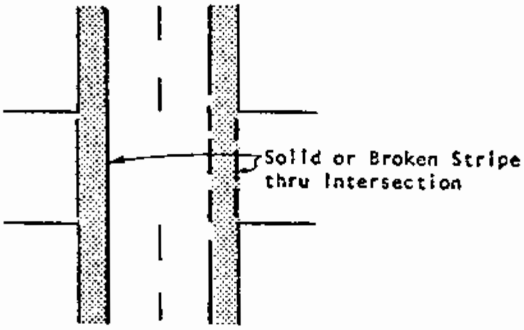
The preceding chapters focused upon factors affecting safety and operations along linear facilities. This chapter is directed to a specific assessment of intersection problems and treatments. Included is discussion of safety of various strategies for treating bike lanes at intersections; a review of problems and current status of warrants and design practices with respect to control of bicycle traffic at intersections, a summary of research leading to development of intersection traffic control warrants which consider bicycle traffic and a presentation of those warrants.

SAFETY OF BIKEWAY INTERSECTION TREATMENTS

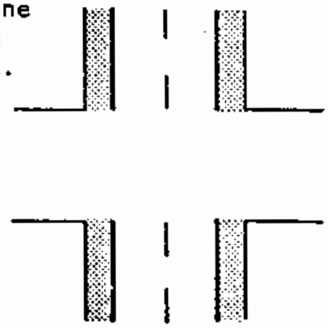
Summary of Treatment Techniques

The "Bikeways -- State-of-the-Art -- 1974" report presented a summary of in use domestic and foreign bikeway treatments at intersections. Treatments identified included:

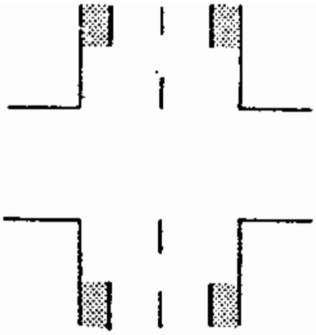
- Lane Continuation -- Bike lane demarcation continued through the intersection.



- Lane Definition to Stop Line -- The bike lane is continuously delineated to the stop line or crosswalk area at which it is terminated.

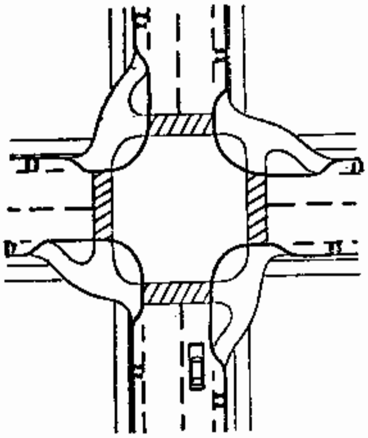


- Lane Termination -- The bike lane is terminated at some point on the intersection approach to encourage positional adjustment by bikes and motor vehicles.

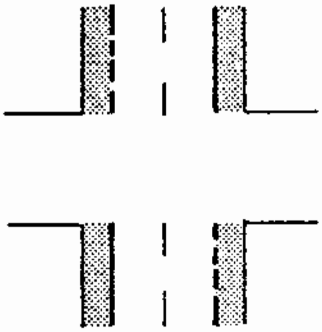


- Designated Directional Lanes -- Provision of specific lanes for directional movement of bicyclists at intersections located immediately to the right of the corresponding lane for motor vehicle movements.

- Offset Crossings -- Bicyclists are channeled onto the sidewalk area and to crossings of the intersecting streets just outside (farther from the center of the intersection) the normal pedestrian crosswalk area. In effect, a bikeway ring around the intersection is created.



- To these in-use treatments was added the concept of the "broken lane delineation". The intent of this treatment is similar to lane termination to encourage adjustment of positional relationships of bikes and motor vehicles, but this treatment provides opportunity for more gradual transition and mixing than the abrupt lane termination treatment.



Findings

> Insufficient data exists to clearly define the effects of bicycle lanes at intersections with regard to safety. Two studies are described which have conflicting conclusions on this point.

The key to evaluating the potential of these treatments in enhancing bicyclist safety at intersections is an understanding of the causes of bicycle-motor vehicle accidents at intersections. Cross has developed an accident causal critical behavior categorization for bicycle-motor collisions and applied this to accidents in Santa Barbara, California. A breakdown of intersection accidents as derived from that study data is shown in Table 47.

Table 47
TYPICAL INTERSECTION ACCIDENTS CAUSAL DISTRIBUTION

Accident Type	Percentage of Intersection Accidents
Cyclist failed to STOP/YIELD at controlled intersection	16.8
Cyclist made improper left turn	6.8
Cyclist rode on wrong side of street	17.9
Motorist collided with rear of cyclist	6.0
Motorist failed to STOP/YIELD at controlled intersection	15.8
Motorist made improper left turn	23.1
Motorist made improper right turn	13.6

SOURCE: Derived from data for Southern Santa Barbara County, California.

These data are only generally representative of bicyclist accident patterns as percentages of accidents in the various categories do vary somewhat from area to area. But they do facilitate understanding of the relative importance of various causal factors of intersection accidents.

The problem lies in interpreting what impact various forms of bikeway treatments at intersections might have on accident patterns and rates of occurrence. Virtually all current literature on this subject is conjectural -- direct and reliable comparisons of safety performance on alternate forms of intersection facility treatments is lacking due to the lack of sufficient data.

Most available data of the sort presented on Table 47 is on facilities without bikeway treatments or does not differentiate between accidents which occurred on bikeways versus other facilities. Many of the types of treatments described have not been employed for a sufficient length of time and in a sufficient number of locations for accumulation of enough accidents for meaningful comparisons. Also important in making comparisons is the problem of estimating accident rates; the method presented in Chapter 2 involving the use of "neutral" accidents as a scaling factor will hopefully circumvent the accident rate computation problem.

Two studies which do provide results of direct comparisons of bike lane treatments are the research undertaken in this project and reported on in Chapter 2 and a Danish study (Danish Council for Road Safety Research).

The Danish work showed that while bicycle facilities decreased the overall rate of bicycle-motor vehicle accidents by some 27 percent, no net change was realized at the intersections as a result of bicycle facility provisions. The pattern of accidents at intersections did change with collisions between through cyclists and turning motor vehicles increasing and collisions between turning bicyclists and through vehicles decreasing. However, there was no change in the net rate of intersection accidents as the above changes offset one another.

Findings based upon the Davis data as presented in Chapter 2 are at conflict with the Danish results. In Davis, the bike lane treatments appear to produce a net decrease in overall intersection accidents; in direct contradiction of the Danish findings, accidents involving through cyclists and turning motor vehicles decrease while those between turning cyclists and through motor vehicles increase with provision of bicycle facilities.

Conclusions

In summary, there is a lack of direct evidence on the effects of various forms of bicycle facility treatment or lack of treatment on intersection safety performance. What evidence exists is inconclusive. Clearly, further research in this area is needed as additional facilities are installed. Lacking direct measures, other measures of intersection performance are needed to evaluate the functional safety qualities of bikeway intersection treatments.

BIKE LANE INTERSECTION OPERATIONS STUDIES

Observation and evaluation of functional and safety qualities of the above types of bikeway treatments at intersections was undertaken. The intent was to determine whether one of those might prove optimal or to identify conditions under which each type of treatment might be most advantageously used. Bike-motor vehicle conflicts were used as criteria in the absence of satisfactory direct performance data such as accident records. Prior to undertaking such studies, the offset crossing was dropped from consideration primarily due to problems with bicyclist acceptance. Although this treatment has been successfully employed in Europe, it essentially involves treatment of bicyclists as pedestrians. All observational experience of U.S. cyclists would indicate certain rejection and disuse of such a facility by the vast majority. Hence the offset crossing treatment was dropped from consideration.

Operations on the other types of treatment were observed qualitatively and, where possible, quantitatively at locations where they had been employed. Most of these observations were qualitative in nature simply because measures of intersection conflict under the various treatments proved extremely difficult to rate in a quantitative manner.

One reason for this is because of the relative scarcity of bicyclists in the traffic stream. Except at sites in close proximity to major bicycle traffic generators, it is difficult to observe significant numbers of bicyclists at intersections within reasonable observation periods. Time lapse photography which is effective in pedestrian studies was not particularly useful in dealing with this problem. The speeds of the vehicles involved make it difficult to evaluate conflict movements and adjustments when film speeds which reasonably reduce observation time are used.

But a far greater problem than simple observation is the fact that clearly definable conflict siutations are relatively rare. Most adjustments to potential conflicts are made in a continuum of motion on the intersection approach. This contrasts with rather abrupt alterations of movement clearly discernable in observations of pedestrian-motor vehicle conflicts. Hence it is often difficult to determine whether a motor vehicle and bicycle have made an adjustment to avoid conflict on their approach to a potential conflict point or whether they are simply not arriving at the point of conflict at the same time (no adjustment).

Following are qualitative evaluations of the various treatments based upon the observational studies conducted. These form the basis for the recommendations in User Manual Volume II.

The "lane continuance" and "lane definition to stop line" treatments tend to induce curb-hugging behavior by bicyclists until they are in close proximity to or into the intersections. This brings through and left turning bicyclists into conflict with right turning motor vehicles as well as making left turns by bicyclists difficult. The "lane continuance" treatment also emphasizes the right-of-way of bicycles in the bike lane over cross street traffic. Hence, the following general recommendations are made relative to the applicability of these treatments.

- Both treatments might be used where right turning motor vehicle traffic and left turning bicycle traffic is limited.

- The "lane definition to stop line" treatment may be appropriate where right turning bicycle traffic is heavy, particularly if through and left turning bicycle traffic and right turning motor vehicle traffic is light.
- The "lane continuance" treatment is appropriate at intersections where bike lanes on major streets cross minor streets particularly at "T" intersections.
- Either treatment may be appropriate where user cyclist skill levels or traffic conditions are such that conflicts for bicyclists weaving to establish proper positional relationships with motor vehicles are potentially more hazardous than crossing conflicts with right turning motor vehicles.

The "lane termination" treatment encourages through and left turning cyclists to leave the right side of the road and establish proper positional relationships with motor vehicles about to execute turning movements. As in the two treatment types which follow, this requires a reasonable level of riding skill and traffic judgment on the part of the cyclists. Also, traffic approach speeds, volumes and number of approach lanes must be such that cyclists can be reasonably able to find gaps to execute weaving and merging maneuvers. One disadvantage of this treatment in comparison to those previously described is that right turning bicycle traffic, which was not involved with motor vehicle traffic on the same approach under those schemes, is forced to merge with right turning and through motor vehicle traffic. The lane termination treatment offers no advantages in performance over the "broken stripe" treatment described below except for requirement of less right-of-way. Hence, it is recommended only when right-of-way precludes deployment of the "broken stripe" treatment.

The "broken stripe" or "broken lane" delineation encourages similar bicyclist behavior to that under the lane termination condition. It has the advantage over lane termination in that it preserves a protected space from which merge-weave movements can be initiated when safe gaps appear rather than creating an abrupt point at which weaving must be initiated. It also maintains a protected area for bicyclists about to execute right turns.

This treatment should be used as a general treatment unless conditions for the "lane continuance" or "definition to stop line" treatments are met or right-of-way is insufficient and the "termination" treatment is necessary.

The "designated directional lanes" treatment is actually a variation of the "lane termination" or "broken lane" treatments above. These provide protected storage space for bicyclist through and left turning queues, normalize the alignment of bicyclists in those queues and eliminate the need for merging of bicyclists and motor vehicles executing the same movement. The treatment is best employed at signalized intersections where through or left turning bicycle movements are heavy and right-of-way is available. The treatment is flexible in that a left turn pocket or through pocket can be provided individually or both can be provided. A specific quantitative study which indicates provision of such designated directional lane increases operational efficiency follows.

BICYCLE TURN LANE INSTALLATION

Purpose

Turn lanes designated for bicycles have been in use in Europe for a number of years; until 1974, they had not been used in the U.S. A study was undertaken in Davis, California to determine acceptance and effectiveness of such lanes.

Methodology

The methodology in this study is the standard before-and-after technique. Observations were made on Anderson Road at Russell in Davis, at the edge of the University of California campus. A standard left turn lane at this location was used by 1,000 persons during the AM peak period.

Observations and counts were made at this intersection before and after installation of a designated bicycle left turn lane. Bicycles and vehicles were timed passing through the intersection to evaluate efficiency of the lane. Motion pictures and video tapes were used to analyze conflicts between the two travel modes.

Findings

> Designated turn lanes can reduce conflict and improve the efficiency of intersections where a large bicycle turning volume exists. Bicyclists have shown a high degree of acceptance of the lane evaluated.

Observations made at the study location before installation of the turn lane indicated that bicyclists making the left turn occupied the dedicated automobile left turn lane, frequently conflicting with motor vehicles also executing left turns. Virtually no cyclists exercised the option to make a pedestrian-like left turn by using the crosswalks and waiting for appropriate traffic signal changes. If the signal was red when they arrived, they typically took a position next to the concrete island and on the left side of the auto turn pocket. To reach the opposite roadside from this position, they had to cross the line of travel of left turning motor vehicles, creating a conflict in which either the bike or the motor vehicle would have to yield in order to exchange positions while passing through the intersection.

Figure 17 shows the designated turn lane that was installed on Anderson Road. Observations showed that 93 percent of the cyclists turning left through the intersection used the new lane.

Table 48 presents the number of conflicts in representative peak period signal cycles before and after installation of the turn lane. The table shows that conflicts were reduced markedly by the lane.

Timing of motorist and bicyclist clearance intervals is a measure of efficiency of the "before" and "after" conditions. Time for autos to clear the intersection was recorded in two ways. Those queued when the signal changed from the red to the green phase were timed from the change in the signal until they had crossed the pedestrian lane crossing the east-west street. Those arriving during the green phase ofthe signal were timed from crossing the stop line to the pedestrian lane crossing the east-west street.

Bicycle time was recorded in a slightly different manner. Those queued up at the stop line when the signal changed from the red to green were timed from the change of the light while those waiting further back in the line were timed as they crossed the stop line in the same way as those who arrived during the green phase ofthe signal were timed.

Table 48
COMPARISON OF AUTO-BICYCLE CONFLICTS
BEFORE AND AFTER INSTALLATION OF LEFT TURN LANES

Movement	Conflict		No Conflict		X^2
	Before	After	Before	After	
Automobile Left Turn					
Standing start after red phase	14	3	2	24	21.43; $p<.001$
Moving turn during green phase	11	2	22	78	18.89; $p<.001$
Bicycle Left Turns					
Standing start after red phase	26	4	63	33	3.91; $p<.05$
Moving turn during green phase	13	3	116	204	11.21; $p<.001$

Results of this analysis are presented on Table 49. The table documents what is obvious from casual observation -- that motor vehicle intersection clearance times are reduced whether they are queued during a red phase or approach during a green phase. The increase in cyclist clearance time can be attributed to the longer path from the designated lane to the pedestrian lane. The high level of acceptance of the lane indicates that the three second increase was insignficant to most cyclists.

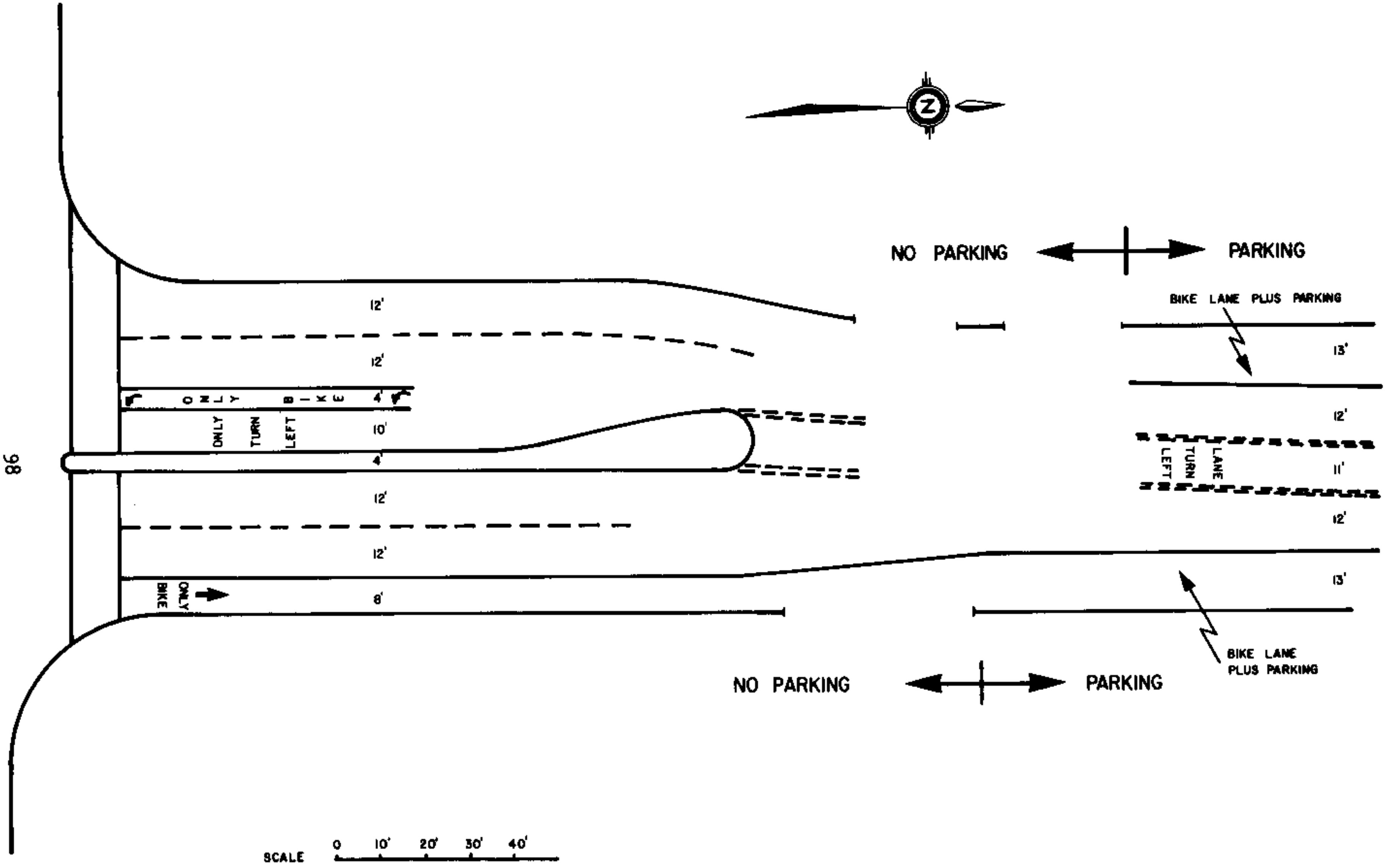


Figure 17
"BIKE ONLY" LEFT TURN LANE AT ANDERSON AND RUSSELL DAVIS, CALIFORNIA

Table 49
COMPARISON OF TRAVEL TIME THROUGH INTERSECTION
BEFORE AND AFTER LEFT TURN LANE INSTALLATION

Movement	Number of Vehicles		Mean Seconds Per Left Turn		Test Value
	Before	After	Before	After	
Automobile Left Turn					
Standing start after red phase	16	27	9.5	8.4	t=1.54; p=.07
Moving turn during green phase	33	80	5.5	5.1	t=1.30; p=.10
Bicycle Left Turn					
Standing start after red phase	89	37	9.3	11.4	t=5.0 p=.001
Moving turn during green phase	129	207	8.4	8.4	

EVALUATION OF BIKEWAY CONFLICT REDUCTION

Purpose

The technique described in this section is designed to provide for quantitative evaluation of bikeway conflict reduction.

Findings

> A technique for estimating conflict reduction has been developed; however, further research is required to establish a factor needed to weight crossing and merging conflicts.

Each of the bikeway treatments described in User Manual Volume II has associated with it certain crossing-turning and merging-diverging conflicts. The relative safety of any treatment is dependent on the number of such conflicts which will occur and is a function of both the treatment and the bicycle and vehicle volumes at the site.

Table 50 illustrates the types of movements through an intersection which are possible and identifies them as crossing, merging, or nonconflicting. The recommended technique in evaluating conflicts is to accumulate all volumes through an intersection into one of the two conflict types. The relative efficiency of each treatment can then be given by the formula:

Net Conflict Score = Total Merge Conflicts + Total Crossing
Conflicts x Merge/Crossing Equivalency Factor

The exact nature of the merge/crossing equivalency factor has not been determined and is an area for future research. For the present, the designer should make a judgemental estimate of the relative safety of crossing and merge-diverge conflicts on the basis of the characteristics of the individual intersection in question and use it in the above evaluation schema.

Table 50
RELATIONSHIP OF INTERSECTION TREATMENT
TO OPERATION CONFLICT TYPE

	TURN MOVEMENT COMBINATIONS									
	Motor Vehicle	L	R	T	L	R	T	L	R	T
Type of Treatment	Bike	L	L	L	R	R	R	T	T	T
Through Intersection		C	C	C	0	0	0	0	C	0
To Stop Line		C	C	C	0	0	0	0	C	0
Broken Lane		M	M	M	0	0	0	0	M	M
Designated Pockets		0	M	M	0	0	0	0	M	0
Lane Termination		M	M	M	0	M	M	0	M	M
No Bike Lane		M	M	M	0	M	M	0	M	M

L = Left turns
R = Right turns
T = Through movements

0 = No conflict
C = Crossing conflict
M = Merge-diverge conflict

TRAFFIC CONTROL AT INTERSECTIONS

Substantial research effort has been directed to assessment of intersection traffic control in terms of bicyclist needs and the effects of bicycles on intersection operations. The sections which follow summarize current problems and practices related to bicycles and intersection control, investigations of traffic control technology as potentially applied to bicycles, preparation of a simulation model for evaluating traffic control device performance in relation to bicycle and motor vehicle traffic and presents warrants for control device application based upon that model.

Intersection Traffic Control Problems

Following are some common problems with current applications of intersection traffic control devices experienced by bicyclists. This listing is not intended to be comprehensive; it is simply illustrative of the types of problems to be dealt with.

Motivated by a natural desire to maintain momentum, bicyclists frequently are in technical violation of STOP controls. Because of their speed and maneuverability characteristics, bicyclists can usually do this safely. But bicyclist violation of STOP controls is a significant causal factor in bike-motor vehicle collisions. Due to this bicyclist behavior, STOP control set against the bicyclist does not protect the bicyclist from right-of-way conflict; it simply places the bicyclist at fault where such conflict occurs.

STOP and YIELD controls pose other sorts of problems for bicyclists. At minor intersections motorists often travel through YIELD controlled intersections at a brisk pace, giving only a cursory glance for cross traffic. Due to bicyclists' low target value, they are frequently overlooked and accidents result. It is preferable that STOP rather than YIELD signs be set against cross traffic when bike routes or lanes are located along minor streets.

At some minor street intersections where sight obstructions exist, YIELD signs have been deployed because the obstruction cannot be removed or a property owner cannot be forced to cut back shrubbery or remove fencing. This is an inappropriate use of the control device. Sight obstructions should be removed where possible. Where they cannot be removed (i.e., if the obstruction is a building), STOP rather than YIELD control should be deployed. This is good traffic engineering practice in general and it should be particularly emphasized at intersections involving bikeways.

Bicyclist problems are perhaps most acute at some of the most advanced installations -- traffic actuated signals. The problem stems from the fact that bicycles are not detected by most commonly employed magnetic inductance loop detectors. Hence, the bicylist is dependent on motor vehicles to "call" the green to his approach.

This may be quite satisfactory when traveling along the mainstream traffic. But a bicyclist attempting to execute a left turn from a turn pocket which has a separate detector for a "minor movement" phase or a bicyclist on a minor street approach may be considerably delayed before a motor vehicle executing a similar movement arrives. In such situations, the bicyclist has no good options; he can get off his bicycle and use the pedestrian actuation button if there is one, violate the signal or just wait.

The simplest remedy, now employed frequently, is to mount a pedestrian actuation button by curbside where cyclists can reach it without dismounting. This is satisfactory for cyclists at curbside but no use to through and left turning cyclists who leave curbside to execute these movements.

When such pedestrian actuation buttons are employed for bicyclists, there is a loss in potential efficiency of intersection operations. Bicyclists can normally clear an intersection in a fraction of the minimum permissible pedestrian crossing phase. But when a curbside mounted pedestrian-type button is provided for bicyclist use, actuations are simply treated as a pedestrian "call". Hence, there is significant potential delay to cross traffic over and above the time necessary to specifically serve a crossing bicycle.

One problem experienced by bicyclists crossing multi-lane streets at signalized intersections is that an amber intersection clearance interval, if set to close tolerances for motor vehicle clearance, may not provide sufficient clearance time for slower moving bicyclists. A bicyclist who entered the intersection at the tail-end of a green phase may still be in the intersection when cross traffic gets the green.

Another traffic control-related problem occurs when bicyclists on sidewalk bikeways are forced to key on pedestrian crossing indicators. Cyclists know that they can easily cross during the pedestrian clearance interval and are typically unhesitant about entering the intersection against a "flashing WAIT" or "flashing DON'T WALK". But if they misgauge the clearance time remaining, they may be caught in the intersection.

Perhaps the most significant problem is the fact that bicyclists are rarely considered part of the street traffic when the type of intersection control device is selected and its details designed. As alluded above, bicycle traffic is at times considered in placement of "STOP" and "YIELD" controls, but far less rigorous justification is usually required in placement of these devices than in the case of traffic signals.

Survey of Previous Efforts

As part of this research program, inquiries were directed to some 45 knowledgeable experts in the fields of bikeway planning and traffic control technology regarding any warrants for signalization of which they were aware and which included consideration of bicycle traffic. None of the respondents was able to report any warrants which gave specific consideration to bicycle traffic.

Literature search proved more productive as a number of instances of direct consideration of bicycle traffic in signal warrants were identified.

- The City of Davis, California, which experiences heavy bicycle traffic, counts bicycles as motor vehicles when justifying traffic signals and this procedure has been accepted by federal and state agencies in approvals of funding for signal installations.

- The British have developed a method for including several vehicle types when calculating saturation flow and selecting signal timings for intersections (Webster, Cobbe, 1966). This method requires that all vehicles be converted to passenger car equivalents. A bicycle was determined to be equal to one-fifth of a passenger car unit (Holroyd, 1963).

- Further research was undertaken in India based upon the above British findings (Sarna, 1967). This work shows that as the proportion of bicycle traffic in an intersection approach increases, the saturation flow rate (capacity) in passenger car units is not lowered.

- Earlier Danish work, partly theoretical and partly empirical generally reinforces the above British and Indian findings (Koefoed, 1954). This study indicates that bicycles up to 1000 per hour are equal to .20 passenger car units. For flows over 1000 per hour, an equivalency of .15 passenger car units is indicated.

- Groth conceived a methodology for computing signal phasing to accommodate bicycle traffic (Groth, 1960). His procedure is based upon arrivals of bicycles at intersections according to a Poisson probability distribution and requires that bicycles flow in single file lanes. The procedure is only applicable to locations where directional turning pockets for bicycles previously described are provided. Groth also examined signal progression to accommodate a steady flow of bicycle platoons. This consisted of checking whether bicycle traffic could fit in motor vehicle progressions.

As evidenced above, consideration of bicycle traffic in signalization decision-making has been the subject of substantial research although knowledge of that research is not widespread in the U.S. However, before presentation of direct research undertaken in this study to develop specific procedures for considering bicycle traffic in intersection control device selections, a discussion of traffic signal hardware and hardware applications possible in resolution of some of the previously noted problems is approprlate.

Traffic Control Technology Potential

Signalization treatments which make specific provision for bicycle movements and help resolve many of the problems identified above are well within the capabilities of existing hardware technology. For instance, loop detection patterns which are capable of detecting a bicycle have been in European use for some time (De Leuw, Cather & Company, 1972).

U.S. manufactured inductance detectors which do detect bicyclists are also becoming available. One such device was tested by the City of Davis during the course of this program and was found sufficiently effective for application in new signal installations. Use of such detectors appears desirable at traffic actuated signal installations on bikeway streets particularly if the bike lane treatment on the intersection approach encourages cyclits to move away from curbside.

San Diego County, California has also undertaken research in inductive detection of bicycles (Massman, 1975). This work indicates that several recently developed signal loop sensors combined with smaller and more sensitive inductance loops than normally used in motor vehicle traffic lanes can detect bikes consistently under all conditions. It was found that bikes could be detected for about one foot off the edge of a 3x3 diamond loop (total loop width 3.75 feet) and that autos were not detected at distances greater than two feet off the loop. Hence, the 3x3 diamond pattern was judged to be an ideal loop dimension for bike detection in a five to seven foot wide bikeway. The research also noted some problems of tuning-out (loss of detection) in the "presence" mode and concluded that "high sensitivity" detector settings were required for "presence" detection but either "normal" or "high sensitivity" settings were satisfactory for detection in the "pulse" mode.

It is well within existing hardware technology capabilities to record bicyclist actuations, whether detected by curbside mounted buttons or inductance loops discussed above as a separate type of "call". One city (Davis, California) has used this capability to provide a "minor movement" phase timing for bicyclists slightly longer than the normal green time allocation for motor vehicle "calls" but far more brief than the allocation for a pedestrian call, thereby minimizing potential delay to all intersection users.

Provision of extensive separate signalization treatment for bicyclists with separate signal heads and separate phasing is definitely feasible in terms of existing technology. Although such installations have not been attempted in the United States, this is a commonly employed treatment in Europe. Possibilities range from simple provision of a bike "scramble cycle" -- a cycle in which all motor vehicle movements are stopped and all bicycle movements allowed to proceed -- to advanced forms of detection and minor movement phasing.

The problem with this approach is that locations at which such treatment might be most needed are busy intersections where intersection delay and capacity may already be a concern. Allocation of signal time for a separate bicyclist phase would detract from the green time available for motor vehicle movement phases, hence, constraining motor vehicle capacity. Whether or not this would be a significant concern would depend upon analysis of the particular intersection involved.

Separate bicyclist phasing would also probably require attitude adjustment for acceptance by current bicyclists (and probably a heavy dose of enforcement to achieve this). Current bicyclist would be likely to attempt to travel on the motor vehicle green phases as well as on the designated bicyclist movement phase thereby defeating the purpose of the installation. While such a behavioral adjustment is possible -- bicyclists respect the separate phasing in Europe -- it must be recognized that while this approach may increase safety, it does so at the expense of bicyclist delay and inconvenience, another example of tradeoff of transportation utility for increased safety.

At current levels of bicycle use, application of such extensive special signalization treatments does not appear generally warranted. Experimental application at locations of extremely high bicycle traffic such as in the vicinity of college campuses seems appropriate.

On bikeway streets or on any street carrying measurable bicycle traffic, amber or a combination of amber and all red phasing can be set to provide a sufficient interval for bicyclists to clear the intersection. While this detracts slightly from intersection traffic carrying capacity, it tends to increase overall (not just bike) traffic safety and is more realistic than the possible alternative: providing a separate signal head for bikes with an advanced amber setting.

Where sidewalks are heavily used by bicyclists and pedestrian crossing indicators do not provide satisfactory information as to whether a safe interval for bicyclist crossing remains, separate indicators controlling bicyclist crossings are feasible and appropriate.

INTERSECTION SIMULATION MODELS

This section describes development and verification of simulation models to estimate warrants for STOP, YIELD and signalized control at intersections which take bicycle traffic into account. Two simulation models were developed -- one for sign-controlled intersections, the other for signalized intersections. The models enable evaluation of total delay and delay distribution to bicycle and motor vehicle traffic at varying flow rates and under varying control assumptions.

STOP and YIELD Sign Simulation Models

In the sign-control model, motor vehicle and bicylist arrivals for each movement are generated using the shifted exponential distribution (Gerlough, Capelle, 1964). This function has been shown to represent a reasonable arrival pattern for motor vehicles in a single lane (Wohl, Martin, 1967). Groth has also demonstrated its applicability to bicycle arrivals after observation of over 20,000 bicycle arrivals (1960). As further illustration of the validity of this application, observed arrival data in Davis, California, is compared to the shifted exponential distribution (with magnitude equal to zero) on Figure 18.

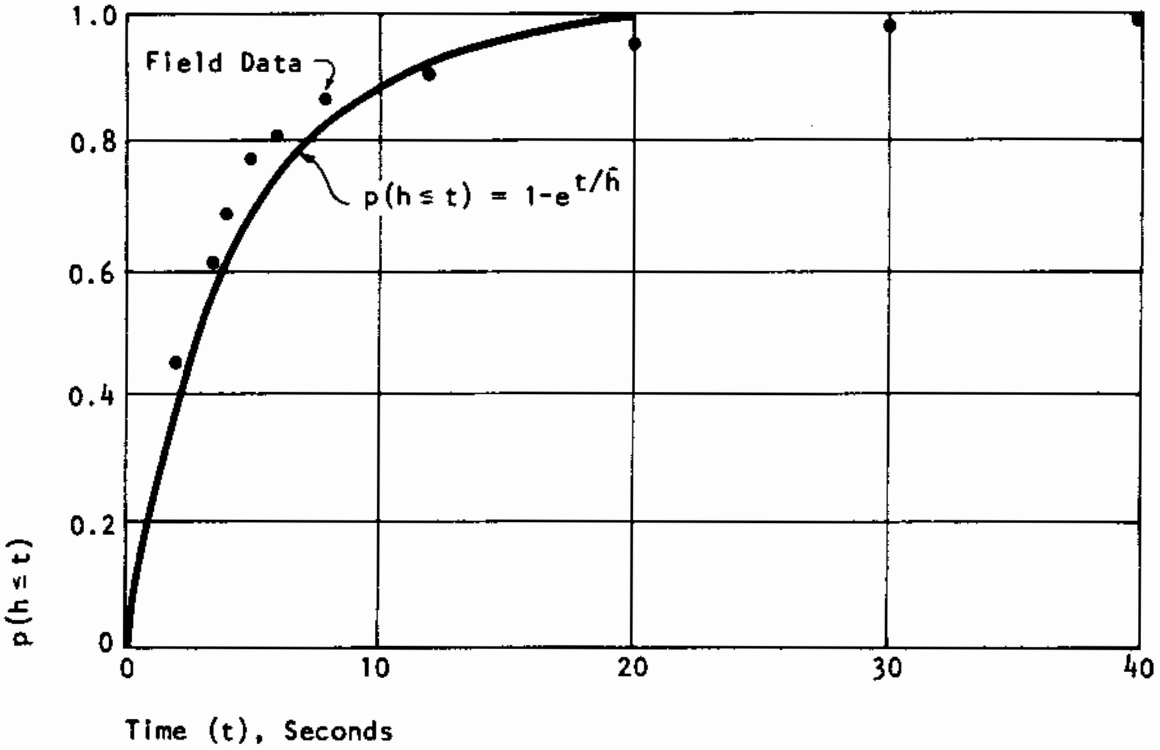
The general form of the shifted exponential distribution is:

$$P(h<t) = 1-e^{-(t-T)/(\bar{h}-T)}$$

$P(h<t)$ is the probability that a headway, h, is less than <u>or</u> equal to time, t. The average headway, $\bar{h}$, is computed from the input flow rate and T is the minimum allowable headway. In the model, T is given as 1.3 seconds for motor vehicles and zero for bicycles. Thus, it is possible (and realistic) for several bicycles to arrive nearly simultaneously in the traffic stream.

Using the above methodology, arrivals in the crossing traffic streams are generated for a one hour simulation time. These conflicting streams are then combined into a sequential series of arrivals which determines whether each vehicle being served at the intersection would experience conflict. When conflict exists, delay is accumulated by vehicles according to a right-of-way logic for each control strategy specified as illustrated in Table 51.

Given the sequence of conflict times and right-of-way logic, delay is calculated by comparing arrival time to the time of occurrence of an acceptable gap in conflicting traffic streams.



$\hat{h}$ = 4.35 sec.
206 Bicycles in Sample
15 Min. of Data
824 Bicycles/hr

Figure 18
CULUMATIVE DISTRIBUTION: ARRIVAL GAPS IN BICYCLE TRAFFIC

Table 51
DELAY LOGIC - SIGN CONTROLLED INTERSECTION

Vehicle Approaches On --	Type Vehicle	Intended Movement	Is Delayed by Traffic In
Main Street	Motor Vehicle	Through	No vehicle streams
		Left	Bicycle and motor vehicle traffic in opposite main street approach
		Right	Bicycle traffic in same main street approach
	Bicycle	Through	No conflicting streams
		Left	Motor vehicle traffic in both main street approaches
		Right	No conflicting streams
Side Street	Motor Vehicle	Through	Both main street motor vehicle and bicycle traffic streams
		Left	Both main street motor vehicle streams and near side main street bicycle traffic stream
		Right	Near side main street bicycle and motor vehicle traffic streams through bikes on side
	Bicycle	Through	Both main street motor vehicle traffic streams
		Left	Both main street motor vehicle traffic streams
		Right	No conflicting streams

Gap acceptance distributions utilized in the model were the subject of extensive research activity. Several different functional forms have been used in simulation models to describe gap acceptance by motor vehicles at intersections. These functions have as an independent variable a random number which can be generated by a computer or selected from a table. The dependent variable is a minimum-sized gap that a particular vehicle is willing to accept.

The only known previous models of bicycles accepting gaps in motor vehicle traffic were proposed by Groth (1960). This minimum acceptable gap was taken to be twice the minimum time required for a bicycle to cross motor vehicle traffic.

Several researchers have studied motor vehicle gap acceptances apart from modeling of intersection performance. Solberg and Oppenlander (1966) proposed a linear relationship between the probit of acceptance and the logarithm of acceptance time as being best suited for modeling gap acceptance. Miller discussed several ways gap acceptance data could be treated (1971). A more recent approach proposed by Ramsey and Routeledge (1973) would have been suitable for this study, except that their method requires complex data on the number of gaps available in each of several time intervals in addition to acceptance-rejection decisions.

Ashworth and Green have outlined factors that will influence the gap acceptance decision. These include the driver's age, sex, driving experience, speed and volume of traffic on the major road, width of the major road, visibility, type of traffic control in effect, weather, light conditions, type of vehicle, the presence of a queue behind the driver, and the nature of the intended maneuver such as right turn, left turn or straight through. It would be extremely difficult, and require large amounts of data, to model several of these variables, let alone all of them. For this modeling effort, some very simple gap acceptance distributions were developed since the models are intended to represent "typical" intersections.

As can be seen from the foregoing, considerable data has been published on the behavior of motor vehicles accepting and rejecting gaps in motor vehicle traffic. A representative sample of this data is presented in Table 52. The critical gap is defined as the size gap that will be accepted by 50 percent of the vehicles. The minimum size gap is virtually never accepted while the maximum gap size is not rejected.

There is considerable variation in the size of acceptable gaps indicated on Table 52. Some studies found it appropriate to lump together gap acceptance criteria for various movements; others showed that small differences between movement types exist. For purposes of this study it was determined to use a single gap acceptance function for all decisions of motor vehicles to accept gaps in motor vehicle traffic. The function used is presented on Figure 19.

Table 52
MOTOR VEHICLE GAP ACCEPTANCE CRITERIA

Researcher	Reference	Conditions	Minimum Gap* (5% level)	Critical Gap* (50% level)	Maximum Gap* (95% level)
Kell	1	Right turn - 36 foot crossing	2.9	5.4	9.9
		Through - 36 foot crossing	3.2	5.7	11.0
		Left turn - 36 foot crossing	3.5	6.3	12.5
Road Research Laboratory	2	Right turn onto major road	-	4.6	-
		Through major road	-	5.5	-
		Left turn onto major road	-	6.5	-
Ashworth - Green	3	Cross 6 lanes	-	6.5	12.0
Raff	4	All movements - 34 foot crossing	-	4.6	-
		All movements - 34 foot crossing	-	4.7	-
		All movements - 41 foot crossing	-	5.9	-
		All movements - 63 foot crossing	-	6.0	-
Surti	5	Right turn - 36 foot crossing	-	4.0	-
		Right turn - 50 foot crossing	-	5.5	-
		Right turn - 56 foot crossing	-	5.7	-
		Right turn - 60 foot crossing	-	5.5	-
		Left or through - 32 foot crossing	-	5.6	-
		Left or through - 50 foot crossing	-	7.0	-
		Left or through - 56 foot crossing	-	7.2	-
		Left or through - 60 foot crossing	-	7.0	-
Solberg-Oppenlander	6	Right turn onto two lane road	4.23	7.36	12.9
		Left turn onto two lane road	4.49	7.82	12.9
		Through two lane road	4.19	7.18	12.9

*Gap size in seconds.

1. Kell, J.H., "Analyzing Vehicular Delay at Intersections Through Simulation," Highway Research Bulletin #356, pp. 38-39.

2&3. Ashworth, R. and Green, B.D., "Gap ACceptance of an Uncontrolled Intersection," Traffic Engineering and Control, 1965-1966, No. 7, pp. 676-678.

4. Raff, Morton S., A Volume Warrant for Urban Stop Signs, The Eno Foundation for Highway Traffic Control, 1950.

5. Surti, Vasant H., "Operational Efficiency Evaluation of Selected At-Grade Intersections," Catholic University of America, Department of Civil Engineering and Mechanics, Unpublished Report, December 1969.

6. Solberg, P. and Oppenlander, J.C., op cit.

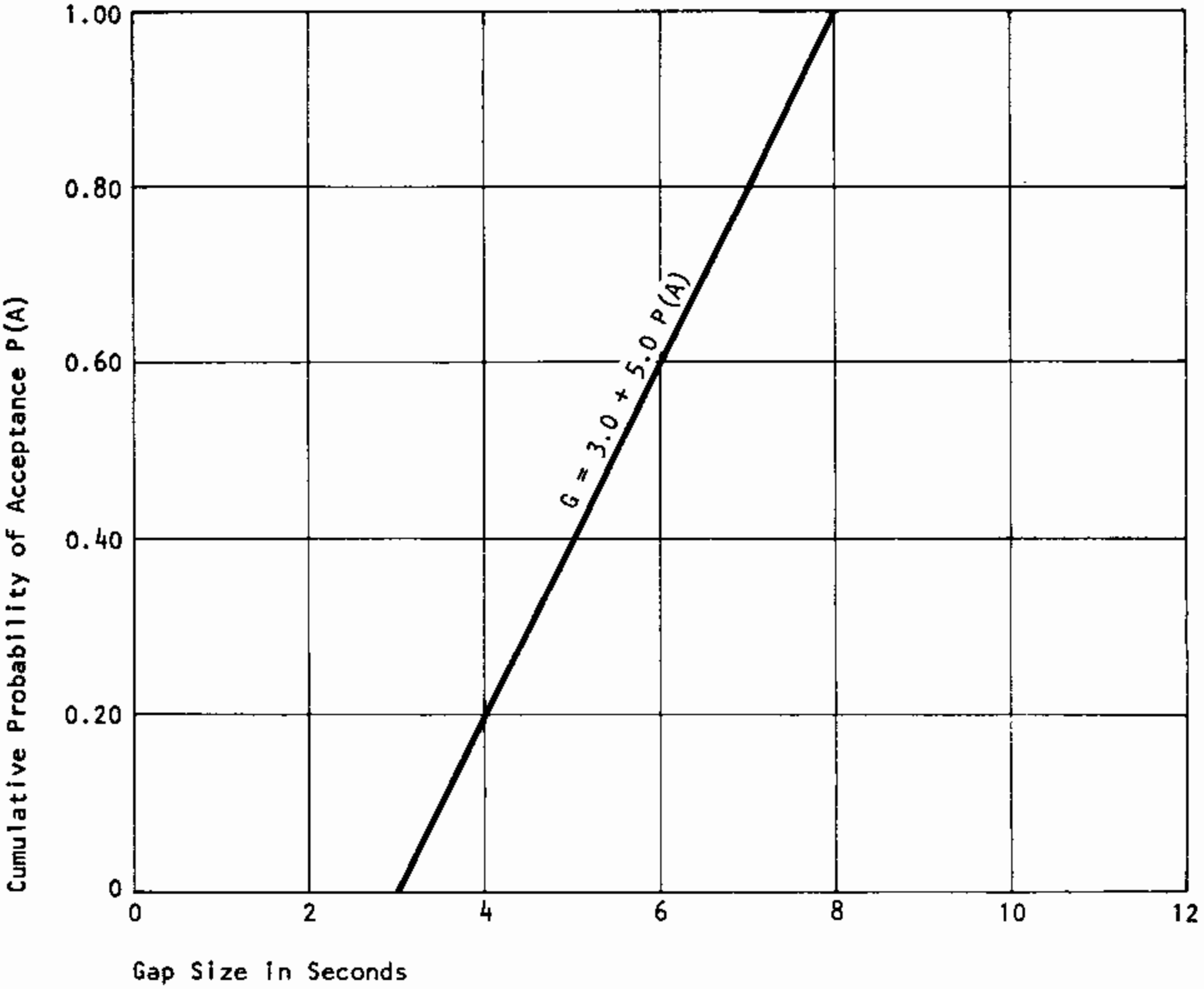


Figure 19
GAP ACCEPTANCE CRITERIA -
MOTOR VEHICLES IN MOTOR VEHICLE TRAFFIC

In order to model the process of motor vehicles accepting gaps in bicycle traffic, a subject not well covered in the literature, basic data was collected. Three types of movements were studied: Crossing a perpendicular stream of bicycle traffic, turning left through a stream of bicycle traffic approaching from the opposite direction, and turning right through a stream of bicycle traffic moving in the same direction. All of the data was collected at intersections or crossings of two lane streets. Street widths varied between 28 and 34 feet, excluding width allocated to parking. The collected data is presented in Tables 53 through 55. The data presented in the tables was used to develop cumulative probability distribution functions for motor vehicle gap acceptance. Three separate functions were used in the models. Straight line linear regression was used to develop the functions with gap size, G, taken as the dependent variable, and the probability of gap acceptance, P(A), applied as the independent variable. All three functions took the form of the equation below. The statistics for each equation are presented in Table 56.

$$G = a + b\ P(A)$$

In the model, a random number between zero and one is drawn from a uniform distribution to determine the minimum acceptable gap for each vehicle. This random number represents the cumulative probability of gap acceptance. Using this probability, a minimum acceptable gap size for the particular vehicle may be determined by application of the above equation.

The final input to the model is the willingness of cyclists to accept gaps in motor vehicle traffic. Two situations were investigated in the field, one involving moving bicycles and the other stopped bicycles. In both situations the decision of cyclists to accept a gap and proceed through motor vehicle traffic was investigated. The motor vehicles were moving at right angles to the intended bicycle movement and occupied two 14-foot lanes. Collected data is presented in Tables 57 and 58. This data was treated as was the data for motor vehicles accepting gaps in bicycle traffic. The linear regression equations developed are presented in Table 59 and have the same form as the previous equation.

$$G = a + b\ P(A)$$

The data showed that there was very little difference in the gap acceptance between moving bicycles and stopped bicycles. In collecting the data, it was difficult to distinguish between stopped and moving bicycles since bicyclists rarely come to a true stop. Because a fine line had to be drawn between stopped and moving bicycles, this data was aggregated for use in the simulation model. A simple linear regression was executed and the results for the combined data are also shown on Table 59. Comparison of the regression to actual data is shown on Figure 20.

Table 53

GAP ACCEPTANCE BY MOTOR VEHICLES IN BICYCLE TRAFFIC - MOTOR VEHICLE FROM STOP CROSSING BICYCLE TRAFFIC MOVING PERPENDICULAR TO MOTOR VEHICLE MOVEMENT

Gap Size In Seconds	Number of Gaps Accepted	Rejected	% Accepted
0.0-1.0	0	18	0
1.0-1.5	3	22	12
1.5-2.0	7	23	23
2.0-2.5	11	28	28
2.5-3.0	11	20	36
3.0-3.5	15	16	48
3.5-4.0	17	8	68
4.0-4.5	21	13	62
4.5-5.0	22	6	79
5.0-5.5	19	2	91
5.5-6.0	13	3	81
6.0-6.5	9	3	75
6.5 and above	46+	0	100

Table 54

GAP ACCEPTANCE BY MOTOR VEHICLES IN BICYCLE TRAFFIC - MOTOR VEHICLE TURNING LEFT THROUGH BICYCLE TRAFFIC APPROACHING FROM THE OPPOSITE DIRECTION

Gap Size In Seconds	Number of Gaps Accepted	Rejected	% Accepted
0.0-1.0	3	22	12
1.0-1.5	6	41	13
1.5-2.0	15	39	28
2.0-2.5	19	35	35
2.5-3.0	27	17	61
3.0-3.5	30	5	86
3.5-4.0	21	3	87
4.0-5.0	42	4	87
5.0-5.5	15	2	89
5.5 and above	47+	0	100

+Indicates that acceptance of large gaps was not noted on the data sheet.

Table 55
GAP ACCEPTANCE BY MOTOR VEHICLES IN BICYCLE TRAFFIC - MOTOR VEHICLE TURNING RIGHT THROUGH BICYCLE TRAFFIC MOVING IN THE SAME APPROACH

Gap Size In Seconds	Number of Gaps Accepted	Rejected	% Accepted
0.0-1.0	4	17	19
1.0-1.5	7	15	32
1.5-2.0	5	12	29
2.0-2.5	13	9	59
2.5-3.0	17	5	77
3.0-3.5	18	5	78
3.5-4.0	18	2	90
4.0 and above	102+	0	100

Table 56
GAP ACCEPTANCE BY MOTOR VEHICLES IN BICYCLE TRAFFIC

	Motor Vehicles Through	Motor Vehicles Turning Left	Motor Vehicles Turning Right
Constant "a"	0.68	0.33	0.07
Constant "b"	5.67	4.60	3.92
Coefficient of Correlation R	0.96	0.94	0.97
Standard Error of Estimate-Seconds	0.55	0.61	0.31

Table 57
GAP ACCEPTANCE BY BICYCLES IN MOTOR VEHICLE TRAFFIC - BICYCLES MOVING AND CROSSING MOTOR VEHICLE TRAFFIC

Gap Size In Seconds	Number of Gaps Accepted	Rejected	% Accepted
0.0-2.0	0	38	0
2.0-2.5	3	28	10
2.5-3.0	6	19	22
3.0-3.5	11	34	24
3.5-4.0	17	16	52
4.0-4.5	19	23	44
4.5-5.0	19	11	63
5.0-5.5	15	3	83
5.5-6.5	18	2	90
6.5 and above	60+	0	100

Table 58
GAP ACCEPTANCE BY BICYCLES IN MOTOR VEHICLE TRAFFIC - BICYCLES CROSSING MOTOR VEHICLE TRAFFIC FROM STOP

Gap Size In Seconds	Number of Gaps Accepted	Rejected	% Accepted
0.0-2.5	0	72	0
2.5-3.0	2	21	9
3.0-3.5	7	22	24
3.5-4.0	8	7	53
4.0-4.5	5	9	36
4.5-5.0	7	5	58
5.0-7.5	35	8	76
7.5 and above	10+	0	100

+Indicates that acceptance of large gaps was not recorded on data sheet.

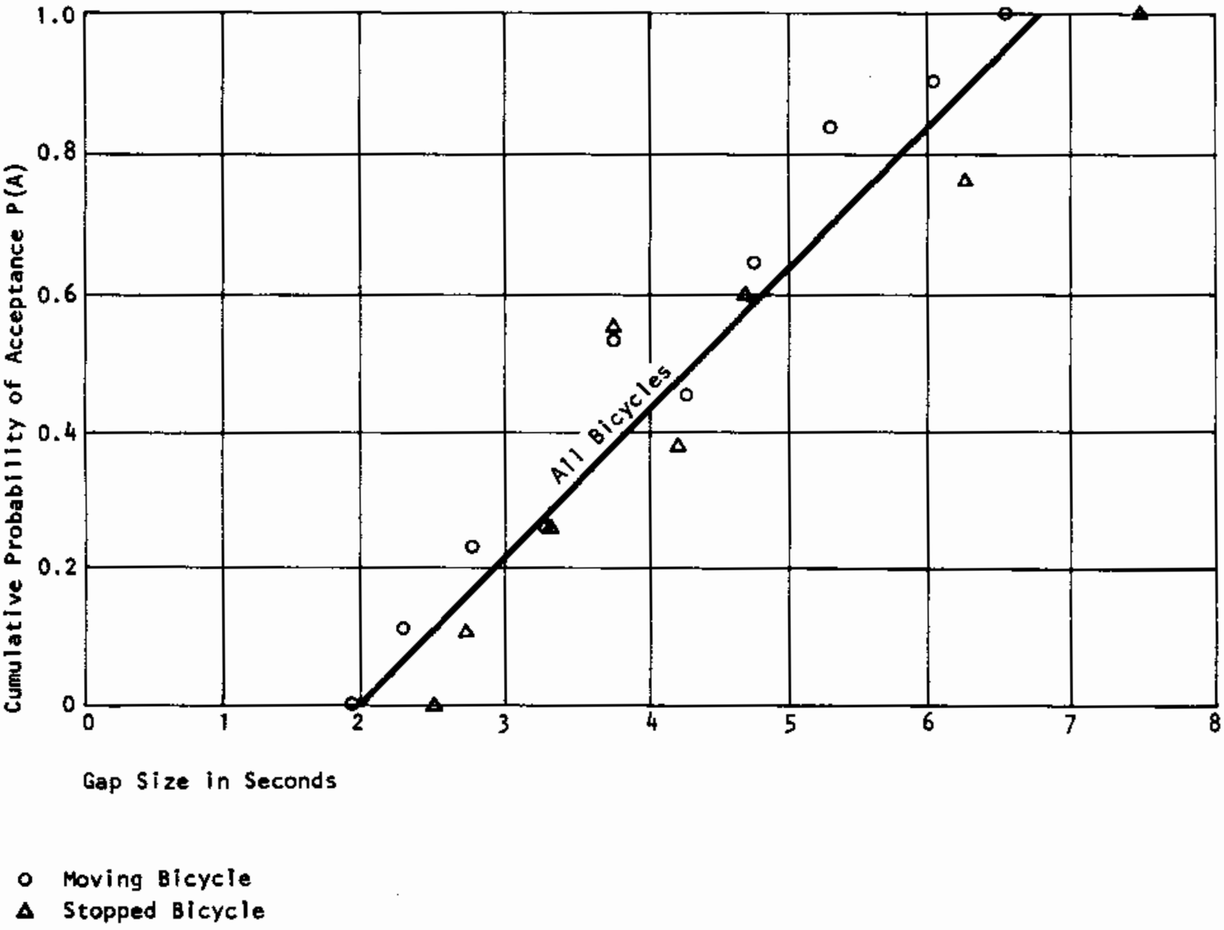


Figure 20
GAP ACCEPTANCE CRITERIA - BICYCLES IN MOTOR VEHICLE TRAFFIC

Table 59
GAP ACCEPTANCE BY BICYCLES IN MOTOR VEHICLE TRAFFIC

	Bicycles Moving	Bicycles From Stop	Moving and From Stop
Constant "a"	1.94	2.18	2.06
Constant "b"	4.38	4.93	4.65
Coefficient of Correlation R	0.98	0.96	0.96
Standard Error of Estimate - σ_G Seconds	0.28	0.52	0.52

In reality it is often necessary for a motor vehicle or bicycle to accept a gap in several conflicting traffic streams composed of both bicycles and motor vehicles. Special gap acceptance functions are developed by the model for this purpose. These functions are based upon the proportion of bicycles and motor vehicles in the traffic streams to be crossed. The following example is provided to explain the procedure. A motor vehicle on the main street wishes to make a left turn. A suitable gap is required in the motor vehicle and bicycle traffic approaching from the opposite direction. The model first computes the proportion of this traffic which is bicycles and the proportion which is motor vehicles. Then a gap acceptance function is computed proportionately from the gap acceptance functions previously presented. Previously determined gap acceptance functions for motor vehicles turning left through bicycle traffic and motor vehicles crossing motor vehicle traffic area, respectively:

$$G = 0.33 + 4.60\ P(A)$$

$$G = 3.0 + 5.0\ P(A)$$

If bicycle traffic is 40 percent of the total and the motor vehicles comprise the remainder, then the composite gap acceptance function would be given by 40 percent of the first equation and 60 percent of the second or:

$$G = 1.93 + 4.84\ P(A)$$

For each potential movement and motor vehicle and bicycle volume level, composite gap acceptance equations would be similarly computed.

Although this proportional method of estimating the combined gap acceptance probability is a simplification of the actual joint probability condition which occurs, it provides satisfactory accuracy at the low proportions of bicycle to motor vehicle traffic normally encountered.

Signalized Intersection Simulation Model

A comparable simulation model for signalized intersections was also developed. The model simulates a one hour operation of an intersection controlled by a two-cycle, fixed-time signal. Basic assumptions are:

- Through bicycles and motor vehicles are served on the green at uniform rates.
- Right turning bicycles proceed without delay unless the queue of bicycles making other movements exceeds six. Then the right turning bicycle is served as is a through bicycle.
- Left turning bicycles are served after motor vehicle queues on the same street are cleared. Once the queues are cleared, left turning bicycles must accept gaps in adjacent and opposite motor vehicle streams.
- Left turning motor vehicles wait for vehicles queued in the opposite approach to clear and then accept a gap in the combined opposed stream of bicycles and motor vehicles.

The model calculates a queue length for opposing vehicle flows at the beginning of a green phase based upon the Poisson distribution, the specified flow rate and a pseudo-random number. If a queue exists when a motor vehicle arrives, it must wait until the queue is served before proceeding. If the motor vehicle is executing a left turn, it must wait an additional service time while opposing queues are served. Once opposing queues are served, the turning vehicle is allowed to proceed when there is an acceptable gap in opposing traffic. Gap acceptance criteria applied are identical to those described previously in connection with the sign-controlled intersection model. Should the delay to the earliest time a vehicle can be served exceed the cycle length, the vehicle is delayed into the subsequent cycle.

Critical parameters in determining motor vehicle delay are the signal settings, demands of other motor vehicles on the same approach and the service rate to motor vehicles. The first two parameters are inputs to the model; the third is determined by the individual vehicle's position in the queue. Table 60 presents two sets of data on service rates of motor vehicles in queue. For the model application, service times of 2.7 seconds for the first vehicle, 2.5 seconds for the second vehicle and an additional two seconds for each subsequent queued vehicle were selected.

Table 60
SUMMARY - MOTOR VEHICLE HEADWAYS

	Bicycles Occupy Adjacent Bicycle Lane, No Motor Vehicles Turn		
Item	Green to 1st Motor Vehicle	1st Motor Vehicle to 2nd Motor Vehicle	2nd Motor Vehicle to 3rd Motor Vehicle
n (number)	62	37	19
$\bar{x}$ (mean)	2.79	2.49	2.29
σ^2 (variance)	0.48	0.38	0.36
$S_{\bar{x}}$ (standard deviation)	0.09	0.10	0.14
	Motor Vehicles in Centerline of Three Lane Approach to Signalized Intersection		
	Green to 1st Motor Vehicle	1st Motor Vehicle to 2nd Motor Vehicle	2nd Motor Vehicle to 3rd Motor Vehicle
n	371	347	352
$\bar{x}$	2.72	2.52	2.05
σ^2	0.49	0.42	0.26
$S_{\bar{x}}$	0.04	0.03	0.03

Bicycles are treated quite similarly to motor vehicles in the model. One difference is that if the bicycle intends to turn right and the queue ahead of it numbers less than six bicycles, the right turning bicycle is assumed to proceed without delay. If the queue of other bicycles is six or greater, the path of the right turning bicycle is assumed blocked and it must wait until that queue dissipates to proceed. Turning bicycles waiting to proceed are not assumed to inhibit the flow of other bicycles.

In the model, a headway of 0.67 seconds was used for service to bicycles. This value was based on considerable research on saturation bicycle flows on urban streets. A brief summary of that research follows. But before moving to that discussion, a brief summary of the model inputs and outputs is in order.

Model Inputs and Outputs

Model input variables consist of cycle time, green time for the side street, traffic volumes on each approach, and the proportion of vehicles turning in each direction.

Output for each hour of simulation time includes:

- Traffic flows occurring in the conflicting approaches to the simulated approach.
- Service time functions developed by the model to generate times within a cycle when turning vehicles can be served.
- Cycle times and green times along with the traffic flows in each approach.
- Proportion of vehicles turning left or right in the simulated approach.
- Delay performance data.

Maximum number of vehicles served before a simulated vehicle is output as an estimate of the maximum queue length occurring in the approach during the simulated hour. Actual queue length could not be measured because of the structure of the model. Had a time interval oriented simulation been done, queues could be determined at regular intervals and a queue length distribution presented.

Saturation Flow Measurement

In order to develop data on saturation bicycle flow rates, an experiment was carried out utilizing a full-scale model of a street with a bike lane approaching a signalized intersection. Figure 21 is a sketch of the test site. Parked motor vehicles were used to represent both parked and moving cars. Eighteen volunteer cyclists, all adults, nine males, nine females, were instructed to ride at a speed at which they would normally ride on urban streets and to treat the signal as they would one at a real urban intersection.

A one minute signal cycle was used to control the simulated traffic. Green was displayed to the moving bicycles for 30 seconds, amber for four seconds, and red for 26 seconds of each signal cycle. The trip time for the cyclists to return to the intersection after passing through it was approximately 40 seconds. Thus, cyclists were bunched at the intersection each time the signal turned green. A strip chart recorder with two event markers was used to record the traffic flow, one pen to indicate the time at which the signal changed phases, the other to indicate the event of a bicycle completing a pass through the intersection.

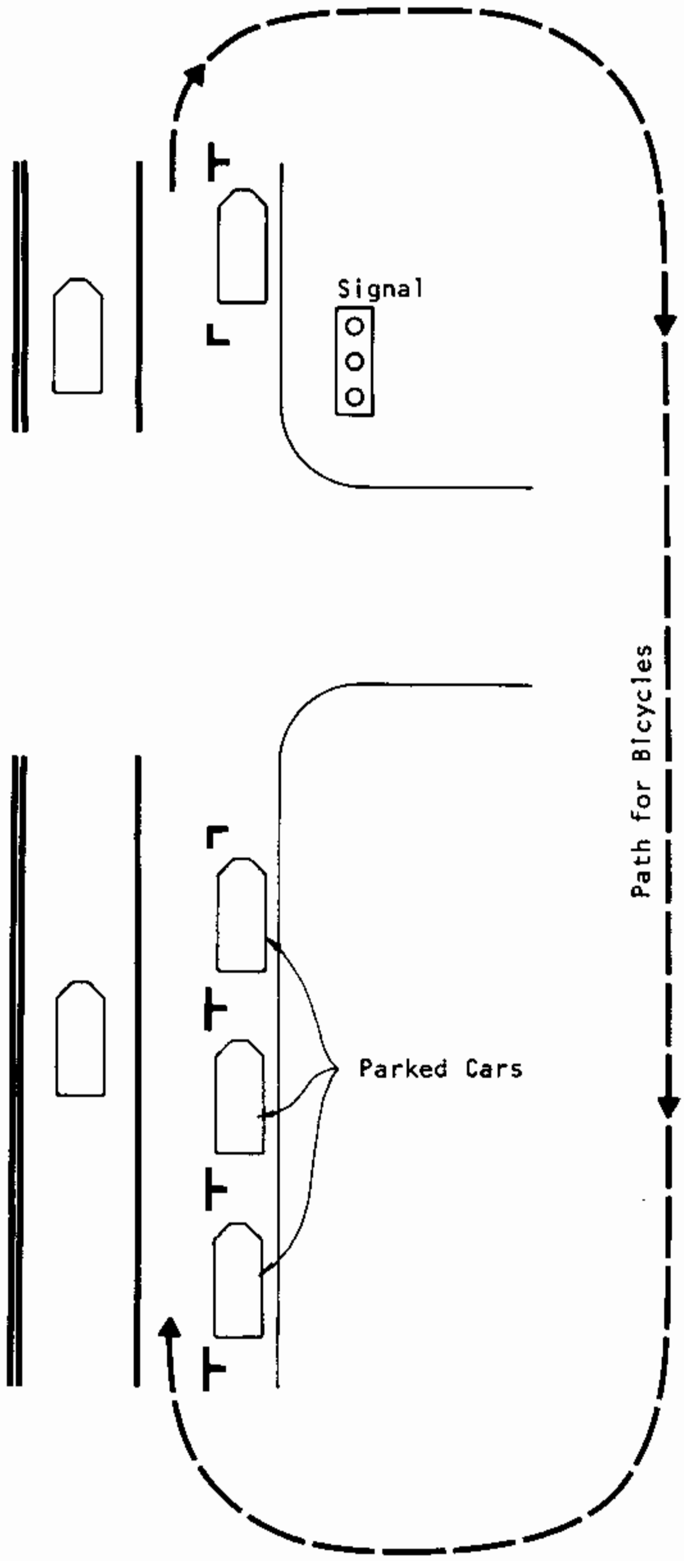


Figure 21
SCHEMATIC OF SATURATION FLOW RATE EXPERIMENT

The experiment was repeated for three different bicycle lane widths: Eleven signal cycles at four foot lane widths, nine at six foot widths, and fourteen at eight foot widths.

From the strip chart, bicyclist headways after the beginning of each green phase were calculated. This data is presented on Table 61. To determine saturation flow rate, the number of headways was divided by the measured time interval between the first and last bicycle served from the queue. Mean saturation flow rate, standard deviation and standard deviation of the mean for each lane width are also shown on Table 61.

Mean saturation flow rates were used in a linear regression analysis to determine a saturation flow rate as a function of lane width. The resulting equation is:

$$y = 0.25 + 0.15\,x \qquad r^2 = 0.99$$

$$(0.07)\ (0.01)$$

where y represents the saturation flow rate in bicycles per second, and x is the lane width in feet for the range four to eight feet. Standard errors of the regression coefficients are shown below the equation.

The standard errors of the coefficients are shown in parameters below them. The high correlation coefficient (r^2) and low standard errors of the coefficients demonstrate that the equation is an excellent representation of the data. However, the fit is to only three data points representing the mean saturation flow rate observed in the field simulation experiment at the three widths tested.

Field Validation

The above experiment was necessary because it was difficult to find existing bicycle lanes of different widths with sufficiently high bicycle flows to measure saturation levels. One location was selected in Davis, California, where conditions were felt to be comparable to the mock bicycle intersection. To validate the experiment, a data sample comparable to the six foot lane simulation data was taken and is presented in Table 62. The mean saturation flow from the field is higher (1.34 vs. 1.15) bicycles/second than the one obtained from the experiment. The standard deviation measured in the field was also considerably larger.

It is believed that these differences are explained by the fact that the real bicyclists observed had more motivation to travel than the experiment subjects and hence were inclined to travel faster, pass, weave and travel in tight groups.

Model Verification

To validate the intersection simulation models, a comparison of travel time as predicted by the model to the measured travel time of vehicles

Table 61
DATA FROM EXPERIMENT TO DETERMINE SATURATION FLOW OF BICYCLE LANE

Cycle #	4-Foot Width			6-Foot Width			8-Foot Width		
	n-1	t	(n-1)/t	n-1	t	(n-1)/t	n-1	t	(n-1)/t
1	7	9.2	0.76	9	7.9	1.14	8	4.7	1.70
2	7	10.6	0.66	12	8.6	1.40	11	8.1	1.36
3	10	14.3	0.70	13	12.1	1.07	8	5.5	1.45
4	8	9.4	0.85	12	9.4	1.28	10	7.8	1.28
5	7	11.4	0.61	12	10.8	1.11	11	7.5	1.47
6	11	14.3	0.77	11	10.2	1.08	8	6.5	1.23
7	13	12.8	1.02	11	10.0	1.10	8	6.2	1.29
8	13	17.0	0.76	12	10.6	1.13	6	4.1	1.46
9	9	11.1	0.81	13	12.2	1.07	6	4.3	1.40
10	11	8.4	1.31				8	4.7	1.70
11	8	9.8	0.82				6	4.2	1.43
12							8	5.6	1.23
13							10	8.2	1.22
14							9	7.6	1.18
Mean	9.45	11.66	0.82	11.67	10.20	1.15	8.36	6.07	1.40
Standard Deviation			0.19			0.11			0.16
Standard Error of Mean			0.06			0.04			0.04

Table 62

SATURATION RATE - BICYCLES LEAVING INTERSECTION*

Number of Bicycles: n	Time Between 1st + Last: t		Saturation Rate (n-1)/t
6	4.0		1.25
7	6.9		0.86
4	3.7		0.81
4	3.5		0.85
4	2.1		1.42
5	2.7		1.48
10	5.8		1.55
7	4.7		1.27
14	10.8		1.20
11	5.3		1.88
10	5.0		1.80
5	3.0		1.33
4	1.8		1.66
		n	13
		$\bar{x}$	1.34
		σ_x	0.35
		$\sigma_{\bar{x}}$	0.10

*No conflicting right turning motor vehicles; bicycle lane width: six feet.

moving through intersections in the field was made. Travel time was chosen for validation as it could be more precisely measured in the field than could delay.

For each type of intersection control condition modeled, travel times of bicycles and motor vehicles proceeding through intersections were measured while concurrent traffic flow and turning movement counts were being made. The individual travel times for vehicles of each type (bicycle or motor vehicle) in one approach were measured by use of a two channel strip chart recorder. Data for each control condition along with statistics on mean travel times, the sample size, and the variance of the sampled distribution are presented in Tables 63 through 67.

Some special adjustment was necessary to the field data collected on bicycle travel times approaching traffic signals. The observation distances were not sufficiently large such that all the delay to the bicycles could be observed since bicyclists decrease their speed when they observe a red indication on a traffic signal as far as one block in advance of the intersection. Thus a time increment was added to the field travel times such that they reflect all delay to bicycles. The adjustment is based on data presented on Table 68.

The simulation models were run to simulate one hour of traffic for each set of field data. Inputs to the models include the observed field traffic flow rate, signal time split in the case of signalized operation, and the proportions of vehicles turning. Comparison of modeled travel times to field measured travel times and delay predicted by the model are also presented in Tables 63 through 67.

Figure 22 illustrates the comparison of field to modeled travel time for bicycles. Statistical analysis of these results indicates the models may be slightly underestimating travel time, hence delay, for bicycle traffic.

Figure 23 illustrates the comparison of field to modeled time for motor vehicles. Statistical analysis indicates the models reliably predict travel time, hence delay, for motor vehicle traffic.

In general, the models are representative in predicting vehicle delay and may be used to obtain an understanding of intersection performance under different mixes of bicycle and motor vehicle traffic, under the influences of various intersection control devices and to develop warrants for installing various intersection control devices.

Warrants for Traffic Control at Intersections

The model described above was exercised to estimate performance under various control options and at different bicycle and motor vehicle traffic levels at two types of intersections:

Table 63
BICYCLES AT STOP SIGNS - VALIDATION DATA

Test #	1	2	3	4	5
Location: Davis, California	8th & "A"	8th & "A"	8th & "A"	4th & "F"	4th & "F"
Date:	4/25/75	4/25/75	4/25/75	4/29/75	4/29/75
Time of Field Study:	4:40-5:00^{p}	5:00-5:20^{p}	5:20-5:40^{p}	7:40-8:20^{a}	8:35-9:05^{a}
Hourly Traffic Volumes					
Bicycles on Side Approach (test flow)	120	177	129	76	62
Motor Vehicles on Same Approach	117	117	81	45	44
Bicycles on Main Street (mean on each approach)	63	114	67	20	30
Motor Vehicles on Main Street (mean each approach)	298	364	334	124	163
Distance Through Intersection (feet)	150	150	150	130	130
Mean Field Travel Time (seconds)	9.51	12.69	12.89	11.91	10.99
Variance	11.8	42.3	12.9	22.9	23.4
Sample Size	40	61	44	48	34
Mean Modeled Delay Time (seconds)	0.96	1.53	1.64	1.18	1.45
Variance	2.2	6.5	12.0	3.4	5.5
Sample Size	105	190	136	83	67
Mean Undelayed Travel Time (seconds)	9.65	9.65	9.65	8.35	8.35
Modeled Travel Time (seconds)	10.61	11.18	11.29	9.53	9.80

Table 64
BICYCLES AT YIELD SIGNS - VALIDATION DATA

Test #	1	2	3	4
Location: A Bicycle Crossing Between Briggs & Stoner Halls, University of California, Davis				
Date:	4/21/75	4/21/75	4/22/75	4/22/75
Time of Field Study:	7:40-7:55[a]	7:56-8:11[a]	7:40-7:55[a]	7:56-8:11[a]
Hourly Traffic Volumes				
Bicycles on Side Approach (test flow)	480	556	598	340
Motor Vehicles on Same Approach	0	0	0	0
Bicycles on Main Street (mean each approach)	0	0	0	0
Motor Vehicles on Main (mean each approaches)	102	142	118	142
Distance Through Intersection (feet)	150	150	150	150
Mean Field Travel Time (seconds)	12.09	11.33	10.57	11.16
Variance	9.8	9.0	7.8	12.2
Sample Size	121	137	132	82
Mean Modeled Delay Time (seconds)	1.23	2.50	0.95	0.98
Variance	13.4	9.6	5.2	8.2
Sample Size	486	544	598	325
Mean Undelayed Travel Time (seconds)	9.65	9.65	9.65	9.65
Modeled Travel Time (seconds)	10.88	12.15	10.60	10.63

Table 65
BICYCLES AT SIGNALIZED INTERSECTIONS

Test #	1	2	3	4	5	6	7	8
Location: 3rd & "F" Davis, Direction:	W	W	W	W	E	E	S	S
Date:	4/1/75	4/1/75	4/1/75	4/1/75	4/3/75	4/3/75	4/25/75	4/25/75
Time of Field Study	8:30-45	8:45-9:00	9:15-30	9:30-45	5:00-5:30	5:30-6:00	7:45-9:00	9:00-10:00
Cycle Time (seconds)	60	60	60	60	60	60	60	60
Green Time to Bicycles	21	21	21	21	21	21	33	33
Hourly Traffic Volumes								
Simulated Approach Bikes	212	476	148	112	318	170	40	18
MVs	104	188	120	176	234	122	166	171
Opposite Approach Bikes	16	36	40	60	28	32	0	0
MVs	72	76	84	128	228	190	61	83
Approach to Left Bikes	8	4	0	8	12	14	313	138
MVs	68	64	48	68	262	170	124	164
Approach to Right Bikes	44	36	40	20	16	32	0	43
MVs	200	156	212	156	308	218	56	96
Distance Thru Intersection(ft)	95	95	95	95	120	120	165	165
Mean Field Travel Time (secs)	18.91	23.33	14.96	22.20	20.35	20.34	11.47	12.89
Variance	164	186	98	140	127	164	6.2	33.8
Sample Size	55	121	37	28	159	85	38	16
Mean Modeled Delay Time(secs)	11.88	14.36	12.44	12.06	12.16	12.50	0.66	1.60
Variance	168	169	158	174	167	180	95	94
Sample Size	212	476	148	122	318	170	40	18
Mean Undelayed Travel Time(secs)	5.40	5.40	5.40	5.40	6.81	6.81	9.37	9.37
Modeled Travel Time (secs)	17.28	19.76	17.84	17.46	18.97	19.31	10.03	10.97

Table 66
MOTOR VEHICLES AT STOP SIGNS

Test #	1	2	3	4	5	6	7
Location:	8th & Sycamore, Davis, California				28th & "K", Sacramento, California		
Date:	4/7/75	4/7/75	4/7/75	4/7/75	4/15/75	4/15/75	4/15/75
Time of Field Study	7:30-8:00	8:00-8:30	4:30-5:00	5:00-5:30	2:45-3:00	3:04-3:34	3:35-3:50
Hourly Traffic Volumes							
Motor Vehicles on Side (test flow)	36	40	84	104	196	130	192
Bicycles on Same Approach	72	6	22	14	0	4	0
MVs on Main Street (mean on each approach)	108	66	141	166	380	361	376
Bicycles on Main Street (mean on each approach)	46	21	47	43	4	13	16
Distance Through Intersection (feet)	270	270	300	300	375	375	375
Mean Field Travel Time (seconds)	19.43	15.47	16.06	16.82	29.66	27.95	38.11
Variance	47	7.4	13	21	179	146	206
Sample Size	18	20	42	52	48	68	48
Mean Modeled Delay Time (seconds)	7.96	8.31	9.17	8.60	15.86	28.65	15.52
Variance	0.5	2.2	14.3	4.2	237	1395	143
Sample Size	39	36	74	106	202	131	182
Mean Undelayed Travel Time (seconds)	7.37	7.37	8.17	8.17	10.50	10.50	10.50
Modeled Travel Time (seconds)	15.33	15.68	17.34	16.77	26.36	39.15	26.02

Table 67
MOTOR VEHICLES AT SIGNLAIZED INTERSECTIONS

Test #	1	2	3	4	5	6	7	8	9	10	11
Location: 3rd & "F" Davis, Direction:	N	N	S	S	W	W	W	W	E	E	E
Date:	4/1/75	4/1/75	4/3/75	4/3/75	4/24/75	4/24/75	4/24/75	4/24/75	4/24/75	4/24/75	4/24/75
Time of Field Data:	4:45-5:15	5:15-5:45	8:30-9:00	9:00-9:30	8:00-8:30	8:30-9:00	9:15-9:45	9:45-10:15	4:45-5:00	5:02-5:17	5:20-5:35
Cycle Time	60	60	60	60	60	60	60	60	60	60	60
Green Time to Motor Vehicles	33	33	33	33	21	21	21	21	21	21	21
Hourly Traffic Volumes											
Simulated Approach MVs	326	236	74	76	98	146	104	156	236	224	200
Bikes	40	18	2	4	96	290	90	98	196	312	232
Opposite Approach MVs	296	258	136	190	34	34	80	130	204	204	212
Bikes	22	14	44	24	0	26	32	60	56	16	28
Approach to Left MVs	220	196	42	64	38	52	80	88	236	204	232
Bikes	350	210	14	38	0	0	0	0	0	0	0
Approach to Right MVs	170	176	130	148	120	154	182	220	220	260	196
Bikes	52	24	334	98	0	20	16	16	24	28	24
Distance Thru Intersection (ft)	300	300	300	300	340	340	340	340	340	340	340
Mean Field Travel Time (secs)	20.50	20.29	15.38	18.23	24.16	26.57	28.56	30.07	26.46	30.90	31.67
Variance	139	111	48	74	149	142	231	196	141	268	383
Sample Size	163	118	38	34	49	72	50	78	57	56	45
Mean Modeled Delay Time (secs)	11.35	11.38	10.19	7.96	18.94	18.57	18.25	19.22	19.01	20.55	20.55
Variance	129	131	122	128	235	188	253	224	200	212	178
Sample Size	326	236	74	76	98	146	104	156	236	224	200
Mean Undelayed Travel Time (secs)	8.17	8.17	8.17	8.17	9.27	9.27	9.27	9.27	9.27	9.27	9.27
Modeled Travel Time (secs)	19.52	19.55	18.36	16.13	28.21	27.84	27.52	28.49	28.28	29.82	29.82

Table 68
BICYCLISTS SPEED AS AFFECTED BY TRAFFIC SIGNAL DISPLAY

Test #	1	2	3
Location:	3rd & "F" Streets - Davis, California		
Date:	5/5/75	5/5/75	5/5/75
Time:	7:40-8:00	8:40-9:00	5:00-5:20
Distance from Stop Line			
Of Beginning Point	225	225	225
Of End Point	50	50	60
Travel Distance	175	175	165
Bicyclist Sees Green At Beginning Point			
Sample Size	47	55	47
Mean Travel Time (seconds)	9.94	10.29	8.99
Variance of Mean	0.28	0.31	0.28
Bicyclist Sees Red or Amber At Beginning Point			
Sample Size	115	78	72
Mean Travel Time (seconds)	12.25	11.62	10.61
Variance of Mean	0.21	0.18	0.26
Mean Speed* on Green (fps)	17.6	17.0	17.8
Mean Speed* on Red (fps)	14.3	15.0	15.1

*Speed computed from mean travel time.

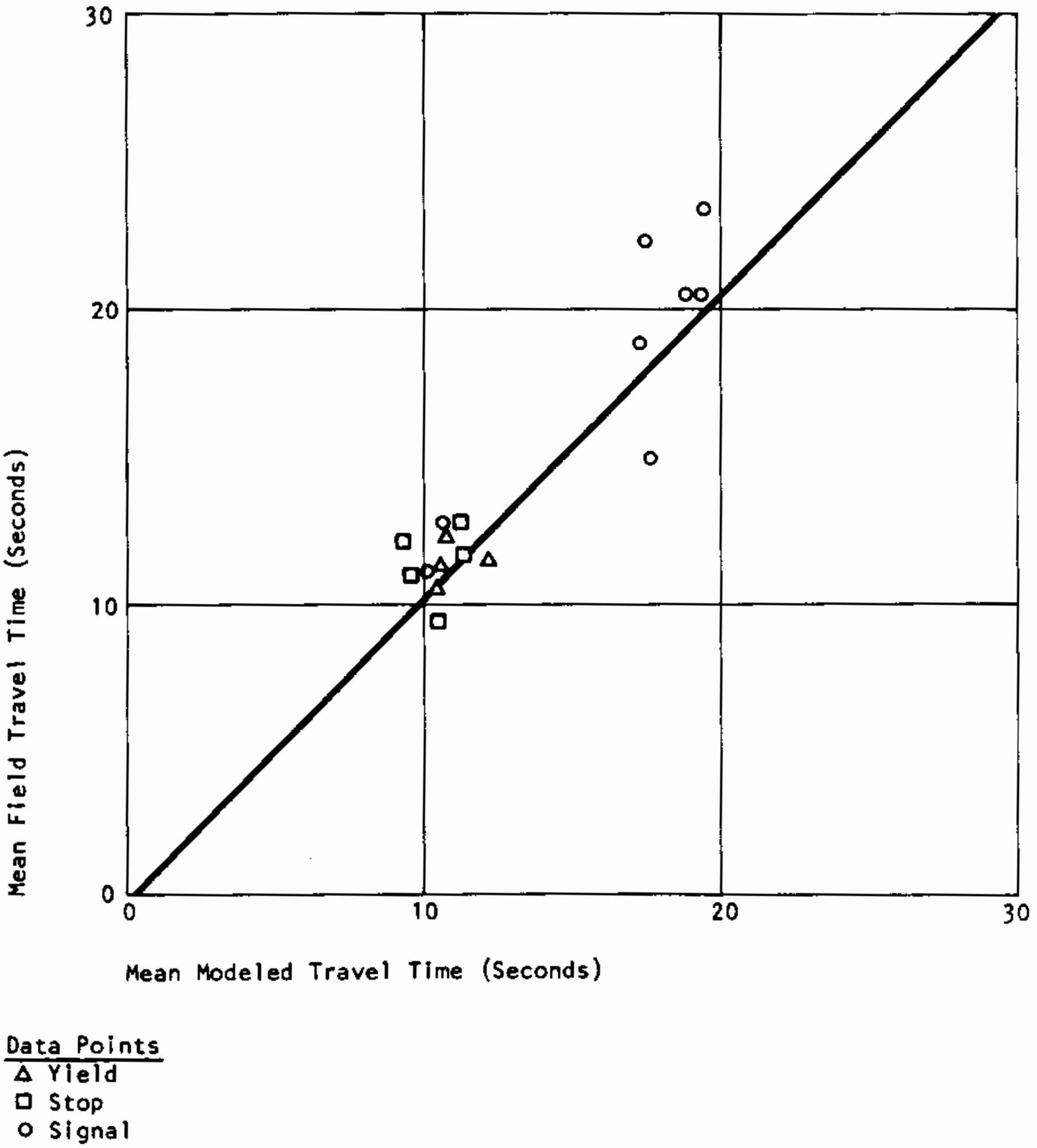


Figure 22
BICYCLE TRAVEL TIMES FIELD-MODEL COMPARISON

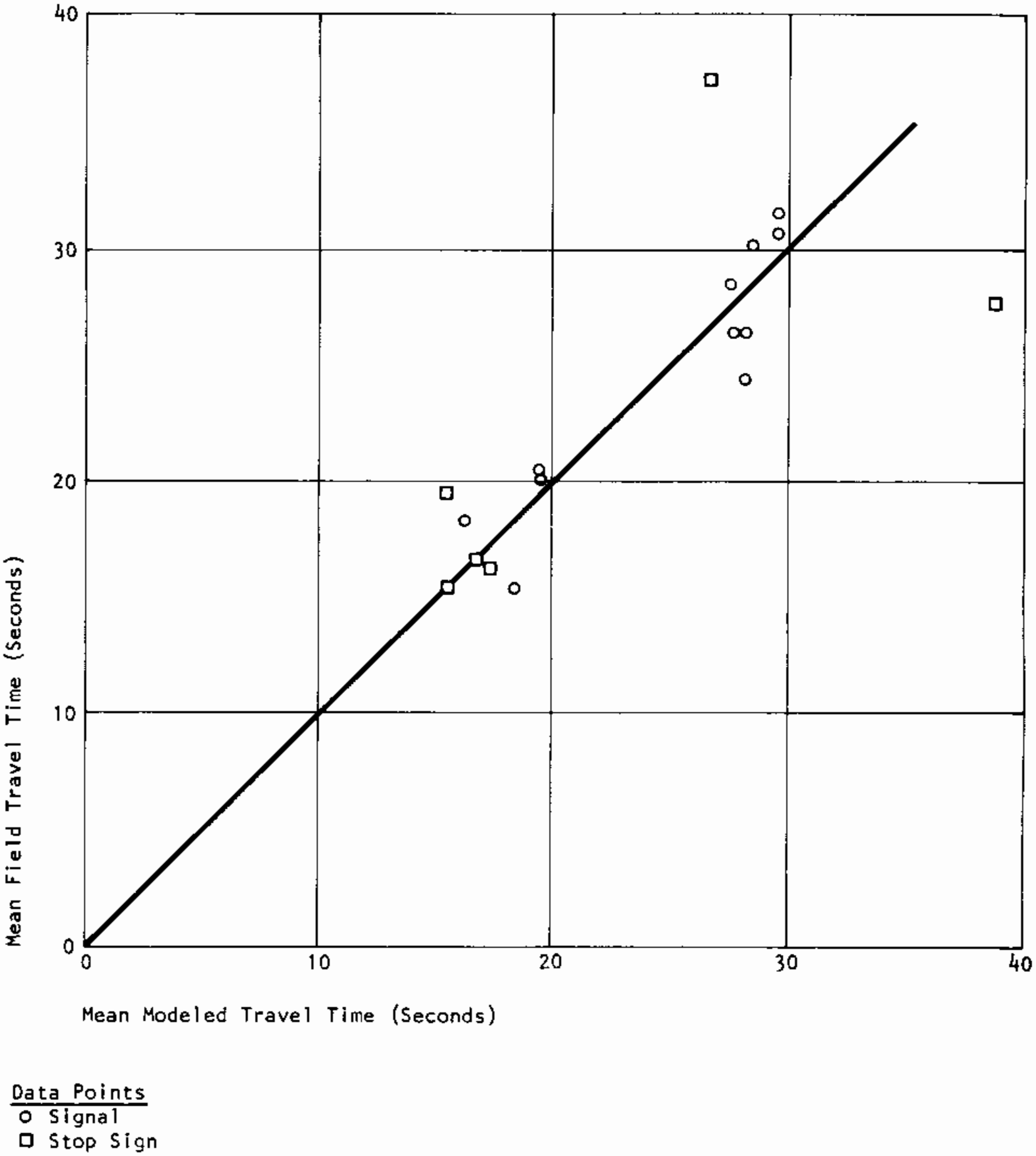


Figure 23
MOTOR VEHICLE TRAVEL TIME COMPARISON : FIELD-MODEL

- The right angled intersection of an exclusive two way bicycle path with a two lane roadway.

- An urban intersection of two laned streets.

For the "bikeway crossing" 128 hours of operation were simulated with motor vehicle flows varied from 50 to 600 vehicles per hour on each roadway approach and bicycle flows varied from 50 to 500 per hour on each bikeway approach. On the basis of comparison of delays indicated by those simulations, the warrants for control of bikeway crossings shown on Figure 24 were developed.

As the simulation model was not structured to evaluate crossings of multi-lane streets, warrants for bikeway crossings of four and six lane streets were drawn from Danish and Netherlands sources. These are indicated on Table 69. Lower volumes warrant signals on multi-lane streets because of the longer safe crossing time required by bicyclists on these wider streets.

Table 69
MULTI-LANE CROSSING SIGNALIZATION WARRANTS

Number of Lanes	Peak Hour Vehicle Volume
4 lanes	800
6 lanes	600

The simulation models were also exercised for a range of traffic mixes for STOP and signalized intersection control for the case of the intersection of two lane streets. Following are warrant recommendations based upon the results of those simulations.

- Stop signs normally provide better service to bicyclists than motor vehicles on the minor approach. Hence, under normal conditions of significantly greater motor vehicle than bicycle traffic on the minor approach, bicycles need not be considered. In an unusual case where bicycle traffic exceeds motor vehicle traffic on the minor street approach (such as on a heavily used minor street bikeway), the intersection can be analyzed as a bikeway crossing according to the warrants previously presented on Figure 24.

- Bicycle traffic on the main street, since it has right-of-way, does contribute to delays of minor street motor vehicles. Hence, bicycles should be counted with motor vehicles in main street traffic; a bicycle to motor vehicle equivalency was computed for this purpose. This was done by comparing mixes of main street bicycle and motor vehicle traffic required to produce the same delay to minor street traffic as is produced by the main street-minor street volume mix given in the existing signal warrant given in the Manual on Uniform

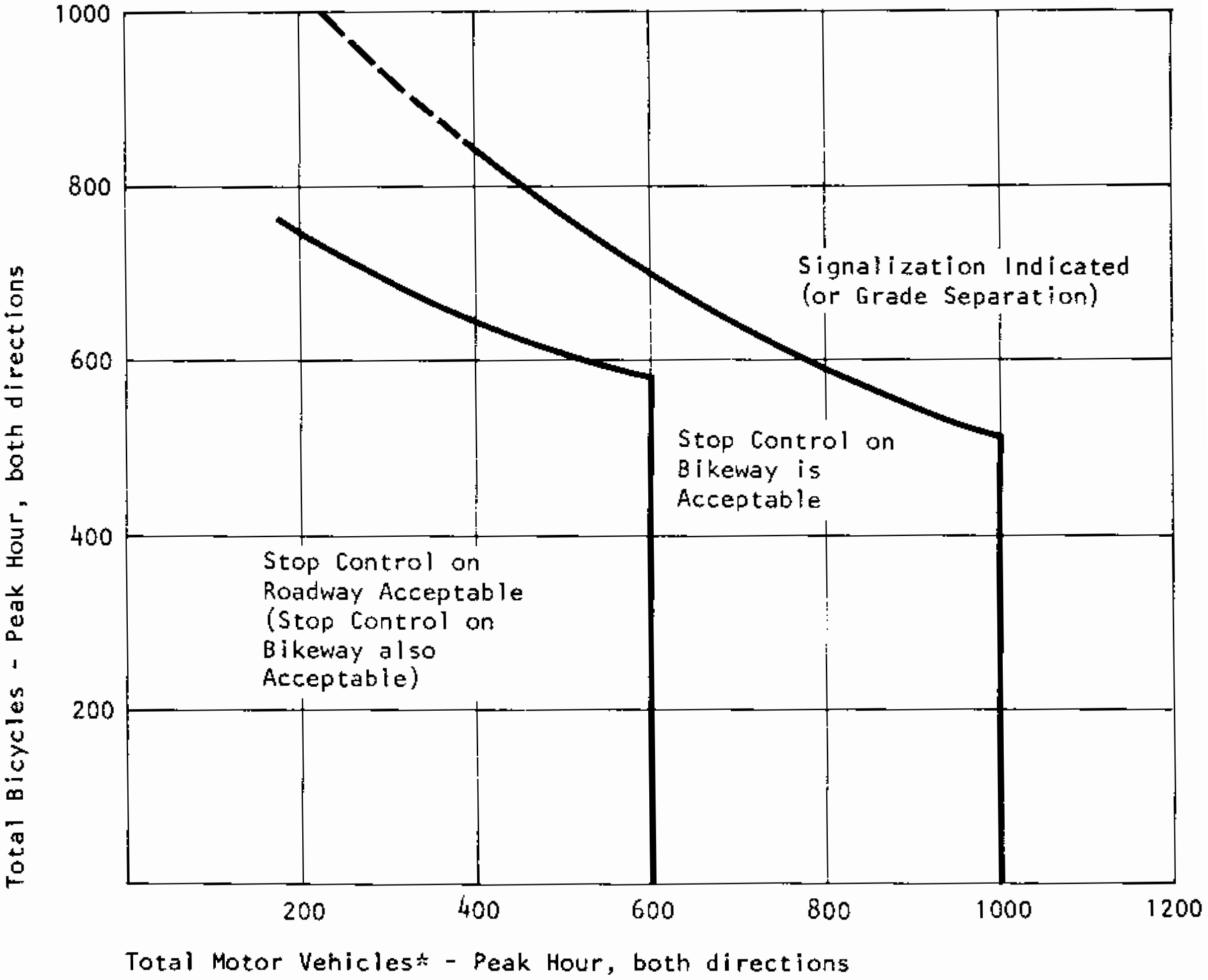


Figure 24
TRAFFIC CONTROL WARRANTS
Independent Bike Path Crossing Two-Lane Roadway

*For stop on bikeway, motor vehicle volume is total in both directions.
For stop on roadway, motor vehicle volume is total in peak direction.

Traffic Control Devices with only motor vehicles considered. Table 70 presents this comparison. A mean value of 0.52 was calculated based upon the number of side street motor vehicles delayed over 30 seconds. On this basis, it is recommended that bicycles be counted as .5 motor vehicles when traveling on the main street and in this way applied to fulfillment of the existing signalization warrants given by the Manual On Uniform Traffic Control Devices.

Table 70
BICYCLE-MOTOR VEHICLE EQUIVALENCY

Motor Vehicles on Side Street Approach	Traffic on Each Main Street Approach		Bicycle Equivalency Motor Vehicle/ Bicycle	Side Street Motor Vehicles Delayed Over 30 Seconds
	Motor Vehicles	Bicycles		
150	250	0	-	4
75	375	0	-	5
150	215	100	0.35	4
75	340	100	0.35	5
150	135	200	0.57	4
75	300	200	0.37	5
150	0	365	0.68	4
75	0	470	0.80	5

CHAPTER 5

LOCATIONAL PLANNING

This element of the program involves research activities directed to determination of recommended procedures for carrying out the process of planning for bikeways in a community, identification of specific locational criteria for bicycle facilities, exploration of the relationship of locational criteria to design and safety criteria, and basic research on several locational criteria. Documentation in this chapter is organized in three major topic areas:

- Part I: Locational Criteria and the Bikeway Planning Process
- Part II: Grade and Air Quality Research
- Part III: Estimation of Bicycle Activity and Survey Research Techniques

PART I -- LOCATIONAL CRITERIA AND THE BIKEWAY PLANNING PROCESS

This section includes a review of:

- On-going bikeway planning process.
- Development of recommended locational criteria.
- A bikeway planning process.
- The relationship of functional safety criteria to locational criteria.

Current Planning Practices

Reviews of planning study reports, direct inspections, meetings with planning officials, active citizens and bicyclists in selected communities with active bikeway programs were undertaken to develop background for recommendations on the bikeway planning process and location criteria. Sites vistied for direct study include Seattle, Washington; the Los Angeles Metropolitan region; Eugene, Oregon; Santa Barbara, California; Missoula, Montana; Hemet, California; the Washington, D.C. metropolitan region; Baltimore, Maryland.

Following are a number of key points gleaned from the case studies:

- There was a general consistency in locational criteria employed in all case sites -- the same factors were perceived to be relevant to plan decision-making. This is particularly remarkable because the criteria upon which planning was based were consensus criteria intuitively acted upon rather than formally articulated and documented principles. The largest difference between case study communities was not the criteria considered but the degree of emphasis placed upon individual criteria in different communities. Table 71 presents a typical set of criteria, in this case adapted from a publication by the City of Seattle.

- In some communities the way criteria were weighted gave rise to serious problems. A typical observation was disuse of facilities which were located by emphasizing "minimized traffic exposure" criteria and downplaying "directness" and continuity criteria.

- Criteria which were often overlooked or underweighted and which most frequently led to difficulty in implementation were those relating to competing use or social value conflicts. Continuing conflicts resulted after implementation in some of these instances.

- Another common failing was initial structuring of a process to plan a preconceived solution before the true problems and the range of options to meet them were identified. For instance, a community might initiate a school bike route planning process when problems involving school-age bicyclists were predominantly occurring at other than school commute times and on trips to places other than schools.

- Physical standards varied widely and at times affected the performance of facilities. Variation in physical standards most often reflected the wide variance and incomplete nature of existing design guidelines. In other cases design guidelines were de-emphasized in favor of other planning criteria.

- A progression in the planning objectives of the more mature bikeway systems was evidenced. Communities which started with initial ad hoc bikeways oriented to recreation or school travel frequently expanded their horizons over time and directed efforts to developing comprehensive utility and recreational bikeway systems. This shift in objectives was usually accompanied by a decrease in earlier emphasis on safety-related criteria and an increased focus on functional criteria such as directness, destination service and barrier penetration.

- External funding played a highly significant role in two senses. Frequently the community's interest in bikeways and the whole process of planning was initiated as the result of a rather limited initial externally funded project -- a school route safety study funded by the Traffic Safety Program or a single recreational route implementation funded by the Bureau of Outdoor Recreation. Such initial externally funded projects are often the seed which leads to far more extensive local commitment to bikeway planning and implementation.

  The second way in which external funding frequently affects bikeway planning relates to earmarked implementation funds. Local funding to implement bikeways is generally limited. Hence, the availability of external funds is a powerful influence and there is strong in-

Table 71

TYPICAL FACILITY PLANNING/EVALUATION CONSIDERATIONS

SYSTEM EVALUATION/PRIORITIZATION CRITERIA

Operational and Safety

- Necessary for network continuity?
- Reduce conflict between bicycles and motor vehicles?
- Reduce conflict between bicycles and pedestrians?
- Likely use?
- Support facilities required?
- Effect on existing transportation systems?

Social Impacts

- Does bikeway element minimize commute times to job, shopping, school, etc.?
- Maximize mobility and access within community?
- Increase mobility on pre-auto young?
- Effect on business volume and sales?
- Access to recreational facilities increased?
- Personal safety increased?
- Community character affected?
- Effect on parking?
- Effect on auto dependence?
- Effect on traffic congestion?

Environmental

- Achievement of separate motorized and non-motorized vehicular circulation?
- Level of motor vehicle air pollution emissions encountered by bicyclists?
- Disturbance of trees, bushes and other flora?
- Scenic views affected?
- Effect on energy needs?
- Conservation of open space, green belts and farmlands?

Funding

- Estimated cost?
- Special funding applicable?
- Right-of-way available?
- Possible to include in existing local, state or federal project?

Policy

- Element essential in overall bikeway plan?
- Consistent with city policy?
- Consistent with local community desires?
- Consistent with city, county, state, federal programs?
- Political support?
- Likelihood of court action?
- Interface with other programs at all levels?
- Encourage alternative transportation mode?

ROUTE ALTERNATIVE AND DESIGN SELECTION CRITERIA

Convenience

- Impediments to bicycle travel (frequency of stop signs, narrow bridges, steep grades)?
- Serve intended bicycling need (transportation or recreation)?

Feasibility

- Can bikeway be provided given site physical constraints?
- What type?

Safety

- Safety of all roadway users enhanced?

Parking

- Will bikeway necessitate removal of some/all parking?
- What is parking demand and turnover?

Access

- Will bikeway affect access to homes, businesses, transit system?

Traffic Flow

- Adverse effect on motor vehicle flow?

Community Response

- Local interests favor bikeway location?
- Any impacts to other desirable features of community?

Transportation System

- Will bikeway affect transit system or goods movement?

Commerce

- Business affected?

Cost

- Probable cost of facility?

clination to de-emphasize other criteria in order to adopt routes which qualify for these funds. In such instances, success or failure of a bikeway is often determined by the extent to which routes favored on the basis of functional criteria happen to coincide with those which qualify for external funds.

- Institutional coordination problems appear more acute in planning and implementing bicycle facilities than other forms of transportation improvements. This is because many more public agencies and private entities are involved either as direct actors in implementation -- such as a park district, school district or recreation department -- or in provision or right-of-way easements -- such as public utility companies or districts. Many of these latter parties have little or nothing to gain in providing bikeways and often have interests at conflict with bikeway provision.

- Community involvement is essential for meaningful planning and implementation. Since there is generally little external initiative for bikeway planning (despite the earlier point on seed money) and since most bikeways must be funded locally, active citizen interest is usually necessary to get a planning process underway and to get plans implemented. During the planning process, citizens play an important role providing inputs to the technical process in such areas as weighing of various criteria, identifying specific bicyclist needs and desires and helping to resolve social value conflicts.

- An active planning staff receptive to innovation and experiment is usually a key ingredient in the success of a bikeway plan.

- Many jurisdictions waste significant time and effort in surveys of bicyclists travel behavior -- particularly origin-destination studies. In general, it appears that these survey results are used by planners to rationalize or justify decisions which are made or could be made on the basis of other readily available information.

- There appears to be no single formula for success in bikeway planning -- no specific type of bicycle facility, pattern of routes or weighting of criteria which inevitably leads to implementation and satisfactory performance. The common thread of success lay in each community operating within the limits of its individual circumstances, playing upon assets and opportunities, and coping as much as possible in the face of problems and constraints.

Recommended Locational Criteria

On the basis of the case studies and additional criteria-specific research, fourteen criteria measures were defined as recommended locational criteria. These include the following:

- Potential Use: The major intent of any bicycle facility should be that it be used. Depending on the objective at stake, this could involve either the improved accommodation of existing traffic or the encouragement of new bicycle use. The facility may be designed for general use or may be directed to a specific element of the bicycling population.

- Basic Width: Operating areas of at least recommended minimum widths for motorized vehicles and bicycles must be available for the facility to be considered as a bikeway.

- Connectivity and Directness: Connectivity implies a clear and uninterrupted path between centers of activity for cyclists. Directness implies minimizing distance and/or energy exertion by the user.

- Safety: Safety is an obvious criterion topic. In location planning, the type of user will determine the degree to which safety is emphasized.

- Grades: The amount of work required to negotiate grades can be quantified as a function of grade steepness and length of grade. Out-of-direction travel is often acceptable to cyclists to avoid steep grades. Grade criteria will vary depending on the age and/or condition of potential cyclists.

- Barriers: Physical barriers to cycle usage should not be avoided, but should be seen as prime opportunities, if breached, for increasing continuity and usage.

- Attractiveness: An attractive environment is greatly desired by recreational cyclists, although less important to those with utilitarian trip purposes.

- Image Projection: A bikeway, even on a local street, must clearly appear to provide continuity and destination service to the user.

- Air Quality: Air quality should be judged for its effect as a regional health factor and for the specific effect on cyclists closely exposed to pollution sources.

- Pavement Surface Quality: While poor surface quality is a negative factor in location planning, assessment of improvement costs can be included in the planning process.

- Truck and Bus Traffic: At high speeds, the aerodynamic effects of trucks compromises mixed or adjoining bike usage. At low speeds on city streets, high truck usage requires adequate width of vehicle lanes. Truck noise is an amenity factor which is especially undesirable for recreation trips.

- Cost/Funding: While a large number of low cost facilities might be constructed within available funds, over-emphasis on this criterion may produce non-optimal unused facilities. Consideration should be given to routes which qualify for special funding from sources external to the planning agency.

- Use Conflicts: These include competition for right-of-way between bicycles and motor vehicles (moving and parked); between bicycles and pedestrians; between government agencies with differing interests, and between social groups which bikeways may bring into contact.

- Security: Security must be considered both in respect to cyclists passing through high crime areas, and to residential locations which might perceive cyclists as a security threat.

The following sections describe in greater detail the locational criteria. It is important that each criterion set is viewed in the context of the trip and user characteristics defined in Chapter 1.

Use of Locational Criteria

As in all types of planning, a set of criteria cannot stand alone as independent measures of satisfaction. They must be considered in the context of the situation of concern and the parties involved. The following paragraphs are intended to set that context as defined by experience in the case studies.

The criteria listed below are not absolutes; they vary according to the particular problem to be solved, the population group to be served, the type of trip, and the agency involved. They are in many cases contradictory (directness of service vs. attractiveness, cost vs. safety, etc.), so that their relative importance must vary with the situation. The criteria are thus tradeoff variables; if the planner understands the trading involved in evaluating alternatives, he will arrive at more logical planning results.

There are two major groups of objectives for a bicycle facility, one of which predominates in any situation:

- To influence more people to use bicycles.

- To serve existing cyclists more safely and efficiently.

It is inevitable that the criteria will be used differently in these situations. The former will generally tend to emphasize attractiveness and amenities; the latter will tend to emphasize safety and service. While some criteria are emphasized, all should be evaluated.

Since the criteria are primarily subjective in nature, a rating or weighting system must be developed as an evaluation tool. With some criteria such as safety, grades and width, conditions which cannot be made "completely acceptable" can be defined and applied as direct tests of a locational alternative. In these cases, failure to be able to satisfy the "acceptable" standard should eliminate the candidate location. A second procedure deals with a composite "score" across all criteria for each locational alternative. In this technique, the varying situations will induce a need to weight some of the criteria differently to reflect community priorities. A weighted total rating is suggested as the basic composite criterion for locational planning.

The fact that locational criteria are not absolutes poses the potential for controversy in any community embarking upon a bikeway planning process. Explicit assertion of priority of one goal over another and one user group over another inherently involves conflicts among competing interests. Since little precise information is presently available to allow quantitative prediction of the results of a proposal, criteria and their weightings are subject to dispute even among those who have reached consensus upon the overall objectives in providing facilities. The primary benefit in using distinct criteria for evaluation and establishing a rating system is that the system can provide a focus for logical discussion of the process and its results. It can identify points of conflict and can demonstrate the effect of changing the relative importance of any particular factor. Providing this framework insures logic and communication in the process.

Relation of Location to Design and Safety Criteria

The bicycle facility locational process consists of measuring each candidate route against a set of performance, quality, and feasibility criteria and then comparing the extent to which each candidate fulfills those criteria, particularly those criteria which are judged most important to the application under consideration. The degree to which criteria are met, hence the locational decision, is partly dependent upon the available design options for each candidate route. Thus, design and safety guidelines and the degree to which they can be feasibly met are relevant and a key determinant in the choice of bicycle facility location.

Locational Criteria Description

Potential Use

Potential use is the basic reason for planning and creating a bicycle facility. Most existing methods of estimating usage are rudimentary and imprecise. They are better used for comparison of alternatives than close prediction of future use. However, it is possible to generate useful estimates of facility use, so long as inherent accuracy limitations are understood. Since detailed discussion of research findings in the area of potential bicycle activity estimation is discussed in detail subsequently, description of recommended methods is omitted here.

Several planning guides have proposed a specific value, in number of bicycles per day, as a minimum criterion (warrant) for creation of a bikeway. Such a proposal usurps the community's right to define its own needs. The correct minimum level of usage should be whatever the community believes is appropriate given both its needs and constraints. It should only be noted that potential rather than observed use is the criterion. If a location has little existing usage, in the absence of other data the conclusion that some impedance which discourages usage exists and should be remedied is equally as reasonable as the conclusion that there is no potential bicycle travel demand.

Basic Width

Basic width is the fundamental physical requirement of a bikeway. If a location cannot provide four feet of operating width for bicyclists, it should not be considered as a potential location for bicycle travel unless it can be improved. If a location requires street widening, removal of parking, or reduction in the number of motor vehicle lanes, these should be appropriately reflected in the rating for this category and in the cost and competing use categories. Meeting bikeway width standards by narrowing motor vehicle travel or parking lanes below standard minimums is unacceptable.

Connectivity and Directness

Connectivity consists of three basic factors, as follows:

- Continuity

  Continuity refers to continuous service and guidance where bicyclists travel or wish to travel. It means logical connection to other bikeway facilities and routes upon which bicyclists can reasonably be expected to travel. It requires that bicyclists not be led into and then abandoned in hazardous situations.

  For all cyclists, the ability to maintain momentum uninterrupted or with as few interruptions as possible -- is important. Observations have shown that cyclists tend to have a very strong desire to maintain the forward mementum their efforts have created. They also naturally desire to minimize their own delay and usually are more comfortable on the move. Hence, a facility with numerous full stops or abrupt turns is likely to be unacceptable. However, in most locations design treatments can be used to maximize the cyclists ability to maintain momentum so it is only important for route choice where such treatments are infeasible.

- Directness

Directness is a quality which indicates the degree to which out-of-direction travel is minimized. It is relatively unimportant to the recreational bicyclist, but of great importance to the utilitarian user. For the utilitarian cyclists, connectivity is desired along the lines which define the minimum distance or "minimum energy" path from origin to destination; little deviation is tolerated. The recreational cyclist is more willing to accept deviations from the minimum distance/minimum energy path to avoid unpleasant environmental conditions or hazardous situations so long as the deviations are not out of scale with trip length and perceived severity of the condition avoided. Thus, "direct connectivity" may be said to be the criterion applicable to utilitarian cyclists while a less demanding "linkage continuity" may be acceptable on facilities intended primarily for recreational cyclists.

Observations from research performed on this project show that for both short and long utilitarian trips, little out-of-direction travel is tolerated. For trips of up to one-half mile, cyclists may object to diversions as short as one block; however, for trips in the one to two mile range this much diversion will generally be acceptable. Cyclists on longer utilitarian trips will generally not perceive a nearby diversionary route to be beneficial if its extra length is significant.

- Destination Service

Closely related to continuity is destination service. The ability to get from one human activity point to another is essential to the fulfillment of the purpose of a utilitarian bicycle trip. If bicycle facilities are to serve such trips, they cannot simply be placed where it is easy to provide bicycle facilities or where planning decision-makers would like bicyclists to go. They must be located to provide convenient, direct access to centers of activity.

Safety

Safety is an obvious criterion in bicycle facility location planning. However, beyond basic minimum levels it should be viewed as a tradeoff variable just as with all other locational criteria. The emphasis safety receives will depend both on the specific situation and the importance placed on other competing criteria in that situation. Measures to improve safety performance have been presented at other points in this research and the tradeoffs between safety and operational convenience and utility qualities inherent in these described. It is the community's responsibility to define an "acceptable" safety level for an existing or proposed facility: No single safety measure can be given.

- User Characteristics

  No discussion of bicycle facility safety can be complete without consideration of user characteristics. Potential users range from small children who may have incomplete knowledge of or concern for the rules of the road, limited experience in judgment of traffic situations, and incompletely developed motor skills in riding a bike, to sophisticated bicyclists having expert physical skills in riding a bicycle and a finely honed sense of judgment in the art of surviving on a bicycle in traffic.

  The various types of cyclists, their riding capabilities and their behavior patterns interact with design and site conditions in affecting the inherent safety quality of any facility alternative. A young child cyclist who travels on a sidewalk facility, stopping at each intersection to carefully check traffic before crossing might be significantly safer on that sidewalk than on an on-street facility. A sophisticated cyclists who tends to travel at a higher speed, attempts to maintain momentum and assert right-of-way through intersections and has better overall traffic judgment than the child cyclist would likely be safer on a street than on a sidewalk.

- Evaluation Procedures

  A safety evaluation is really an evalution of existing or potential conflicts. Often the existence of a large volume of cars adjacent to a bicycle facility is taken to be an inherently unsafe situation. This is generally not true. High traffic volume is a hazard only if there is close and continual conflict between vehicles and bicycles.

  Potential conflicts can best be categorized into four categories: parallel, right turning, left turning, and crossing conflicts. Each of these conflicts should be evaluated separately and combined for a final safety ranking of these conflict types.

  Parallel conflicts are caused by two conditions: Close proximity of auto and bike travel, and speed differential between the two. Conditions for bicycle and motor vehicle mixed use are detailed in Chapter 2 of this report.

  Normal procedures for selection of bikeway treatments at intersections involving left turn, right turn and crossing conflicts are presented in Chapter 4. Table 72 presents additional discussion of special design conditions based on research detailed in Chapter 4.

Table 72
SAFETY EVALUATION OF RIGHT-TURNING CONFLICTS

Design Condition	Conflict Potential	Specific User Problems		Proposed Forms of Solution
		Inexperienced Cyclist	Sophisticated Cyclist	
Unchannelized intersection				
Controlled	Minimal			
Uncontrolled	Minimal-Mild			
Exclusive right-turn lane Controlled	Mild	Weave across turn lane or hug curb lane and wait	Weave across turn lane	
Free right-turn lane Uncontrolled at signalized intersection	Moderate	Weave thru moving traffic or hug curb	Weave thru moving traffic	Specific design solutions
Exclusive double right-turn lane	Severe - must be corrected or alternative location picked	Weaving across two lanes of traffic		Elimination of double right-turn lane; Separate bicycle signal phasing; Grade separation of bicycles and motor vehicles; Physical restraint to force bicycle to act as pedestrian (last resort -- bicyclist acceptance is unlikely).
Exclusive free double right-turn lane Uncontrolled at signalized intersection	Severe - must be corrected or alternative location picked	Weaving across two moving lanes of traffic		Elimination of double right-turn lane; Grade separation

Grades

Grades not only influence bicyclists' route choices, but affect the operational safety and feasibility of bicyclists' maneuvering in the traffic stream as well. Bicyclists may accept substantial out-of-direction travel as well as reduced safety and amenity conditions in order to avoid significant energy expenditure on an upgrade. Some cyclists do not have a choice; they are simply physically incapable of riding uphill at an acceptable riding speed. Bicycle speed reductions caused by grades affect bicyclists' safety in maneuvering with motor vehicles at intersections. Downhill grades which increase bicyclists' speeds also are significant because they affect bicyclist behavior in mixing with traffic and bicycle stopping distance requirements.

The subject of human work effort in riding a bicycle on the level and upgrades is complex and has been a subject of special research in this project. That research is detailed in a subsequent section.

An evaluation of grades should be done at least whenever candidate routes have markedly differing grades. Work effort calculations should be conducted for each route to determine ranking. The ranking should also consider the trip type, so that routes for recreational trips can be classified by energy requirements where required by a particular program's objectives.

Another application of grade evaluation methodology relates to planning for recreational cyclists -- the concept of defining and marking "high energy" and "low energy" recreational routes so as to provide recreational bicycling opportunity within the physical capabilities of the full range of potential bicyclists. This is a significant concept. For the "fit" recreational bicyclist, grades are not necessarily something to be avoided; they can add interest and challenge to a ride. But if a recreational route includes such challenges for the fitter individuals, it may preclude individuals at the other end of the fitness scale from using the facility at all. The grade evalution methodology as detailed in this study can be used for defining bicycling opportunities for particular subgroups of the bicycling public.

Barriers

Barriers are the antithesis of bikeway continuity: places where it is extremely difficult or hazardous, if not impossible, for bicyclists to travel. Barriers include natural features such as bodies of water, steep ridge lines and the like, and manmade objects such as elevated rail lines and freeways with limited points of street crossing. Existence of a facility which permits motor vehicles to penetrate a barrier does not necessarily imply that bicyclists will be able to do so. For example, bicyclists are often barred from bridges carrying motor vehicle traffic across major water barriers. Similarly, though not specifically barred, it can be extremely difficult for bicyclists to negotiate their way through a busy interchange at a major freeway crossing.

As a locational criterion, barriers are not necessarily to be avoided. In fact, the breaching of barriers may be one of the most important factors in providing continuity and increasing bike usage. As such, barriers should be evaluated for feasibility of breaching. Breaching with a bikeway may be infeasible in some obvious cases, such as long bridges with no sidewalks and low potential usage. In many cases it would seem more reasonable to carry the occasional bicyclist on a bridge maintenance or patrol vehicle, graduating to a more formalized bicycle transit service if this clientele developed. Such a scheme is now in successful use on the Coronado Bridge in San Diego, California, employing bike-carrying trailers which are attached to the rear of regularly routed transit vehicles as they reach the ends of the bridge structure.

While barriers could be included under the category of connectivity, their specific nature and potential for service when breached suggest a separate evaluation. Each barrier should be evaluated for potential for increased service, difficulty of breaching, cost of breaching and possibility for solutions other than physical solutions. Those barriers for which cost of improvements is clearly excessive will eliminate a candidate route from consideration. All others should be carried forth in the evaluation process.

Attractiveness of the Bicycling Environment

Given the close interaction between the bicyclist and his environment, it is natural that the attractiveness of the environment be a consideration in route choice. This is a quality which has different importance for the two basic purposes: utilitarian and recreational travel. The utilitarian rider generally considers attractiveness as a nice thing to have if it coincides with the directness of his path. For the recreational cyclist, the attractiveness may be the primary motivation for his trip, and he will seek out attractive locations. Weighting of this category will thus vary depending on the purpose.

Attractiveness is the most subjective criterion in this set, being a highly personal factor: some people do like to ride along a junkyard to see what's new. Thus any rating system will be greatly influenced by the values of the rater. The important point is that attractiveness consider many factors including view, sound, and (in the case of parks, trucks, and buses) smell.

A few elements related to attractiveness, such as air quality, noise level, and presence of trucks can be quantified and are presented in following sections. Other less quantifiable elements may include:

- Natural settings
- Points of scenic, architectural or historical interest
- Points where interesting human activities may be briefly observed
- Points where interesting diversions from the ride may be briefly engaged in
- Geometric interest; routes with horizontal and vertical undulations to break monotony but not so severe as to require significant extra effort or sharply constrain speed.
- Convenient rest points with shade, water, and possibly restroom facilities.

Imageability

Whereas continuity, directness, and destination service may be skillfully designed into a bikeway system, to the stranger or occasional user these characteristics may not be readily apparent. Imageability is the characteristic concerned with how the facility appears to the user, rather than how it actually is. While two routes may be rated equal in connectivity, a route that uses clearly defined paths such as major streets will appear to be more effective, especially to the new user.

While imageability is an inherent characteristic of some routes, it can be designed into others. Effective use of bikeway trail markers and destination signs can be used to improve the imageability of bikeways on local streets. Route maps and descriptions can improve imageability in recreation areas. Thus imageability should be rated in terms of the final treatment proposed for the facility rather than the inherent characteristics.

Like attractiveness, imageability is largely a subjective criterion. No minimum standards can be defined to rule out a route; such a standard does not exist. Imageability should be thought of as a factor that enhances a route, in varying degrees, rather than an absolute standard.

Air Quality

Air quality is a potentially important locational criterion since air pollution has more serious implications for persons involved in physical exercise such as bike riding. Exercise increases lung uptake of a pollutant by minimizing air flow through the nose and maximizing air flow to the mouth (the nose tends to eliminate a significantly higher portion of reactive gases than does the mouth), ventilating the lung more uniformly and hence exposing more reactive lung tissue and increasing the replacement of a gas which reacts at a given point within the lung.

There are two critical aspects of air pollution as a locational criterion for bicycle facilities. These are:

- concentrations of various types of pollutants which could cause long or short term health effects as a result of exercise, and
- length of exposure at which concentrations of pollutants would produce such health effects.

Air pollution rarely if ever consists of only one toxicant. Complex mixtures of pollutants are prevalent in the air over most urban centers. In assessing these diverse pollutants as locational criteria for bicycle facilities, it is important to consider how each type exists as a concentration in the atmosphere. For instance, photochemical oxidant or smog exists as a dispersed-area phenomenon. Hence, its presence in concentration sufficient to pose short or long term health concerns to bicyclists is not meaningful as a criterion for selection of one route over another at a location within an established corridor. On the other hand, since gross concentrations of photochemical oxidant do vary between major subareas of a region, this variance of a concentration might be used as a locational guideline for regional recreational bicycle facilities.

Specific research on the effects of oxidant (O_3) on bicyclists was undertaken as a part of this program. The results of that research is presented in a subsequent section.

Other types of pollutants are typically found in limited site or line concentrations; carbon monoxide (CO) is a typical example. If such concentrations are at levels which could pose potential health effect problems for cyclists, their existence would constitute a reasonable criterion for selection of one route alternative over another. However, examination of available technical data indicates that in all but the most extradordinary conditions, the likely length of exposure of bicyclists to site concentrations of pollutants such as CO at typical ambient worst-case concentrations would not be a concern.

Pavement Surface Quality

The fact that bicycles do not have the shock-absorbing capability of motor vehicles means that the quality of the surface will have a significant impact on usage of a facility particularly if there is a more satisfactory alternative. Ride quality, stability and tire damage can be involved. High surface quality should be considered as an essential part of the bikeway design. If the desire of the community is to use only existing facilities with a minimum of capital improvement, ratings of surface quality on candidate routes is particularly critical.

Truck Traffic

Truck and bus traffic is a significant factor affecting the acceptability of a candidate route. Because trucks and buses are larger than automobiles, the level of their presence may influence cyclist perception of a street's safety. At high speeds they create aerodynamic disturbances which could cause a cyclist to lose balance and fall. The ambient noise levels along the street also significantly increases, thereby decreasing amenity for bicyclists.

A review of technical literature provided little support for defining a specific level of truck traffic as a maximum along parallel bikeways. A standard maximum percentage of trucks should definitely not be used as a criterion, since the type and absolute number of trucks are the real issues.

Physical encroachment by trucks is generally not of concern on bike lanes, since traffic engineering standards for lane design account for truck size. Truck widths of 96 inches for general use and 102 inches for non-interstate use will fit within the standard 12 foot lane, though they may be a problem where substandard lanes exist.

- ### Recreational Vehicles

  One specific concern is a facility used heavily by recreational motor vehicles. Interviews with experienced cyclists indicate that drivers of these vehicles are often unfamiliar with their equipment -- of its length, projecting mirrors, or handling characteristics. In locations where these vehicles and bicycles must share a right-of-way, good locational planning should provide extra separation between cyclists and vehicles.

- Aerodymanic Disturbances

  The potential for aerodynamic disturbances which might overturn a bicyclist is primarily a function of truck speed and available lane width. Evaluation of this potential effect is discussed in Chapter 3.

- Noise

  The concern for traffic noise, particularly that caused by trucks, is predominantly an amenity factor rather than a safety criterion. There is some difference in the noise levels which would be experienced by the bicyclist under typical street dimensional relationships over a wide range of traffic volumes, truck percentages, and surface street operating speeds. But the street is an extremely noisy and unpleasant place for the bicyclist to be as long as there is any measurable percent of trucks. There is no clear breaking point at which noise generated by trucks or traffic in general would become an absolute concern. This assessment is based upon analytic procedures presented in FHWA's "Manual for Highway Noise Prediction" (Report No. DOT-TSC-FHWA 72-2). Procedures presented in that manual could be utilized to make comparative noise evaluations of alternative routes under study. However, carrying out such an analysis is worthwhile only when comparing alternative routes having gross differences in travel speeds, percentage of trucks and total traffic volume.

To summarize, presence of heavy trucks is definitely a negative factor in the acceptability of a street as a bicycle facility candidate. However, no specific volume of trucks should be regarded as an absolute negative criterion.

Cost and Funding

Facility cost is a criterion in two senses:

- in determining whether a facility is built, and
- in determining what facility is built.

While locational planning is primarily concerned with the second condition, the overall quality of planning combined with political conditions will determine whether the facility once planned and designed is built.

As a location planning criterion, cost is an extremely powerful influence -- so powerful that special care must be taken to assure that it does not overwhelm the user-desired elements. Given a limited budget, the planner may have the option of creating a limited number of costly routes or a larger number of economical routes. In choosing between high cost and low cost alternatives, it is necessary to insure that the options selected fulfill the bicyclists' needs since an unused facility is costly regardless of the expense.

Source of funds is also a factor in cost. Although most facilities will be funded by local sources, some routes may qualify for state or federal funding. The temptation to distort a network to qualify for these sources must again be tempered by the need mentioned above for satisfaction of users.

Creating a rating system for the cost criterion involves the relatively straightforward process of estimating both capital and operating costs for each alternative route, and identifying external funding sources where they are different for contending alternatives. The cost data should be scaled to be comparable to the user-related criteria to avoid over-emphasis.

Competing Uses

Competing use is used herein to denote basic conflicts between populations affected by the bicycle planning process. Three major conflicts have been identified: bicycle vs. motor vehicles, bicycle vs. the penetrated neighborhood, and governmental agency vs. agency.

Other kinds of conflict are certainly conceivable as, for instance, the potential interaction between bicyclists and pedestrians on a sidewalk bikeway. However, that type conflict is taken into account in design criteria. The type of conflict described as competing uses herein is one which involves denial of a use because of a real or supposed incompatibility -- not decreased quality of service or satisfaction due to introduction of an additional use.

- Bicycle vs. Motor Vehicle

  The conflict between bicycle and motor vehicle referred to here is not that defined in the section on safety. Rather, it is the conflict in use of available facilities. An existing right-of-way can support a varying combination of motor vehicle and bicycle facilities; the relative demands of each mode will determine the feasibility of creating a bikeway on a specific right-of-way. The possibility of resolving this type of conflict frequently can be subject to analysis and technical policy decision. For instance, on a street of single family residential character, street parking space available on one side of the street may be sufficient to serve all on-street parking needs. Parking could be eliminated on one side to provide sufficient space for lane redefinition and inclusion of bicycle facilities. But in a high density residential area, analysis of parking conditions might indicate residents' strong dependence on all existing on-street space for storage of vehicles and parking removal would be technically infeasible. Similar types of analysis might be made of traffic conditions to determine feasibility of eliminating a motor vehicle travel lane on a multi-lane street.

In other cases, decisions regarding resolution of competing use conflicts cannot be made on the basis of technical feasibility; social value judgments and political considerations enter the picture. A common example is the situation in which parking removal on one side of the street along the length of a candidate route is technically feasible for the entire length in question and socially feasible except at a few limited points at which roadside business has a vested interest in parking immediately adjacent to the individual establishments. In these kinds of situations, decision-making may be lifted from the technical planner's hands and is often postponed until complete plans are forwarded to elected officials for approval and funding. In the light of this decision-making uncertainty, or the fear that disapproval of this specific alternative will cause disapproval of a more comprehensive system plan, there is a tendency for planners to anticipate and preempt public officials' decision-making. Some planners tend to assume that invariably elected officials will decide against the bikeway plan and in favor of the local property interests. This presumption of automatic plan rejection should never be made by a technical planner. Elected officials should be permitted to exercise their prerogatives and responsibilities in these sorts of situations. The value judgments they make may well run contrary to planners' conditioned expectations. Preferably the planning process would be structured to obtain early resolution of this type of conflict situation so that the process could continue on the basis of certainties rather than assumptions.

- Bicyclist vs. Penetrated Neighborhood

A second type of conflict that may occur in locational planning is that between the bicyclist and the penetrated neighborhood. This conflict may occur whenever there is a clear difference in apparent lifestyle between the cyclists and the residents whose homes they pass. The conflict may be racial, it may be socio-economic, or it may be one of lifestyle. If the planner is aware of this type of conflict, he can attempt to deal with it in the planning process rather than struggling with adverse reaction when his plans are made public.

- Governmental Agency vs. Agency

  A final type of competing use occurs when one agency has responsibility for bicycle planning and another (such as a water or utility district) has responsibility and control over a right-of-way ideal for biking but used for other purposes. Often these other agencies may have no interest in aiding bikeway development and may in fact have sound reasons, such as added maintenance and insurance costs, for opposing bicycle usage of the right-of-way. Situations of this type should not be rejected out of hand. The objective should be to maximize the public's benefit rather than that of the specific agency. In those cases, solutions should be investigated as with any other alternative, and any special costs associated with bicycle facilities on the competing right-of-way should be accounted for.

Security

Security is a locational factor which relates to both users and non-users.

- Residence Security

  Bikeways are sometimes perceived as facilities which bring with them bicyclist users who are thought to be a threat to the security and safety of the neighborhood. In other cases, it is not the bicyclist users who are perceived as the threat, but other persons who might be able to use a secluded bikeway to gain surreptitious entry to homes and property.

- Bicyclist Security

  Bicyclists' concerns for security of their persons and property are much more genuine and well-founded. An obvious response to concern for property is provision of effective bicycle parking facilities at bicycle trip activity generators. Unfortunately, all but the most elaborate and costly bicycle parking facilities are little more than theft-retardant and only minimally effective unless open to relatively continuous public view.

  Personal security of bicyclists is of greater concern. A number of locational and design considerations can help minimize this concern. Areas of high street crime can be readily identified from police records or may be identified from survey results. Where these areas interdict potential bike routes, routes should either be modified to skirt the area of concern or the facility should be located where it will be open to relatively continuous public view and ready scrutiny of enforcement officers. For instance, a bicycle path passing through a park area would preferably be located in an open meadow rather than a secluded wooded area. An overpass treatment open to view is preferable to an underpass treatment in shadow. When an underpass is necessary, its sight distance properties should allow cyclists to see prior to entering if anyone is loitering there. The possibility of street crime should not preclude building a bicycle facility, particularly when there appears to be real potential for use. But it is good reason to use prudent judgment in locating and designing the bicycle facility so as to minimize crime potential.

The Bikeway Planning Process

This section summarizes a structural process for systematic development of bikeway plans. The process was developed on the basis of the case studies and other experience in bikeway planning. The process is not one used in any of the specific cities. Rather, it is a composite which emphasizes the strengths and attempts to avoid the pitfalls of processes observed in communities studied directly or through reports.

Need For Systematic Planning

When a jurisdiction chooses to act upon a bicycle-related issue, often the tendency is to react along the lines of the initial vision of the problem, accepting or rejecting courses of action within that limited framework. This can easily result in leaping to a solution without really defining the true problem and the range of potential solutions.

The appropriate solution to an identified bicycle planning problem must arise out of a systematic planning process, rather than using "planning" only to implement a preconceived solution.

The Process in Brief

Figure 25 presents a schematic representation of the recommended planning process. As shown in the figure, the planning sequence is as follows:

1. Identify problems and objectives.

2. Identify bicycle travel potential.

3. Identify bicycle corridor opportunities and constraints (concurrent with Step 2).

4. Compare potential travel and corridor opportunities/constraints.

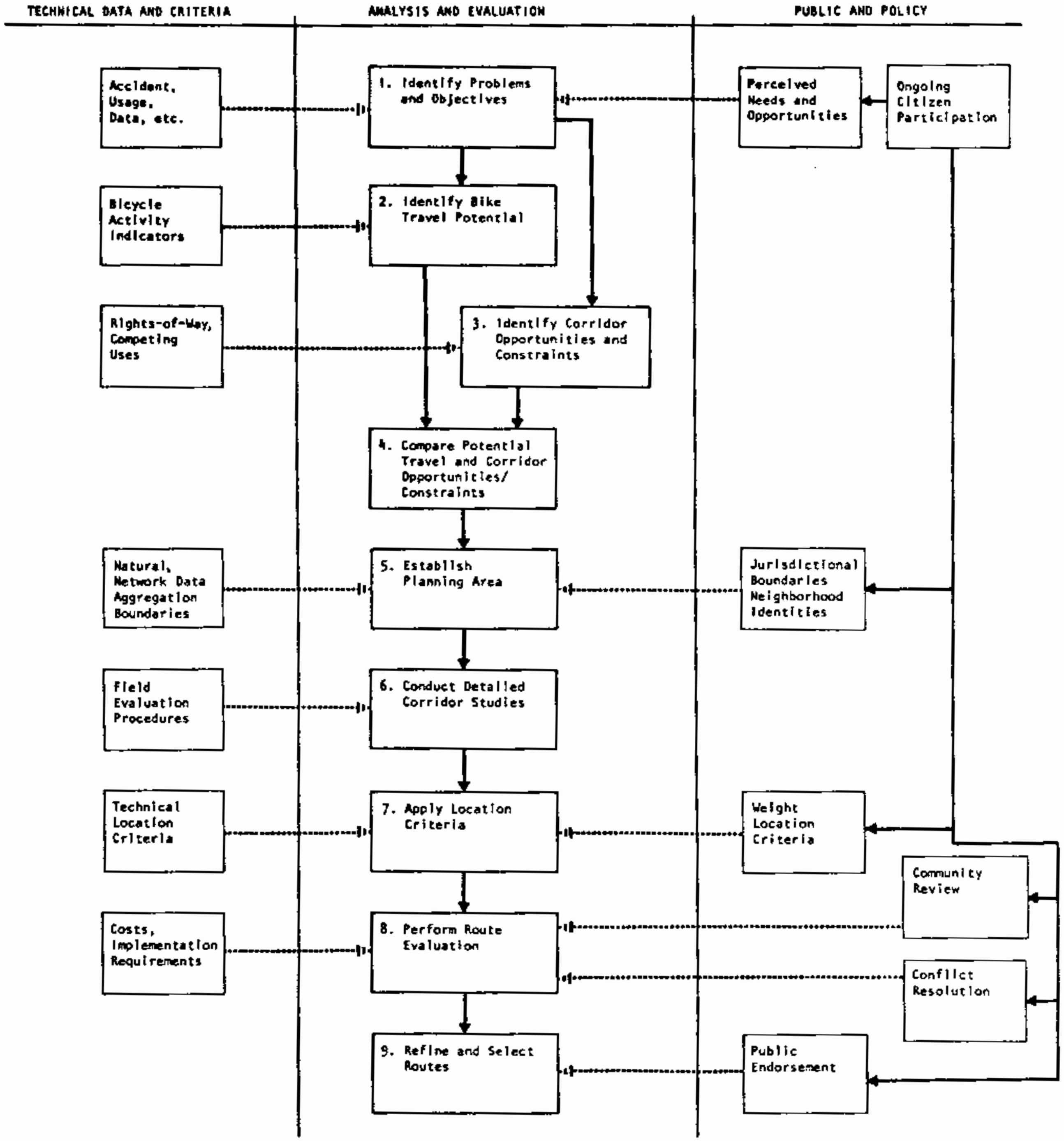


Figure 25
BICYCLE FACILITY PLANNING PROCESS

5. Establish individual planning areas.

6. Conduct detailed corridor studies.

7. Apply locational criteria.

8. Perform route evaluation.

9. Refine and select routes.

Throughout the process, active community participation and review is recommended. With such community involvement and the use of a systematic process with clear objectives, the successful planning of bike facilities should be assured. The classic planning process requires continuing effort, and bikeway planning is no different. The minimum commitment should involve achieving yearly goals by modifying and expanding the bikeway plans and funding as required to meet community requirements and by being flexible enough to enable responding to unique situations and taking advantage of emerging opportunities.

The various elements of the planning process are discussed in detail in the following sections of this chapter.

Step 1: Identify Problems and Objectives

The intent in this step is to allow the planning agency to focus on true problems and objectives at the start and to prevent an early presumption that what is "needed" is a specific facility such as a bikeway system. Ideally, the acting jurisdiction would like to answer a question such as "What do we need?" But this answer is the result of planning, not its beginning. More appropriate at this initial step is to identify the problem at the root of any desire for bikeway improvements.

The Problem

The problem to be solved may be a high rate of bicycle accidents or potential accidents; auto traffic congestion which might be eased through encouragement of bike use; a public demand for more outdoor recreation opportunities; or many others. It is likely that several problems will be identified. The key point is: The problem should be defined without reference to any particular solution. (For example, a high bike accident rate should not be interpreted immediately as a need for a bikeway, but rather explicitly as an accident problem.) This prevents a hasty narrowing of the scope of concern, which might result in overlooking far better solutions.

Once the problems are thus defined, the proper tone is set for identification of their causes. Who is involved? Where? When? The purpose here is to understand the problem as well as possible.

The Objective

Simply put, the objective is to solve the problem. More specifically, the objective should define and describe the future condition which is to be reached. Sometimes the effort of identifying problems and their causes will show clearly that a physical facility (typically a bikeway system) is needed. In other instances, it may be necessary to conduct a brief study to answer this question: "Can anything other than a physical facility better solve the problem?" If other candidate solutions are generated, they can be carried through the planning process as alternatives.

The result of this step, then, is a statement of the objective to be reached, in as much detail as possible. At a minimum it should state what constitutes a solved problem, such as a particular reduction in accidents. This will allow a solution or alternative solutions to be developed to meet this need.

The remainder of this bicycle facility planning process assumes that a bikeway or similar facility is at least one of the plausible solutions to the problem at hand. If this is not the case, a more general planning process should continue.

Step 2: Identify Bike Travel Potential

Once the problems and objectives are defined and it is established that a bikeway facility is at least one of the plausible alternatives, the next step is to assess the demand for or potential use of such facilities. The product of this step should be estimates of major bike travel flows by general location and type.

Research on techniques for identifying potential bicycle travel demand and activity corridors is presented in detail in a subsequent section. Potential methods include:

- Bicycle traffic counts.
- Bicycle accident records.
- Motor vehicle traffic counts and flow maps.
- Existing regional travel data.
- Major travel generator identification.
- Community group participation.
- Special surveys.

Step 3: Identify Corridor Opportunities and Constraints

The foregoing techniques relates to identification of potential bicycle trip patterns and trip desires. An activity which can be undertaken concurrently with those tasks involves identification of potential physical corridors for bicycle travel and specific barriers to such travel.

Initial Corridor Identification

The initial screening of routes should be one which attempts to identify reasonable candidates for a bicycle facility. On a street map of the study area all streets having continuity and providing important linkages across the area should be identified or "flagged" together with notation of topography, barrier and other problems or benefits. A corridor can be a single street or a family of parallel adjacent streets. Where parallel minor streets are about as continuous as nearby major streets, such families of streets should generally be defined.

In addition to streets other opportunities for bike travel should be identified on the map. Some of these include the following:

- green belts;
- parks;
- utility rights-of-way;
- drainage rights-of-way;
- stream courses;
- railroad rights-of-way;
- freeway and parkway rights-of-way; and
- beach fronts.

In addition, corridors which would appear to have particular intrinsic merit for recreational bicycling could be specially flagged on the map.

Identification of Bicycling Obstacles

Any locations posing obstacles to bicycle travel should be identified on an overlay to the corridor map. Obstacles should be separated into two groups:

- Absolute barriers to bicycle travel, such as:
  - elevated rail embankments,
  - rivers, streams, canals, bays and other large bodies of water, and
  - freeways.
- Bicycle impediments which can be crossed by a bicyclist but only with difficulty, such as:
  - busy streets at locations without traffic signals,
  - steep grades (up and possibly down), and
  - freeway interchanges.

Key penetration points to barriers and obstacles should also be distinctly flagged on this overlay. This provides a basis for later determining the feasibility of breaching obstacles.

Step 4: Compare Travel Potential and Corridor Opportunities/Constraints

This step consists of three distinct elements:

- Screen Travel Potential Against Corridor Opportunities

  Patterns of travel potential can be very effectively screened against identified corridor opportunities using graphic overlay techniques. Additional corridors constituting special recreational opportunities should also be identified. Areas where bike trip potential is unserved by identified corridors would also be denoted. One result of this process is identification of "high-potential" corridors for which demand coincides with candidate routes.

- Check Locations of Bicycling Obstacles

  High-potential corridors flagged above are screened against barriers and impediments to bicycling identified in STEP 3. There are two objectives:

  - identify key corridors which match travel desire lines but which are interrupted by barriers;
  - find specific barriers/impedances which "explain" the unserved areas already identified.

- Search for Alternate Corridors

  Where high-potential corridors conflict with bicycling obstacles, and where areas are unserved because of obstacles, alternate corridors are sought. Studies of barriers/impediment penetration schemes are then initiated where these conflict with "flagged" corridors or explained unserved areas.

Step 5: Establish Individual Planning Areas

At this point, if the overall planning area is large, it is appropriate to subdivide it into smaller study areas (subareas). The rationale for such subdivision is multi-fold:

- Such subdivision facilitates planning at a scale of detail consistent with the subtleties of bicyclists' decision-making. This is necessary if the plan is to have any relevance to individual behavior.

- It enables the planner to understand all the factors which contribute to the success or failure of individual proposals and the system as a whole.

- Disaggregation into small planning areas increases the likelihood of consensus of goals and opinions within the area.

- It is possible to finish a subarea plan and get implementation started within a shorter time frame. This demonstrates positive intent and also opens up the possibility of test programs to measure plan effectiveness, public attitudes, and usage parameters. This allows the planner to approach the remaining subareas with a narrowed set of options, based on these "trial runs."

  Factors which should be considered in establishing and utilizing study subareas are:

  -- Size

  -- Boundary Requirements

  -- Local vs. Areawide Conflicts

Size

A reasonable area for local planning is on the order of two miles square. Several factors influence this:

- the size of total planning area

- the intensity of activity within it; and
- the configuration of barrier conditions which constitute the ideal lines for subarea delineation.

Boundary Conditions

There are two key considerations in determining subarea boundary lines:

- Physical Barriers: There should be a relatively limited set of bike facilities which traverse subarea boundaries. Accordingly, barriers such as freeways and bodies of water are good dividers between study subareas.
- Planning Units: It is desirable to utilize established boundaries of planning units (e.g. census tracts, jurisdictional boundaries) since it is often necessary to supply plans and planning information according to defined planning units.

Where planning unit boundaries coincide with physical barriers to bicycling, these are natural boundaries for subareas. In other instances the planner must balance the need to carve out relatively independent subareas with limited linkages between them, and the desirability of employing established boundaries for data compilation and decision-making.

Local vs. Areawide Conflicts

In optimizing internal bikeway systems in individual study subareas, a danger exists that the areawide system might lack cohesiveness. This danger can be minimized by:

- Drawing subarea boundaries along physical barriers having limited points of penetration, so that subareas are relatively independent of each other.
- Identifying routes of areawide significance during establishment of study subareas.
- By being continually conscious of the total planning area concept while dealing with localized issues.

In some situations, a clear conflict is posed between local and areawide system optimizations. In such instances, each case must be judged individually in accordance with overall planning objectives. For example, if an overriding objective is safety of young cyclists, an option which caters to local area riders might well be favorable; if the overall program objective is to encourage bicycling as an alternative to automobile use, an option which optimizes the areawide system might be favorable.

Potential conflicts between localized and areawide objectives are inherent whether the planning is done on an areawide basis or by use of study subareas. Subarea planning merely brings these conflicts into the open.

Step 6: Conduct Detailed Corridor Study

The next stage in the planning process involves detailed site exploration of potential facility corridors. Each of the initial corridors including those matching travel desire lines, those created to serve areas unserved, and those defined in response to barrier and obstacle conditions are reviewed for physical design possibilities and constraints. The design procedures detailed in other sections of this report are appropriate tools for this task.

Specifying Locational Criteria

It is at this point that locational criteria enter the process. Essentially the detailed corridor study is the site reconnaissance and initial route refinement step, built around the collection of locational criteria data. This brief discussion avoids redundant enumeration of the criteria, and instead places emphasis on two key factors in the process:

- The importance of field reconnaissance, and
- Resolution of competing use conflicts.

Field Reconnaissance

The field inventory/assessment procedure presented in User Manual Volume II is employed to evaluate both on-street and off-street corridor potentials. In addition, contact is initiated with agencies and jurisdictions controlling off-street corridor rights-of-way to determine their feasibility of use. Based upon field assessment results, the physical treatments possible in each corridor are then defined preliminarily, rated qualitatively and roughly costed. The field reviews also provide a more refined identification of barriers and obstacles, and provide insights into their possible design solutions.

There are two key points with respect to field reconnaissance:

- It should be done prior to preliminary route design; and
- It would preferably be done on bicycle.

Field review at this stage is a critical step. Prior to this step all planning activities have involved working from data, maps and the planner's personal insight and familiarity with the study area. Successful bicycle facility design requires a close working knowledge of the subtle details which affect bicyclists' behavior. Such a knowledge can come only through field observation, preferably done astride a bicycle.

In a number of programs reviewed in this study, field inspection was done only after a route and its preliminary design had been selected. The problem with this approach is that although it saves the cost of a more extensive field inventory, it seeks only to identify and correct defective conditions in the preliminary proposed plan. It fails to seek out opportunities either on the given route or a parallel one which might be superior to the preliminary defined plan. Moreover, it is conceivable that the added field inspection cost for several route alternatives may well be offset by the cost of wasted design effort in cases where designs are detailed and then scrapped in light of field evidence gathered later.

Use Conflicts

The field inspections also identify and evaluate competing use conflicts. These are situations in which existing uses would necessarily be eliminated or curtailed in order to provide a bicycle facility within the given route corridor. Need for elimination of parking or a travel lane in order to provide a bike lane are examples of competing use conflicts. The field inventory identifies the fact that such a conflict exists. If possible, it also gathers relevant data.

Field inventory resources may not be sufficient to determine whether a particular use conflict is an irresolvable obstacle to use of a particular type of treatment in the corridor. In such cases, the planner must determine whether the conflict merits additional studies, or should simply be presumed to be irresolvable and the alternative discarded. This determination will depend on a number of factors including the importance of the facility to the system; the inherent attractiveness and quality of the alternative itself assuming the conflict did not exist, and the quality of other alternatives which could fulfill the same function as the proposal at conflict. This determination might be reserved until the initial formal evaluation of the alternatives (Step 7).

The intent in anticipating these conflicts is to allow development of possible counter-measures such as adjustments to physical form as well as to identify alternatives which should be discarded due to irresolvable conflicts.

Costs

Costs for each candidate route and design option should be preliminarily estimated. Funding sources for the various types of facilities should be identified at this stage.

Step 7: Apply Locational Criteria

As Figure 25 shows, Application of Locational Criteria enters into the detailed study of route/facility alternatives. This step is devoted to collecting the information needed to evaluate the alternatives on each criterion. This information is then applied in the next step, the actual evaluation of routes.

The role of the Locational Criteria, then, is to provide a systematic means of judging the relative merits of each alternative. This is the heart of the planning process, for it controls the selection of a plan. In the evaluation, the facility (or alternative) is rated against each criterion such as use, safety, and barriers. This permits two analyses:

- First, it allows the identification of major problems with the proposed facility, such as an inherently high risk of accidents.

- Second, this process leads to the combining of individual criteria ratings to form an overall indication of the acceptability of the plan.

Step 8: Potential Route Evaluation

In this step locational criteria are utilized to evaluate alternative routes. Two parallel lines of approach are involved:

- Assessment of Each Alternative

- Comparison of Alternatives

Assessment of Each Alternative

The planned (or alternative) route is assessed for its performance on each of the locational criteria. At least a level of minimum acceptability should be reached on each criterion. Where failures are identified, revision or rejection of the plan is required.

This process consists of two elements:

- Defining criteria to be used; and

- Measuring acceptability of the alternative against each criterion.

It is intended that the locational criteria described previously constitute a comprehensive "shopping list" rather than standards for evaluating bicycle facilities. It should be noted that each community and each situation may require modifications to the list of criteria and to their measures of acceptability.

Comparison of Alternatives

Where more than one alternative is under consideration, they should be ranked against one another as an aid in selecting a preferred alternative.

In order to compare alternatives, each one must be ranked against selected criteria, and a procedure for combining ranks is needed.

The differing needs and priorities of communities make it impossible to provide a standard ranking procedure. This again must be done locally. It should be consistent and as objective as possible, and should reflect local needs and values. But it need not be complex.

In some cases, it may be convenient to assign numerical ratings (e.g., from one to five) to each alternative's performance on each criterion. This may be refined further through identification of the relative importance of each criterion under the circumstances, with weights applied to the ratings to reflect this. Ratings can then be summed across all criteria to yield a weighted average ranking of each alternative.

It should be noted that a formal composite ranking may not be required. In many cases the alternative facility locations will quickly reduce to one simply by elimination of all which fail on one or more important criteria.

The central point in this evaluation process is not its elegance or rigor, but in its appeal to common sense and judgment. Its essential inputs are not explicit rating schemes, but local needs and values. The suggestions of this manual are intended to enhance local knowledge and permit its application, not to replace it.

Step 9: Refine and Select Routes

To this point either one or several alternatives may have been considered, with many informal revisions and refinements to the original concepts as the process was followed. This step merely formalizes and continues that effort of revision and refinement.

Cyclic Process

Completion of the route evaluation step as just described may well have highlighted some specific weaknesses of the initial plan or alternatives. These may require only minor adjustment, or they might necessitate a major revision of a candidate route. When major changes are indicated, it is often advisable to consider the entire planning process a cyclic one and repeat the sequence of steps with the new information gained in the initial evaluation. This aids in keeping the process logical and defensible.

Final Check

In addition to revisions based on application of locational criteria, one final test should be performed. This is a recheck of the revised facility's location against trip potential/desire lines initially identified. The objective in this step is to insure that the system which has emerged after screening against cost, functional safety, physical design feasibility and other criteria still bears a reasonable relationship to indicated bicycle travel desires. If a system does not respond to travel desires, it simply will not be well used -- no matter how satisfactorily it meets other criteria. In any areas where correspondence is lacking between system service and travel desire, either a feedback process in which corridor searches are reinitiated must be undertaken or a specific rationalization for accepting this situation must be prepared.

Community Review

An extremely significant element of the bikeway planning process is to review the "selected" system with the community. In this way, public endorsement of the plan as a whole can be developed. If the public does not endorse and actively support a bikeway plan, that plan is unlikely to be implemented. Ideally, community inputs and reactions should be received at all stages of the process and at a minimum the final plan must be reviewed and endorsed by the citizenry.

While increasing state and federal monies are becoming available to local jurisdictions for planning and implementation of bicycle facilities, the total "external" funding available to local communities in relation to total implementation funding requirements for a bikeway plan is often relatively small. Thus, funds for a bikeway implementation must in large measure be allocated from local sources. Bikeways must compete for funds with other local facilities and services needs such as schools, fire and police protection, parks, street maintenance, transit services, social services and the like. Without public endorsement of the plan and an active group of citizenry supporting it, meaningful allocations will never be made. To gain such endorsement, public participation throughout the planning process is essential. However, aside from ongoing citizen review and input, at the conclusion of the process there must be a significant event of public affirmation which lends a mandate and momentum to carry the plan through the final stage of funding and implementation, a process which may be more political than technical.

Appointment of an official bicycle committee composed of citizens and staff is a useful method of creating a knowledgeable group of varied backgrounds and alliances to serve as the catalytic nucleus of citizen action and support. Such a committee frequently is formed in response to citizen concern and lobbying for bicycle facilities and is an ideal forum for community input. The bikeway planning process includes a variety of opportunities for public participation such as:

- Representation on the bicycle committee.
- Attendance at bicycle committee meetings.
- Correspondence and communications.
- Response to questionnaires and surveys.
- Participation in plan review meetings and hearings.
- Participation during consideration for final plan adoption.
- Commentary on funding priorities.
- Participation in fund raising activities.
- Review of specific design proposals.
- Critiquing experience with facilities, laws, ordinances, enforcements and safety education.

To achieve maximum benefit from public input, a communications program should be initiated which not only informs highly involved persons but also creates a sense of awareness within the total community. Committee agenda minutes and special reports as well as exhibits, fliers, newsletters, posters and mass media coverage are all techniques for consideration. In addition to communications, citizen interest and confidence in the bikeway planning program can be kept fresh by a bicycle committee which:

- Can produce results on schedule;
- Gives conscientious consideration to all input whether positive or negative; and
- Is able to initiate speedy action on deficiencies identified by the public which can be readily addressed.

The last item is one which staff members on the bicycle committee should take the lead to help implement early action.

PART II -- GRADE AND AIR QUALITY RESEARCH

This part describes conduct of original research on two locational criteria -- cyclists grade climbing and physiological performance capabilities, and the effects of air quality on bicyclists.*

Grades and Physiological Capabilities

Bicyclists physiological capabilities, particularly the ability to ride up grades, are an important consideration in bikeway locational planning and facility design. They determine whether bicyclists will be able to ride on routes passing over natural features of terrain or man-made facilities which impose changes in elevation.

Despite the importance of grade criteria, a wide range of conflicting standards for grade profiles are presented in current U.S. and European bikeway planning guides. For this reason, original research was undertaken in this project to provide a scientific basis for recommended grade profile relationships. That research is summarized herein and is organized as follows:

- A discussion of basic physiology concepts related to bicyclists is presented.
- A mathematical equation which relates human work efforts to grade riding factors is derived. Variables in the equation are age, weight, sex, aerodynamic drag area, traveling speed, pedaling cadence, and work level of the cyclist; the weight, tire inflation pressure, and wheel diameter of the bicycle; the air speed, and the gradient.
- Validity of the equation is established by comparison of predicted effort levels to physiological measurements on subjects riding uphill grades.
- Application of the grade evaluation methodology is demonstrated through design examples.

Basic Exercise Physiology Applicable to Bikeway Design and Location

Human work is accomplished through the burning of chemical fuels There are two such bodily processes:

- Aerobic metabolism refers to the burning of fuels in the presence of oxygen. This is the method of energy conversion in a sustained manner for long periods of time.
- Anaerobic metabolism is a process in which high energy phosphates are released to achieve very high levels of muscular effort possible only over short periods of time (usually less than two minutes).

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*References 2 and 3 of Chapter 5 provide full details of this research.

Fundamental life-sustaining basal processes also require oxygen. This is referred to as basal metabolism (BMR). The muscular effort characteristic of high energy championship athletic performance may necessitate energy at rates 50 times the BMR, but only for a few seconds. Steady-state, aerobic activity for the average healthy young man extends up to approximately twelve times the BMR. Highly trained endurance athletes possess the highest aerobic work capacities and can sustain activity requiring oxygen at rates up to 17 times BMR for two to three hours.

Factors Influencing Aerobic Capacity

Aerobic capacity (VO_2max) is a measure of the quality of the cardiorespiratory system, including the pumping of the heart, and the efficiency of blood flow distribution and oxygen utilization. In addition to athletic prowess, there are other factors which influence one's aerobic capacity, including body size, age and one's sex. Furthermore, there is a rather wide range of values in the total population of any group.

Table 73 shows maximum aerobic capacity for healthy, untrained males and females of various ages as drawn from three studies: A study of active, untrained Swedish males and females by Astrand and Rodahl; a study of untrained males in Boston by Robinson (1938); and a study of sedentary untrained males at Davis, California.*

Figure 26 presents additional data from the studies at Davis on maximum aerobic capacity. The dominant line denotes mean values for sedentary, untrained males. Lighter lines indicate plus or minus one standard deviation, and encompass approximately 68 percent of the normal untrained population. Other values are given for trained athletes and nontrained patients with coronary artery disease to further illustrate the range of aerobic capacity.

The mean values for children and young adults under 20 indicate that even at very young ages, they are capable of higher aerobic capacity than most middle age agults. Furthermore, since most of them tend to be more active than adults, their standard deviation is not quite as large. No differences between males and females are evidenced before puberty. Thereafter, values for females are between 80 and 90 percent of those for males of corresponding age. Peak values for both sexes are reached shortly after puberty and are followed by a gradual decline with advancing age. The values depicted on the figure and table vividly support

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*Values used in compiling Table 73 have been adjusted for slight inherent differences in measurements made using motor driven treadmill and bicycle ergometer techniques.

Table 73

MAXIMAL OXYGEN UPTAKE FOR HEALTHY, NONTRAINED MALES AND FEMALES
(ml/min kg)

	Age Range	-3 S.D.	-1.15 S.D.	-0.67 S.D.	$\bar{x}$	+0.67 S.D.	+1.15 S.D.	+3 S.D.
Females	20-29	23.9	32.0	34.2	37.1	40.0	42.2	50.3
	30-39	20.3	29.5	31.5	34.7	37.9	39.2	49.1
	40-49	22.1	27.1	28.4	30.2	32.0	33.3	38.3
	50-65	18.3	23.1	24.6	26.4	28.2	29.5	34.5
Males	20-29	28.4	37.6	40.1	43.4	46.7	49.2	58.4
	30-39	24.2	32.3	34.5	37.4	40.3	42.5	50.6
	40-49	23.5	30.9	32.8	35.5	38.2	40.1	47.5
	50-59	19.9	27.7	29.7	32.5	35.3	37.3	45.1
	60-69	16.4	23.8	25.7	28.4	31.1	33.0	40.4
	70-82	9.2	18.4	20.9	24.2	27.5	30.0	39.2

The standard deviation for the various groups varied from 2.7 to 5.0.

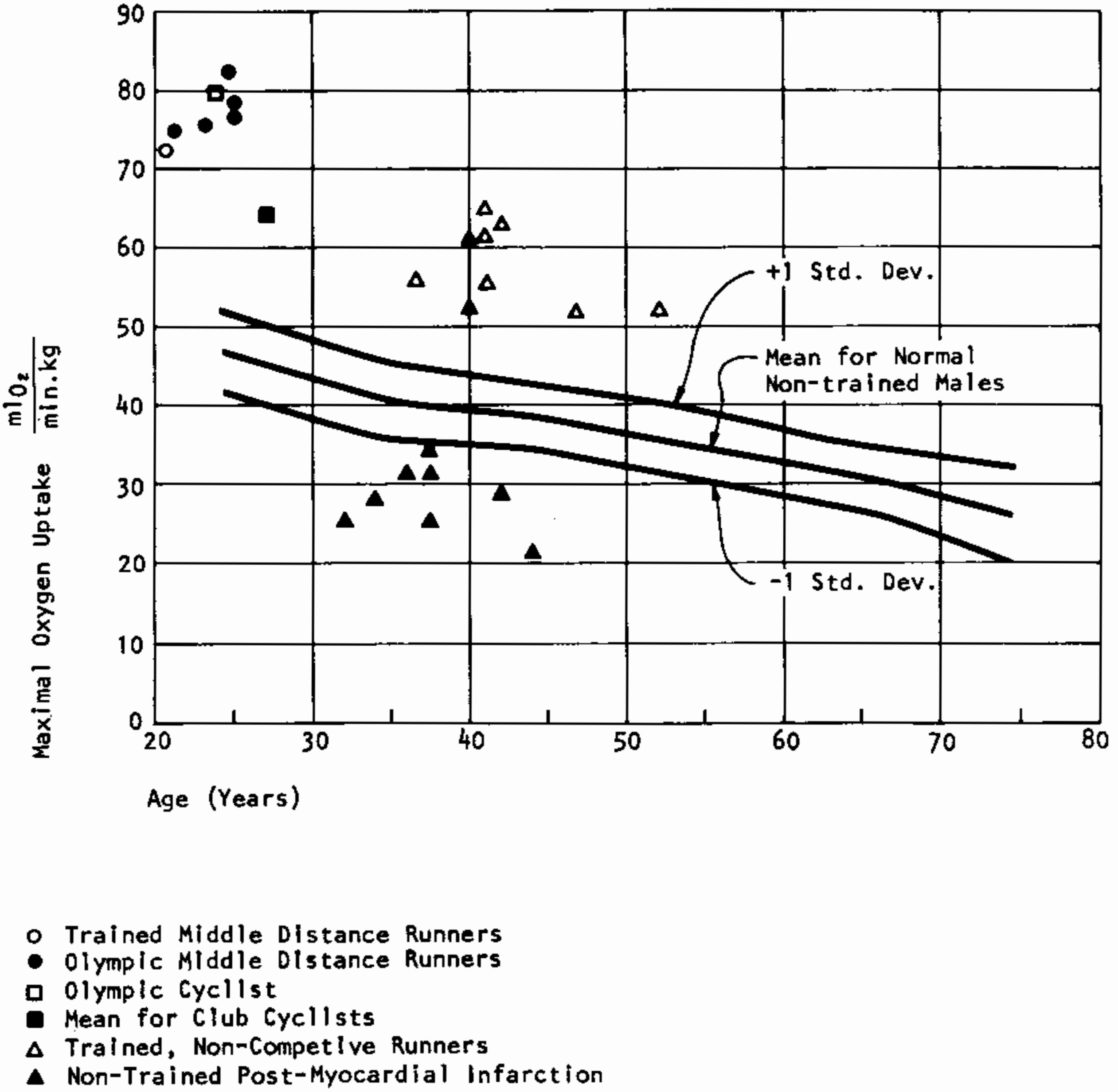

Figure 26
PHYSIOLOGICAL WORK CAPACITY RANGE

the fact that there is a wide variability in aerobic capacity in relation to age, sex, training level and presence of cardiovascular disease.

While aerobic capacity sets the limit for sustained physiological work, people cannot approach this capacity for more than a few minutes. The duration over which various levels of work within the aerobic range can be undertaken is given in Figure 27. The upper curve indicates limits for well trained athletes; the lower for untrained individuals. As data for untrained subjects is limited, it is likely that most would actually fall within the shaded area. The key point is that if a bicyclist wished to ride continuously for periods of one hour or more, he must ride at a level of effort which does not exceed between 50 and 90 percent of his maximum aerobic capability, depending upon his level of training.

While the above notion is of little importance in terms of design of bikeway grade separations or location of facilities for short-haul commuter traffic, it is of utmost significance in the selection of routes with grades acceptable to a recreational touring population. Recreational bikeways must be designed for the aerobic capacity of most potential users, with attention given to appropriate combination of grades and acceptable minimum speeds such that cyclists are not forced to work too close to their aerobic maximums for prolonged periods of time. In using Figure 27 for estimating acceptable grade, speed combinations for the recreational touring cyclist something less than the maximum prolonged duration of aerobic work is suggested. In the present paper, 50 percent of the maximum predicted time is used to indicate the "maximum tolerable" time for aerobic work.

Individuals can exceed their maximum aerobic capabilities -- that is, work in the anaerobic range -- but only for brief periods of time. Figure 28 presents work duration tolerances transitioning from the upper limits of aerobic capability into the anaerobic range. The curve in the figure reflects capabilities of ordinary cyclists who have approximately 70 percent of the capability achieved by champion endurance athletes.

In applying Figure 28 to estimate acceptable grade-speed combinations, it is suggested that 33 percent of the maximum duration (to exhaustion) be used. This is conservative in the case of healthy young male adults, but appropriate for young children, most women and middle-age adult males. Older persons and those with cardiorespiratory disease should not be required to exceed their aerobic capacity, even for a few seconds.

Grade Evaluation Equation Development

Net power required to propel a bicycle at a constant velocity is given by the product of that velocity and the forces required to overcome air drag, rolling and mechanical resistance, and gravity (on uphill segments). According to principals of elementary mechanics, this relationship can be shown to be given by the following equation:

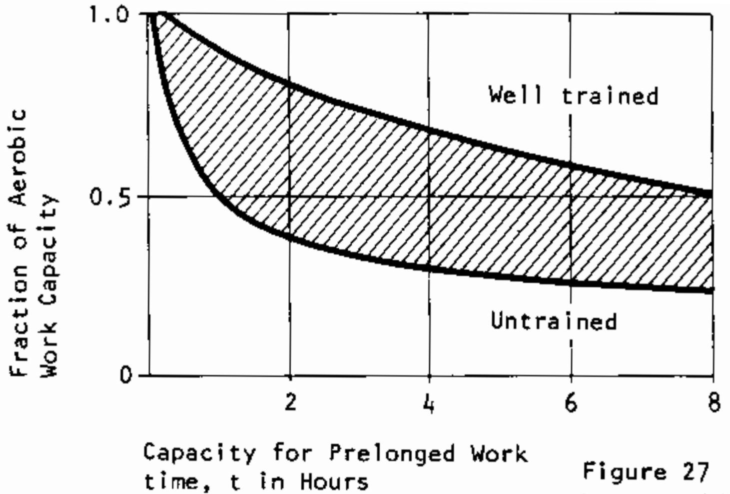

Figure 27
WORK DURATION CAPABILITY AEROBIC RANGE
(Source: Astrand & Rodahl)

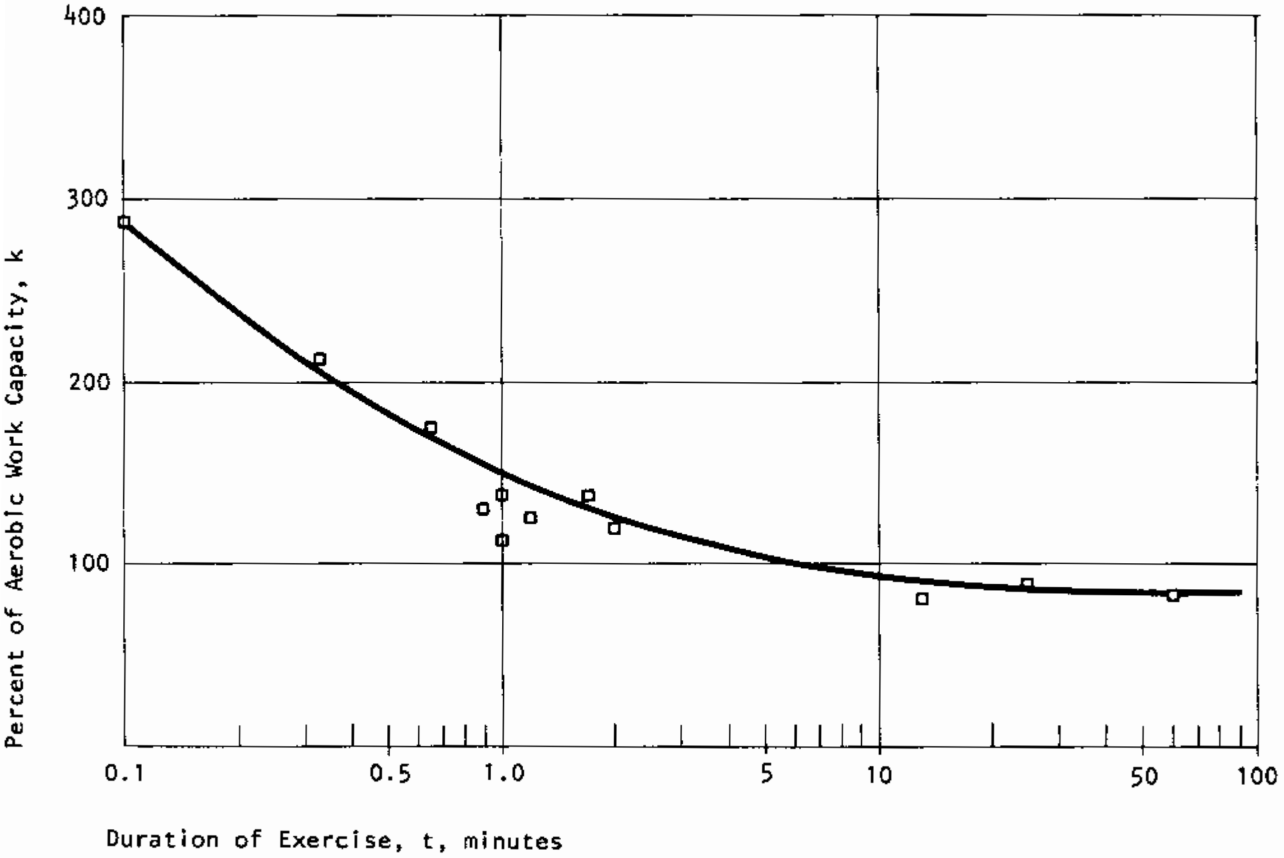

Figure 28
WORK DURATION CAPABILITY ANAEROBIC RANGE
(Source: Modified from D. R. Wilkie)

$$P_R = \left[\phi(W_B + W_R) + \left(0.005 + \frac{0.15}{T}\right)(W_B + W_R) + 0.00256(v + q)^2 A_D\right] v$$

where

W_B = bicycle weight (lbs)

W_R = rider weight (lbs)

ϕ = the angle of the hill to the horizontal

v = bicycle travel speed (MPH)

q = wind velocity (MPH)

A_D = bicycle and rider drag area (sq. ft.)

T = tire inflation pressure (psi)

This above expression gives only the net power requirement at the bicycle's rear wheel; it does not precisely define the level of physiological effort required of the bicyclist to produce this net power output. This is because the conversion of metabolic (aerobic or anaerobic) to mechanical work on a bicycle is a function of the pedaling rate and the amount of mechanical work to be done.

Attempts were made to use existing data found in the literature to define the relationship between metabolic and mechanical energy. However, this effort was not entirely successful because so few tests were conducted at slow pedaling rates. As a result, a series of experiments were conducted as part of this project to define the relationship of the metabolic work rate to net power produced for a wide range of pedal frequencies.

The experiments consisted of having three male subjects ride a bicycle ergometer at pedal frequencies ranging from 30 to 120 complete revolutions per minute (rpm) while working against resistances that produced a net power output ranging from 0 to 1,200 kilogram meters per minute (kg.m/min).

This data was combined with that of Bannister and Jackson (1967) and a series of curves showing the effect of pedal frequency and required metabolic work rate for net power outputs of up to 2,000 kg.m/min were developed. These are shown on Figure 29.

By knowing the pedal frequency of the cyclist and the net power output required, Figure 29 can be used to determine the metabolic work

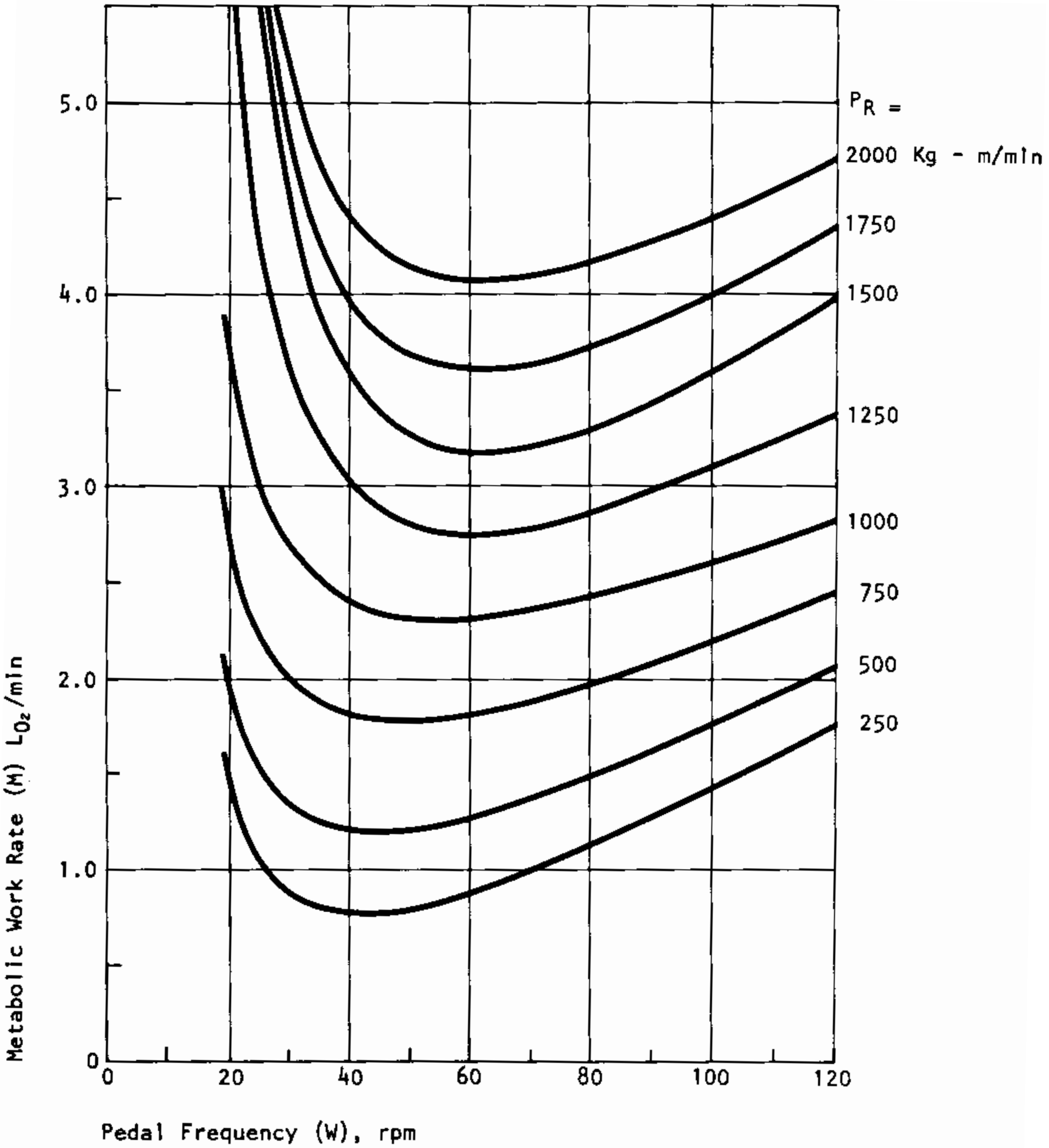

Figure 29
PEDAL FREQUENCY - METABOLIC - MECHANICAL WORK RELATIONSHIP

rate at which the cyclist must perform. This metabolic work rate can be compared to the cyclist's individual capabilities to determine how long he or she could perform on a given grade at a given speed.

Figure 29 can also be used in combination with the net power equation and the relationship between velocity, bicycle size, gear ratio selected and pedal frequency,

$$W = 28.01\frac{v}{DR}$$

where

W = pedal frequency

v = speed (MPH)

D = wheel diameter (ft.)

R = gear ratio

to determine the grade an individual could ride at a specified level of effort (percent aerobic work capacity). The following steps illustrate this process.

- First, the pedal frequency-bicycle size-bicycle gear ratio-velocity relationship is solved for the given bicycle and speed parameters to determine necessary pedal frequency.

- The desired percentage of the indivudual's maximum aerobic work capacity is taken and converted to the units of Figure 29.

- Figure 29 is entered at the above determined values of pedal frequency and work rate and the net power requirement is determined from the curve which intersects the point given by the above values.

- Finally, the net power equation is solved for the grade which could be climbed.

The procedure just outlined can be somewhat simplified if one assumes that cyclists always pedal at an optimal pedaling rate. In this case, Figure 29 may be replaced by a single expression defining the relationship of metabolic to mechanical work. This relationship is given on Figure 30. Using this figure one can simply enter at the specified metabolic work rate, determine the net power and then solve the net power equation for grade.

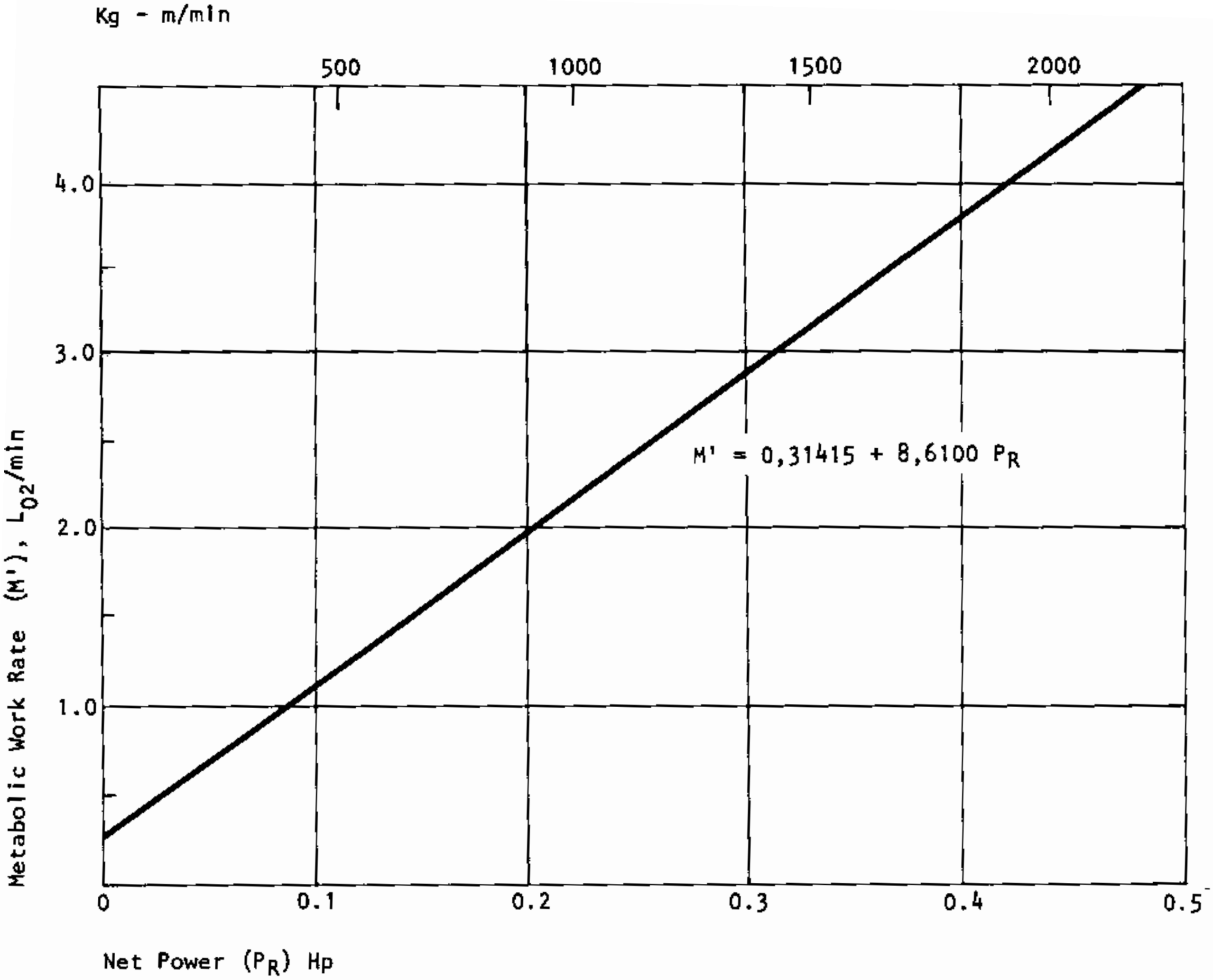

Figure 30
METABOLIC TO MECHANICAL WORK RELATIONSHIP

Validation of the Grade Evaluation Procedure

To verify that the procedures above accurately describe the relationships between grade and bicyclist work effort, a series of tests were undertaken in which cyclists work rates were measured while riding on uphill grades. Six subjects were each tested at speeds of 7.5, 10, 12.5 and 15 MPH on grades of 0, 1, 4 and 6 percent. Comparison of test results, indicated by the solid points on Figure 31, to predicted values indicated by the lines on the figure, shows extremely close correlation between measured and predicted vlaues. On this basis the grade evaluation methodology is judged satisfactory as a planning and design instrument.

Practical Application of the Grade Evaluation Procedure

In application of grade evaluation procedures to a location or design problem, it is important to consider the range of physiological capabilities of various cyclists who might use the bikeway. Table 74 presents data on a set of cyclists who might be considered reasonable design types for grade evaluation. Except for the post-cardiac case, all are representative of the low-normal (25th percentile) range of physiological capabilities within their respective age groups. In each grade evaluation, the recommended procedure is for the grade to be evaluated for each of the representative cyclists. Then, if the grade is not satisfactory for some of the cyclists, the planner must determine whether this fact is important in light of the objective of the specific facility and the likely cyclist propulation who might wish to use it. For instance, the 55 year old male and female cyclists might be considered the cyclists whose capabilities would be used as a design control on a recreational facility in a retirement community but not on a commuter-oriented route in an urban center.

To simplify application of the grade evaluation methodology, grade to work capability relationships have been solved for each of the design cyclists. These are presented on Figures 32 through 37. In each it is assumed that the cyclist is riding a three speed bicycle in the closest to optimal gear ratio possible. For design purposes a minimum steady-state climbing speed of six miles per hour should be used. Curves for ten miles per hour climb speed are also shown on the figures for comparison purposes.

Practical application of the grade evaluation methodology is illustrated in the sample locational choice and grade design problems below.

Sample Design Problem

The following design problem is posed:

A grade separation will necessitate an elevation change of 20 feet for bicyclists. No site constraints are present but reasonably

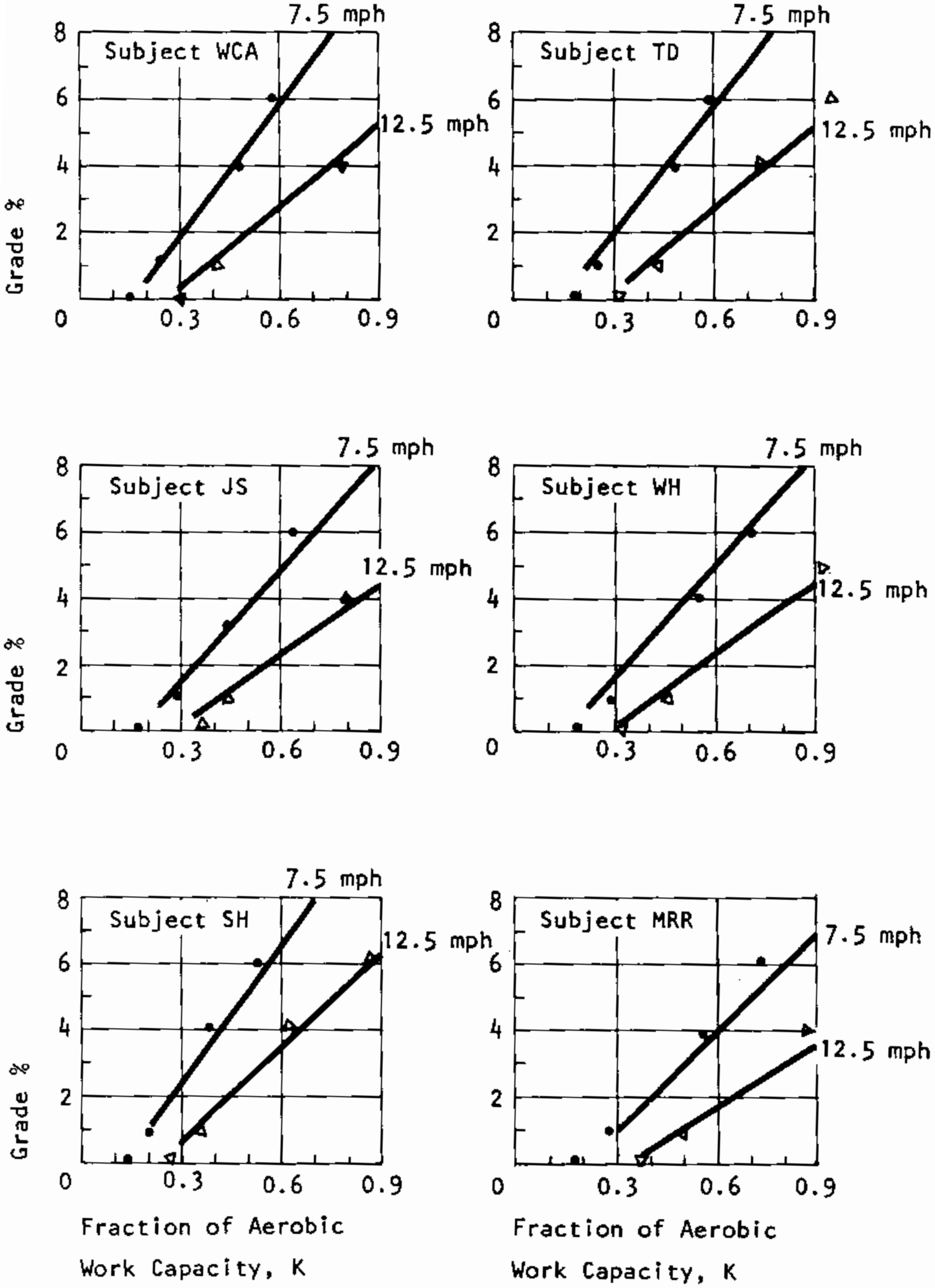

Figure 31
COMPARISON: MEASURED TO PREDICTED GRADE-WORK RELATIONSHIP

Table 74
REPRESENTATIVE CYCLIST TYPES

Cyclist	Age (yrs)	Sex	Wheel Dia. D ft.	Tire infl.prss. T psi	Bike Wt. W_B lb.	Rider Wt. W_R lb.	Max. aerobic work rate, O_2, ml/min-Kg	Drag Area A_D ft^2	Comments
1	12	M	2.25	60	35	90	41	3.0	
2	22	M	2.25	60	35	160	41	4.0	
3	30	F	2.25	60	35	130	33	3.5	
4	40	M	2.25	60	35	175	25	4.0	Post-coronary subject
5	55	M	2.25	60	35	185	30	4.0	
6	55	F	2.25	60	35	145	25	3.5	

Note: All subjects were assumed to be riding a 3-speed bicycle with gear ratios of 1.9, 2.5 and 3.4.

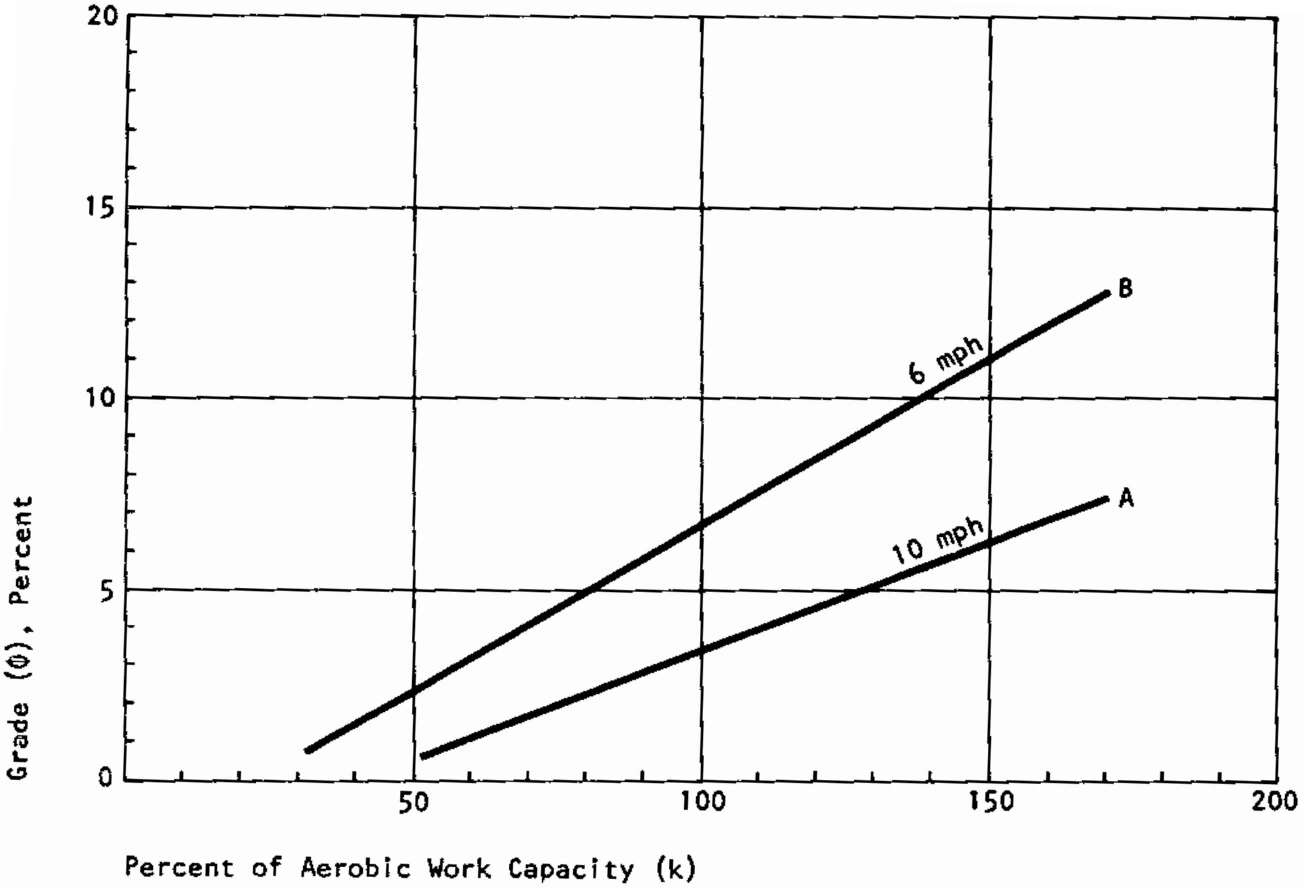

Figure 32
GRADE VS AEROBIC WORK CAPACITY -
12 YEAR OLD MALE DESIGN CYCLIST

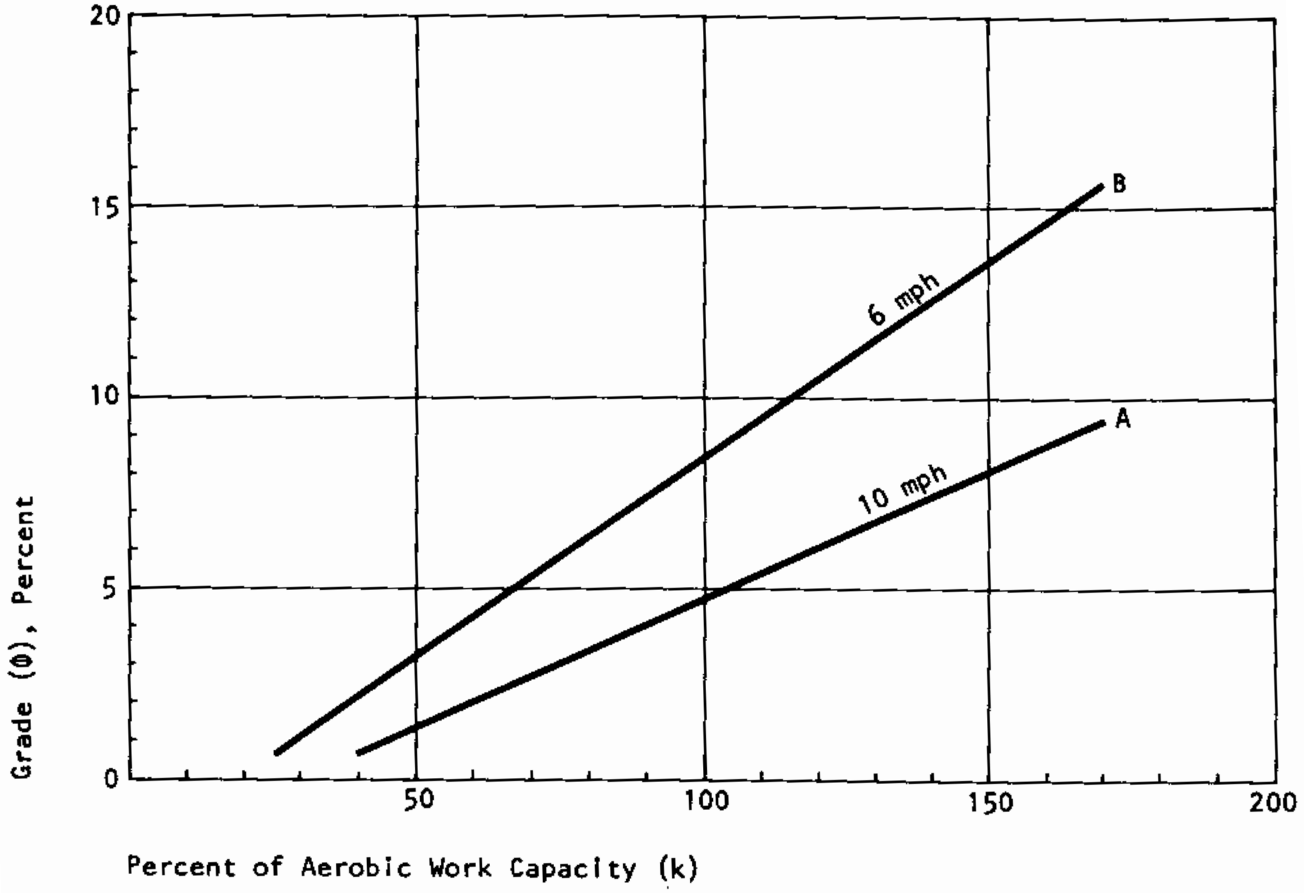

Figure 33
GRADE VS AEROBIC WORK CAPACITY -
22 YEAR OLD DESIGN CYCLIST

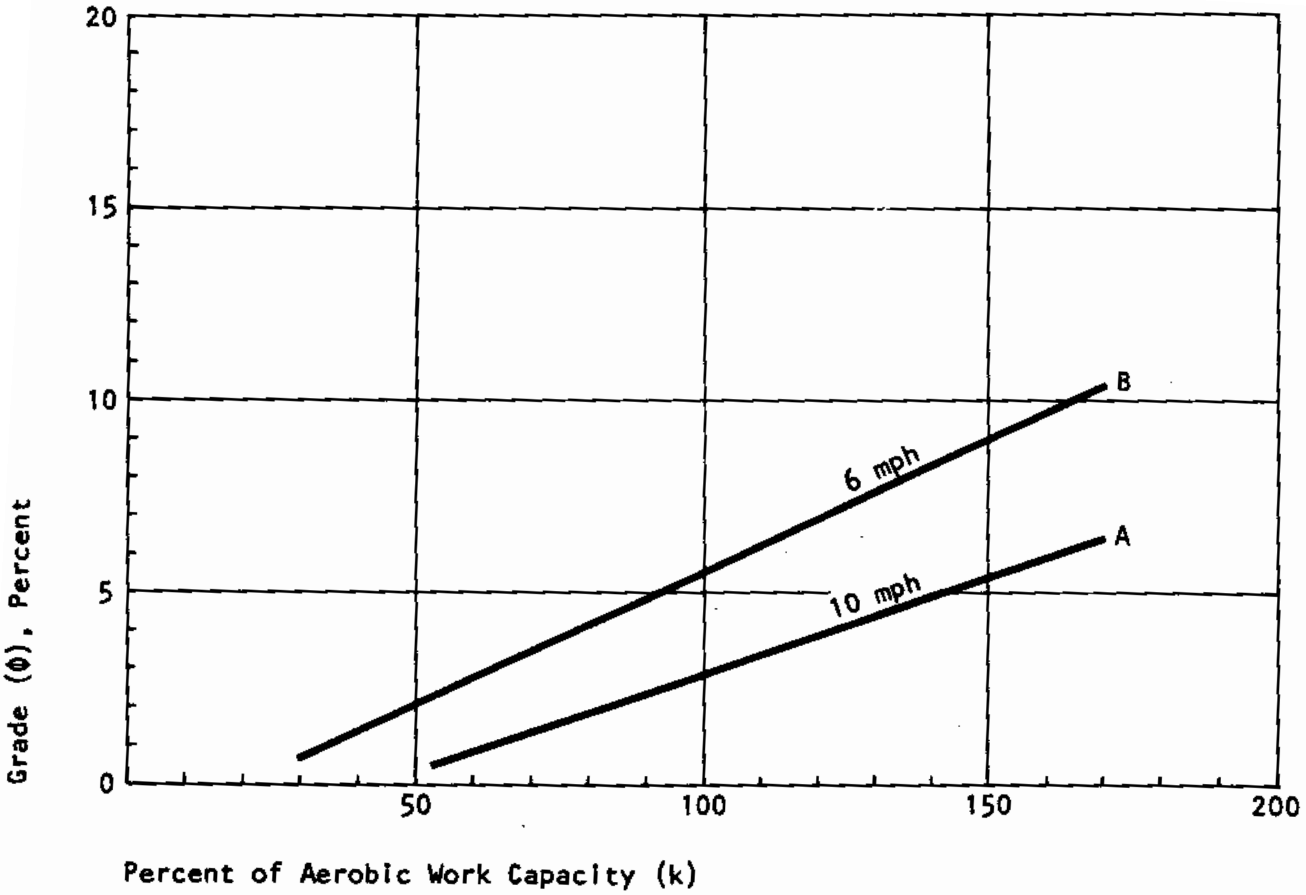

Figure 34
GRADE VS AEROBIC WORK CAPACITY -
30 YEAR OLD FEMALE DESIGN CYCLIST

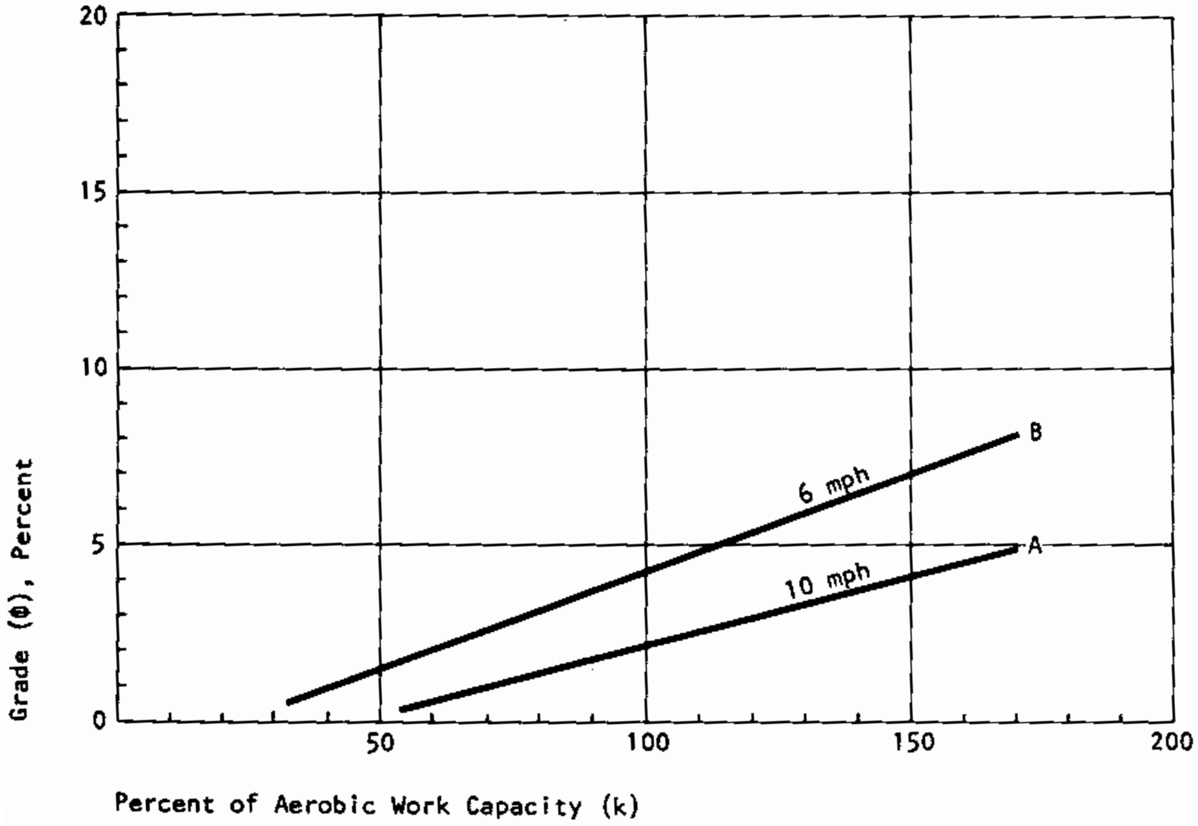

Figure 35
GRADE VS AEROBIC WORK CAPACITY -
40 YEAR OLD MALE (POST CORONARY) DESIGN CYCLIST

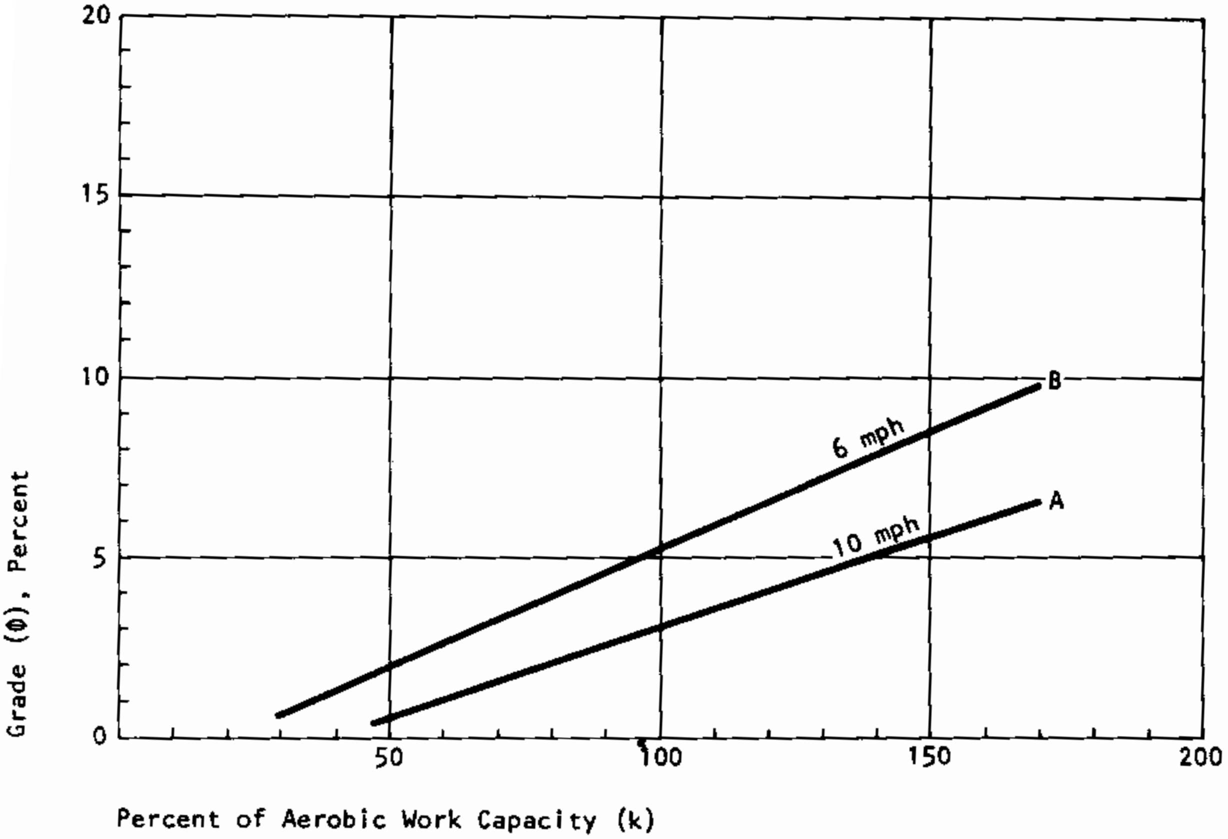

Figure 36
GRADE VS AEROBIC WORK CAPACITY -
55 YEAR OLD MALE DESIGN CYCLIST

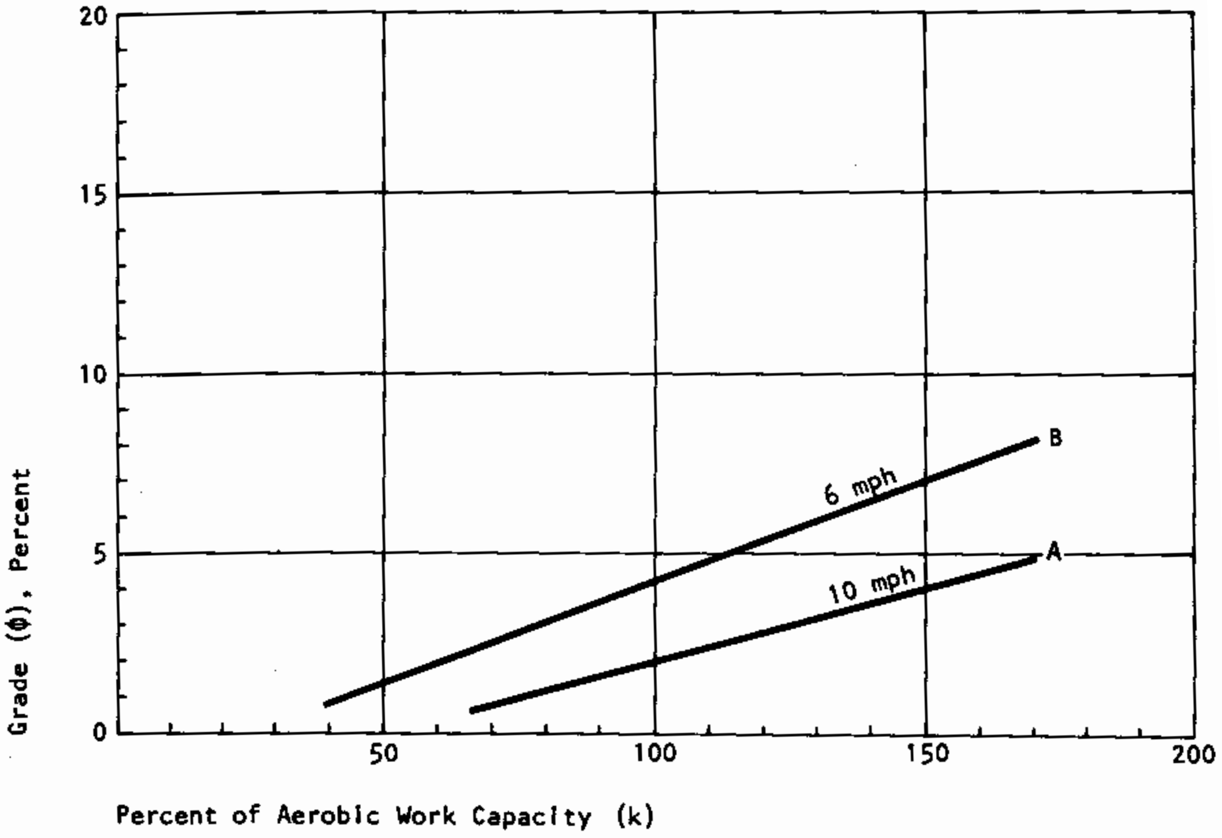

Figure 37
GRADE VS AEROBIC WORK CAPACITY -
55 YEAR OLD FEMALE DESIGN CYCLIST

short approaches are desired to limit costs.

Analysis procedures for design involve a trial and error solution comprised of the following steps:

1. Select a grade profile to suit the change in elevation required.
2. Calculate deceleration distance from the base of the grade to the point at which speed drops to a steady-state climbing speed.
3. Subtract deceleration distance from total grade distance -- determine time to climb this distance based on steady-state speed.
4. Determine aerobic work requirement for various anticipated design cyclists for the chosen grade from Figures 32 through 37.
5. Determine maximum time that each cyclist can work at the above work rate.
6. Compare calculated time for climbing to maximum allowable time each cyclist can work and evaluate for acceptability. If unacceptable, repeat the process under new grade profile assumptions.

This procedure is carried out for the specifications in the sample design problem below.

<u>Step 1</u>: The designer assumes an approach grade of eight percent.

Grade Length (L) = 20 feet/8 percent = 250 feet.

Step 2: The distance cyclists' initial momentum will carry them up the hill (L') until a steady-state speed of six miles per hour is reached is approximately by:

$$L' = (V_i^2 - V^2)\frac{1}{2gG}$$

where

V = steady state climb velocity (assumes 6 MPH)

V_i = initial approach velocity

g = acceleration due to gravity (32.2 ft/sec^2)

G = grade (ft/ft)

<u>Step 3</u>: Assuming an initial approach speed of 15 MPH, L' = 79 feet. The distance cyclists must pedal upgrade at six miles per hour (1) is given by L-L' = 171 feet. Critical travel time (t) = distance/speed = 171 feet/6 MPH = 19.4 seconds.

Step 4: Next, cyclist work rate on the six miles per hour steady-state segment is determined from Figures 32 through 37. These values are entered on Table 73.

Step 5: The duration each cyclist can perform at the above work rate is determined from Figure 28 if the work rate is in the anaerobic range or 27 if the work rate is in the aerobic range. Acceptable work durations are estimated as one-third the exhaustion level durations given in Figure 28 or one-half those given in Figure 27 and these are entered on Table 75.

Step 6: Acceptable work durations determined in Step 5 are compared to the required work duration determined in Step 3.

Assessing the results on Table 75, it can be seen that only the 22 year old male can ride the grade working in the aerobic range. The 12 year old male, the 30 year old female and the 55 year old male would be forced to work in their anaerobic range but the 19.4 seconds required to ride the grade would fall within their duration tolerances. Only the 40 year old post-coronary patient and the 55 year old female would be unable to ride the grade within reasonable limits of effort and duration. The designer may accept this result or may elect to repeat the evaluation, testing a less steep grade profile.

Locational Choice Example

The following locational choice situation is posed: One alternative for a recreational route involves a five percent grade extending .5 miles while a second alternative involves a three percent grade extending .8 miles. Which alternative should be selected?

The approach to this locational problem is similar to the design problem above except that the trial and error iteration is eliminated -- the grade/length parameters are specified and the question is simply whether cyclists can ride them.

For each grade, required duration of grade riding is determined by dividing the grade lengths by six miles per hour. Riding duration is converted to minutes. Necessary riding duration at this speed for both grade profiles is shown on Table 76. Note that effect of the cyclists initial velocity was omitted in this calculation as grade lengths are relatively long.

Figures 32 through 37 are entered at the appropriate grade percentages to determine the percent of aerobic work capacity required of each cyclist to ride the given grades at six miles per hour. These values are shown on Table 76.

Table 75
SUMMARY OF AEROBIC WORK CAPACITY

Subject	Percent Maximum Aerobic Work Capability (k)	Time to Exhaustion	Permissable Exercise Duration One-third Time to Exhaustion
12-year-old male	114	155 seconds	51 seconds
22-year-old male	95	440 seconds	146 seconds
30-year-old female	134	90 seconds	30 seconds
40-year-old male*	166	42 seconds	14 seconds
55-year-old male	138	84 seconds	27 seconds
55-year-old female	166	42 seconds	14 seconds

* Post-coronary patient.

Table 76
EVALUATION TABLE

Cyclist	Work % Required		5% Grade Work Duration		3% Grade Work Duration	
	5%	3%	Required	Capability	Required	Capability
12 Year Male	82	58	5 min	10 min	8 min	22 min
22 Year Male	67	45	5	15	8	120
30 Year Female	90	60	5	4	8	22
40 Year Male*	112	73	5	1	8	10
55 Year Male	93	64	5	3.3	8	15
55 Year Female	110	75	5	1	8	10

* Post-coronary patient.

Many of the values of work requirement indicated on the table are well within bicyclists' aerobic work range and times to exhaustion are well above those plotted on Figures 27 or 28. For individuals performing at higher percentages of their capability, acceptable duration levels, equal to one-third exhaustion levels shown on Figure 28, are indicated on Table 76. For persons working in the aerobic range, values recorded on Table 76 are one-half the maximum durations indicated on Figure 27.

As can be seen from Table 76, riding the five percent grade would require all but the two most fit cyclists to ride in excess of their duration tolerances. On the longer three percent grade, none of the test cyclists approach their duration tolerances as given on Figure 28 and hence no entries are made in the last column on the table. On the basis of this analysis, a normal conclusion would be that the longer, three percent grade should be favored.

Effects of Photochemical Oxidant on Bicyclists

This section documents detailed research undertaken in this project to investigate the effects of photochemical oxidant on bicyclists. In this work, bicyclists were exposed to ambient levels of oxidant (O_3) and measurements made of effects on pulmonary function, blood biochemical changes and exercise performance. Conclusions were made regarding effects of exposure to O_3 and estimates were made of reasonable levels of bicycling exercise when exposed to high ambient concentrations of photochemical oxidant. Reference 4 of Chapter 5 provides full details on this research.

Air Pollution

Air pollution is comprised of particulate matter, liquid droplets, and gaseous compounds which when added to the air in significant concentrations, produce a measurable effect on man or other animals, vegetation, or materials. Many substances which may be classified as pollutants occur naturally in the ambient environment although generally only in minute quantities. Air pollution is said to exist when the concentrations of these substances reach levels at which they produce measurable effects on man, animals, vegetation or materials.

Pollutants may be primary in nature, having been emitted directly from a specific source such as an auto exhaust or industrial stack, or may be secondary, arising either from interactions among primary pollutants or from interaction of primary pollutants with normal atmospheric constituents.

Air pollution rarely consists of only one toxicant; rather, complex mixtures of pollutants from both primary and secondary sources seem prevalent. Primary pollutants include fine particles (less than 100μ diameter), coarse particles (greater than 100μ diameter), sulfur compounds, organic compounds, nitrogen compounds, carbon compounds, halogen compounds, and radioactive compounds. Important representative secondary pollutants, usually formed as products of photochemical reactions involving primary automobile emissions (hence, called photochemical oxidant or smog), include ozone (O_3), peroxy acyl nitrates (PANs), formaldehyde, and organic hydro-peroxides.

The Rationale of Focusing on O_3

Air pollution research has been directed to control of the most hazardous pollutants, usually after a considerable amount of study of the toxic effects of a specific pollutant at various dosages and under diverse exposure conditions. From a number of such investigations it has been recognized that O_3, the predominant oxidant in photochemical smog (most prevalent in Los Angeles air pollution mixtures), is among the most toxic pollutants found in the atmosphere (Stokinger and Coffin, 1968).

Though completely different in nature from the smog of disasters in London, England, Donora, Pennsylvania, Meuse Valley, Belgium and elsewhere, it has been demonstrated in well controlled experiments that significant anatomical and biochemical lesions occur in the lungs of rodents exposed intermittently to levels of O_3 typical of the South Coast Air Basin (Los Angeles) during the smoggiest seasons (DeLucia et al, 1975). This is in contrast to other pollutants, which cause such changes only at levels well in excess of normal ambient levels. Stokinger and Coffin (1968) view carbon monxide (CO) as the only other pollutant which has atmospheric levels closer to its level of toxicity than O_3, but since CO is a primary polluntant its dispersion into the atmosphere reduces concentrations to relatively low levels, except in close proximity to thoroughfares where it is emitted from automobile exhausts.

Though commonly accepted, yet not well described experimentally, exercise-mediated potentiation of oxidant (and other pollutant) effects at the .27 ppm oxidant alert level is cause for cessation of athletic events, restriction of physical education classes activity, and curtailment of strenuous exercise in recreation programs.

Recently, bicycling activities have provided a primary focus on exercise-smog interactions. Several statements have been written concerning the inadvisability of locating bicycle routes close to heavily traveled transportation routes, due to the hazards of exercising in smog (Grob, 1974; Everett, 1974). Some precautionary measures have been proposed to minimize the inhalation of roadside pollutants. Despite good intentions, the major problem has been the failure to recognize that secondary pollutants, dispersed over a wide geographical area, pose a greater acute and chronic health hazard than the primary pollutants found concentrated near the roadsides. Fortunately, national research emphasis is currently on photochemical air pollutant investigations, involving O_3 and PANS, rather than primary pollutants such as CO, NO, and hydrocarbons.

This research, conducted in the context of this bikeway research program, was designed to provide basic information concerning the threshold levels of O_3 required to induce deteriorative change in lung function and aerobic exercise performance. The purpose was to provide a quantitative basis for air quality-related criteria for bikeway location and use.

Methodology

The specific object of this experiment was to measure the effect of cyclist exposure to common ambient levels of O_3 on pulmonary function, blood biochemical changes and exercise performance.

Six healthy, non-smoking males volunteered to participate in the study. All were average or above in aerobic capacity for their age. Only one subject had previous history of respiratory problems, having received medication as a youth to suppress an asthmatic condition.

As a preliminary to the experiment, aerobic capacities of the subjects were measured. Maximum oxygen uptake (VO_2 max) tests were performed on a Monark bicycle ergometer. Subjects pedaled at a constant frequency of 60 revolutions per minute. Work loads were increased at two minute intervals until subjects neared exhaustion and voluntarily terminated the exercise bout. Expired air exhausted from the Hans-Rudolph respiratory valve was routed through a plexiglas sampling chamber and then through a Parkinson Cowan gas meter. Toward the conclusion of each workload level, samples of expired air were drawn and analyzed for percent O_2 and percent CO_2, using a Beckman E_2 oxygen analyzer and Godart Pulmoanalyzer standard temperature. From this data and measured ventilation rate, maximum oxygen uptake (VO_2) max test was completed if values from the first test deviated significantly from those the subject had recently achieved in other experiments.

A series of twelve one hour experiments including four filtered air controls, four breathing low O_3 (.15 part per million ppm), and four breathing high O_3 (.30 ppm) were completed. There was one resting experiment and three exercise protocols involving workloads of 25 percent, 45 percent, and 65 percent of VO_2 max, respectively, at each level of exposure (i.e., 0, .15, .30 ppm, respectively) The order of occurence of the 12 protocols was randomized for each subject, and a minimum of three to five days was required before the next protocol was administered. The subject was not informed whether he was receiving O_3 or not for any of the twelve conditions imposed. Ambient conditions were determined periodically to insure that metabolic heat and water given off by the subject during exercise did not substantially alter his thermal comfort.

Analysis

A short battery of pulmonary function tests were administered to the subject shortly before and after each testing protocol. The subjects also returned to the laboratory for pulmonary function testing four hours post exposure and 24 hours post exposure, having been instructed to keep their activity minimal until the post-24 hours tests had been completed. Residual volume (RV) measurements were obtained with the oxygen dilution method of Wilmore (1969). Standard determinations of vital capacity (VC), forced expired volume, one second ($FEV_{1.0}$) and maximal midexpiratory flow rate (MMFR) were made from the spirometric tracings and corrected to BTPS. RV, passive vital capacity, and forced maximum breathing maneuvers were done twice at each measurement period to insure that representative values were obtained.

Blood draws were performed just prior to or following pulmonary function measurements. Blood biochemical tests performed included determination of the level of acid-soluble non-protein sulfhydryl in whole blood and erythrocyte lysis and enzymatic assays.

Measurements of respiratory metabolism, heart rate and ventilation patterns were conducted as follows: At minutes 14-15, 29-30, 44-45, and 59-60 of each one hour protocol, VE values and expired air temperature were determined. A 1-1/2 liter aliquot of expired air collected in a rubber bag was transferred into a Beckman E_2 oxygen analyzer via a glass syringe. The remaining air contained in the bag was analyzed for percent CO_2 by attaching the bag to a Godart Pulmoanalyzer.

At minutes 14, 29, 44, and 59 the respiratory rate was determined by use of a subcutaneous temperature probe inserted into the mouthpiece of the Hans-Rudolph respiratory valve. Heart rate was determined at minutes 14, 29, 44, and 59 by recording the nonclinical three lead electrocardiogram (EKG) on a Sanborn 500 Viscocardiette.

Results

By randomizing the sequence of protocols for each subject it was possible to conduct a single blind experiment wherein the subject was not aware of the O_3 level for the various protocols. In the more severe exposures (65 percent of VO_2 max, .15 ppm O_3; 45 percent of VO_2 max, .30 ppm O_3, and 65 percent of VO_2 max, .30 ppm O_3), the appearance of subjective signs of discomfort allowed all subjects to deduce that they had inhaled O_3. In the remaining five, O_3 protocols could not be discriminated from a respective control protocol, since no clear cut signs developed.

- Pulmonary Function Measurements: No consistent increase in RV following O_3 inhalation was observed. A 7.2 percent increase in post-exercise control exposure RV exceeded all increases for O_3 inhalation protocols except the 7.7 percent (ns) RV increase immediately following the 45 percent VO_2 max, .30 ppm O_3. Similarly, vital capacity (VC) was mainly unaffected by O_3 exposure, although a twelve percent decrement ($P < .05$) in the extreme conditions of the 65 percent VO_2 max, .30 ppm O_3 exposure was observed. The significance of this small percentage decrease is amplified by the consistency of the VC measurements in control protocols (maximum changes of 99.3 to 101.6 percent of pre-exposure values). The decrement in VC was transient in that VC returned to control levels four hours post-exposure.

- Forced Expired Volume, 1 Second ($FEV_{1.0}$): The $FEV_{1.0}$ determinations appeared to be somewhat more sensitive than VC. A significant decrease (12 percent, $p < .05$) in $FEV_{1.0}$ was evoked by the 65 percent VO_2 max, .30 ppm O_3 protocol, while a 5.7 percent diminution of $FEV_{1.0}$ was noted at 45 percent VO_2 max, .30 ppm O_3. The latter was not statistically significant but appears meaningful in the light of control figures which were consistent (97.8 to 102.3 percent of pre-exercise values). As with VC, following four and 24 hours of recovery, essentially normal values were obtained.

- Maximal Mid-Expiratory Flow Rate (MMFR): A more variable measure than other pulmonary function parameters, MMFR on control and low workload protocols with O_3 varied between 92.9 and 120.3 percent of control, with standard deviations of up to 20 percent. Subsequent to the 65 percent VO_2 max, .30 ppm O_3 protocol, MMFR decreased to 82.0 ± 13.2 percent of control ($P < .05$), showing the greatest relative change compared to other parameters calculated (RV, VC, $FEV_{1.0}$). Four hours following this protocol, MMFR was 92.6 ± 8.6 percent of pre-exposure values ($P < .05$).

- Exercise Performance: Oxygen consumption (VO_2) measurements did not show any effect of O_3 exposure. Even in the most severe protocols, despite the fact that breathing pattern was substantially altered from that of control bouts, VO_2 remained essentially constant.

  Ventilation volume (VE) measurements, similarly, were unaffected by O_3 exposure.

  In contrast to O_2 consumption and ventilation volume, the respiratory rate (RR) of the subjects was observed to undergo a time-dependent increase during the 65 percent VO_2 max, .30 ppm O_3 protocol. With other exposure protocols, RR was not affected.

- Blood Biochemical Changes: In humans, blood enzyme levels and levels of low molecular weight reducing substance have been shown to change following 2-3/4 hour inhalation of .5 ppm O_3. In that study, (Buckley et al., 1975) intermittent exercise sufficient to double minute ventilation was required (15 minutes exercising, 15 quiesent). It was of particular interest to compare our protocols, demanding more work, but involving lower O_3 levels and shorter exposures to those reported. Non-protein sulfhydryl (NPSH), used as intracellular antioxidants and substrates for many reactions requiring a transfer of reducing equivalents in the erythrocyte, were not altered by O_3 inhalation. No consistent changes associated with O_3 exposure protocols were noted. The mean pre-exposure levels of blood NPSH for all subjects ranged between 770 and 864 nanomoles/ml blood for the 12 protocols administered. When calculated on the basis of hemoglobin (to correct for fluid shifts during exercise) mean pre-exposure values ranged between 5.0 and 7.5 μ moles/g Hb. Following exposure, mean values per ml blood ranged between 755 and 881 nanomoles per ml (92-109 percent of respective controls). Mean post-exposure values expressed per g Hb ranged between 5.5 and 7.1 μ moles/g Hb (91 - 122 percent of respective controls).

Activities of red blood cell G6PD, 6PGD, and GR have been related to maintenance of functional integrity of the erythrocyte, since cases of deficiencies of these enzymes have been often correlated with clinically observed hemolytic conditions. In the present study, the activities of these three enzymes were not altered by O_3 inhalation.

This research with lower levels of O_3 exposure than the previously described work of Bates, did not show significant pulmonary function changes at low ventilation volumes similar to these obtained in the exercise Bates imposed. Approximately three- and four-fold increases in resting VE were incurred at the 25 percent and 45 percent VO_2 max work loads, respectively, without producing noticeable changes in pulmonary function. However, it was shown in the present study that exposure to .15 and .30 ppm O_3 at the most difficult work load, entailing 65 percent of VO_2 max and a seven-fold increase in VE for one hour resulted in marked symptoms of discomfort and also impaired lung function. Thus, a single one hour exposure to levels of O_3 approximating current smog alert levels for oxidant can produce rather distinctive changes in lung function, in the face of fairly severe aerobic work loads. This indicates clearly that exercise must be included to discern thresholds of air pollutant toxicity, especially since individual variability is so distinct. Subject RS, for example, had a 28 percent loss of VC and MMFR, and a 25 percent decrease in $FEV_{1.0}$ immediately following work for one hour at 65 percent VO_2 max, .30 ppm, whereas for the same protocol subject MR decreased VC by four percent, $FEV_{1.0}$ by seven percent, and increased his MMFR by five percent. For each individual, the response to ambient O_3 levels is apparently dictated mainly by the exercise stress administered, since at rest subjective signs of discomfort and altered pulmonary function were not observed. At the opposite extreme, 65 percent VO_2 max, .30 ppm O_3, all subjects reported symptoms and performed less effectively on at least one pulmonary function test. Furthermore, the general trend in the 65 percent VO_2 max, .15 ppm O_3 and 45 VO_2 max, .30 ppm O_3 protocols, was at least a marginal deterioration in resting pulmonary function parameters for all subjects, with subjects RS and TB reporting heavy symptoms and demonstrating larger and longer lasting effects than other subjects. The percent of control values for pulmonary function and ventilatory measurements obtained with the most sensitive individuals, RS and TB, are given in Table 77.

Table 77
RESTING AND EXERCISE PULMONARY FUNCTION, PERCENT OF CONTROL

65% VO_2 max, .15 ppm O_3 Subject	RV	VC	FEV	MFFR	RR at 60 minutes	$\bar{x}$ TV at 60 minutes
RS	125.8	89.3	89.5	84.2	175.6	72.0
TB	99.1	88.4	91.8	94.2	139.5	71.2
45% VO_2 max, .30 ppm O_3 Subject						
RS	112.0	82.0	82.7	72.9	137.9	94.0
TB	121.7	90.2	94.2	101.1	134.3*	91.7*

*Respiratory rate and tidal volume from 45'.

- Decrements in work performance associated with O_3 inhalation: For both of the two most sensitive subjects, responses to 65 percent VO_2 max, .30 ppm O_3, including increased RR, decreased TV, increased work of breathing, and fatigue were accompanied by excessive inability to work at 65 percent VO_2 max for the full hour. For both, the workload was dropped by lowering either the pedaling rate or the frictional resistance setting of the ergometer.

Whereas a performance decrement in high school cross country runners was attributed to photochemical oxidant (Wayne et al, 1967), it was not actually possible to separate psychological factors from physiological changes. However, inhalation of artificial photochemical smog (Holland et al, 1968), high and low ambient levels of O_3 (Follinsbee et al, 1975) and 0.27 ppm PAN or 50 ppm CO, alone and in combination, (Raven et al, 1974) did not cause alterations in exercise VO_2. The smog-mediated interference with the O_2 uptake systems in the respiratory tract, blood, and muscle is apparently minimal, but as shown in the present study, either volitional or subconscious alteration of breathing patterns when exercising in smoggy environments can lead to performance decrements, especially in sensitive individuals. Since a well-defined biochemical lesion related to O_3 exposure, namely oxidation of SH groups of proteins and non-protein compounds, is presumed to be characteristic of many pulmonary irritants, it is likely that important receptor sites are stimulated by O_3 inhalation and initiate reflex reaction to minimize penetration of airborne chemicals into the delicate parenchymal tissues of the lung (Alarie, 1973). With ventilation held constant, as in the present experiment, decreased TV can substantially reduce the effective ventilation which reaches alveolar exchange areas. A greater fraction of ventilated air merely ebbs and flows in the larger non-exchange airways, possibly limiting O_2 extraction.

In a recent study, Follinsbee et al (1975) showed that a two hour exposure to .37, .50, or .75 ppm O_3 at rest, or with intermittent exercise sufficient (15 minutes, every half hour) to increase VE 2.5 times, gave substantially different ventilatory patterns during a post-exposure test of exercise response to work requiring approximately 75 percent of VO_2 max. It is surprising that a "primer" exposure to two hours of low exercise and smog can damage lung tissue enough to alter the mechanics of ventilation throughout an exercise bout lasting only three minutes. The brevity of the work bout at 75 percent of VO_2 max prevents assessment of work capacity, but considering TV was 50 percent lower than control following the O_3 pre-exposure, a performance decrement (i.e., maximum work time at 75 percent of VO_2 max) max would be expected.

- Blood biochemical changes with low level O_3 exposure: Ozone and other oxidants are thought to exert toxicity at the cellular level by virtue of their ability to react with important cellular constituents (Menzel, 1970). Ozone, for example, is highly reactive with various amino acids, vitamin-derived coenzymes, unsaturated fats, and SH ligand. Marked oxidation of lung SH has been demonstrated in rodents exposed to high levels of O_3 (2.4 ppm), but with ambient levels, significant lung SH decrements have not been reported, perhaps due to enzymatic reduction of the disulfide reaction products back to SH at a rate roughly equivalent to the formation of the S-S (DeWae et al, 1975).

It is extremely important to determine if metabolic lesions such as SH oxidation and membrane destruction occur in human tissues as well as in animal models because: 1) appropriate preventive and therapeutic measures can be implemented to counteract the effects of the gas; and 2) it is important to identify sensitive human populations that may exist. In this light, the demonstration of NPSH oxidation and altered blood enzyme levels in human volunteers exposed to 0.50 ppm O_3 for 2-3/4 hours is an important finding (Buckley et al, 1975), suggesting penetration of free radicals past the lung tissues and into blood of humans after a near-ambient exposure regimen.

In the present study, where lower O_3 levels, but higher exercise demands were utilized, simplified tests for SH and enzyme activities in blood were also performed. Failure to observe changes in blood NPSH and erythrocyte G6PD, 6PGD and GR activities is possibly indicative of a limit in the sensitivity of standard enzyme and SH measurement as indices of low grade biochemical changes which are thought to occur. In blood (a fluid tissue comprising 7 - 8 percent of the body weight of an adult man), a vast amount of actual change is required to alter a metabolic parameter encompassed in a total volume of five to six liters. For example, to produce a ten percent change in blood NPSH level, oxidation of approximately two millimoles of NPSH would be required. One hour inhalation of 70 liters (BTPS) air containing .30 ppm O_3 provides 50 μ moles of inhaled O_3; hence, each O_3 molecule inspired would have to result in an oxidation of 40 blood NPSH ligands. Such a stoichiometry of O_3-mediated SH oxidation exceeds the normal test tube stoichiometry reacted per O_3 molecule (Mudd, 1969).

If absorption of O_3 by the respiratory tract is incomplete, if pulmonary tissues react with O_3 radicals to produce stable products incapable of further free radical reactions, or if compensatory protective mechanisms reverse oxidative lesions mediated by O_3 or its free radical reaction products, then measurable blood biochemical alterations of direct oxidative origin are even more unlikely, especially to the extent of having physiological significance. With regard to the physiological significance of blood biochemical changes, it is important to stress that the loss of NPSH resulting from _in vitro_ treatment of erythrocytes with SH binding agents causes no interference with thiomediated cellular function until almost all the NPSH is bound (Jocelyn, 1973). Similarly, oxidation of SH active sites of enzymes and slight inhibition probably results in no metabolic changes of consequence, since great excess of functional capacity is present for most enzymes and in particular those of the hexose monophosphate shunt and disulfide reduction pathways.

Implications for Bicycle Facility Location and Bicycle Activity

Since photochemical oxidant, O_3, is a secondary pollutant, it tends to be dispersed at consistent levels over wide areas. Hence, it provides no basis for location of a bikeway on one or another of a set of neighboring streets. However, there is variation in the levels of oxidant concentration over a region. Thus, it would be reasonable to emphasize location of regional recreational bicycle facilities in areas of highest air quality. It might also be reasonable to consider ambient levels of smog when considering the desirability of a public policy to encourage bike use such as by providing bikeways.

Exposure to air pollutants experienced by an individual cyclist is a function of the level of work effort in riding as well as the ambient level of pollutant. This is because bicycling or any other form of exercise will increase the lung uptake of a pollutant by:

- Minimizing flow through the nose, which has a much higher uptake of reactive gases than the mouth (Yokohama and Frank, 1972).
- Increasing the flow past the mouth, thus decreasing the relative uptake of the oral surfaces (Yokohama and Frank, 1972).
- Ventilating the lung more uniformly and hence exposing more reactive tissue sites.
- Increasing the replacement of gas which reacts at a given site, since the rate of breathing is faster. In addition, since exercise increases the pressure in the pulmonary circulation, a greater danger of pulmonary edema exists.

Hence the individual cyclist has two options for reducing exposure to pollutants:

- Decreasing the intensity of the ride, or
- Riding at times when and places where concentrations of pollutants are low.

Cyclists can easily reduce the exercise intensity of their rides by reducing speeds and avoiding or further limiting speed on upgrades. Since workloads requiring something in excess of 45 percent VO_2 max, .30 ppm O_3, led to subjective discomfort and pulmonary function decrements in most subjects in the present study, the following speeds and grades appear as reasonable initial guidelines for cyclists seeking to obtain a relatively safe ride, even in moderate-to-heavy photochemical smog. For an average college-age male, 50 percent of VO_2 max would sustain a cycling speed of approximately 14 MPH on the flat whereas, an average 70 year old male would be limited to ten MPH to remain within 50 percent of his VO_2 max. For individuals who react normally to smog-induced lung insult, the sequelae to one to two hour recreational rides at these speeds should be easily tolerated. For young women, approximately 12 - 13 MPH cycling on flat roads would appear reasonable (about 50 percent VO_2 max). On four percent grades, 7.5 MPH should not be exceeded by the average young adult male, a speed which an average college age female could likely sustain on 2-1/2 percent grades without exceeding 50 percent of VO_2 max. Cyclists should resist the temptation to gain a hard workout on rides taken on smoggy days. Following are possible means of avoiding bicycling in high concentrations of photochemical oxidant.

- Since O_3 is created in reactions requiring sunlight, oxidant levels have a diurnal characteristic with peak levels occurring sometime between 12 AM and 6 PM (Stephens, 1973). By riding earlier or later than this period, a significant improvement in air quality would be experienced.

- Both seasonal and geographical factors have important effects on the smog levels in which a cyclist rides. In general, warmer weather increases photochemical smog levels and also aggravates the effects of smog on lung tissues. Except for rare occasions, significantly lower levels of photochemical pollutants occur during fall, winter, and early spring. A premium can be placed upon consistent riding during the less smoggy seasons, with less emphasis on riding during the summer smog peaks.

- Pre-existing respiratory infections greatly increase sensitivity to air pollutants. Thus, it is imperative that full recovery from such illnesses as chest cold, flu, bronchitis, etc., be achieved before cycling in smog is undertaken (Stokinger, 1957)

Since the focus of the present research has been on O_3, liberty to generalize about other air pollution constituents is limited. However, it is important to note that whereas O_3 is definitely a threat at ambient concentrations over wide areas, other pollutants (e.g., CO, lead, oxides of nitrogen, and oxides of sulfur) can exist in heavy concentrations in localized pockets. Carbon monoxide appears especially hazardous due to its interference with O_2 transport (Dinman, 1971). However, since a period of hours is required for CO to reach equilibrium saturation in blood, it is unlikely that quick transit on a bicycle through normal and even commonly occurring maximal concentrations (i.e., at major intersections) would cause the rider to experience meaningful exposure to high CO levels.

It should also be recognized that the ability to tolerate or adapt to short-term changes as reported herein may easily lead to false security, and result in neglecting long term changes in the lung. Such debilitating changes as lung cancer, chronic bronchitis, emphysema, and lung fibrosis could result from years of pollutant exposure.

A final point of emphasis concerns the possibilities of synergistic effects between two or more pollutants. SO_2, presumably non-toxic at normal ambient levels in most cities, was shown to cause diminution in pulmonary function of mildly exercised humans when combined with levels of O_3 that could not mediate such responses if administered alone (Hazucha et al., 1974). Clearly, additional studies should be designed to define the threshold levels of pollutants which can be tolerated without adverse effects to cyclists exposed to a mixture of primary and secondary pollutants.

PART III -- ESTIMATION OF BICYCLE ACTIVITY AND SURVEY RESEARCH TECHNIQUES

This section documents evaluation of existing data and identification of techniques for estimation of bicycle travel activity, review of survey techniques applicable to bikeway planning and assessment of the feasibility of bikeway cost-effectiveness evaluations. Its organization is as follows:

- Bicycle activity estimation techniques recommended for application;
- Survey techniques and pitfalls relevant to bikeway planning; and
- Further discussion of advanced forecasting techniques, original research and existing data on usage factors and cost-effectiveness feasibility.

Recommended Bicycle Activity Estimation Techniques

Recommended techniques for current use in estimating bicycle travel potential are rational procedures which should rely upon readily available data. Sophisticated procedures in the vein of bicycle-specific trip generation/modal split, distribution and assignment models are not recommended for general use at this time due to the current instability of parameters upon which such models would be logically based.

Recommended techniques for identifying potential bicycle travel demand and activity corridors include the following:

- Bicycle traffic counts;
- Bicycle accident records;
- Motor vehicle traffic counts and flow maps;
- Existing regional travel data;
- Major travel generator identification;
- Community group participation; and
- Special surveys.

Bicycle Traffic Counts

The simplest source for bicycle travel data is a bicycle traffic count program, which leads to a "flow map" of bicycle volumes.

Problems inherent to this approach are:

- It says little about bicyclists' origins, destinations or trip purpose.
- It reflects the configuration and quality of the existing bike route/street system, rather than where riders would prefer to travel or what latent demand there might be for the bike facilities. Thus, bike counts indicate only the minimum potential demand.
- Costly manual counting is normally required since bicycles will not usually register on pneumatically actuated traffic counters.*
- Counts must be rather closely spaced to give a representative picture of bike travel activity since bike traffic may vary sharply within short street segments.

Despite these problems, this technique may be useful in some circumstances, such as:

- Where ridership is fairly static, and the analysis is responding to existing deficiencies; and
- In providing checks on other data, such as survey results.

Some communities have developed systematic counting procedures in which a very fine-grained set of bike counts on the entire network are initially taken and analyzed. It is contended that, on the basis of existing count relationships, it is possible to project bike volumes on the entire network by taking new bike counts at a very limited number of key indicator stations. This technique offers a reasonable chance of success in a community where the situation remains relatively static but if the system is perturbed by anything more than marginal change -- the opening of new major activity centers, the addition of new bicycle facilities or elimination of bike travel barriers which would significantly change the accessibility pattern in the community or the attractiveness and safety of bicycling -- the entire count model must be recalibrated. (Popish)

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*Mechanical traffic counters actuated by magnetic conductors have been successfully employed for counting bicycle traffic on off-street facilities "Oregon DOT Bikeways Progress Report," February 1973. However, their applicability for counting mixed traffic is constrained by inability to distinguish between bicycles and motor vehicles. The inability to effectively count bicycles using common pneumatically activated traffic counters has been documented in a test program undertaken in San Diego County, California (Taylor, 1974).

Accident Records

Accident records are useful in several ways:

- To indicate hazardous locations or circumstances for bike travel. This includes review of bicycle and motor vehicle accidents.
- To indicate whether the hazardous situations at these points will respond to physical treatments such as improving traffic control, geometrics or provision of a bikeway facility.
- In some cases, to provide an indirect measure of overall patterns of bicycle activity.

It must be recognized that accident records are an incomplete indicator. Personal decisions of whether or not to make a trip by bicycle and what route to travel are both influenced by the form and quality of existing bike facilities. Certain areas may be so hazardous -- literally unpassable -- that people simply avoid them when bicycling or don't bicycle at all. As a result, these areas are not indicated in the accident statistics. But accident records are a useful preliminary indication of the patterns of bicycle activity and identify important points or corridors of concern.

This type of information is usually readily available in local law enforcement records. However, in most communities with normal levels of bicycling activity it is necessary to analyze bike accident records for several prior years to obtain a sufficient number of incidents for patterns to emerge. Along with accident location analysis, it is important to determine whether the types of accidents found can be eliminated by provision of physical facilities.

Motor Vehicle Traffic Counts and Flow Maps

Another indirect indicator of bicycle activity is motor vehicle traffic counts and motor vehicle flow maps. This is because:

- Utility-oriented and some recreational bicycle traffic, like motor vehicle traffic, tends to concentrate on the fastest and most direct streets.
- Bicycle traffic tends to have as its destinations many of the same activity centers as motor vehicle traffic.

Motor vehicle traffic volume patterns are most suitable as indicators of potential bicycle activity in small and medium-sized communities, particularly when they are self-contained communities rather than part of a larger metropolitan area. Within a large metropolitan area, there is a tendency for long-distance regional traffic to be mixed with and mask local traffic. However, with the exception of freeway and expressway facilities, even in the larger urbanized areas motor vehicle flow maps remain a useful indicator of likely bicycle trip patterns.

Existing Regional Travel Data

Another indirect method of estimating potential bicycle activity involves use of existing regional travel data. Most jurisdictions over 50,000 population and many smaller communities have available a reasonably representative transportation data base. Typical data collected includes:

- Numbers, purposes and modes of person-trips on an average day;
- Trip length frequencies for each trip purpose;
- Origin-destination patterns; and
- Household socio-economic data.

There are several advantages to using such data:

- It is readily available;
- Because trip purpose breakdowns exist, the variation in bicycling propensity with trip type can be explicitly considered in gauging potential for bicycle trip-making;
- Area-specific estimates of bicycle activity can be built since data includes trip origins and destinations; and
- Likely travel desire corridors can be identified from linked origin-destination data.

Possible applications of regional travel data include the following:

- Development of short-trip travel matrix

  Respondent trip length distributions can be compared by purpose to typical acceptable bicycling trip lengths. This is a useful exercise for indicating the bicycle's potential share of the total trip market.

  Using a bicycle trip action radius determined from local data if available; data from other jurisdictions; or hypothetical values, one can modify a regional trip matrix or set of matrices (by trip purpose) to develop a travel matrix which contains short trips only. These are trips which are likely to be highly susceptible to diversion to bicycle.

- Trip assignment

  With a short-trip matrix and standard traffic assignment procedures, it is possible to develop a specific network loading of short trips. This even more closely defines prime corridors for study focus and gives a measure of anticipated relative bike traffic volume. Unfortunately, because of the short lengths of many bicycle trips and the large analysis zones in most travel data bases, a high percentage of the trips in the prime bicycling range appear as intrazonal trips or are not represented at all. Hence they are not assigned to the transportation network. The extent to which this occurs varies with sizes and analysis zones.

  The fact that many biking-length trips are represented as intrazonal trips is not necessarily a serious drawback. In some situations, trips represented as intrazonals may in fact be so short that they would likely make limited use of any bicycle facility that would be provided. Trips susceptible to diversion to bicycle facilities (trips of more than several blocks) would be normally represented on the network.

  In the typical coarse-grained travel models most of the potential benefit of assigning bicycle trips to a network is lost. More profitable analyses can be made simply by examining and plotting origin-destination matrix data. Typically, network assignments will remain useful for zones up to one mile square, although smaller zonal scale is obviously preferable. Usefulness of such data will vary according to the size of the bicycle planning area. Obviously assignments from a regional model with a one-square mile zonal structure will provide little input to bicycle planning for an isolated five-square mile community on the region's fringe.

- Bike-Specific Model

  It is theoretically possible to develop a bike-specific model using existing transportation planning software. Networks could be coded, typically with all lengths coded at the same speed. Travel speeds of about 10 to 12 miles an hour are reasonable except where grades or other speed constraints exist. European efforts have shown the applicability of conventional and advanced transportation planning trip distribution and mode split models for the bicycle mode. (Richards, 1970) However, for the United States existing data and trends are not satisfactory to develop specific household bike trip generation or mode split parameters at this time. Factors which are involved include:

- bicycle ownership;
- availability of facilities;
- changes in public attitudes towards utilitarian bicycling;
- changes in the economics of travel (sharp increases in energy cost);
- other social incentives (e.g., concern for air quality); and
- public policies (e.g., combat air pollution).

Although such information will probably emerge in the future, such bike-specific model applications appear impractical now.

For the present, it seems most advisable to utilize travel model data where available to examine existing total travel within bikeable range and to estimate bike potential from that rather than attempting to synthesize a bicycle trip matrix directly. There is current direct application for conventional travel model methods in the area of network accessibility analysis. This is described later in this chapter.

Major Travel Generator Identification

The identification and location of obvious major bike trip generators is an activity which might be substituted for the analysis of regional travel data. However, it is best done to supplement such work. While this information in a sense parallels that which can be gleaned from regional travel data, it is extremely valuable in that it can be plotted at the fine scale of detail at which bike travel decision-making is normally made. The area of influence of many types of activity centers can be readily defined, thereby giving information not only about the major destination centers but the trip patterns to those centers as well. Some of the types of bicycle travel activity generators which should be specifically located on street maps include these:

- Schools: Distinguish by type and indicate catchment areas based upon school districts or student and/or employee residence statistics;
- Community parks and recreation areas: Identify catchment areas on the basis of competing zones and influence and distinguish among facilities offering bike activities and those with only bike access;

- Community activity centers: (such as libraries, City Halls, social centers); Define tributary areas if appropriate;

- Employment concentrations: Identify white collar and blue collar employment separately since the propensity to ride bicycles may be significantly different between these groups and define origin-destination patterns or trip length distributions from employee zip code lists, journey-to-work statistics or other information sources;

- Transportation terminals: Focus on identification of express bus and rapid transit stops and stations (local bus and long distance inter-city transportation facilities normally have limited importance); and

- Shopping areas: Potential sites for light convenience shopping are most important; identify catchment area.

The identification of activity centers gives a general indication of the major points bicyclist destinations in a community, a general indication of bicyclists' trip purposes, and a general indication of bike trip patterns based upon the catchment areas of various sites.

Community Involvement

Travel patterns of bicyclists can be estimated simply by asking people. This may involve formal surveys (discussed in the next section) or public meetings, community workshops and the like.

Two potential problems should be kept in mind:

- Overstatement of Usage

  There is often a vast gap between what people say they would like to do (or would do) under certain conditions and what they actually do when those conditions are met. This is particularly true with popular subjects such as bicycling. As a result, people are quite likely to overstate their usage of specific facilities.

- Non-Representative Sampling

  Capabilities, attitudes and needs of highly skilled and experienced bicyclists (which is a relatively limited group) differ greatly from those of casual and potential bicyclists. Provisions which seem non-essential to experienced cyclists may be highly significant in motivating other cyclists, and vice-versa. Thus, extreme caution must be used in designing the citizen participation process and in interpreting their inputs to avoid biases.

Public participation can be quite time consuming and costly, and this needs to be considered in designing the citizen involvement process. However, the method is a powerful one, and has the additional benefits of enhancing credibility of study findings, correcting mistakes on the part of the planner and soliciting early public support for recommendations.

Surveys

The use of surveys is an obvious means of developing projections of bicycle usage. A number of survey techniques could be used:

- Questionnaires (mail-back);
- Personal interviews; and
- Telephone interviews.

Surveys may be directed at existing and potential bicycle facility users or at the general public. The type of survey and its target group will determine the type of information which can be collected.

- Comprehensive Origin-Destination Surveys

  As discussed in a previous section, comprehensive origin-destination surveys have already been conducted in numerous urban areas. These are typically based on personal interviews at the household level, and utilize sophisticated sampling and analysis techniques. Use of the existing data base should be considered prior to conducting additional surveys.

- Special Surveys

  Special surveys directed toward existing and potential bicyclists or the general public can provide useful information for estimating bicycling potential. In particular, they can yield information on:

  -- Origins, destinations and purposes of travel;

  -- Attitudes, concerns and needs of bicyclist; and

  -- Attitudes, concerns and needs of non-users.

  These types of information cannot be discerned from bicycle traffic counts or the like.

- Survey Guidelines

  The section which follows presents guidelines for avoiding some of the common pitfalls associated with past bike-related surveys.

Survey Research In Bikeway Planning

This focus on survey research grew out of the case studies of bikeway planning processes and reviews of published survey-based usage data in connection with research on forecasting methods. From those reviews it is apparent that bikeway planners frequently fall prey to pitfalls in application of survey research techniques. Some of these pitfalls included:

- Redundant survey efforts: Use of surveys for obtaining data to make planning decisions which could be reasonably made on the basis of other readily obtainable information; or use of surveys to provide data justifying decisions based on such other information. A common case of this is the detailed bicyclist origin-destination survey.

- Poor sampling techniques: Most frequently this involves surveys of persons non-representative of the target population for the bikeway facilities being planned or situations in which there is no way of knowing whether respondents are representative of the target population or not. Failure to check for systematic bias in nonresponse is frequent.

- Failure to distinguish between pragmatic planning and research needs: This involves waste of effort both in measurement of data which is generally transferrable from other studies -- such as bicyclist trip length-frequency distributions -- and gathering of information which may be of academic interest but of little relevance to an ongoing pragmatic planning process.

- Over-valuation of stated reactions to hypothetical alternatives: This includes acceptance of such things as cyclists' stated willingness to divert to bicycle facilities or estimates of how far and how frequently they would ride if provided facilities. Cyclists reactions to proposals should be tempered by indicators of actual performance.

- Poor analysis and reportage: Failure to assess and/or report statistical reliability of findings.

In response to these identified shortcomings, the following key steps in applying survey techniques are outlined for bikeway planners:

Definition of Objective and Outputs

- The most important point at this early stage is simply to be sure that this step is in fact carried out. Too often a survey is launched without a clear understanding of exactly what it can or will produce.

- Specificity is essential. First, general objectives in data collection should be agreed upon; then the intended contribution of a survey should be spelled out in detail. This is best done by writing out mock-ups of the tabulation outputs (whether to be one by hand or computer), maps, and tables needed, to be sure that "what you get is what you want".

- This implies that the anlysis should be designed first. This is correct; it should be, and with the survey objectives firmly in mind. Only in this way is the great danger of collecting the wrong data avoided. This cannot be stressed too highly; yet it is amazing how rarely it is done.

- If objectives are clearly identified, it may become evident that a survey is not really needed or adequately cost-effective. To further insure against the possibility of doing an unneeded survey, this entire step should be undertaken with this question foremost: "Could we satisfy our study objectives any other way?"

- There may be reasons for a survey quite unrelated to data needs. These often have to do with a desire to justify or give publicity to a plan. These may or may not be valid; in any case, they should be explicitly recognized and not masked.

Selecting a Survey Design

- The essential need here is to reach the desired target population group. Thus it is mandatory to define who is in this group -- it may be only bicyclists or bike owners or it may be the entire community.

- The design or strategy should involve selecting an approach which will reach the target group as effectively as possible within budget. This means, for example, that a random telephone survey would be an unlikely choice for reaching experienced bikers, since most calls would be to unqualified households.

- This step cannot be done independently of the two discussed next (sampling and instrument design). There are important tradeoffs among the choices within each step; for example, if the required data needs dictate a long interview, the number of interviews and alternative collection methods will be limited. As a rule of thumb, the following guide is recommended.

Survey Type	Length
-- Self-administered (e.g.,mailback)	1-2 pages maximum
-- Telephone interview	15 minutes
-- Home interview	45-60 minutes
-- Travel stop	1-5 minutes

- Response rates vary widely according to type of survey. Generally, mail surveys achieve a lower response than others; the telephone survey is somewhat more effective; and the home interview and traveler surveys obtain highest percentages of response. However, many other factors such as wording, format, length, subject, interviewer appearance and demeanor, and population surveyed are also important, and no simple rule of thumb should be applied.

- Survey work can be very expensive. Great care must be taken to recognize all costs before beginning.

- Often surveys take far more time to produce results than expected. This is because of questionnaire approvals, weather, slow (mail-back) or low rates (in other methods) of response, and delays in processing and analyzing data (particularly if computer analyses are used). Avoid study designs which leave too little slack in the time schedule for delays; an extra 50 percent is not too much.

Sampling

- In general, full enumerations (100 percent samples) are very seldom used. They are extremely expensive and usually add little if anything to the useful accuracy of the results. The major exception is in the case of a very small population(i.e., up to perhaps 200) in which samples would be too small for reliable inferences to be drawn.

- The major concern in survey sampling is to avoid bias, or non-representative results. Much of this requires only thoughtful common sense; for example, to learn about the desires of the bike-riding population one should not survey just the members of a bicycle touring club, for their needs, desires, skills, and bike use are likely to be quite different from those of casual bikers.

- There are many clever statistical designs for sampling, including simple random, stratified, cluster, systematic, and various composite sampling techniques. The application of these principles in any reasonably large survey should be guided or at least advised by a competent statistical technician, to avoid embarassing (or worse) errors. Properly used, statistical survey principles can save much effort and money.

- Statistical inference, the power to draw from a sample reliable conclusions about the whole population, is mainly controlled by absolute sample size -- not the proportion of the population sampled. Ignore any advice to use "a straight ten percent" or other proportion. Get a statistician if in doubt.

Instrument Design

- The instrument must be clear and of interest to the respondent. Otherwise unsuspected and even undetected response biases as well as refusals will occur.

- The instrument should always be pretested, along with the procedure for administering it. Pretesting invariably uncovers points of misunderstanding, difficulty, or delay.

- Questions can all too easily be poorly worded, resulting in useless or no responses. This is especially true of items concerning future behavior of the respondent or his/her household "if a bikeway were provided". Great care must be taken in design of such items, and their results should be used with skepticism in any case. (No matter what the resnonses show, 40 percent of a community's population is not going to suddenly start riding bikes regularly!)

- Bias is as important a consideration in instrument design as in sampling. Even if the sample is perfrectly representative and the response rate very high, ambiguities in the questions themselves may render the responses useless or unreliable.

- The temptation to include extra "interesting" questions should be resisted. They make the survey more expensive and less reliable, annoy the respondent, and usually never get analyzed anyway.

Survey Conduct

- The field staff must be well trained and rehearsed, particularly for face-to-face or telephone interviews. The most common problem is in inconsistency of approach among different interviewers, possibly resulting in different interpretations of the same question by different respondents.

- Close supervision is essential with a staff of any appreciable size (over one). Problems arise virtually hourly and must be resolved quickly.

- Close track must be kept of nonresponse. Every attempt should be made to obtain responses from the initial sample, in order to avoid under-representation of the kind of people who may not be easily found or convinced to participate.

Analysis and Reportage

- Confidentiality of response is usually essential. There should be no possibility that a particular response could be traced to an identifiable person unless expressly permitted by that person. Otherwise credibility of the surveying agency will be damaged and the whole process of survey research tainted as well. If a respondent believes "confidential" responses will be back-traced, responses offered may be invalid.

- As already noted, the analysis should be designed along with the instrument and sampling plan.

- Reportage should be organized by the initial objectives, and aimed at a specific audience. Generally, voluminous reports with many tabulations are needless, costly, and even counterproductive because they are invariably hard to follow. Nonetheless, they are far too common. Emphasize and illustrate main points, and stop.

Research on Bicycle Usage Determinants

In development of the recommended procedures for estimating bicycle activity discussed previously and in an attempt to advance the state of the art in that area, research was undertaken into basic factors influencing the decision to use a bicycle. Following are factors identified as determinants on the level of bicycle use.

- Trip Length
- Trip Purpose
- Climate
- Age
- Bike Ownership
- Cost
- Occupation
- Status

The pages which follow discuss how these factors influence bicycle use and how they can be used to gain some sense of the potential for bicycle activity in a community. Other interesting relationships between bicycle usage and a number of other factors -- correlations between bicycle use and such factors as income or education level -- do exist and have been reported on in numerous published reports. While such relations are of academic interest, they are not useful as planning instruments -- for instance, it is not socially acceptable nor reasonable in the context of an areawide bikeway plan to place fewer bikeways in low income areas simply because persons from low income households ride bicycles less frequently. In this report discussion of factors related to bicycle use has been limited to those factors which have direct utility in the planning process.

Determinants of Bike Use

Trip Length

Trip length is a factor in the likelihood of making trips by any mode. Its importance in the choice to make a trip by bicycle is heightened by several factors:

- The bicyclist must do physical work to propel himself over the distance to be covered. Very naturally there is a decreasing willingness to undertake the greater physical efforts imposed by increasing distance.

- A bicycle is inferior in terms of travel time to motor vehicles for all but the shortest trips, and the time difference expands with increasing distance.

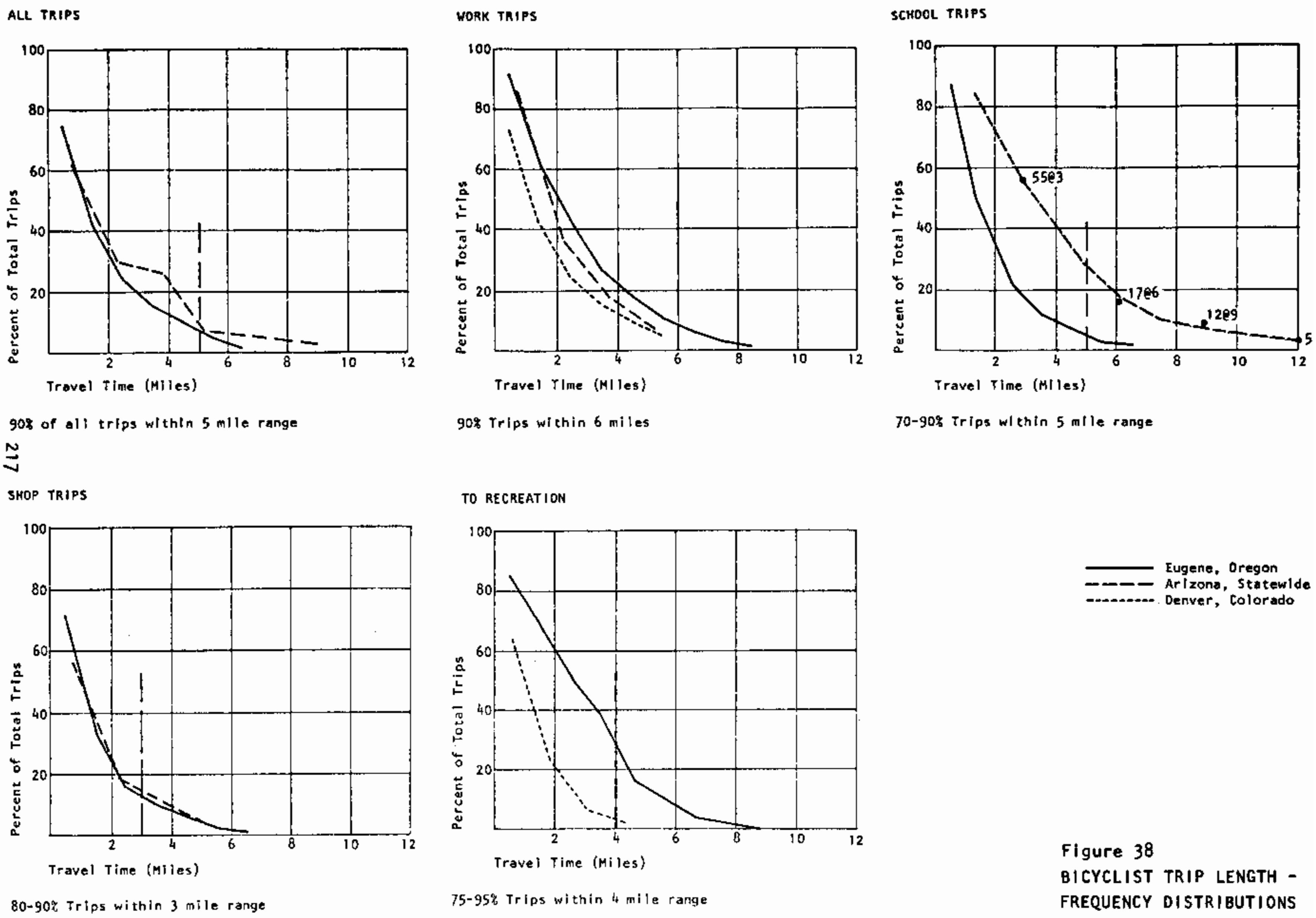
- Even if the potential bicyclist is not swayed by the travel time savings achievable by motor vehicle, at typical bike speed the distance which can be covered within a realistic travel time budget is sharply limited.

Typical bicycle trip length distributions are illustrated on Figure 38. The figure shows the variation of trip length-frequency by trip purpose category. For each purpose there is a relatively clear "cut-off" distance beyond which only small numbers of trips are observed. Cutoff values range from three to six miles. These values may be used to define in general the potential bike service area of an activity center. They can also be used to operate on regional transportation planning data to define a "short trip matrix," an origin-destination table of trips within reasonable bicycling range.

Trip Purpose

Trip purpose is a significant determinant of the likelihood to use the bicycle as a transportation mode. Each trip type has a set of characteristics associated with it which may make the bicycle absolutely or relatively unsatisfactory for fulfilling the purpose of the trip. For instance, bicycles are not very useful for carrying large packages. As noted previously, the probability of selection of a bicycle as the travel mode is considerably affected by trip length. Differing trip purposes have different characteristic trip length-frequency distributions.

Table 78 shows distribution of bicyclist trips by purpose categories as indicated in surveys taken in several urban areas. Trip purpose mentioned most often among respondents in each of the surveys reported was recreation. Where percentages could be determined, over half the respondents in each study area claimed that they either made recreational trips or ranked recreation as their most important bike activity. (This exaggerates the probable level of recreational use, since some surveys included trips to recreational sites in this category.) A similar problem arises when exercise is specified as a trip purpose. In many cases the bicycle is used for transportation on a purposeful trip with the underlying motivation for choice of the bike as the mode travel being the exercise



90% of all trips within 5 mile range

90% Trips within 6 miles

70-90% Trips within 5 mile range

80-90% Trips within 3 mile range

75-95% Trips within 4 mile range

Figure 38
BICYCLIST TRIP LENGTH -
FREQUENCY DISTRIBUTIONS

Table 79
TRIP PURPOSE SUMMARY

Trip Purpose	Arizona, Statewide		Santa Clara Co., Ca.		Fresno, Ca.		Santa Barbara Ca.		Tempe, Arizona		Washington, D.C.		Boise, Idaho	Berkeley, Ca.	Lexington, Kentucky
	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	Rank	Rank	Rank
Recreation	55	1	70	1	63	1	88.3	1	77	1	47	2	1	1	1
Shopping	11	3	38	3	16	2	36.0	2	43	5	--	-	4	3	3
School	21	2	20	4	10	3	30.0	3	58	4	7	7	2	2	2
Work	3	5	8	5	6	4	23.7	4	16	6	11	6	3	4	4
Social (visiting)	6	4	68	2	--	-	--	-	65	3	39	3	-	-	-
Exercise	11	3	--	-	--	-	--	-	--	-	--	-	-	-	-
Personal business	--	-	--	-	--	-	--	-	--	-	32	5	-	-	-
Touring	--	-	--	-	--	-	--	-	--	-	35	4	-	-	-
Around the neighborhood	--	-	--	-	--	-	--	-	75	2	67	1	-	-	-
Other	--	-	--	-	5	5	--	-	7	7	--	-	-	-	-

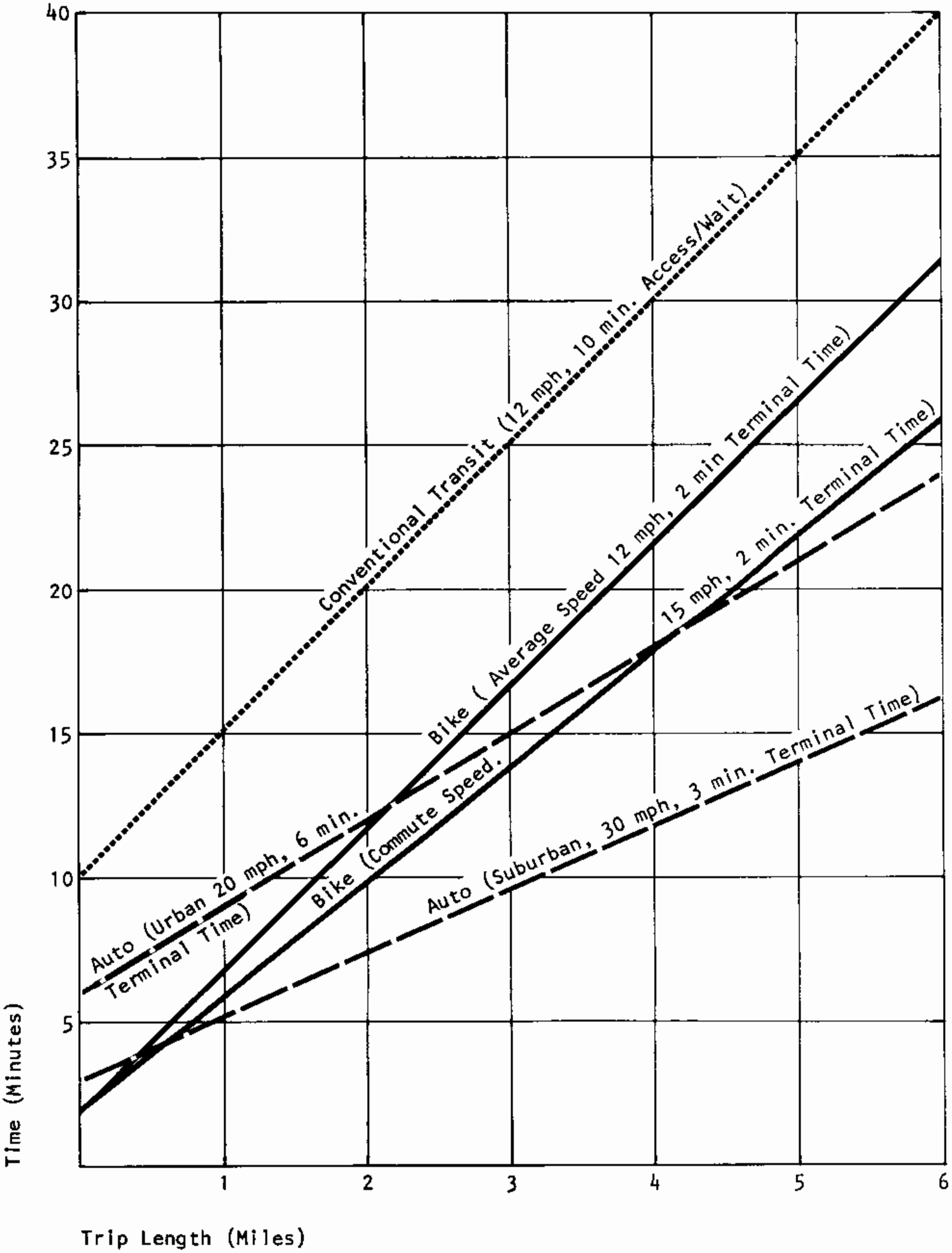


Figure 39
MODAL TRAVEL TIME COMPARISON

-- employment-related attire requirements,

-- ability to change clothes or shower at place of employment before work,

-- personal motor vehicle needed/not needed during course of day,

-- tiring physical labor involved/not involved in employment activity, and

-- personal safety (crime harassment, theft -- etc., as well as safety from automobile traffic)

- School Trips

  School trips are the utilitarian trip type having most probability of being served by bike. Nearly all school trips except those made to commuter (non-resident) colleges are within easy bicycling range. In addition, students below mid-high school grades generally do not have the option to travel by motor vehicle. On college campuses the bicycle is a particularly attractive mode, not only because it eliminates the need to compete for scarce and expensive parking spaces, but also because it is particularly useful for getting from one place to another on campus. For elementary school children, riding a bicycle to school is a positive status symbol. For college students it is at least neutral. Only among junior high and high school age groups is riding a bicycle for transportation perceived as a negative status symbol. But for all youth below driving age, the bicycle is a primary means of independent personal mobility.

  For these reasons virtually all school trips can be regarded as potential candidates for bicycle travel. Although heavy traffic, busing, school policy and parental judgment may serve to reduce the bicycle riding potential somewhat, particularly for younger elementary school students; and since schools at all levels have available information on enrollment districts and student residence locations, tasks of specific route planning and estimating route usage potential are straightforward.

- Shopping Trips

  Shopping trips pose mixed potential for bicycle activity. Only a relatively few "convenience" type trips involving the purchase of a few small items are likely to be made by bicycle.

Planning exercises related to shopping trips should be limited to simply identifying locations of convenience shopping centers and attempting to assure service to these locations on routes planned primarily to serve other trip purposes.

- Recreation

  In planning for bicycle transportation to recreation activity sites, neighborhood and regional recreation centers must be considered separately. In the case of neighborhood centers, "tributary areas" to competing activity centers are defined. Normally all trips within a center's tributary area will be within reasonable bicycling range. For each activity center, logical routes from subsegments of the tributary area are defined. Usage potential of any route is proportional to the number of households served, total activity at the recreation center and character of the activities taking place at the center.

  For bicycle transportation to regional activity centers, trip length once again becomes a factor. Methods similar to those used for work trips should be used to estimate bike trip potential and corridor demands.

- Other Trip Types

  A motor vehicle trip type in which there is high potential for diversion to bicycle activity is the trip to "serve passenger." Some of these involve "kiss-n-ride" trips to transit stations. Numerous others are relatively short trips involving parents driving children to such activities as music or dancing lessons, extra-curricular school functions, the dentist and others. The pattern of this trip type is random and difficult to quantify in any meaningful way for planning purposes. But it is possible to deal with "passenger" trips to specific activity centers such as transit stations in much the same way as trips to recreation activity centers.

  The potential for use of bicycles on personal business trips is generally limited as is the potential for adult bike trip-making for purposes of social visits. Generally, the unusually high response in the social or "visit friends" category on bicyclist surveys does not reflect true utilitarian trips. The response is attributable to young bicyclists and their tendency to answer in this way rather than give the probably more correct response of aimless play riding (which cannot be served with physical facilities).

  Non-home-based trips are extremely unlikely to be made by bicycle since they involve the joint probability that the prior home based trip was made by bicycle and that the bicycle will be an acceptable form of transportation for the current trip. No attempt should be made to quantify these trip types for route planning purposes.

Climate

Four types of climatological factors and their various combinations affect the potential for bicycle activity:

- Extremely cold temperatures,
- Precipitation,
- Extreme heat, and
- Significant prevalent wind.

In areas experiencing significant cold with snow covered and icy pavements in winter, bicycle activity will drop to nearly zero during these periods. This is not just because it is rather unpleasant to ride a bicycle while exposed to these elements; the presence of snow or icy pavements makes control and balance on a bicycle extremely difficult. Clearly this has an implication for usage justifying the cost of facilities. An important factor often overlooked is that if bicycle activity is impossible or extremely unattractive for a significant portion of the year, this may affect the likelihood of bicycling on certain utilitarian trips at other times of the year when bicycling is possible and attractive. Even if the principal employed person in a household could conveniently bicycle to work for nine months out of the year, if a household must own a second family car primarily for work commute purposes during the season when bicycling is not a viable transportation means, then that car will likely be used for commute purposes year round.

Precipitation has been assumed to be as absolute a deterent to bicycle activity as cold weather, particularly in cases where there is a seasonal expectation of a high probability of rain on almost any given day. But actual effect of this climatological factor is somewhat contrary to expectation. In areas where in certain seasons precipitation falls very often such as in the Pacific Northwest, there is evidence that rain has a less detrimental effect on bicycle activity than in areas where far less precipitation might fall but where its likelihood of occurrence is far less predictable. This seems to reflect a greater capability for physical and psychological adaption to adverse weather conditions which are both predictable and relatively continuous over a period of time as opposed to intermittent and relatively unpredictable adverse conditions.

Age

Figure 40 presents a typical distribution of bicyclist age as measured in an area of typical non-homogeneous distribution of total population age. The distribution of bicyclists' age is in contrast to the age distribution of the total population and illustrates the disproportionality of bicyclist age concentration in the youth and young adult groups in relation to the total population age distribution. Age distribution of bicyclists is in a state of flux, with significant growth of the bicycling population among adult categories.

Since there is a tendency to clustering by age among residence areas, at times it may be possible to utilize census data on resident age distribution to identify high potential and low potential bicycle trip generation areas. However, two words of caution are advised. The level of detail at which resident age clustering becomes significant may be too fine-grained to be relevant to estimation of bicycle activity for purposes of facility location. Secondly, in relatively large areas having unique population age distributions, age may no longer be a reliable indicator of the potential for bicycle activity. Factors which induce age clustering on an unusually large scale may also induce other changes in expected behavior. For instance, in an adult retirement community or enclave, site conditions and peer reinforcement may induce far more active bicycling by senior citizens than would be the case if the same individuals were dispersed in a normal residential mix. An illustration of this is Hemet, California where nearly 60 percent of the population is above 60 years of age and where persons over 60 years of age are estimated to account for 50 percent of the active cycling population. Thus age distribution must be tempered by knowledge of special area characteristics when determining its influence on bicycle potential.

Bike Ownership

In order to ride a bike, a person must have one available. And ignoring the opportunities to rent a bicycle or borrow from friends, bike availability can be presumed to be equivalent to personal ownership of a bicycle or ownership in the household. In 1973, an estimated 37 percent of the United States population owned bicycles. Considering sales in the intervening period, perhaps as much as 45 percent of the United States population owns bicycles (Bicycle Institute of America, "Booming Bikeways," Volume 8, No. 1, New York, N.Y., March 1973). Since many of these bicycles are available to other household members than their owners, a greater percentage of the population may be potential bicyclists.

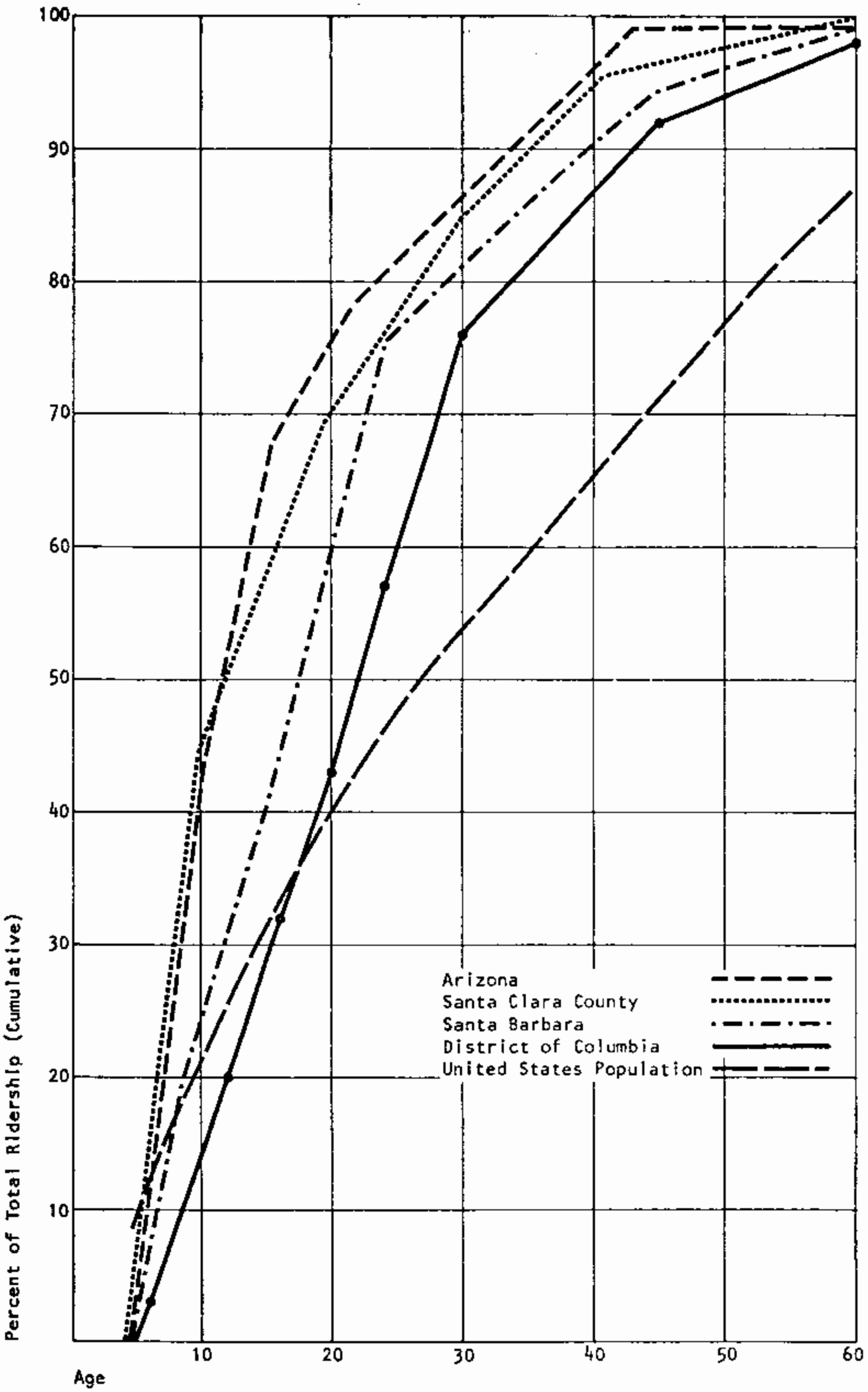


Figure 40

BICYCLIST AGE TYPICAL DISTRIBUTIONS

Table 80 presents bicycle ownership and ridership in a number of communities for which data was available. Although there are few sites in which data permits direct comparison of ridership to ownership levels, the table inferentially indicates a fairly parallel relationship between ownership and ridership. Thus, it might be theorized that a reasonable growth method of estimating and planning for bicycle activity would be to determine bicycle ownership in various sub-areas of the community, thereafter focusing facilities planning efforts in sub-areas having high or average ownership levels and placing less emphasis on areas of low bicycle ownership.

Table 80

BIKE OWNERSHIP VS. RIDERSHIP

Location	% Bike Owners	% Bike Riders
U.S.	37	
Santa Clara County, Ca.		49
Arizona	46	41
Santa Barbara, Ca.	41	47
Fresno, Ca.	41	
Eugene-Springfield, Ore.		39
Ann Arbor, Mich.		29

However, there are drawbacks to this planning strategy. Current bicycle ownership (and usage rates) may very closely reflect the existing conditions for bicycling in a community or sub-area thereof. Such conditions can sharply change if measures are undertaken to change the safety, attractiveness and public attitude toward bicycling. There may be a latent ridership potential far divergent from the existing ownership pattern. A low ownership pattern may, in fact, be indicative of tremendous opportunities to bring about increased bicycle activity through bicycle facility provision or other measures rather than an indication that no facilities should be provided. This latter hypothesis is reinforced by the fact that unlike the case of a motor vehicle, there is a relatively minor economic barrier to ownership and operation of a bicycle. A sturdy, functional three- or ten-speed bicycle can be bought new for as little as $50 or $100, respectively. Once acquired, it costs virtually nothing to operate. Thus, bicycle ownership statistics may be useful for little more than indication of immediate use potential and may be a misleading indicator of longer term opportunities and needs.

Cost

Estimated operating cost differentials between the bicycle, automobile and transit are presented on Figure 41. Sheer cost, and comparison of cost and travel time differentials to accepted estimates of the value of time, indicate that cost saving potential is not a dominant consideration for most persons who are in reasonable bicycling distance of their destinations. While cost is a motivating factor to some who now use bicycles, it appears clear that other factors are much more important than cost to those who choose other modes.

Occupation & Status

A number of relationships between bicycle use and social station have been identified in surveys of bicyclists. However, specific social status variables which are useful as predictors of bicycle activity have not been determined. Available data show conflicting and inconclusive evidence of the effects of status-related factors.

Table 81 presents indicators of bicycle use among adults in various occupation categories.

Although these data compare ownership in one case and bicycle use for work trips in the other, some useful inferences can be drawn.

- Probability of bicycle ownership varies among employment categories. The pattern tends to conform to expectations based upon information on bike ownership in relation to income and educational attainment.

- Differences in usage rates for work trips among occupational categories does not significantly reflect differences in ownership rates.

- The lower work-trip usage rate among the managerial-business category conforms to intuitive expectation that usage by this group would be discouraged by employment-related image or status concerns. However, analysis of the Davis data showed that this apparent difference was not a direct function of occupation. Age and residence distance from place of employment tended to explain differences in bike usage rates for work trips among occupational categories.

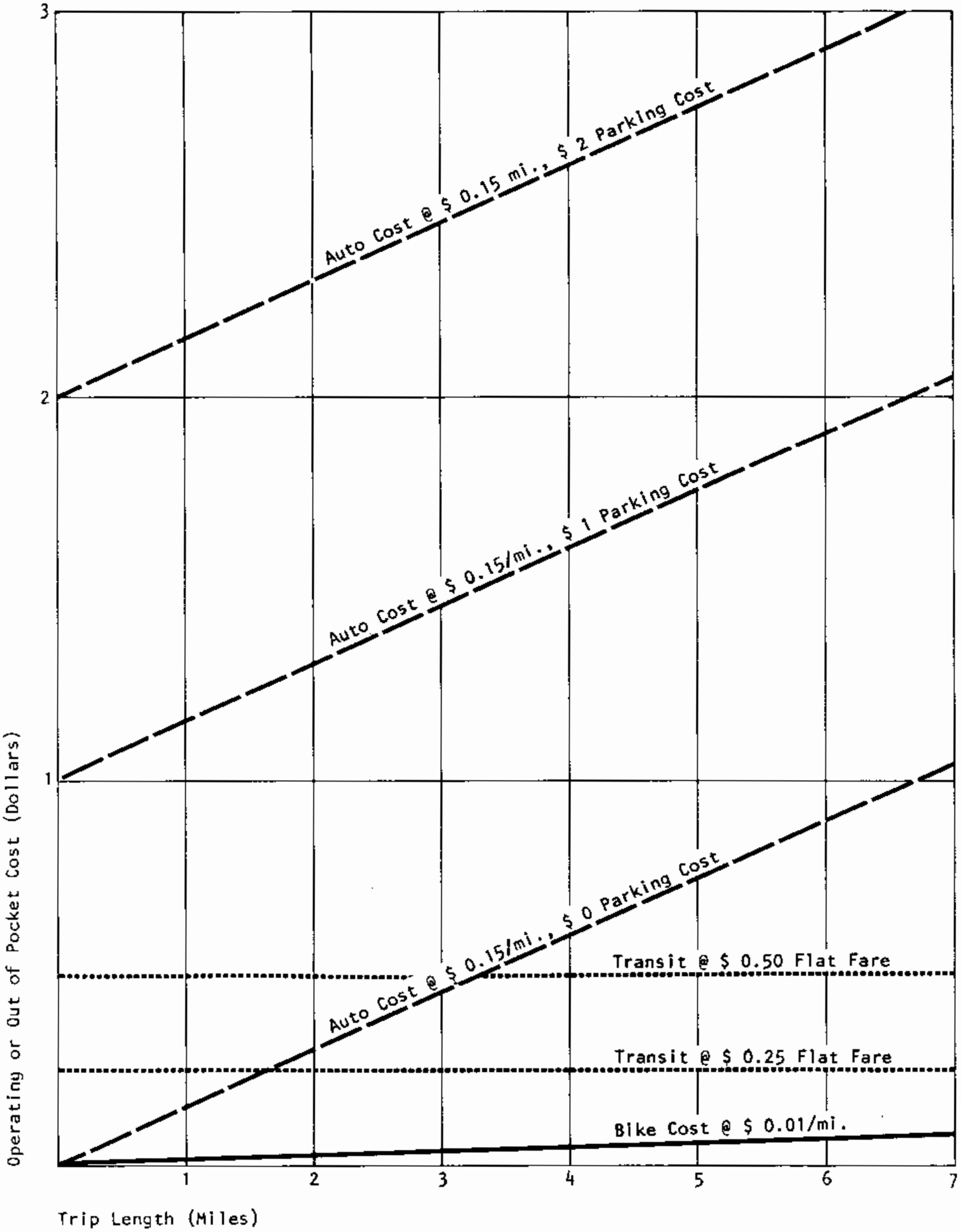


Figure 41
MODAL COST COMPARISON

Table 81

INDICATORS OF BICYCLE USE AMONG ADULTS BY OCCUPATIONAL CATEGORY

	Arizona		Davis	
Occupation	Bike Owners %	Non-Owners %	Make Bike Work Trips %	Never Bike Work Trips %
Professional-Technical	68	32	29	71
Managerial-Business	66	34	11	89
Sales	50	50	32	68
Clerical	50	50	26	74
Skilled/Semi-Skilled	52	48	-	-
Service	54	46	25	75
Unskilled	50	50	22	78

- The Davis data give some notion of a reasonable upper limit of bike mode split for work trips within reasonable bicycling distance range which might be achieved under conditions approaching ideal. (Note that persons included in the "user" category are full time employees but may make as few as one trip per week by bicycle.) From these studies, a reasonable maximum work mode split assumption for travel on a daily basis under ideal conditions for trips within previously noted "cutoff" range appears to be about 20 percent.

Advanced Forecasting Techniques

Numerous planners have expressed the desire for forecasting techniques paralleling conventional transportation models for estimating bike mode split potential and trip patterns within an urban area. Interest in forecasting is a healthy indication that the bicycle is recognized as a viable element of the transportation system to which meaningful planning effort should be devoted. Such techniques have been successfully employed in European transportation planning programs, but sophisticated forecasting techniques for application in the United States do not appear on the immediate horizon, nor are they needed to achieve satisfactory bikeway planning and design.

In this research we have examined European models ranging from disaggregate, probabilistic models to aggregate, deterministic techniques. (Project Bureau Integrate Verkeer, 1974; Richards, 1970.)

Two key points regarding the different between U.S. and European situations appear far more significant than model techniques utilized. First, the European transportation planning models which explicitly estimate bicycle trips as a primary transportation mode are generally not used for purposes of planning bikeway facilities. Bikes are included in the models because their share of the travel market is sufficiently large that their specific inclusion is needed to rationalize the prediction of usage of other modes. The specific intent of the models is for planning of transit and motor vehicle networks -- the scale of model information is usually too broad-grained for decision-making related to bicycle facilities -- and the bike mode is included simply to achieve proper calibration of trips on the other modes of travel.

Secondly, the situation relative to bicycle use in Euorpe is quite different from that in the U.S. European usage patterns are stable. Change in usage rates is occurring measurably but that change is a marginal incremental one and hence, usage patterns may be characterized as stable. The implication of this is that modal choice relationships calibrated upon current or relatively recent data will remain valid over time -- at least sufficiently accurate for planning decision-making.

In the U.S. the situation is radically different. The rate of utilization of bicycles is undergoing rapid and substantial change. And there is tremendous variability of use even within relatively small geographic regions. Thus, a model calibrated upon current data would not likely provide reasonable projections of bicycle activity only a few years hence since the realtionship of usage to its determining parameters is unstable. And such a model calibrated in one area of a region might not provide a reliable current use estimate for another area in the region -- to say nothing of transferability to other regions -- because of substantial areal differences in usage trends.

The sections which follow further explain the problem.

In order to develop relationships of bicycle activity to objective quantifiables such as bike ownership, measurements of the relationships of activity to the objective quantifiables must be done relative to a fixed attitudinal framework. And not only is it extremely difficult to define such an attitudinal framework, attitudes relative to bikes and bicycling are shifting rapidly with time so that the relationships between bicycle and relevant objective factors which hold now are unlikely to hold in the future.

For example, as late as 1965, the adult bicyclist was a relatively rare individual. The adult who did own a bicycle and at least occasionally used it for recreation or exercise would not think of using it for a purposeful trip, such as a work trip, unless willing to be thought of as being highly eccentric. By contrast, by 1975 adult bicyclists are relatively common and while a professional person who rides a bike to work might be thought of as "a bit of an enthusiast," the whole perspective in which a utility cyclist is viewed is far less negative and may perhaps be even positive. As a result, adults who own bikes are likely to ride them far more frequently than they might have ten years ago. Thus, dramatic changes in trip generation rates in relation to ownership would be expected and additional changes in such rates can be anticipated as social acceptability of bicycling continues to change.

Another complicating condition is the fact that the likelihood of choosing to use the bicycle for trips currently made or to make new trips by bicycle is highly system-sensitive. System-sensitivity implies far more than the ability to get from trip origin to trip destination by traveling for a certain distance or time. In the case of bicycling choices, or a large number of factors including such things as the level of effort required (which must take into account such things as adverse grades) and the perceived safety and amenity of the routes traveled upon.

The implication of system-sensitivity for estimation of the relationship of bicycle trip generation to objective factors such as bicycle ownership, trip length, or trip purpose is that some sort of index of system quality must be associated with each data point relating bike use probability to those objective factors. Complicating this is the fact that such a system quality measurement is itself an individual perceptual one rather than an objective measurement. It's important to note that when we speak of system variables in this context, we are speaking of qualities quite distinct from the kinds of system performance utility measurements employed in conventional transportation analyses -- things like cost and travel time.

To summarize the problem, the set of determinants of bicycle use comprise a multi-dimensional array and include not only a set of objective and relatively easily quantified variables, but a number of other variables which are extremely difficult to measure and more difficult to project. These can loosely be described as attitudinal variables and variables related to subjective perception of system quality in relation to service of specific trips. As a result, it is extremely difficult to estimate a model which explains bicycle usage behavior on the basis of existing data. Moreover, even if such a model were estimated, it would generally not be transferrable to areas other than the one for which it was estimated. Even in this area it would likely remain representative only for a short period of time. Estimation of a model having time and locational transferability does not appear to be a viable exercise for the near term future.

The fact that viable advanced bike usage models cannot be developed at this time does not bode ill for bikeway planning decision-making. In the early years of the automotive age, perhaps through the immediate post-World War II period, transportation planning involved relatively simple decision-making. Needs were obvious and virtually any "obvious" facility commitment would have significant payoff in benefit. Hence, there was little need for elaborate forecasting as a basis for justifying facilities. Since justification seemed obvious, as did priorities, the primary purpose of forecasting was to scale the physical design of the facility. For purposes of physical design scaling, rather gross forecasting methods were satisfactory. However as the transportation system developed to the point where basic requirements of accessibility were reasonably met, individual projects offered only marginal benefit increments. It became important to develop means of evaluating justification and relative priority of facilities since intrinsic worth and worth relative to other potential actions could no longer be perceived intuitively. The need for reasonably precise decision-making instruments gave rise to the "science" of transportation planning with its feasibility and benefit analyses which in turn demanded sophisticated forecasts of travel activity.

It can be asserted with some truth that the status of bicycle facilities today closely parallels the status of highways in the 1920's and 1930's, that most needs and justifications seem obvious and that sophisticated techniques of forecasting bicycle activity are not required. This is not to say that model techniques have no place in current planning. In the course of this research application of an existing interactive transportation model battery for purposes of bikeway accessibility evaluations and strategic link analyses was demonstrated and showed promise for large scale evaluations on which manual evaluations are inefficient. However, simple forecasting techniques outlined previously in this report are relevant to current bikeway planning. More sophisticated techniques will evolve in time as they become truly needed.

Similar comments can be made regarding cost-benefit analysis of bicycle facilities. Costs of bicycle facilities can be estimated with reasonable accuracy -- at least the public sector costs thereof. And this report provides the basis of a methodology for predicting accident reductions which bicycle facilities might provide -- reductions which, when the accident estimation procedure is perfected by further research, can be translated as a quantified benefit.

But it is very difficult to quantify other specific benefits which would appertain to an individual user of a facility. The fact that only general estimates of usage can be made compound the problem. Fortunately, the need for and justification of facilities can usually be made on the basis of functional qualities.

VERIFICATION

Within the constraints of this project it is not practical to undertake a formal verification of planning procedures and design specifications by developing several community bikeway plans, implementing them and measuring usage performance. A true before and after verification study could require as much time as went into this research effort. And multiple verification projects would be necessary due to the variable weighting of the criteria and guidelines in differing situations. However, it has been possible to postdictively assess planning and design procedures by comparing decisions indicated by the procedures identified in the user manuals with actions taken in prior local planning studies and the eventual results which followed implementation of those studies.

This procedure has two drawbacks. There has been limited follow-up to most bikeway implementations. Hence data for postdictive comparisons has been limited. And since weighting of criteria is a subjective process, there is no certainty that different planners might not make differing locational decisions though faced with the same circumstances.

However, it is possible to characterize some of the differences between decisions made by individuals preparing actual bikeway plans or designs for various jurisdictions and those which would probably have been made in the same situation by the research team who prepared this report or a person relying upon this report and the user manuals which accompany it.

- With respect to design standards and locational criteria, many individuals have a tendency to act in either of two extremes. Some make rigid application of whatever standards or guidelines they have adopted and make little or no effort to adapt to the particular circumstances of an individual design situation. This "by the book" approach can result in failure to construct needed facilities simply because total conformance to the guidelines is not feasible. Or a facility may be located in the wrong place because design to optimal physical specification can be achieved there to a fuller extent than on the most desirable travel route.

  At the other extreme is a "seat of the pants" approach in which planning and design guidelines are given short shrift. This often results in bikeways constructed in marginal situations and having compromised utility and safety qualities.

  The approach suggested in this report and the associated user manuals contrasts to both of the above in that it suggests some minimum and optimal design criteria set in an evaluation framework which emphasizes assessing the acceptibility and implications of tradeoffs on various criteria. Hence, the recommended procedure may lead to selection of routes along cyclists' preferred line of travel even though this may necessitate less than optimum physical design. Such routes are often rejected in favor of a parallel alternative or no facility provision in the "by the book" approach. Conversely, the recommended procedure frequently results in a more elaborate design or outright rejection of facilities accepted in the "seat of the pants" approach. This simply reflects the fact that the research team (and, hopefully, persons who use these manuals) have the benefit of a far greater resource of information and experience than has been available to local jurisdiction staff members in the past. As a result, manual users can confidently be flexible in location and design selection without crossing the bounds of inadequate design.

- Decisions in bikeway planning by local jurisdictional staff often tend to give more consideration to localized opposition to specific proposals than would the authors. This is not because the "outsiders" on the research team are unaware of or insensitive to local opposition; such opposition is clearly recognized as a key factor in planning. Rather, it stems from the fact that the typical local jurisdiction staffer involved in bikeway development usually has a number of other duties, many of which also involve conflict and controversy. And no matter how sympathetic such an individual is toward bikeways, specific route and design details are usually not considered of sufficient priority that the planner is willing to take a particularly strong position in the face of opposition. Such persons are likely to move to a compromise solution more readily than a person who is not involved in other duties and controversies considered more pressing.

  Another factor is that local staff frequently tend to presume what the decision of elected officials would be on issues of controversy. Acting upon that presumption, they preclude an actual decision on the issue by those officials. For example, it is natural for a traffic engineer whose traffic operations improvement proposal was rejected due to local merchant opposition to the parking removals which that project entailed to presume that elected officials would be equally persuaded to reject a bikeway proposal which involved similar parking removal. The approach recommended herein is to carry that issue forward to the appropriate public policy decision-makers and give them the opportunity to make determinations on the merits of the situation rather than immediately backing off to a compromise position when conflict surfaces.

- The staff planner developing a bikeway system is often acting under the pressure of community demands for bikeways and tends to focus on schemes which respond to obvious existing needs and which are readily

> implementable. He attempts to provide the maximum amount of visible physical facilities as quickly as possible, usually under the constraint of limited funding resources. Typically this results in large amounts of low cost linear facilities of uncomplicated design. Critical barrier or bottleneck areas which might involve extensive design work, high cost improvements, controversy and extended negotiation and which limit the amount of visible facilities produced with available funds are frequently avoided. By contrast, the methodology put forward herein places a premium on identifying and treating the critical barrier areas.

The characterizations of typical local jurisdiction staff decisionmaking in the foregoing are not intended in a pejorative sense. There are numbers of highly skilled and effective bikeway planners among local jurisdiction staffs. And many of the planning decisions were subject to post evaluation before there was any substantial background of bikeway planning guidelines or experience in this country.

Overall, differences reflected in the comparison of actual community bikeway plans to hypothetical decisionmaking based upon the principles reported herein lends a confidence that criteria presented in the user manuals provided the best guidance for bikeway planning which can be given at this time and that procedures and criteria are generally applicable.

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