From January 1, 1973, Through December 31, 1975. Arizona Department of Transportation, Phoenix, Computer printout from Safety Project Services, Jan. 27, 1976.
2. Robbins, E. O., II. A Study of Cyclist Behavior and Characteristics on the College Avenue Bikeway. Arizona State Univ., Engineering Rept., Dec. 1974.
3. Final Review Draft of the Arizona Bicycle and Foot Path Study. Bivens and Associates, Inc., Phoenix, Feb. 15, 1973.

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

Effect of Bicycle Lane Usage on Vehicles in the Adjacent Lane

Stephen B. Loop, Idaho Transportation Department, Boise
Robert D. Layton, Department of Civil Engineering, Oregon State University

This paper presents an approach for investigating the effect of bicycles in a bicycle lane on the characteristics of the traffic stream in the adjacent lane. Previous work related to this subject is reviewed, and a possible model to analyze the impact of bicycles on level of service is proposed. The model uses the difference in vehicle speed with and without the presence of bicycles. The application of this model to capacity analysis is discussed, and a program of expansion and testing is recommended. The method of data collection employed is presented. A limited data set from a field study is analyzed, and the results are tested for statistical significance. The results of this analysis indicate that there is a measurable reduction in speeds with bicycles present and reinforce the need for further study.

Bicycle sales in the United States more than doubled between 1968 and 1973. In the same period, automobile sales increased approximately 14 percent. In 1973, bicycle sales totaled 15.3 million while automobile sales were only 11.4 million. The Bicycle Institute of America reports that in 1969 only 15 percent of all bicycle riders were adults. However, one year later, adult bicycle ridership doubled to 30 percent. It is estimated that there is one bicycle for every two people in the United States (1).

Numerous surveys have indicated that a latent demand for bicycle commuting exists that is not realized because of the lack of adequate facilities (2). One survey (3) indicates that the majority of those persons who use on-street bicycle lanes are commuters, but the survey included only cities in which there were universities.

Increased use of bicycles is frequently advocated as a strategy to limit the increase in motor vehicle traffic. If one assumes that there is an increase in the number of bicyclists who use the streets, then the reduction in vehicle trips represented must be compared to the decrease in roadway vehicle capacity that is caused by the presence of bicycles. The primary situations that affect capacity include bicyclists riding in the traffic stream and bicyclists riding in adjacent striped bicycle lanes. In the first situation, the bicycle affects the traffic stream characteristics in a manner similar to the presence of trucks, buses, and turning vehicles. The effect on roadway capacity in the second situation results from both the effects of traffic stream characteristics and a reduction in the physical dimensions of the facility.

There has not been sufficient study devoted to this topic. Currently, it is difficult to provide more than a qualitative assessment of the impact that the large increase in bicycle use has had on roadway vehicle capacity. There are no quantitative adjustment factors that can be applied to a capacity relation to account for the presence of bicycles.

PURPOSE AND SCOPE OF STUDY

The purpose of this paper is to provide insight into the effect that the presence of bicycles in bicycle lanes has on the level of service on urban streets. The characteristics studied include the effect of street width, the interaction of vehicle and bicycle volumes, and the influence of weather. The reduction in approach width that results from the presence of a striped bicycle lane is taken into account by using accepted capacity analysis techniques. The problem of right-turning vehicles that cross through a bicycle lane and left-turning bicyclists who cross through the lanes is not dealt with in this study.

The data and discussion presented here are intended to describe a possible methodology of capacity analysis that would account for the presence of bicycles in bicycle lanes. Data were collected along bicycle lanes in Eugene, Oregon, under conditions with and without bicycles. The results are compared with data from a previous study in West Lafayette, Indiana. Inferences are made from the data collected, and possible applications to capacity analysis are explored. These inferences and applications are only preliminary in nature and are intended to stimulate further study that is more comprehensive in nature.

REVIEW OF PREVIOUS WORK

A literature search was conducted to determine the nature and extent of previous research in this area. The results of that search are included in an unpublished annotated bibliography (4). The articles on the location of bikeways primarily discuss the characteristics of streets that are compatible with bicycle lanes or the problems of locating streets where bicycle lanes would be most used. The articles dealing with operations are primarily concerned with the means for preventing automobiles from intruding into bicycle lanes and for dealing with the signing and traffic control problems within bicycle lanes.

Two articles were found that touched on this subject. The first by Smith (5) discussed the reduction in capacity on a street because of lane width reduction that results from a bicycle lane. The effects of bicycle lane usage on traffic flow in the adjacent lane were studied by Jilla at Purdue University (6). The two variables chosen as indicators were the difference in mean speed and the difference in lateral displacement of vehicles in the adjacent lane, which results from the presence of bicycles. The data presented represent a good source for comparison purposes, and basic concepts were used to design this study.

PROPOSED MODEL

The level of service provided by a facility is described in part by the speed of operation and the volume present. It is suggested that the difference in mean speed that results from the presence of bicycles would be a legitimate indicator of the change in level of service. For purposes of the proposed model, the relation between speed and volume is expressed in terms of density of flow as follows:

$$\text{Density} = (\text{vehicles/kilometer}) = [\text{volume(vehicles/hour)}] \div [\text{speed(kilometers/hour)}] \quad (1)$$

The density of vehicles measures the freedom that vehicles have to maneuver. Because of the requirement of greater headways at higher operating speeds, the relation between speed and volume at a given level of service is not linear. This relation is shown in Figure 1. However, for the small range of speeds and at the lower speeds considered in this model, the error is negligible.

Assuming that the volume of traffic that desires to pass through a given route remains constant, the change in density could be calculated as follows:

$$\text{Change in density} = \Delta(\text{vehicles/kilometer}) = [Q(Sp_A - Sp_B)] \div [(Sp_A)(Sp_B)] \quad (2)$$

where

Q = flow rate (vehicles per hour),
Sp_A = mean vehicle speed without bicycles present, and
Sp_B = mean vehicle speed with bicycles present.

Conversely, the reduction in volume necessary to maintain a constant density and thereby level of service could be found by using the following:

$$\text{Reduction in volume} = \Delta(\text{vehicles/hour}) = Q_A\,[(Sp_B/Sp_A) - 1] \quad (3)$$

where Q_A = flow rate (vehicles per hour) without bicycles present.

The volume of vehicles present is expected to influence the amount of speed reduction that is caused by the presence of bicycles. As the volume of vehicles increases, the relative ease of a motorist to respond to an external factor (the bicyclist) is reduced. Therefore, the expected differences in mean speed should be related to the volume of vehicles present. Also, since the change in speed is a result of the interaction between vehicles and bicycles, the total volume of vehicles present must be known. And, since the change in speed is a result of the interaction between vehicles and bicycles, the total volume of both bicycles and vehicles, during the study period, must be known to reflect the number of interactions. Other factors that must be included in the data set for capacity analysis are the weather conditions, the width of the bicycle lane, and the character and width of the street.

The reduction in speed that results from the presence of bicycles reflects the impact on the level of service and may ultimately permit estimation of the reduction in capacity (or service volume) for the uninterrupted traffic flow that is created by bicycle lanes. As shown in this study and previous research, the bicycle in a bicycle lane may reduce vehicle speed significantly. As the volume of bicycles and vehicles increases, more interaction between bicycles and vehicles occurs. The reduction in vehicle speed may be a function of the normal speed of operation and the frequency of these interactions, i.e., the bicycle-vehicle interactions per kilometer in 1 h. The frequency of bicycle-vehicle interactions is given as follows:

$$\text{Frequency of interactions} = \text{vehicle}^2\,(\text{kilometers/hour}) = [(Q_V)(Q_B)/(S_V)(S_B)]\,[(S_V - S_B)] \quad (4)$$

where

Q_V = vehicular volume (vehicles per hour),
Q_B = bicycle volume (bicycles per hour),
S_V = traffic stream speed (kilometers per hour), and
S_B = bicycle mean speed (kilometers per hour).

Since the data base is limited, it is difficult to quantify the impact on street capacity. The presence of bicycles in a separate parallel lane may reduce the traffic stream speeds up to about 10 percent on streets where the average speed is about 48 km/h (30 mph). The greatest speed reduction occurs when traffic volumes are low, and, consequently, speeds are high. Unless bicycle volumes are also high, the driver can accelerate to the normal speed of operation after passing the bicycle, which only temporarily reduces the level of service.

For higher traffic volumes, normal operating speeds are lower, and the reduction in speed that is created by the presence of bicycles is small. At high traffic volumes (1000 to 1700 vehicles/h/lane), any reduction in the speed of a vehicle would influence the vehicles behind it and consequently the level of service. In this and other research (6), speed reductions of the magnitude found at higher traffic volumes of 1.5 to 3 km/h (1 to 2 mph) would be expected to alter the service volume level very little.

The relative importance of street width reduction on capacity, in relation to the effect of the level of usage of the bicycle lane that would cause the reduction, depends on the character of the street. For example, on High Street in Eugene, Oregon, as given by the Highway Capacity Manual, the reduction in capacity because of a narrower street width is about 20 percent. The reduction in street width should not be considered alone; the number of lanes and the lane widths should also be considered in capacity analysis, as suggested by Smith (5). In this example, lane widths of 3.51 m (11.5 ft) are provided for cases in which 1.52 m (5 ft) of the street is used as a bicycle lane. Although the original lane widths were 4.27 m (14 ft), lane widths that are greater than 3.66 m (12 ft) would contribute very little to an increase in capacity. Therefore, a capacity reduction of 20 percent for lanes that are 0.15 m (0.05 ft) narrower than 3.66 m (12 ft) appears unreasonably large (Figure 2).

The effect of street width in reducing capacity is more pronounced and well-defined on streets where a reduction in the number of lanes accompanies the reduction in street width. For example, an 11.58-m (38-ft), three-lane, one-way street with a 2.44-m (8-ft) parking lane would be reduced to a 7.62-m (25-ft) width for traffic movement, if a 1.52-m (5-ft) bicycle lane were added. Thus, this addition of a bicycle lane would permit only two 3.81-m

(12.5-ft) vehicle traffic lanes. The reduction in capacity based on analysis by using the Highway Capacity Manual would be about 20 percent. With a reduction in the number of lanes, the reduction in capacity is probably greater than 20 percent. Even though the lanes are increased from 3.05 m (10 ft) to 3.81 m (12.5 ft), the loss of a lane would seem to be of greater influence than the difference in lane width. However, if the parking lane were replaced by a 1.52-m (5-ft) bicycle lane, a 10 percent increase in capacity would be realized, based on the additional 0.91 m (3 ft) of width for vehicles; the effect of the presence of bicycles is ignored.

Relations that describe the effects of the level of usage of an adjacent bicycle lane on the capacity of arterial streets and highways are shown in Figure 3. This discussion is for uninterrupted traffic flow conditions and moderate speeds of about 72 km/h (45 mph). For the conditions represented by region A, the service volume of the adjacent traffic lane is not affected by the presence of the bicycle lane. The volume of vehicles and the volume of bicycles are both low. The speed of a vehicle would be significantly reduced by the presence of a bicycle, but there would be few bicycle-vehicle interactions with the small number of bicycles and vehicles present. Consequently, the driver could accelerate to the normal operating speed, after passing the bicyclist, with little or no effect on the other vehicles in the traffic stream.

The service volume in region B with low-vehicle volumes and high-bicycle volumes may be reduced a little because the normal operating speeds would be reduced by the presence of bicycles. The quantity of bicycles present, an average of one bicycle for every 120 to 150 m (400 to 500 ft) for a bicycle volume of 200 bicycles/h, would not permit recovery to the normal higher speeds of operation. The density of the traffic stream would be unchanged, and, consequently, there would be a reduction in service volume.

For region C conditions, that is, high vehicular volumes and fewer bicycles, a small reduction in service volume would be expected. The lower speeds of operation for high-volume conditions would be reduced further by the presence of bicycles. With the high vehicular volumes, a vehicle that is slowed by the presence of a bicycle would also slow the traffic behind the vehicle. However, since the change in speed would be small, there would be little reduction in service volume. At capacity, the vehicles in the traffic stream have no freedom to maneuver; thus, the lateral friction created by bicycles would have little effect, unless the traffic lanes and the bicycle lanes were narrow.

As the volume of bicycles increases with high-traffic volumes, shown as region D in Figure 3, the additional bicycle-vehicle interactions do not have much of an added effect. If the vehicles at high volumes are slowed down, the vehicles in the traffic stream behind them will also slow down. The presence of additional bicycles would not further slow these trailing vehicles.

The region in Figure 3 shown by the cross-hatching represents conditions in which the greatest effect on capacity may be found. At these volumes, the operation of individual vehicles influences other vehicles in the traffic stream; however, individual vehicles are not completely restricted in their operations. Figure 4 shows a model of the relations for the capacity reduction factors that may be expected under various vehicle and bicycle volume conditions. These factors must be further modified when applied in capacity analysis to take account of the nearness of the bicycles to the vehicles in the traffic stream. Effect of nearness to traffic stream has not been investigated here; however, the findings of the Purdue study (6) indicate its importance.

As shown in Figure 4, the reduction in formal operating speeds would have the greatest effect on the reduction in capacity. In the center of this figure, which is the area of greatest bicycle influence, the location of the reduction factor would be a function of the frequency of interactions and the normal operating speeds. On the right side of the figure, the dominating influence of flow near capacity would control conditions.

The quantification of these reduction factors will require a coordinated data collection and analysis program. Once developed, these factors could be used in existing capacity analysis procedures.

COLLECTION OF DATA

It was decided that data would be needed to supplement the data currently available to determine if bicycles significantly affect the level of service on urban streets. The city of Eugene was chosen as the study site because of its extensive system of bicycle lanes. There is also a large segment of students at the University of Oregon who commute by bicycle. Three specific sites were chosen that were based on three criteria: the volume of bicycles, the volume of automobiles, and the character of the street. Two of the streets chosen are one-way with parking on one side and a bicycle lane on the opposite side. One of the streets is inbound toward the central business district and the other is outbound. The third street is two-way with parking on both sides and bicycle lanes on both sides between the parking lane and travel lane. The point where the data were collected is adjacent to the campus. In all cases, the bicycle lanes are 1.52 m (5 ft). Vicinity maps for the three sites are shown in Figure 5.

Method

There are three major areas of concern in the collection of data. These include equipment, procedures, and classification scheme.

The equipment used was a hand-held radar speed meter. It was chosen because of its ease of operation and quick set-up time. It also has the advantage of being totally inconspicuous to the vehicle operator, thus eliminating the possibility of the sampling procedure affecting the characteristics of the population being sampled. The model of equipment used provided a direct and instantaneous read-out of speed for each vehicle desired. Therefore, the speeds were logged continuously. It also allowed the data to be stratified prior to taking the sample. The total number of vehicles and bicycles passing by the checkpoint during each sampling period was tallied.

For the procedure, sites were chosen that provided an opportunity to park in an inconspicuous location. When possible, parking lots were used; otherwise a street location between two parked cars was used. A special effort was made to eliminate any bias that would result from the physical attributes of the locations such as automobiles in platoon, automobiles slowing down to make a turn, and vehicles approaching a stop light.

The classification scheme is as follows. The population of vehicles was divided into two categories before the sampling process began: the case in which a bicycle is not present, and the case in which a bicycle is present. Because of the limited number occurring in the second category, 100 percent of the speeds were sampled. Since the population is stratified for the purpose of comparing the mean speeds in each category, the sample was not allocated by proportional or optimal methods.

Figure 1. Relation between density and level of service.

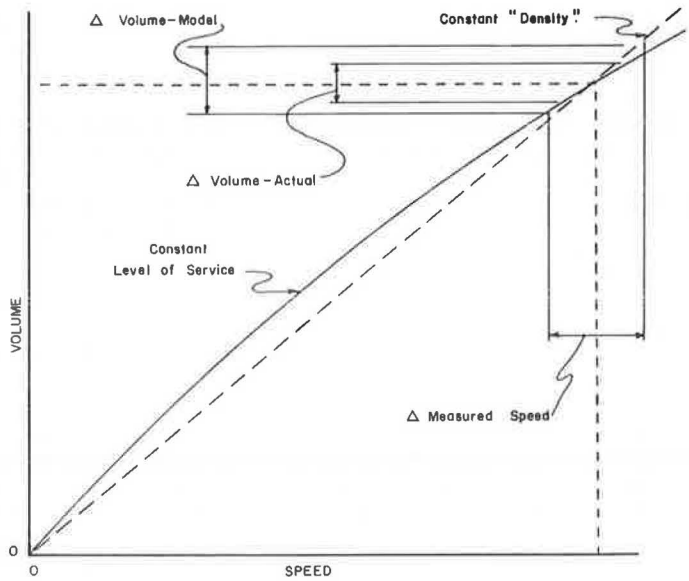


Figure 2. Capacity loss due to physical presence of bicycle lane.

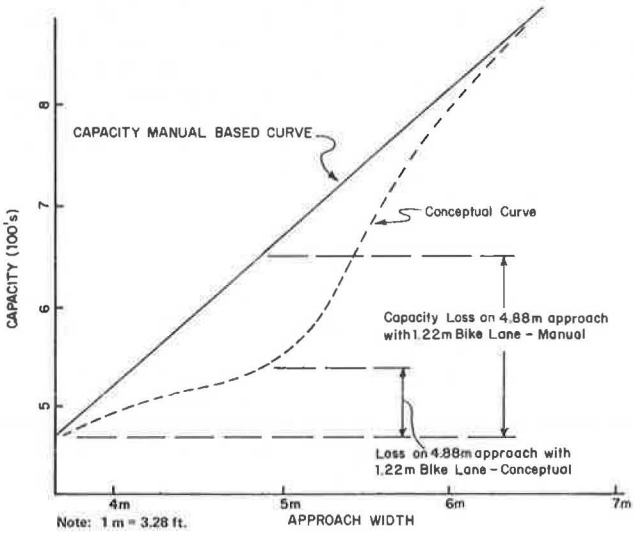


Figure 4. Model of capacity reduction factors for bicycle lane effects.

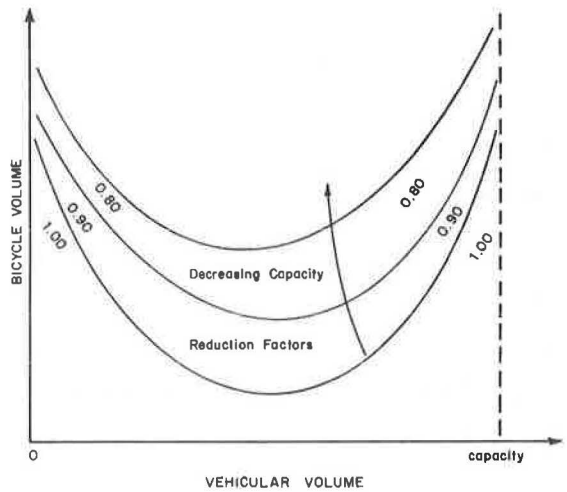


Figure 3. Effect of bicycle volumes on level of service.

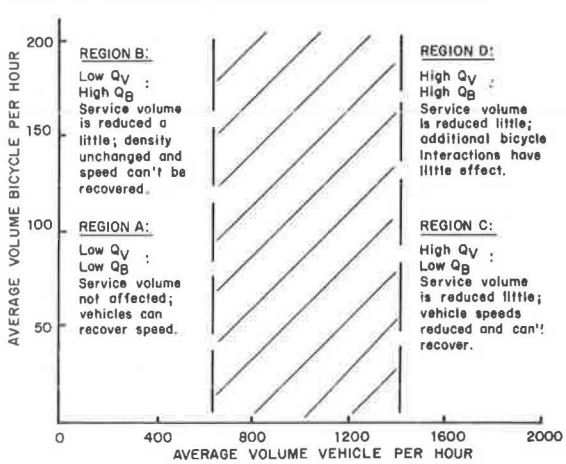
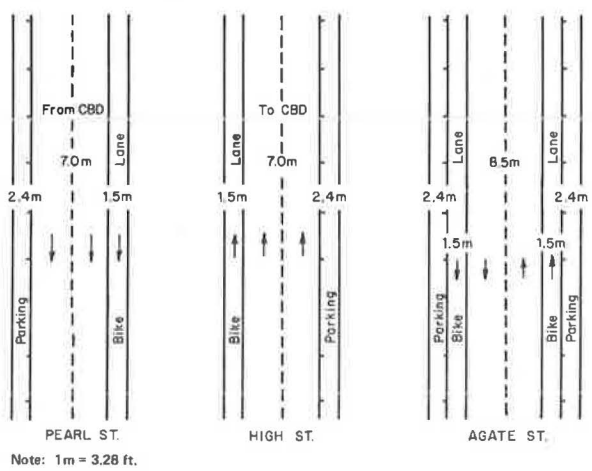


Figure 5. Sampling sites.



Statistical Analysis

An estimate of the mean speed with the desired degree of accuracy was obtained by calculating a minimum sample size. The expected range of speeds was taken into consideration, and a maximum difference between the population mean and the sample mean of 0.6 km (1 mile) was considered acceptable. The level of significance in testing the data was 10 percent. Based on data from other speed studies, the standard deviation was assumed to equal 2.48 km/h (4 mph). Therefore, the minimum sample size required to meet the above criteria was calculated by using the following formula:

$$n = (z_\alpha/2^\sigma)/e \qquad (5)$$

where

n = required sample size,
z = estimated standard deviation of the population [1.645 (α = 0.10)], and
e = maximum error desired.

The minimum value of n calculated to provide a statistically significant sample is about 43.

Confidence limits were established for each of the sample means. Since the value of n was less than 100, the Student's t-statistic was used instead of the z-statistic for a standard normal distribution. The formula to calculate the confidence limits (CL) is as follows:

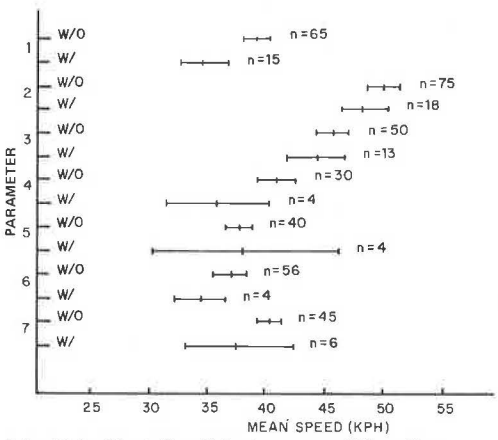
$$CL = x \pm \{ [t(\alpha/2, \sigma)] (s/n) \} \qquad (6)$$

where

x = sample mean,
$t(\alpha/2, \sigma)$ = Student's t-statistic,
s = standard deviation of sample, and
n = size of sample.

The differences in means between the various cases were tested by using the two-tailed Student's t-distribution. The null hypothesis was that the population means for the two cases were equal. This was tested at the 10 percent significance level.

Figure 6. Confidence intervals for mean speeds.



Notes: 1 kph = 0.6 mph; W = with bicycles present, and W/o = without bicycles present.

ANALYSIS OF DATA

The data were analyzed to anwer the following questions. The first question asked if there was a significant difference in speed as a result of the presence of bicycles. A negative answer would have indicated that the effect of bicycles on the level of service is limited. The second question considered the effect of the different weather conditions present during the survey period. Comparisons were made between rainy and nonrainy weather for the two cases by using the same time of day and location for both cases. The results of the comparisons were used by analyzing the effect of the number of vehicles per hour and the number of bicycles per hour on the number of interactions per hour between vehicles and bicycles. Because of the limited number of occurrences of some of the penomena, the results that are derived may have limited validity.

Comparisons of Mean Speeds

Standard parameters were calculated for each of the speed samples. These include the sample mean and the standard deviation. Confidence intervals of 90 percent were calculated for each sample. These intervals are shown in Figure 6. It can be seen that the desired accuracy of plus-or-minus 1.61 km/h (1 mph) is not achieved in many of the samples. This occurs primarily in the case for a bicycle present on days of inclement weather.

A test was made to determine the significance of the

Table 1. Comparison of means for vehicle speeds for bicycles present versus not present and for rain versus no rain.

Sample	Street	Weather	$\bar{X}_1$	$\bar{X}_2$	$s(x_{1i})$	$s(x_{2i})$	n_1	n_2	t-statistic	ν	$t_{(\alpha/2,\nu)}$	Reject
Bicycles versus no bicycles[a]												
1	Pearl	Cloudy	39.40	35.41	5.68	5.41	65	15	2.47	78	1.666	Yes
2	Agate	Cloudy	49.89	48.18	7.16	5.28	75	18	0.94	91	1.664	No
3	Pearl	Cloudy	45.71	44.19	5.89	5.12	50	13	0.84	61	1.671	No
4	High	Rainy	40.99	36.21	5.41	3.83	30	4	1.70	32	1.695	Yes
5	Pearl	Rainy	37.95	38.22	3.60	6.61	40	4	-0.14	42	1.683	No
6	Pearl	Rainy	37.53	35.00	6.20	2.03	56	4	0.81	58	1.672	No
7	Pearl	Rainy	40.35	38.09	4.26	5.54	45	6	1.17	49	1.678	No
8[b]	Pearl	Rainy	38.54	37.24	5.10	5.01	141	14	0.91	153	1.645	No
Rain versus no rain[c]												
1[d]	Pearl	—	39.40	37.52	5.68	6.20	65	56	1.72	119	1.658	Yes
2[e]	Agate	—	35.41	33.80	5.41	2.03	15	4	0.14	17	1.740	No

Notes: 1 km/h = 0.62 mph.
[a] $\bar{X}_1$ = speed of vehicles without bicycles present and $\bar{X}_2$ = speed of vehicles with bicycles present.
[b] Sample 8 is the total of samples 5, 6, and 7.
[c] $\bar{X}_1$ = speed of vehicles in dry weather and $\bar{X}_2$ = speed of vehicles in rainy weather.
[d] Sample 1 is taken from the population of vehicles without bicycles present.
[e] Sample 2 is taken from the population of vehicles with bicycles present.

difference between the means for the two cases, that is, speed without bicycles present versus speed with bicycles present for each sample. The hypothesis test was conducted at a 10 percent level of significance for the null hypothesis in which the true difference between the population means is zero. The Student's t-statistic was used because of the small size of the samples. As given in Table 1, there was a significant difference in only two of the samples.

There is a decrease in the mean speed differences as the vehicular average hour volume (AHV) increases. A mean speed difference of 4.83 km/h (3.0 mph) for the bicycle present versus the bicycle not present cases is found when the AHV is 340 vehicles. When the volume increases to 890 and 914 vehicles/h, the speed differences of 2.25 km/h (1.4 mph) and 2.42 km/h (1.5 mph) respectively are smaller.

The test to determine whether there is a significant difference between the vehicle speeds on a rainy and a nonrainy day is given in Table 1. There is a significant difference at the 10 percent level with no bicycle present between speeds on rainy days and speeds on nonrainy days. However, in the second case with bicycles present, the difference in mean speeds on rainy days versus mean speeds on nonrainy days is not significant at the 10 percent level. Thus, data from the second case tend to support the fact that the difference in speed between the two cases was greater on dry days than on rainy days.

RESULTS AND CONCLUSIONS

The purpose of this study was to investigate the effect of bicycle lanes on the level of service on urban street systems. A model of capacity effects based on reductions in vehicle speeds was suggested. A large cross section of bicycle lanes across the nation must be sampled to get sufficient data for this purpose. There are five main results from this study, and they are as follows:

1. There appears to be a small decrease in mean vehicle speed as a result of the presence of bicycles.
2. During rainy weather, the mean speed of vehicles is reduced because of the climatic conditions; therefore, the presence of bicycles does not noticeably affect mean speed.
3. The amount of reduction tends to decrease slightly; i.e., it is inversely proportional to an increase in vehicle AHV. This may be a result of drivers having less freedom to respond to outside influences.
4. There is less reduction in speed on wider streets since there is more room for lateral movement. Thus, if there is sufficient room, motorists will move away from the lane, and the decrease in speed will not be noticeable.
5. The reduction in capacity may be a function of the frequency of bicycle-vehicle interactions and speed of operation. Further data collection and analysis are needed to quantify this relation.

ACKNOWLEDGMENTS

Special thanks are due to Alva Williams of the city of Eugene, Oregon, for his assistance in data collection and especially for loan of his radar equipment. Thanks are also due to Harry A. Burns, Jr., of Gainesville, Florida; R. Gary Hicks of Oregon State University; and William Tebeau of the Oregon State Highway Division of the Department of Transportation for making available material that is in their personal libraries. This research was made possible by a graduate fellowship from the Federal Highway Administration of the U.S. Department of Transportation and the cooperation of the Oregon Department of Transportation. Preparation of the final manuscript was assisted by the Idaho Department of Transportation.

REFERENCES

1. Bicycling in Tennessee: Inventory of Users, Facilities, and Programs. Barton-Aschman Associates, Inc., Minneapolis, Sept. 1974.
2. Mesa Bicycle Study. City of Mesa, Arizona, 1974.
3. B. Kroll and R. Sommer. Bicyclist's Response to Urban Bikeways. AIP Journal, Vol. 42, No. 1, Jan. 1975.
4. S. B. Loop. Bicycle Transportation: An Annotated Bibliography. Department of Civil Engineering, Oregon State Univ., unpublished rept., 1976.
5. D. T. Smith, Jr. Research on Safety and Location Criteria for Bicycle Facilities. De Leuw, Cather and Co., San Francisco, Dec. 1973.
6. R. J. Jilla. Effects of Bicycle Lanes on Traffic Flow. School of Civil Engineering, Purdue Univ., Joint Highway Res. Project JHRP-74-10, Dec. 1974.

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

An Experimental Study of the Defensive Driving Course

Ronald M. Weiers, School of Business, Indiana University of Pennsylvania

This study employed the systems concept that the overall success of a social product results from a combination of adoption rate and effectiveness and that product design improvement involves the generation of an attractive alternate product design, which is evaluated and compared with the conventional design on the basis of appropriate adoption rate and effectiveness measures. Group interviews and preliminary marketing research that involved actual and potential consumers of a defensive driving course were used to identify a number of salient course characteristics. The scope of the study was limited by confining the investigation to a single important course di-