Safety Impacts of Bicycle Lanes

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In September 1977 bicycle lanes were implemented on a 1.3 mi section of a one-way arterial pair in the central part of Madison, Wisconsin. On Johnson Street the bicycle lane was placed on the left side whereas on Gorham the lane was in the conventional location on the right side. Bicycle accident data and estimates of bicycle use in Madison for the 4 years before and after the introduction of the bicycle lanes were used to evaluate the safety impacts of the bicycle lanes. A statistically significant increase in bicycle accidents between the before and after periods was found, but the increase was traced to two specific types of accidents on Johnson Street that occurred primarily in the first year of the after period. In subsequent years the increase was not statistically significant in contrast to a significant increase in total bicycle accidents in the city. Recommendations for countermeasures to reduce the initial accident problems associated with the left-side bicycle lane are made.

As part of the overall development of transportation facilities in the City of Madison, Wisconsin, the Madison Department of Transportation (MDOT) published its *Bicycle Facilities Plan* in 1974 (*1*). The plan provides for an extensive network of both on- and off-street bicycle facilities. Bicycle routes on local streets were signed to provide access to major generators such as the University of Wisconsin and the State Capitol area. Heavy bicycle traffic through and within the university campus was provided for by combined bus-bicycle reserved lanes on University Avenue.

A significant concentration of student housing is situated east of the Capitol (Figure 1). Because of the high concentration of private and governmental offices in the Capitol area and the limited land area, no local streets are available to provide a continuous through bicycle route in both directions. Consequently, many bicyclists choose to use the Johnson Street-Gorham Street one-way arterial street pair on the north side of the Capitol.

BICYCLE LANE DESIGN

In order to provide a continuous and convenient bicycle facility through the corridor to the north of the Capitol, bicycle lanes were installed in September 1977 for the 1.3-mi Johnson-Gorham Street one-way pair. As shown in Figure 1, the most convenient extension of the eastbound bicycle lane on University Avenue required placing the exclusive bicycle lane on the left side of Johnson Street. That location allowed eastbound bicyclists on University to turn right onto Bassett Street (one-way southbound) and then turn left on Johnson without waiting for the green traffic signal at Johnson and Bassett. The left-side bicycle lane also minimized the conflicts with vehicles entering and leaving Johnson on the Capitol side (right-hand side) of the street. On Gorham Street the conventional placement of the on-street bicycle lane on the right side provided a direct connection to the existing westbound bicycle lane on University Avenue.

On Johnson Street west of Butler Street the 39-ft-wide pavement was restriped to provide a 6-ft bicycle lane on the left, two narrowed through traffic lanes, and a right-hand curb parking lane with no parking during peak hours. East of Butler Street the 44-ft-wide pavement was striped for a 13-ft combined parking and bicycle lane on the left side, a 10-ft through lane and a 21-ft combined through and parking lane. In contrast on Gorham Street, the combined 13-ft bicycle and parking lane was located on the right side and the two through vehicle lanes on the left side. Preferential lane signing and pavement markings were used to designate the intended uses of the bike lane; for example, "Left Lane-Bicycles and Left Turns Only" signs were placed in areas where parking was prohibited.

PURPOSE OF STUDY

The primary purpose of this study is to evaluate the effects of the new bicycle lanes in the Johnson-Gorham corridor on bicycle safety. A secondary purpose is to identify any differences in safety between the conventional right-side bicycle lane on Gorham Street and the left-side bicycle lane on Johnson Street. If accident problems are found, potential countermeasures will be identified.

STUDY METHODOLOGY

The purpose of introducing the bicycle lanes on Johnson and Gorham was to provide additional mobility to bicyclists by providing an alternative to either riding in the regular traffic lanes or using the sidewalks. The bicycle accident rate on Johnson and Gorham had not been viewed as being excessive. The general expectation, however, was that the number of bicycle accidents would be reduced or at least stay the same because the bicycle lanes would separate the bicyclists from both automobile and pedestrian traffic. The observed increase in bicycle accidents after the introduction of the bicycle lanes led to this overall study of the impact of the bicycle lanes on bicyle safety.

The methodology used for evaluating the safety impacts of the new bicycle lanes is that of a simple before-and-after study

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FIGURE 1 Location of Johnson Street and Gorham Street bicycle lanes.

involving a single location. There are four primary threats to the validity of a before-and-after study:

- History (other causes at the same time),
- Maturation (trends over time),
- Regression to the mean, and
- Instability because of chance or random fluctuations in the data (*2*).

Two of the four threats to validity, history and regression to the mean, do not appear to be relevant. During the 8-yr period chosen for the before-and-after study, no specific causes for changes in the bicycle accident rate, such as a major new educational campaign or enforcement of traffic regulations, were identified. Also, regression to the mean should not be a problem because the study location was not selected on the basis of prior accident experience. The remaining two threats to validity are discussed in the next sections.

TRENDS IN BICYCLE USE AND ACCIDENT DATA

As shown in Figure 2, the MDOT has historical data on bicycle accidents dating back to 1955. The dramatic increase in bicycle accidents that began in 1970 appears likely to be correlated with bicycle use as measured by total bicycle shipments to dealers in the United States (see Figure 2). The growth in bicycle availability in Madison no doubt preceded the national growth curve by at least 1 year.

A bicycle traffic counting program was begun by the MDOT in 1974. Initially, bicycles were counted at three intersections within the central Madison area where bicycle trips are concentrated. Counts at the intersections on the east and west side of the central area are continuing but the third intersection in the university campus area was dropped because of the large variation in the count volumes. All bicycles entering the two intersections are counted for 2 hr during the a.m. and p.m. weekday peak periods once a month. The intersection counts are factored to produce an estimate of total daily bicycle trips citywide based on a 1974 home interview survey of bicycle travel. The east-side count location at the intersection of Johnson and Franklin Streets is within the study corridor. Consequently, the citywide estimate of bicycle travel should provide a good estimate of bicycle use within the study corridor.

The bicycle lanes on Johnson and Gorham Streets were opened in September 1977. In order to take advantage of the bicycle use data dating from 1974 and to obtain the largest possible number of bicycle accidents, 4-yr before-and-after study periods ranging from September 1973 to August 1977 and September 1978 to August 1981, respectively, were selected.

A reasonable correlation exists between the total bicycle accidents and the citywide estimates of bicycle trips ($r = 0.518$) for the 1974 to 1981 time period (Table 1). When the low estimate of trips in 1978 is omitted, the correlation increases to 0.633. Thus, increased exposure provides a partial explanation for the observed increase in bicycle accidents citywide; however, the total bicycle accident rate still grew by 20 percent from before to after. When the total bicycle accidents for the before period are expanded by 7.7 percent to account for the

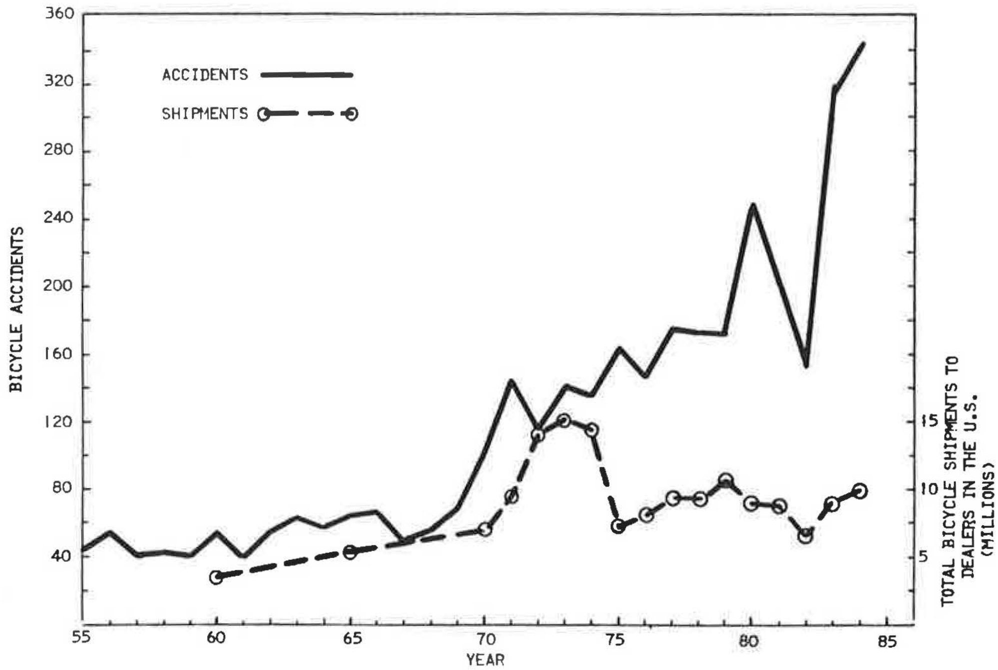

FIGURE 2 Bicycle accidents in Madison and total bicycle shipments to dealers in the United States.

TABLE 1 BICYCLE ACCIDENTS AND TRIPS IN MADISON, 1974 TO 1981

Year	Total Accidents	Johnson and Gorham Accidents		Estimated Daily Trips	Total Accident Rate per 1,000 Daily Trips
		Number	Percent of Total		
Before					
1974	135	7	5.2	86,000	1.6
1975	163	8	4.9	68,100	2.4
1976	146	12	8.2	79,000	1.8
1977	175	9	5.1	75,100	2.3
After					
1978	173	20	11.6	59,100	2.9
1979	172	8	4.7	77,400	2.2
1980	247	14	5.7	97,600	2.5
1981	200	9	4.5	97,900	2.0
Summary					
Before					
Total	619	36	5.8	308,200	2.0
Average	155	9		77,050	
After					
Total	792	51	6.4	332,000	2.4
Average	198	12.8		83,000	
Increase (%)	+27.7	+41.7	+11.1	+7.7	20
Expanded Before Accidents[a]					
Total	665[.001][b]	38.8 [0.03][c]			
Average	167[0.01][c]	9.7 [0.18][c]			
Increase (%)	+18.6	+31.4			

[a]Before accidents expanded by 1.077 to account for increase in daily bicycle trips.
[b]Level of significance of increase based on chi square (2).
[c]Level of significance of increase based on cumulative Poisson distribution.

increase in bicycle trips, the total accidents increased by 18.6 percent. As shown in the summary at the bottom of Table 1, the increase in total accidents is statistically significant at the 0.001 level based on a chi square test (*2*), whereas the increase in the average total accidents is significant at the 0.01 level based on the cumulative Poisson distribution.

The total bicycle accidents in the Johnson and Gorham study area corridor increased from 36 in the before period to 51 in the after period, a 42 percent increase. As shown at the bottom of Table 1, expansion of the before accidents in the corridor results in 38.8 accidents or an average of 9.7 per year. Based on the cumulative Poisson distribution, the increase in accidents (expanded before versus after) is statistically significant at the 0.03 and 0.18 levels for the total and average accidents, respectively.

The maturation or trends over time threat to the validity of the before-and-after analysis can now be addressed explicitly given the available data on total bicycle accidents in Madison and the annual estimates of daily bicycle trips. If no information on exposure as measured by the daily bicycle trips was available, then it would be reasonable to assume that the bicycle accidents on Johnson and Gorham would increase at the same rate as the total bicycle accidents. This would result in an estimated $36 \times 1.277 = 46.0$ accidents in the after period compared with 51 actual accidents. Based on a Poisson distribution with a mean of 46.0, 51 or more accidents would be expected 25 percent of the time. Thus, the increase from 46 to 51 accidents is not statistically significant.

An alternative interpretation of the available data is that the bicycle accidents on Johnson and Gorham are independent of the overall citywide accident trend and the only relevant "other" cause is the increased exposure. The time-series data on annual accidents for the before and after periods shown in Table 1 tend to support this hypothesis. Except for the first year of the after period (1978), the study-area accidents are consistent with the annual rates for the before period. This interpretation may increase the probability of a Type I error in which a statistically significant change is identified when in fact trends over time, not the bicycle lanes, are responsible for the change. This is good in that potential safety problems will be less likely to be overlooked. Consequently, this second interpretation will be emphasized in the subsequent analysis.

Another factor that would potentially affect the bicycle accident experience is change in the volume of traffic on Johnson and Gorham. Analysis of annual traffic count data for two locations on each street for the 8 years showed substantial year-to-year fluctuation but little overall change. The average volumes on Gorham declined by 5.3 percent from before to after, whereas the volumes on Johnson increased by 3.2 percent. Thus, any possible impact of the change in traffic volumes on bicycle accidents is likely to be small.

STATISTICAL METHODOLOGY

The last of the four threats to the validity of the before-and-after study, instability because of chance or random fluctuations, can be addressed directly using statistical tests. The null hypothesis for this study is that there is no change in the overall bicycle accident rate from the before to the after period in the study corridor where the accident rate is based on the estimated daily bicycle trips for the two time periods. An equivalent null hypothesis is that the number of before accidents, expanded by 7.7 percent to account for the increase in bicycle trips, is equal to the number of accidents in the after period.

The accidents for the before period are assumed to have a Poisson distribution with a mean equal to the number of accidents in the before period. Then, the probability that the observed number of accidents in the after period could have come from the same population as the before period can be computed from the cumulative Poisson distribution (*3*). If this probability is low enough, say 0.05 or less, then the hypothesis that the before and after accident levels come from the same population can be rejected. Thus, the introduction of the bicycle lanes has led to a statistically significant change in accidents. If there is a reduction in accidents from before to after, then the relevant equation for the cumulative Poisson distribution is

$$Pr(X_a \leq k \mid m = X_b) = \sum_{x=0}^{k} m^x e^{-m}/x! = 0.05 \tag{1}$$

where

X_a = number of accidents in the after period,
X_b = number of accidents in the before period, and
m = mean of the cumulative Poisson distribution.

If the accidents in the after period, X_a, satisfy Equation 1, then there is only a 5 percent chance that the after conditions are the same as the before conditions, that is, the distributions are significantly different at the 0.05 level. The percent accident reduction required to satisfy Equation 1 is given by

$$\% \text{ reduction} = \frac{k - X_b}{X_b} \times 100\% \tag{2}$$

Lunenfeld gives curves of percent reduction as a function of X_b for various levels of significance as shown in Figure 3 (*4*). The curves were originally developed by Michaels (*5*) and later expanded by Datta et al. (*6*).

In the present study, bicycle accidents, in general, increased from the before to the after period so the percent reduction curves were of limited use. Instead, the statistical significance of an increase in accidents from the before to the after period was determined directly from the upper tail of the cumulative Poisson distribution:

$$Pr(X_a > k \mid m = X_b) = 1 - \sum_{x=0}^{k} m^x e^{-m}/x! = 0.05 \tag{3}$$

at the 0.05 level of significance when the terms are the same as in Equation 1. For this study the tests for the statistical significance of changes in accident levels were based on either Equation 1 or Equation 3. The percent reduction curves were used only to provide a general indication of the magnitude of the change that would be statistically significant as a function of the number of before accidents.

CHANGES IN ACCIDENTS BY TYPE

The changes in bicycle accidents between the before and after period by accident type for Johnson Street, Gorham Street, and

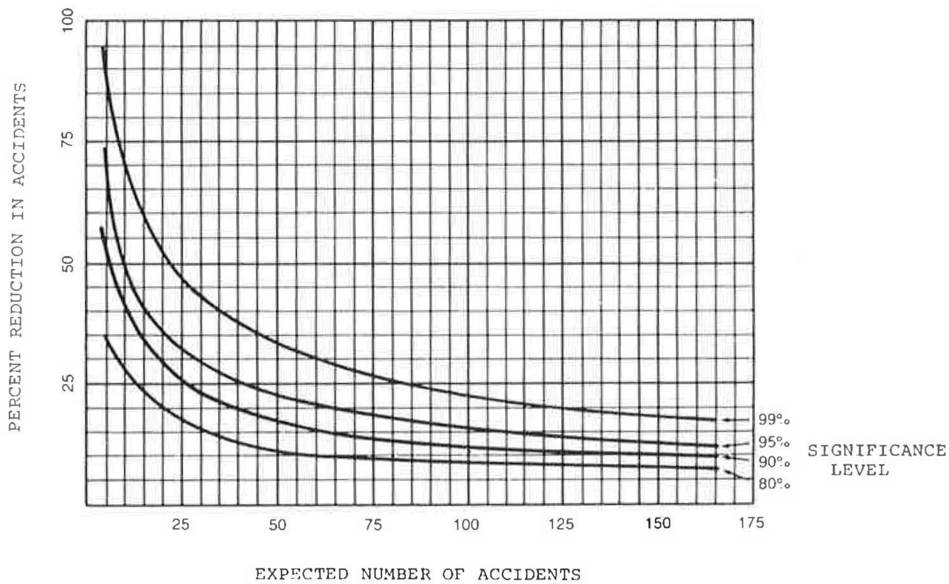

FIGURE 3 Statistical significance of percent reduction in accidents based on the cumulative Poisson distribution (*4*).

the total corridor are shown in Table 2. The before accidents are expanded by 7.7 percent to account for the difference in bicycle use between the before and after periods. For the corridor as a whole, the increase in midblock accidents is significant at the 5 percent level (95 percent confidence level) but the increase in intersection accidents is only marginally significant (18 percent level). Both Johnson and Gorham contribute to the increase in midblock accidents with the increase for Gorham significant at the 7 percent level. In contrast, the change in total intersection accidents is significant for Johnson but is insignificant (minor decrease) for Gorham.

Considering the overall change in bicycle accidents on Johnson and Gorham, it can be seen from Table 2 that there was a significant increase on Johnson (0.05 level of significance) but not on Gorham. Similarly, considering the individual categories of accidents, the changes in accidents tend to be more significant on Johnson than on Gorham; although the impacts on safety are mixed. These differences in significance level are

TABLE 2 STATISTICAL SIGNIFICANCE OF CHANGE IN ACCIDENTS

	Johnson Street				Gorham Street				Total			
Accident Type	Before[a] (no.)	After (no.)	Change[b] (%)	Level of Significance	Before[a] (no.)	After (no.)	Change[b] (%)	Level of Significance	Before[a] (no.)	After (no.)	Change[b] (%)	Level of Significance
Total	29.1	39	34	.05	9.7	12	24	–	38.8	51	31	.03
Intersection	18.3	24	31	.11	7.5	7	−7	–	25.8	31	20	.18
Midblock	10.8	15	39	.15	2.2	5	127	.07	12.9	20	55	.05
Angle	8.6	9	5	–	4.3	5	14	–	12.9	14	9	–
Northbound automobile	4.3	8	86	.08	4.3	5	14	–	8.6	13	51	.09
Southbound automobile	4.3	1	−77	.07	0.0	0	0	–	4.3	1	−77	.07
Automobile turns in front of bicycle	8.6	17	98	.007	3.2	5	56	–	11.8	22	86	.006
Automobile left turn	3.2	16	400	.001	0.0	0	0	–	3.2	16	400	.001
Automobile right turn	5.4	1	−81	.03	3.2	5	56	–	8.6	6	−30	–
Bicycle going contraflow	9.7	7	−28	–	0.0	2	–	.01	9.7	9	−7	–
On sidewalk or crosswalk	7.5	4	−47	.14	0.0	2	–	.01	7.5	6	−20	–
On street	2.2	3	36	–	0.0	0	0	–	2.2	3	36	–
Other	2.2	6	173	.02	2.2	0	−100	.11	4.3	6	40	–

[a]Before accidents multiplied by ratio of citywide estimate of bicycle trips for after versus before period, 332,000/308,200 = 1.077.
[b][(before-after)/before] × 100%.

in part the result of the substantially lower number of accidents on Gorham. As shown in Figure 3, much greater percentage changes are required to have a significant change when the number of accidents is small.

The total number of accidents on Johnson is three times larger than on Gorham in the before period and 3.25 times greater in the after period. This major difference may be explained in part by the higher volume of automobile traffic on Johnson [22,800 average daily traffic (ADT) on Johnson versus 17,700 ADT on Gorham]. Also, the much higher level of contraflow bicycle accidents on Johnson indicates that many bicyclists use Johnson (including legal use of sidewalks) for westbound travel against the flow of traffic. This would reduce the volume of bicycle traffic on Gorham. The relative volume of bicycle traffic on Gorham compared with Johnson may also be reduced by the availability of two other one-way westbound streets in addition to Gorham in the overall east–west corridor between the university and the near east side of Madison. No comparable eastbound alternative to Johnson exists.

In evaluating the four major accident categories at the corridor level (total accidents), only the "car turns in front of bike" category has a statistically significant change (0.6 percent level). Within that category, the increase in left-turn accidents is highly significant whereas the number of right-turn accidents actually decreased (significant at the 20 percent level). The left-turn accidents only occurred on Johnson Street, which is reasonable because the bicycle lane is on the left side of the one-way street. In the after period with the bicycle lane in operation, automobiles making left turns from Johnson into side streets must cross the bicycle lane, creating a potential for accidents. In the before period on Johnson, bicyclists traveling on the right side of the right lane created a potential conflict with right-turning automobiles. In fact, it is shown in Table 2 that right-turn accidents exceeded left-turn accidents on Johnson in the before period and that the decrease in right-turn accidents from before to after is significant at the 3 percent level. As expected with the addition of the bicycle lane on the right side of Gorham, right-turn accidents on Gorham increased although the increase is only marginally significant.

The greatest change in accidents between before and after occurred in the "left turns by cars in front of bike" category on Johnson—a fivefold increase. The comparable "right-turn" accident category on Gorham also experienced a substantial increase (56 percent). The nonstandard, left-side location of the bicycle lane on Johnson may be the primary reason for the difference in accident experience. Drivers do not expect bicyclists to be in the left-hand lane and bicyclists are more familiar with having automobiles on their left rather than on their right. Data on the year-to-year changes in the left- and right-turn accidents are presented in a subsequent section. The data suggest that the high level of after period accidents resulted from initial unfamiliarity with a novel situation because accidents dropped sharply after the first year of the after period.

The accident changes shown in Table 2 for the other major accident categories for Johnson and Gorham individually are not more than marginally significant except for the "other" category on both Johnson and Gorham. A detailed review of the reasons for each of the "other" category accidents did not reveal any clear relationship with the new bicycle lane.

Finally, the changes in the two individual categories of angle accidents for Johnson are significant at better than the 10 percent level but move in opposite directions with the net result of little change for total angle accidents. In the after condition on Johnson, northbound automobiles must cross two lanes of traffic before crossing the left-side bicycle lane. Apparently, drivers are preoccupied with avoiding cars as they cross Johnson and thus fail to see bicyclists in the bicycle lane. In contrast, for the before condition, bicyclists in the standard location in the right-hand lane would be closer to northbound drivers and apparently more visible. Similar logic explains the observed reduction in accidents involving southbound drivers.

TIME-SERIES ANALYSIS

A year-by-year comparison of the Johnson and Gorham accidents with the total bicycle accidents (expressed as "Percent of Total") is shown in Table 1. The percentages vary within a narrow range of 4.5 to 5.7 percent except for one outlier at 8.2 percent in the before period and one at 11.6 percent in the after period. The overall correlation between the Johnson and Gorham and the total accidents for the 8-yr period is not large (r = 0.423), but when the after period outlier for 1978 is removed, the correlation increases substantially to 0.724. Thus, the year-by-year data suggest that the Johnson and Gorham accidents for 1978 should be analyzed as a special case.

The average annual number of Johnson and Gorham bicycle accidents during the before period equals 9.0. The cumulative Poisson distribution with a mean of 9.0 can be used directly to test the hypothesis that an observed number of accidents in a subsequent year comes from the before population. For 1978 with 20 bicycle accidents, the probability of 20 or more accidents occurring based on the Poisson distribution with a mean of 9.0 is only 0.001. Thus, it is clear that the level of Johnson and Gorham bicycle accidents in 1978 is significantly different from the before period. No adjustment for bicycle use is necessary because the estimated trips for 1978 are much lower than for the before period. Also, 1978 was not an abnormal year for total bicycle accidents in Madison.

DISTRIBUTION OF ACCIDENTS BY TYPE AND YEAR

As discussed previously, the aggregate data on accidents by year show that the accident rate in the first year of the after period was significantly higher than the average for the before period, but in subsequent years the accident rate was similar to the before period. In order to identify possible reasons for the observed increase in accidents, the distribution of accidents by type was tabulated for each year for Johnson and Gorham separately. The results for the most significant accident types are given in Table 3.

The time-series data in Table 3 show a marked increase in two types of accidents on Johnson in 1978 following the introduction of the bicycle lane. Comparison of these 1978 accident levels with the expanded annual averages for the before period shows highly significant statistical differences. The accidents for subsequent years are not significantly different from the before period averages except for the "left turns by car" category. A similar analysis for Gorham is not relevant because there is no clear initial increase in accident rates in 1978.

TABLE 3 DISTRIBUTION OF BICYCLE ACCIDENTS BY YEAR FOR JOHNSON AND GORHAM

	Johnson			Gorham		
Year	Total	Angle north-bound	Left Turns by Automo-bile	Total	Angle north-bound	Right Turns by Automo-bile
Before						
1974	5	1	1	2	1	0
1975	6	1	0	2	2	0
1976	8	0	1	4	1	3
1977	8	2	1	1	0	0
After						
1978	16[.004][b]	5[.005][b]	7[.001][b]	4	1	2
1979	7	1	4[.01][b]	1	0	1
1980	10	1	3[.05][b]	4	2	1
1981	6	1	2	3	2	1
Summary						
Before						
Average	6.75	1.0	0.75	2.25	1.0	0.75
Average × 1.077[a]	7.3	1.1	0.8	2.4	1.1	0.8
After average	9.8	2.0	4.0	3.0	1.2	1.2

[a]Expanded by 7.7 percent to account for greater bicycle use in after period.
[b]Indicates level of significance of accident rate for that year compared with expanded average accident rate/yr for before period.

The time-series data for Johnson and Gorham suggest that introduction of a left-side bicycle lane (Johnson) will result in an initial increase in accidents, whereas the more conventional right-side bicycle lane (Gorham) will not. After a reasonable period of time, neither bicycle lane location appears to cause additional accidents.

CONCLUSIONS

In comparing total bicycle accidents in Madison for the before and after periods, the statistical analysis shows that the after period total is significantly higher. Similarly, for the bicycle lane corridor on Johnson and Gorham, the after period accidents are significantly higher than the before period accidents. More detailed analysis, however, shows that when the atypical first year of the after period (1978) is removed, the accidents on Johnson and Gorham are not significantly higher than the before period. Time-series analysis of the Johnson and Gorham data by accident type shows that the primary sources of the 1978 atypical accident levels are the two Johnson Street categories: (a) angle accidents involving a northbound automobile and (b) automobiles making left turns in front of bicycles. Both of these accident types have a logical relationship to the left-side bicycle lane on Johnson. The accident levels for these two accident types were much reduced in subsequent years indicating that drivers and bicyclists were adapting to the presence of the left-side bicycle lane.

Given the initial adverse accident experience with a left-side bicycle lane in Madison, other similar new bicycle facilities should be implemented only in conjunction with special signing to alert both bicyclists and motorists to the potential hazards. At a minimum, signs identifying the existence, location, and intended use of the bicycle lane should be highlighted with red flags for the first several months. The signing should be designed to reduce the "angle" and "car turns in front of bicycle" accidents that were significant for the Johnson Street (left-side) bicycle lane. Special lane markings for the bicycle lane at intersections should also be considered.

It is possible that locating the Johnson Street bicycle lane on the right side of the street would have reduced the initial high-accident experience with the left-side bicycle lane. The right-side bicycle lane on Gorham did not experience a significant increase in accidents; however, the right-turn traffic volumes from Gorham across the bicycle lane are certainly much lower than the right-turn volumes that exist on Johnson. Detailed analysis of automobile turn and cross-traffic volumes on both Johnson and Gorham would be required to estimate accidents as a function of exposure to turning movements and cross traffic.

Overall, the bicycle lanes on Johnson and Gorham streets did not have a negative impact on bicycle safety. Except for the first year of bicycle lane implementation on Johnson Street, the bicycle lane corridor accidents did not increase significantly compared with significant increases in bicycle accidents city-wide. Also, except for the first year of implementation of the left-side bicycle lane, there is no clear indication that left-side bicycle lanes are less safe than the conventional right-side bicycle lanes.

Communities that implement bicycle lanes should plan ahead to collect data on accidents and bicycle use so that even more comprehensive before-and-after studies can be completed. The data collection effort will also permit early identification of any safety problems in both the before and after periods.

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