Risk Factors for Bicycle-Motor Vehicle Collisions at Intersections*

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In 1992, 722 bicyclists were killed in the United States in collisions with motor vehicles[1], and an estimated 650,000 people were treated in emergency rooms for bicycle-related injuries.[2] It is remarkable that, for a traffic safety problem of this magnitude, so little research has been conducted to establish the causes of these accidents. Instead, design standards for roadways and bicycle facilities, individual project designs, and laws and policies regarding bicycling are based almost entirely on opinion. The quality of the results is highly variable.

This paper reports a study of bicycle-motor vehicle collisions in the city of Palo Alto, California. The study compares personal characteristics and bicycling behavior-age, sex, direction of travel (with or against traffic flow), and position on the road (roadway or sidewalk) of bicyclists involved in accidents with similar data for the general population of bicyclists observed along the same streets. This comparison enables us to identify factors that are correlated with increased risk of bicycle-motor vehicle collisions, and to suggest engineering practices that reduce this risk.

Methods

Accident Records

From 1981 to 1990, one of the authors, Diana Lewiston, analyzed all police reports of bicycle accidents in Palo Alto. This study considers only the period from July 1985 through June 1989. (Earlier data were entered in an incompatible computer format and are no longer available.) During this period, bicycle-motor vehicle collisions accounted for 314 of 371 bicycle accidents for which a substantially complete police report was available (85 percent). The remaining accidents involved single bicycles, or collisions with another bicycle, a pedestrian, or, in one case, a train, which resulted in the only fatality during the study period. Since they constitute the majority of all reported bicycle accidents, this study considers only the incidence of bicycle-motor vehicle collisions.

Bicycle accidents at intersections accounted for 237 of 371 total bicycle accidents (64 percent), and 233 of 314 bicycle-motor vehicle collisions (74 percent). We define an intersection broadly as any point where turning or crossing movements are possible for the bicyclist or the motorist. The definition therefore includes not only the junction of two roadways, but also points where driveways, sidewalks, or paths meet a roadway, or where sidewalks or paths meet a driveway.

The large fraction of accidents that occurred at intersections indicates that these are the major points of conflict between bicyclists and motorists. Overtaking accidents, in which a bicyclist in the roadway was struck from behind by a motorist traveling in the same direction, accounted for only 5 of 314 bicycle-motor vehicle collisions, and sideswipes for 8. The remaining non-intersection collisions included those in which a bicyclist overtook a parked or parking motor vehicle, a motorist opened the door of a parked car into the bicyclist's path, or a motorist or bicyclist changed lanes improperly.

There is no national reporting system for bicycle-motor vehicle accidents. If an accident is fatal, however, it is almost always well documented and reported. The Fatal Accident Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA) reported that only 31 percent of bicyclist fatalities in motor vehicle accidents in the United States in 1992 occurred at intersections.[1] NHTSA's classification follows the Manual on Classification of Motor Vehicle Traffic Accidents (ANSI D16.1-1989)[3], which defines an intersection as a crossing of two or more roadways not classified as driveways. Our use of intersection corresponds more nearly to the Manual's “junction,” defined as either an intersection or the connection between a driveway and a roadway. FARS statistics for 1992 show 39 percent of fatalities at junctions.[4]

* This article originally appeared in ITE Journal, published by the Institute of Transportation Engineers, September 1994, pages 30-35.

Table 1. Percentage Distribution of Intersection Accidents by Bicyclist Characteristics

	17	18	Female	Male	With Traffic	Against Traffic	Roadway	Sidewalk
Entire city	35	65	31	69	73	27	65	35
Middlefield, Embaracadero, and El Camino Real	34	66	25	75	63	37	54	46

In urban areas the value increases to 44 percent, somewhat closer to our findings. It is possible that non-intersection accidents are more likely to result in fatalities.

Table 1 shows the distribution of bicycle-motor vehicle collisions at intersections, catalogued according to four characteristics that are easily observed and might be relevant for accident risk: bicyclist age, bicyclist sex, direction of bicyclist travel (with or against the direction of traffic on the roadway), and bicyclist position (either in the roadway, including bicycle lanes and private driveways, or on the sidewalk, including bicycle paths and crosswalks).

The table shows that 35 percent of victims were aged 17 or younger, while 65 percent were 18 or older, and that 31 percent were female and 69 percent were male. It is obviously not possible to conclude from these figures that older bicyclists or male bicyclists are at greater risk: the actual risks depend on the age and sex distribution of the bicyclist population that is exposed to potential accidents. For the same reason, it is impossible to draw any conclusions about the risks involved in bicycling with or against the direction of traffic, or on the roadway or the sidewalk, without knowing how many bicyclists in each category were exposed.

Exposure Counts

In order to study the distribution of these four characteristics in the population of bicyclists that is exposed to accidents, the City of Palo Alto's Transportation Division arranged to conduct bicyclist counts in May 1987, including counts at intersections along three major arterial streets, Middlefield Road, Embarcadero Road, and El Camino Real, on which many bicycle accidents had occurred (92 of 233 bicycle-motor vehicle intersection accidents). Table 1 shows that the distribution of the selected bicyclist characteristics in accidents along these streets is similar to that in the entire city.

Middlefield Road is a residential street, except for one neighborhood shopping center and a two-block business district. It varies from two to four lanes in width, carries about 16,000 motor vehicles per day, and has on-street bicycle lanes for a portion of its length. The posted speed limit is 25 mi/h. Embarcadero Road is a four-lane residential street carrying about 22,000 motor vehicles per day; the posted speed limit is 25 mi/h, but the measured 85th percentile speed is 37 mi/h. It includes a small neighborhood shopping center at one end and a moderate-sized shopping center at the other and, opposite it, a high school.

Portions of Middlefield and most of Embarcadero are too narrow to accommodate bicycle lanes; accordingly, the city has designated sidewalks in these places as bicycle paths. (Bicycle lanes are portions of the roadway designated for the use of bicycles. Bicycle paths are physically separated rights of way for the exclusive use of bicycles and pedestrians.) The paths are signed "Bicycles May Use Sidewalk," and their use is optional. In accordance with a local ordinance these sidewalks are further signed for one-way bicycle travel, although this prohibition is often ignored and rarely enforced.

El Camino Real is a six-lane divided state highway (Route 82) located primarily in a business district, with parking permitted and many commercial driveways. It carries about 46,000 vehicles per day at a posted speed limit of 35 to 40 mi/h and has no bicycle facilities.

Middlefield and Embarcadero have continuous sidewalks on both sides, and El Camino Real has them for most of its length in the city.

Bicyclists were counted at four intersections along Middlefield Road, at two intersections along Embarcadero Road, and at three intersections along El Camino Real. The intersections chosen offered a representative mixture of arterials, collectors, and neighborhood streets; adult commuters, college students, and schoolchildren; and on-road bicycle lanes, sidewalk bicycle paths, and roadways without special bicycle facilities. All but two intersections were signalized; these two had stop signs on the minor street.

Nearly 3000 cyclists were observed during a one-day count of 8 hours at each intersection. For each cyclist entering any leg of the intersection, observers trained by the Transportation Division collected data on approximate age (estimated as either 17 years of age and under or 18 and older), sex (male or female), direction of travel (with or against the direction of traffic on the roadway), and position (either in the roadway, including bicycle lanes, or on the sidewalk, including bicycle paths and crosswalks).

Data Analysis

Data analysis is based on figures for the May 1987 bicyclist counts and for July 1985–June 1989 police-reported accidents, extending approximately two years before and two years after the exposure counts. To eliminate as many extraneous influences as possible, the accidents analyzed were restricted to those that took place at intersections along the three arterial streets where the counts were made. Of 92 such accidents, information for all four variables was available for 89; only these 89 accidents are analyzed here. The results identify risk factors for bicycle-motor vehicle collisions at intersections.

We quantify the risk of a bicycle-motor vehicle collision in two ways. First, we define the risk for any group of bicyclists as $(a/A)/(b/B)$, where a is the number of accidents that occur to the group, A is the total number of accidents, b is the number of bicyclists in the group, and B is the total number of bicyclists. In this study A = 89 and B = 2976. Risk is proportional to the accident rate per bicyclist: the lower the risk, the lower the likelihood of an accident. By definition, the average risk of all bicyclists in the study is exactly 1, in arbitrary units.

We also make a number of binary comparisons between groups, by calculating the ratio of their risks. We test this ratio for statistical significance by calculating the expected number of accidents for each of the two groups, based on the assumption that accidents should be distributed in the same proportion as exposures. We then compare the number of accidents expected to the number observed, using a χ^2 test with Yates's correction for continuity and one degree of freedom. This test determines the probability p that any discrepancy (equivalent to a risk ratio different from 1) is due to chance rather than to a real difference in risk. We report the result as an upper bound, and only when $p<0.05$. If $p<0.01$ the upper bound is given only as the next higher power of ten.

The analysis sums accident and exposure data from Middlefield, Embarcadero, and El Camino Real. Because the risk of a bicycle-motor vehicle collision should be proportional to the number of motor vehicles as well as to the number of bicyclists, these three streets, which have different traffic volumes, might be expected to have different accident rates per bicyclist, and it might therefore be misleading to combine data from them. Analysis of the three corridors separately, however, shows that the overall risk (as defined above) along Middlefield is 1.08, along Embarcadero 0.97, and along El Camino 0.96—for all practical purposes identical. For the four major binary comparisons listed in the next section, "Results," we have also analyzed the data for each corridor independently; we find that, although the risks and risk ratios naturally vary somewhat from corridor to corridor, the same patterns emerge. We therefore feel confident that no errors are introduced by combining the three corridors in order to increase the statistical significance of the comparisons. Unless specified, the results presented here are based on this combined data.

Table 2. 18 and Older Compared to 17 and Younger

Category	18 and Older			17 and Younger			Risk Ratio	
	Bicyclists Observed	Accidents Reported	Risk	Bicyclists Observed	Accidents Reported	Risk	18 to 17	p
All bicyclists	1543	59	1.3	1433	30	0.7	1.8	0.01
Female	363	15	1.4	489	7	0.5	2.9	0.03
Male	1180	44	1.2	944	23	0.8	1.5	
With traffic	1418	45	1.1	1135	11	0.3	3.3	0.001
Against traffic	125	14	3.7	298	19	2.1	1.8	
Roadway	1265	39	1.0	740	9	0.4	2.5	0.02
Sidewalk	278	20	2.4	693	21	1.0	2.4	0.01

Results

Age

Table 2 compares the accident risk for bicyclists 18 and older with the risk for those 17 and younger. The important columns are "Risk," "Risk Ratio," and "p"; the other columns show the data from which these numbers are derived. The table shows that older bicyclists incur a risk of colliding with a motor vehicle 1.8 times as great as younger ones, and the difference is statistically significant ($p<0.01$). The older bicyclists have a higher risk in all six major subgroups; in four the difference is significant.

This finding was unexpected: we had anticipated that older, more experienced bicyclists would have fewer accidents. The 1992 FARS, for instance, reports that the fatality rate per million population for bicyclists between the ages of 5 and 15 was more than two and a half times greater than the rate for older bicyclists.[5] U.S. Consumer Product Safety Commission statistics show 61 percent of bicycle injuries occurring between the ages of 5 and 14.[2] We suggest these explanations for our result:

- It might conceivably be a statistical anomaly, although the highly significant result for bicyclists riding with traffic ($p<10^{-3}$) makes this unlikely. The accident rate for older bicyclists was greater in each of the three study corridors; in the Embarcadero corridor the risk ratio was 3.3, and this was statistically significant at $p<0.03$.
- Few previous studies have allowed for the numbers of bicyclists exposed to accidents in each age group. (A new Consumer Product Safety Commission Study attempts to classify accident characteristics and estimate rider exposure based on telephone surveys.[6]) The FARS per capita rate is based on population figures, but the fraction of the population that cycles is far greater for children than for adults. Where there are a large number of younger bicyclists on the road, they may dominate accident statistics even if their accident rate is less than that of older bicyclists.

Table 3. Male Compared to Female

Category	Male			Female			Risk Ratio, Male to Female	p
	Bicyclists Observed	Accidents Reported	Risk	Bicyclists Observed	Accidents Reported	Risk		
All bicyclists	2124	67	1.1	852	22	0.9	1.2	
17	944	23	0.8	489	7	0.5	1.7	
18	1180	44	1.2	363	15	1.4	0.9	
With traffic	1819	43	0.8	734	13	0.6	1.3	
Against traffic	305	24	2.6	118	9	2.6	1.0	
Roadway	1448	35	0.8	557	13	0.8	1.0	
Sidewalk	676	32	1.6	295	9	1.0	1.6	

Table 4. Against Traffic Compared to With Traffic

Category	Against Traffic			With Traffic			Risk Ratio, Against to With	p
	Bicyclists Observed	Accidents Reported	Risk	Bicyclists Observed	Accidents Reported	Risk		
All bicyclists	423	33	2.6	2553	56	0.7	3.6	<<0.00001
Roadway	108	5	1.5	1897	43	0.8	2.0	
Sidewalk	315	28	3.0	656	13	0.7	4.5	<0.00001
17	298	19	2.1	1135	11	0.3	6.6	<<0.00001
18	125	14	3.7	1418	45	1.1	3.5	0.0001
Female	118	9	2.6	734	13	0.6	4.3	0.001
Male	305	24	2.6	1819	43	0.8	3.3	<0.00001

- Younger bicyclists may ride more slowly or cautiously, or in larger groups that are more easily seen by motorists. Analysis of individual accidents shows that older cyclists are more likely to be the victims of motorist errors—in particular, failure to yield during a left turn or at a traffic control device.
- The Effective Cycling program then being offered in the Palo Alto middle schools, and other safety measures, may have had a positive influence on the behavior of younger bicyclists. If so, it might be beneficial to extend similar educational measures to adult bicyclists.

Sex

Although Table 3 shows a slightly greater overall risk to male bicyclists than to females, this difference is not consistent across subgroups and is not statistically significant. The value of this ratio in the three corridors separately ranged from 0.7 to 2.6, none statistically significant. We conclude that accident risk does not depend on the bicyclist's sex.

FARS, in contrast, reports that the fatality rate for males in 1992 was seven times as high as for females.[5] Again, this rate is based on population figures, rather than on the number of male and female cyclists actually on the road.

Direction of Travel

Table 4 shows that all categories of bicyclists traveling against the direction of traffic flow are at greatly increased risk for accidents—on average 3.6 times the risk of those traveling with traffic, and as high as 6.6 times for those 17 and under. This result is readily explained: because motorists normally scan for traffic traveling in the lawful direction, wrong-way traffic is easily overlooked. To give only a single example, a motorist turning right at an intersection scans to the left for approaching traffic on the new road, and cannot see or anticipate a fast-moving wrong-way bicyclist approaching from the right. (This is the one of the most common types of bicycle-motor vehicle collisions in Palo Alto.)

This finding provides compelling justification for current traffic law, which requires bicyclists on the roadway everywhere in the United States to travel in the same direction as other traffic. It also implies that vigorous enforcement of this law, for both adults and children, can substantially reduce the number of bicycle-motor vehicle collisions, and should receive high priority in any bicycle program.

Two points about Table 4 deserve comment. First, the conclusion is extremely robust: wrong-way bicycling is risky at an overwhelmingly high level of significance—$p \ll 10^{-5}$ for the category as a whole, $p<10^{-5}$ in four out of seven subgroups, and $p<10^{-4}$ and 10^{-3} for two others. In the remaining subgroup, on the roadway, only 5 percent of bicyclists (108 of 2005) traveled against traffic, and only 5 accidents occurred there (compared to 2.5 expected); these small numbers limit any statistical significance.

Second, wrong-way bicycling is dangerous for all subgroups of bicyclists—including those traveling on the sidewalk, who may at first seem to be protected against collisions with motor vehicles. In fact, sidewalk bicyclists enter into conflict with motorists at every intersection (including driveways), and these are exactly the points where most bicycle-motor vehicle collisions occur. Wrong-way sidewalk bicyclists are at particular risk because they enter the point of conflict from an unexpected direction, just as they would on the roadway.

Nonetheless, unlike the roadway, the direction of sidewalk bicycling is usually unregulated or ineffectively regulated. Off-road bicycle paths are normally intended for two-way travel, and whether intended for it or not are almost invariably used that way.

Table 5. Sidewalk Compared to Roadway

Category	Sidewalk			Roadway			Risk Ratio, Sidewalk to Roadway	p
	Bicyclists Observed	Accidents Reported	Risk	Bicyclists Observed	Accidents Reported	Risk		
All bicyclists	971	41	1.4	2005	48	0.8	1.8	0.01
17	693	21	1.0	740	9	0.4	2.5	0.03
18	278	20	2.4	1265	39	1.0	2.3	0.01
Female	295	9	1.0	557	13	0.8	1.3	
Male	676	32	1.6	1448	35	0.8	2.0	0.01
With traffic	656	13	0.7	1897	43	0.8	0.9	
Against traffic	315	28	3.0	108	5	1.5	1.9	
17, female	225	4	0.6	264	3	0.4	1.6	
17, male	468	17	1.2	476	6	0.4	2.9	0.04
18, female	70	5	2.4	293	10	1.1	2.1	
18, male	208	15	2.4	972	29	1.0	2.4	0.01
17, with traffic	455	5	0.4	680	6	0.3	1.2	
18, with traffic	201	8	1.3	1217	37	1.0	1.3	
17, against traffic	238	16	2.2	60	3	1.7	1.3	
18, against traffic	77	12	5.2	48	2	1.4	3.7	
Female, with traffic	210	2	0.3	524	11	0.7	0.5	
Female, against traffic	85	7	2.8	33	2	2.0	1.4	
Male, with traffic	446	11	0.8	1373	32	0.8	1.1	
Male, against traffic	230	21	3.1	75	3	1.3	2.3	
17, female, with	159	0	0.0	244	2	0.3	0.0	
17, female, against	66	4	2.0	20	1	1.7	1.2	
18, female, with	51	2	1.3	280	9	1.1	1.2	
18, female, against	19	3	5.3	13	1	2.6	2.1	
17, male, with	296	5	0.6	436	4	0.3	1.8	
17, male, against	172	12	2.3	40	2	1.7	1.4	
18, male, with	150	6	1.3	937	28	1.0	1.3	
18, male, against	58	9	5.2	35	1	1.0	5.4	

Sidewalks and paths can present risks even for bicyclists traveling in the direction of traffic. These risks are discussed in the next section.

Position on the Road

Table 5 compares the risks of bicycling on the sidewalk (including bicycle paths and cross-walks) and on the roadway (including bicycle lanes). Because the idea that sidewalk bicycling can be dangerous may be unfamiliar or counter-intuitive, Table 5 analyzes the risks for every possible combination of observed bicyclist characteristics (age, sex, and direction of travel).

The average cyclist in this study incurs a risk on the sidewalk 1.8 times as great as on the roadway, and the result is statistically significant ($p<0.01$). The risk on the sidewalk is higher than on the roadway for both age groups, for both sexes, and for wrong-way travel; the risk for right-way travel on the sidewalk appears to be less than that on the roadway, but this result is misleading, as explained in the Appendix. Altogether the sidewalk risk is higher for 24 of the 27 categories, and for six of these the difference is statistically significant; for many groups the number of accidents expected is too small to attain significance.

The greatest risk found in this study is for bicyclists over 18 traveling against traffic on the sidewalk. Each of these three characteristics is hazardous in itself; combined, they present 5.3 times the average risk.

Table 5 demonstrates that sidewalks or paths adjacent to a roadway are usually not, as non-cyclists expect, safer than the road, but much less safe. This conclusion is already well established in existing standards for bikeway design, although in our experience it is not widely known or observed. Two principal standards, the 1981 AASHTO *Guide for Development of New Bicycle Facilities*[7] and the California Highway Design Manual's chapter on "Bikeway Planning and Design"[8], find that the designated use of sidewalks as bikeways is "unsatisfactory." The 1981 AASHTO *Guide* and the 1983 version of the California Manual[9] offer an extensive list of reasons for this recommendation, including wrong-way travel and blind conflicts at intersections and driveways. (Palo Alto's sidewalk bicycle paths were established before these design criteria were adopted.) The California Manual also finds that "bike paths immediately adjacent to streets and highways are not recommended," and the 1983 version enumerates many of the same reasons that apply to sidewalks. The revised 1991 AASHTO *Guide for the Development of Bicycle Facilities*[10] incorporates language on paths nearly identical to that of the 1983 California Manual.

Tables 3 and 4 bear out the explanations given for these design recommendations. Table 4 shows that wrong-way sidewalk travel is 4.5 times as dangerous as right-way sidewalk travel. Moreover, both Table 4 and Table 5 show that sidewalk bicycling promotes wrong-way travel: 315 of 971 sidewalk bicyclists (32 percent) rode against the direction of traffic, compared to only 108 of 2005 roadway bicyclists (5 percent).

Even right-way sidewalk bicyclists can cross driveways and enter intersections at high speed, and they may enter from an unexpected position and direction—for instance, on the right side of overtaking right-turning traffic. Sidewalk bicyclists are more likely than roadway bicyclists to be obscured at intersections by parked cars, buildings, fences, and shrubbery; their stopping distance is much greater than a pedestrian's, and they have less maneuverability.

In addition to the hazards of motor vehicles at intersections (including driveways), sidewalks also present bicyclists with conflicts with pedestrians, joggers, skateboarders, roller skaters, and wheelchairs, and with fixed objects such as parking meters, utility poles, signposts, benches, trees, hydrants, and mailboxes. These hazards, which are not included in the present study, might further elevate the accident rate for sidewalk bicyclists.

Conclusions

Our results show that bicyclists 18 or older incur 1.8 times as great a risk of collisions with motor vehicles as younger ones. Adult bicyclists as well as children would therefore be logical candidates for educational and enforcement measures.

There is no significant dependence of risk on the bicyclist's sex.

Bicyclists traveling against the direction of traffic, whether on the roadway or on the sidewalk, and regardless of age or sex, incur much greater risk than those traveling with traffic (on average 3.6 times as great), at an overwhelmingly high level of significance. This finding implies that vigorous enforcement of the laws against wrong-way bicycling on the roadway, for both adults and children, can substantially reduce the number of bicycle-motor vehicle collisions, and should receive high priority in any bicycle program.

Bicyclists on a sidewalk or bicycle path incur greater risk than those on the roadway (on average 1.8 times as great), most likely because of blind conflicts at intersections. Wrong-way sidewalk bicyclists are at even greater risk, and sidewalk bicycling appears to increase the incidence of wrong-way travel.

Bicycling on the roadway in the same direction as adjacent traffic, whether or not bicycle lanes are designated, is not associated with increased accident risk for any group. In fact, Table 5 shows that every group of bicyclists riding with traffic on the roadway, with one insignificant exception, incurs a risk equal to or less than the study average (by definition 1). If all bicyclists in the study had been riding with traffic on the roadway, there would have been about 67 intersection accidents instead of 89.

These results suggest that urban roadway design—not only bikeway design—must take into account that intersections, construed broadly, are the major point of conflict between bicycles and motor vehicles. Separation of bicycles and motor vehicles leads to blind conflicts at these intersections. It also encourages wrong-way travel, both on sidewalks or paths and on the roadway at either end, further increasing conflicts. Shared use of the roadway in the same direction of travel leads to fewer conflicts and fewer accidents.

Thus the aim of a well-designed roadway system should be to integrate bicycles and motor vehicles according to the well-established and effective principles of traffic law and engineering, not to separate them. This conclusion is in accord with the 1981 and 1991 AASHTO *Guides* and the California Highway Design Manual, and with our own experience as bicyclists. The goal of integration can be promoted through the use of wide, smooth outside lanes that encourage bicyclists to travel on the roadway rather than on an adjacent sidewalk or path. This study did not examine the difference, if any, between roads with and without designated bicycle lanes.

Sidewalk bicycling adjacent to busy streets with many intersections presents special dangers, and should not be encouraged through the construction or designation of bicycle paths parallel to the street. Where sidewalk bicycling is permitted, it is desirable to maintain clear sight lines at intersections of sidewalks with streets and driveways. In some locations, it may be preferable to prohibit sidewalk bicycling altogether, or to restrict it to one-way travel.

Sidewalk bicycling is common in residential areas by young children too inexperienced to ride in the street. Since traffic speeds and volumes tend to be lower on these streets, and residential driveways are much less busy than business driveways, potential conflicts are reduced, but they are not eliminated. Nevertheless, this type of sidewalk bicycling is accepted, and it may be impractical to prohibit it. But, as the design standards state, it is inappropriate to sign these sidewalks as bicycle facilities, and it remains important to provide clear sight lines at intersections.

Acknowledgments

The authors would like to thank Gayle Likens of the City of Palo Alto Transportation Division for facilitating access to the accident reports and for arranging collection of the exposure data on which this study is based. We would also like to recognize the contributions of Dr. Jannette Carey to an earlier study related to this one.

Appendix: A Paradox of Interpretation

This appendix discusses a statistical paradox that will be of interest to mathematically inclined readers but does not alter the study conclusions.

Despite the clear findings described under "Results," an inhomogeneous population, such as the one in this study, can present certain pitfalls in interpretation. Among bicyclists riding with the direction of traffic, those 17 years old or younger have an accident rate on the sidewalk 1.2 times as high as on the roadway (Table 5). Those 18 or older have an accident rate on the sidewalk 1.3 times as high as on the roadway. What is this ratio for the combined group—that is, for all bicyclists riding with traffic?

It seems plausible that this value should be between 1.2 and 1.3, but it turns out that this is not the case. The risk ratio for the combined group is actually 0.9. In other words, the sidewalk appears to be safer than the roadway for the group of all bicyclists riding in the direction of traffic, but more dangerous than the roadway for *both* subgroups that compose the whole, those 17 or younger and those 18 or older!

Table 6. Risk with Traffic by Age Group

Category	Sidewalk			Roadway			Risk Ratio, Sidewalk to Roadway
	Bicyclists Observed	Accidents Reported	Risk	Bicyclists Observed	Accidents Reported	Risk	
17, with traffic	455	5	0.4	680	6	0.3	1.2
18, with traffic	201	8	1.3	1217	37	1.0	1.3
Total with traffic	656	13	0.7	1897	43	0.8	0.9

To see why this is so, look at Table 6, which shows the relevant rows from Table 5. The combined risk on the sidewalk is an average of the risk to those 17 or younger and the risk to those 18 or older, weighted according to the numbers of bicyclists. On the sidewalk, younger bicyclists predominate, 455 to 201. The weighted average is therefore closer to the lower value, 0.4, than to the higher one, 1.3.

On the roadway the situation is reversed. Older bicyclists predominate, 1217 to 680. The combined risk is therefore weighted toward the higher value, 1.0—enough so that the risk for the roadway becomes slightly higher than that for the sidewalk.

To put it another way, the combined group consolidates two age subgroups with very different risk patterns. Riding on the sidewalk is associated with (puts a bicyclist "at risk" for) being young, which is correlated with a low accident rate (although it is lower still for the roadway). Riding on the roadway is associated with being older, which is correlated with a high accident rate (although again it is lower for the roadway). The sidewalk and roadway therefore show comparable accident rates. Table 5 shows many other such anomalies in which the risk for a combined group lies outside the range for the subgroups.

In such cases, the statistics for individual subgroups give a truer picture than the combined values. If all the bicyclists in Table 6 had been riding on the roadway, at the risk found there, about 53 accidents would have occurred, compared to the actual 56. If all the bicyclists had been riding on the sidewalk, there would have been about 69 accidents. Although this analysis does not demonstrate that the blind conflicts discussed earlier are responsible for the increased hazard on the sidewalk, even in the direction of traffic, it does show that riding on the roadway is clearly safer.

In general, combining subgroups cannot only obscure the meaning of a statistical analysis—it can *reverse its outcome*. This result is known in statistics as Simpson's paradox, after the British statistician E. H. Simpson.[11] It is never possible to be sure there is no hidden factor that will completely undermine an analysis in this way.

Simpson's paradox illustrates the importance of finding the causes of accidents as well as statistical correlations. Analysis of individual sidewalk accidents in Palo Alto shows that many of them are associated with wrong-way travel. In the same way, many more sidewalk accidents than roadway accidents turn out to be associated with blind conflicts at intersections and driveways. Roadways are designed to eliminate blind conflicts at intersections and driveways; sidewalks are not. This causal analysis lends credibility to the statistical results showing increased accident rates on sidewalks. It suggests that sidewalk bicycling, especially against the direction of traffic, is dangerous in itself, not because of some extraneous characteristic that happens to be more common among sidewalk riders. It also suggests that bicycle safety can be improved by providing clear sight lines at the intersection of sidewalks with streets and driveways, and, in some cases, by prohibiting bicycling on sidewalks or by restricting its direction through signs or ordinances.

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