Bicycle Tracks and Lanes: a Before-After Study

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ABSTRACT

This paper presents a before-after crash, injury and traffic study of constructing bicycle tracks and marking bicycle lanes in Copenhagen, Denmark. Corrections factors for changes in traffic volumes and crash / injury trends are included using a general comparison group in this non-experimental observational study. Analysis of long-term crash trends points towards no significant abnormal crash counts in the before period. The safety effects of bicycle tracks in urban areas are an increase of about 10 percent in both crashes and injuries. The safety effects of bicycle lanes in urban areas are an increase of 5 percent in crashes and 15 percent in injuries. Bicyclists' safety has worsened on roads, where bicycle facilities have been implemented. Design of bicycle facilities and parking conditions for motor vehicles clearly seems to have safety implications, especially at intersections. The study has revealed a few points in relation to this. Construction of bicycle tracks resulted in a 20 percent increase in bicycle / moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage, whereas marking of bicycle lanes resulted in a 5 percent increase in bicycle / moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage. The changes in traffic do result in health benefits due to more physical activity, less air pollution and less traffic noise. The positive benefits may well be much higher than the negative consequences caused by new safety problems.

INTRODUCTION

The traditional Danish bicycle track with a curb to the carriageway and a curb to the sidewalk is depictured in Figure 1 along with a bicycle lane. The first bicycle tracks in Denmark were introduced in Copenhagen as early as 1910. Since then about 8,000 km of bicycle tracks and paths with a dividing verge to the carriageway have been constructed so about every ninth km of road have these bicycle facilities in rural and urban areas in Denmark.

FIGURE 1 Photos of bicycle track (left) and bicycle lane (right).

Many studies of bicycle tracks have been undertaken in Northern Europe. A meta-analysis of 11 studies shows a reduction of 4 percent in crashes, and the crash reduction is almost the same for pedestrians, bicyclists and motorists respectively (*1*). Danish results show that construction of bicycle facilities leads to fewer and less severe crashes in rural areas, but more crashes in urban areas primarily due to increasing crash rates at intersections (*2*). Studies show that constructing bicycle tracks and paths increase bicycle traffic volumes (*1*).

Three studies of marking bicycle lanes in urban areas indicate an increase in crashes of about 10 percent primarily due to more crashes at intersections (*3-5*). No reliable studies of bicycle lanes impact on traffic volumes have been found.

The before-after traffic, crash and injury study, which is presented in the following, includes construction of one-way bicycle tracks on both road sides along 20.6 km of road and marking of one-way bicycle lanes on both road sides along 5.6 km of road in Copenhagen, Denmark. These bicycle tracks were constructed during the years 1978-2003 and the bicycle lanes were marked 1988-2002. The width of bicycle tracks are about 2-2.5 meters, whereas bicycle lanes are about 1.5-2 meters. The volume of motor vehicles 6-18 o'clock on a weekday on the studied roads varies from 5,000 to 28,000 and the corresponding volumes of bicyclists are 1,000-17,000. A Danish report describes the study in detail (*6*).

SECOND-BEST METHODOLOGY

Randomized experiments (*7*), where the experimental units like roads are randomized to treatment like bicycle lanes, are often viewed as the best way to study road safety effects. In our case, a randomized experiment has not been undertaken.

The safety effects of bicycle facilities are therefore studied using an observational study methodology. The Empirical Bayes method (*8*) is viewed by many as the best of the non-experimental observational methods. The Empirical Bayes method accounts for three major possible biases in before-after crash studies; regression-to-the-mean effects, crash trends and traffic volumes.

However, the Empirical Bayes method has not been used in this study. One thing is that using this method includes a very time-consuming effort to calculate many crash models, which is needed in this case because the bicycle facilities have been applied over a long period, and hence many different before and after periods are part of the study. Such crash models include relationships between crashes / injuries and traffic volumes for different types of intersections and road links.

A second but much more important thing is that some of the roads, where bicycle facilities have been applied, are the most trafficked in Copenhagen in terms of bicyclists and pedestrians. The crash models that need to be developed if the Empirical Bayes method were to be used could be of the kind shown in general in Formula 2 and 3 later in this paper. Such crash models are relatively reliable to use in order to predict the number of crashes, if traffic volumes on the road or at the intersection, where you wish to predict crash figures, are pretty normal compared to the traffic volumes that the crash models are based upon. In the Copenhagen case, many of the studied roads / intersections are in the far end of the traffic volume axis, i.e. much trafficked, and we are therefore close to or outside the boundaries of the possible crash models' valid area. The prediction of crash figures for these much trafficked roads / intersections are unreliable, because the beta figures of the crash models becomes crucial for the prediction, and these beta figures change from model to model primarily due to uncertainty, because the models are based on a relatively low number of roads / intersections. The prediction results for regression-to-the-mean effects and figures for expected crashes and consequently safety effects will therefore be relatively unreliable, because most of the crashes in this study actually take place on the much trafficked roads.

Instead a stepwise methodology is used. First, a general comparison group is used to account for crash trends. Second, changes in traffic volumes are taken into account. And third, an analysis of long-term crash trends is made in order to check for abnormally high or low crash counts, i.e. regression-to-the-mean, in the before period. It was chosen to use equally long before and after periods, which for the individual studied roads was of 1-5 years duration. The expected number of crashes in the after period is calculated based on a formula, here shown in the general form:

$$(1) \quad A_{Expected} = A_{Before} \cdot C_{Trend} \cdot C_{Traffic} \cdot C_{RTM} \ ,$$

where $A_{Expected}$ is the number of crashes / injuries expected to occur in the after period if bicycle facilities were not applied, A_{Before} is the number of crashes / injuries that occurred in the before period, C_{Trend}, $C_{Traffic}$ and C_{RTM} are correction factors for crash trends, traffic volumes and regression-to-the-mean respectively.

The study of bicycle facilities is part of project including studies of reconstructions, markings, signal-control and traffic calming schemes in the City of Copenhagen. A major effort was made in order to register all physical changes to the road network in the period 1976-2004. Several hundred schemes were identified.

Several intersections and links had undergone more than one reconstruction or other scheme. Only "clean" schemes are studied, meaning that the roads, where bicycle facilities have been applied, no other scheme has been implemented in before and after periods and in the year(s), when the bicycle facility was applied.

Unchanged roads with known developments in traffic volumes were used to set up a general comparison group. The Copenhagen Police District covers the entire area of the City of Copenhagen, and there is no indication that crashes are registered differently in one city quarter compared to another. The general comparison group consists of 110 km of roads with 170 locations, where motor vehicle and bicycle / moped traffic is counted yearly or every fourth to sixth year. A total of 24,369 crashes and 8,648 injuries occurred on the 110 km of roads in the period 1976-2004.

Since a general comparison group has been chosen instead of a matched comparison group, an effort was made in order to avoid consequences of larger differences between general comparison group and treated roads, where bicycle facilities were applied. Trends for different types of crashes and injuries of the general comparison group were compared. Trends for intersection and link crashes are very similar, and hence no need for sub-grouping. However, trends for different crash / injury severities and transport modes exhibit rather different developments. It was found reasonable to describe trends by 7 crash sub-comparison groups and 5 injury sub-comparison groups. These sub-groups are defined in Table 1.

TABLE 1 Definition of 12 Sub-comparison Groups (in Brackets: Number of Crashes / Injuries 1976-2004)

	Bicycle/moped [a]	Pedestrian [b]	Motor vehicle [c]
Crashes with killed / severe injuries	1 (2,197)	2 (1,445)	3 (1,584)
Crashes with minor injuries and no killed / severe injuries	4 (1,289)	5 (1,228)	
Property damage only crashes	6 (3,316)		7 (13,310)
Killed and severe injuries	8 (2,235)	9 (1,477)	10 (1,907)
Minor injuries	11 (1,359)	12 (1,670)	

[a] Crashes involving cyclists / moped riders and injuries in these crashes,
[b] Crashes between pedestrians and motor vehicles and injuries in these crashes,
[c] Crashes only with motor vehicles involved and injuries in these crashes.

So the correction factor C_{Trend} is actually 12 different correction factors, which is the number of crashes / injuries in the sub-comparison group in the after period divided by the number of crashes / injuries in the sub-comparison group in the before period. The individual correction factor, e.g. $C_{Trend,1}$, is then multiplied with the same sub-group of crashes, which occurred on the treated road in the before period, $A_{Before,1}$, as part of Formula 1.

The correction factor $C_{Traffic}$ is based on changes in traffic volumes on the treated road and in the general comparison group. The relationship between traffic flow and crashes / injuries is non-linear. Danish crash prediction models for links (Formula 2) and intersections (Formula 3) are most often of the following kinds:

$$(2) \quad E(\mu) = \alpha \cdot N^{\beta},$$

$$(3) \quad E(\mu) = \alpha \cdot N_{pri}^{\beta_1} \cdot N_{\sec}^{\beta_2},$$

where $E(\mu)$ is the predicted number of crashes / injuries, N is the motor vehicle daily flow on the link, N_{pri} and N_{sec} are the incoming motor vehicle daily flow from primary and secondary directions at intersections, and α, β, β_1 and β_2 are estimated parameters. β is often close to 0.7, and β_1 and β_2 are often close to 0.5 in the many models that have been developed during the last decades in Denmark, whereas α varies between the different types of roads and intersections (*9-16*). Figures for α varies, because the level of safety depends on the type of road and intersection. In this case, incoming bicycle / moped flow is also known, and here the sparse number of crash prediction models indicate that bicycle / moped flow only influence the number of crashes involving cyclists and moped riders. Formula 2 and 3 are then used to set up formulas for C_{Traffic}:

$$(4)\quad C_{Traffic,pmv,link} = \left(\frac{\dfrac{MV_{after}}{MV_{before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.7},$$

$$(5)\quad C_{Traffic,bike,link} = \left(\frac{\dfrac{MV_{after}}{MV_{before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.7} \cdot \left(\frac{\dfrac{BM_{after}}{BM_{before}}}{\dfrac{BM_{CG,after}}{BM_{CG,before}}} \right)^{0.7},$$

$$(6)\quad C_{Traffic,pmv,intersection} = \left(\frac{\dfrac{MV_{pri,\,after}}{MV_{pri,\,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{MV_{\mathrm{sec},\,after}}{MV_{\mathrm{sec},\,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,\,before}}} \right)^{0.5},$$

$$(7)\quad C_{Traffic,bike,intersection} = \left(\frac{\dfrac{MV_{pri,\,after}}{MV_{pri,\,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{MV_{\mathrm{sec},\,after}}{MV_{\mathrm{sec},\,before}}}{\dfrac{MV_{CG,after}}{MV_{CG,\,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{BM_{pri,\,after}}{BM_{pri,\,before}}}{\dfrac{BM_{CG,after}}{BM_{CG,before}}} \right)^{0.5} \cdot \left(\frac{\dfrac{BM_{\mathrm{sec},\,after}}{BM_{\mathrm{sec},\,before}}}{\dfrac{BM_{CG,after}}{BM_{CG,\,before}}} \right)^{0.5},$$

where $C_{\mathrm{Traffic,\,pmv}}$ is the traffic correction factor for pedestrian and motor vehicle crashes / injuries (see Table 1), $C_{\mathrm{Traffic,\,bike}}$ is the traffic correction factor for bicycle-moped crashes / injuries, MV, MV_{pri} and MV_{sec} are motor vehicle daily flow at the treated site on link, primary and secondary direction respectively, BM, BM_{pri} and BM_{sec} are bicycle-moped daily flow at the treated site on link, primary and secondary direction respectively, and MV_{CG} and BM_{CG} are motor vehicle flow and bicycle-moped flow in the comparison group respectively.

Flow data from before and after periods are used, hence, increases and decreases in traffic volumes from before to after are accounted for. The change from before to after in motor vehicle traffic varied from -26 percent to +29 percent, however, most treated roads experienced a minor decrease. Similar the change in bicycle-moped traffic was between -28 percent and +90 percent, most treated roads experienced a larger increase. However, Formula 6 and 7 have been used for the intersections, where traffic volumes for side streets are known.

Traffic volumes are known for only about a tenth of the intersections. The rest of the intersections (minor side streets) have been treated as links using Formula 4 and 5.

The analysis of long-term crash trends is made in order to check for abnormally high crash counts, i.e. regression-to-the-mean, in the before period. The analysis is made using a before-before period, which is a 5-year period 8 to 12 years before applying bicycle facilities. The before-before period is chosen because it most often will be prior to an eventual black spot identification period or other type of systematic crash investigation period that may have lead to applying bicycle facilities. This before-before period is then used to calculate an expected number of crashes and injuries in the before period of the treated roads by making corrections for crash trends and traffic volumes:

$$A_{Expected,\,Before} = A_{Before-Before} \cdot C_{Trend} \cdot C_{Traffic}$$

The C_{RTM} correction factor is then calculated as the expected number of crashes in the before period divided by the observed number of crashes in the before period, and likewise for injuries. However, because not all treated roads can undergo this type of analysis, the C_{RTM} is set to be the same for all treated roads and is only used, if there are statistically significant differences between the expected and observed numbers of crashes and injuries in the before period.

Of the 23 roads, where bicycle tracks were constructed, it is possible to make this calculation for 9 roads, and the calculation was possible for 5 of 10 roads, where bicycle lanes were marked. Several roads have been excluded of this analysis because they have been changed by other schemes in the period between 12 years before the bicycle facility was applied and the before period. Some roads have been excluded of the analysis because crash records only are available back to 1976.

TABLE 2 Expected and Observed Crashes and Injuries in the Before-Before and Before Period, where Bicycle Tracks and Bicycle Lanes have been Applied

		Observed BEFORE-BEFORE	Expected BEFORE	Observed BEFORE	Change in safety (percent)	
					Best estimate	95% CI [a]
Bicycle tracks	All crashes	686	460	484	-3 [b]	-21 ; +20 [b]
	All injuries	211	128	140	+10	-13 ; +38
Bicycle lanes	All crashes	411	333	337	+1	-12 ; +18
	All injuries	111	89	84	-7	-31 ; +25

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The results of the analyses of long-term accident trends, which are shown in Table 2, indicate no general abnormally high or low crash counts, i.e. regression-to-the-mean effects, in the before period. Meta-analyses have been used to calculate best estimates for safety changes and related confidence intervals. Table 2 shows that the best estimate for the change in safety, where bicycle lanes have been marked, is an increase of 1 percent (+1) in crashes. This means that the observed number of crashes in the before period is 1 percent higher than expected. The 95% confidence interval for bicycle lanes, all crashes, is between a fall of 12 percent (-12) and an increase of 18 percent (+18), meaning that the best estimate of a change in safety is within this interval with 95% certainty. A glance on the confidence intervals in Table 2 reveals that all intervals include 0 or no change, which means that none of the best estimates are statistically significant different from 0. In other words, Table 2 indicate no abnormally high or low crash counts in the before period. Results from breakdowns into different accident / injury severities and transport modes do neither indicate abnormal crash counts in the before period. The general correction factors for regression-to-the-mean effects are then set to 1.

Due to major differences in correction factors for crash trends and traffic volumes and that the bicycle facilities have been applied over a long time span it is founded reasonable to use meta-analysis rather than simple sums of crashes and injuries in order to describe best estimates for safety effects and the variance of these effects. The meta-analysis methodology used is described by Elvik (*17*). Fixed effects models have been used for homogeneous mean effects, i.e. only random variation in estimated effects. Random effects models are adopted to heterogeneous mean effects.

Effects on traffic volumes are simply estimated by taking the traffic development in the general comparison group into account. Hence, no traffic model has been used. Parallel streets to the treated roads have been checked for major construction works in the before and after periods, however, no such construction works have been identified.

RESULTS OF BEFORE-AFTER CRASH AND INJURY STUDY

Bicycle Tracks

The construction of bicycle tracks has resulted in a slight drop in the number of crashes and injuries on road links between intersections of 10 and 4 percent respectively, see Table 3. The two figures may be found in Table 3 in the “Links” rows and the “Best estimate” column. In the confidence interval column it may be seen that none of these safety effects on the links are statistically significant, because the intervals include 0 or no change. At intersections on the other hand, the number of crashes and injuries has risen statistically significant by 18 percent. A decline in road safety at intersections has undoubtedly taken place after the construction of bicycle tracks. If figures for links are combined with those for intersections, an increase of about 10 percent in crashes and injuries has taken place.

The safety effects of the various bicycle track projects are statistically significant different in some cases, hence heterogeneous safety effects. The safety effects mentioned above are therefore not general. The reason for this is that the crash composition and road design are different on those individual streets, where bicycle tracks have been constructed. Some road designs with bicycle tracks are safer than others.

The decline in road safety arises, because more pedestrians and bicyclists / moped riders are injured at intersections. There are statistically significant increases in injuries at intersections of 30 and 24 percent respectively for these two road user groups. No major changes in injuries have occurred to motorists.

The increase in injuries to women is 18 percent, whereas there is only a small rise in injuries to men of just 1 percent. The increase in injuries is especially large among females under 20 years of age on foot and bicycle, as well as female pedestrians over the age of 64. On the other hand, there is a considerable fall in injuries among older bicyclists and children in cars of both sexes. The figures for men and women and four age groups have been rescaled in order to account for different trends in the general comparison group.

TABLE 3 Safety Effects of Bicycle Tracks

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Crashes	All	2,987	2,663	2,911	+10 [b]	-2 ; +23 [b]
	Injury	1,313	784	875	+12	+2 ; +23
	Property damage only	1,674	1,879	2,036	+6 [b]	-8 ; +22 [b]
Injuries	All	1,476	857	937	+9	+0 ; +19
	Fatal	25	19	22	+10	-1 ; +23
	Severe	757	606	665		
	Minor	694	231	250	+8 [b]	-17 ; +40 [b]
Intersections	All crashes	2,010	1,840	2,171	+18 [b]	+6 ; +32 [b]
	All injuries	938	541	636	+18	+6 ; +31
Links	All crashes	977	823	740	-10 [b]	-26 ; +10 [b]
	All injuries	538	316	301	-4	-17 ; +12
Pedestrians, all injuries	Total	469	271	315	+19	+2 ; +38
	At intersections	267	154	197	+30	+7 ; +57
	On links	202	117	118	+7	-16 ; +35
Bicyclists and moped riders, all injuries	Total	574	369	406	+10	-4 ; +26
	At intersections	353	230	285	+24	+5 ; +46
	On links	221	139	121	-13	-32 ; +10
Motorists, all injuries	Total	433	217	216	+4 [b]	-24 ; +43 [b]
	At intersections	318	157	154	-3 [b]	-32 ; +39 [b]
	On links	115	60	62	-1 [b]	-28 ; +37 [b]

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The crash composition has changed markedly after the construction of bicycle tracks. Table 4 shows that the construction of bicycle tracks resulted in three statistically significant gains in road safety. Rear-end crashes where motor vehicles hit bicycles / mopeds from behind have fallen by 63 percent due to the traffic separation. Crashes with left-turning bicycles / mopeds have fallen by 41 percent and crashes with bicycles / mopeds against parked motor vehicles have decreased by 38 percent.

These safety gains were more than outweighed by new safety problems, where the number of crashes has risen statistically significant. Rear-end crashes where a bicycle / moped hit another bicycle / moped from behind has risen by 120 percent. Crashes with right-turning vehicles have risen by 140 percent. All kinds of right-turn crashes have increased in numbers. Crashes with left-turning motor vehicles against bicycles / mopeds have risen by 48 percent. Lastly, crashes between bicycles / mopeds and pedestrians or entering / exiting bus passengers have also risen significantly.

Prohibiting parking is one reason why the construction of bicycle tracks brings about more crashes and injuries. Prohibiting parking on a road with a bicycle track results in motor vehicles being parked on minor side streets and consequently more turning traffic, especially at right of way regulated intersections. The construction of bicycle tracks and prohibition of parking resulted in an increase in crashes and injuries at intersections of 42 and 52 percent respectively. The construction of bicycle tracks combined with permission to park also resulted in an increase in crashes and injuries at intersections but of only 13 and 15 percent respectively. On road links with parking ban, there was a 24 percent increase in crashes, whereas on links with parking permitted crashes fell by 14 percent. When parking is permitted, there are fewer parking crashes, rear-end crashes and pedestrian crashes. This means that illegally parked motor vehicles causes more crashes than legally parked vehicles. The total width of drive lanes is reduced when parking is permitted, resulting in increased safety for pedestrians when they cross the road.

TABLE 4 Effects on Crashes of Bicycle Tracks Divided into 11 Crash Situations

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Single vehicle crash	All crashes	170	151	142	-3	-23 ; +22
	MV [c]	134	127	111	-8	-29 ; +19
	BM [d]	36	23	31	+16	-30 ; +91
Rear-end crash	All crashes	718	674	584	-7 [b]	-22 ; +12 [b]
	MV and MV	517	490	483	+1	-11 ; +15
	MV and BM	173	164	57	-63	-73 ; -49
	BM and BM	28	20	44	+120	+37 ; +253
Frontal crash	All crashes	77	71	92	+34	-2 ; +82
Right-turn crash	All crashes	160	169	397	+140	+98 ; +190
	MV and turning MV	47	41	73	+70	+15 ; +151
	Turning MV and BM	81	104	282	+129 [b]	+57 ; +233 [b]
	Turning MV and Ped [e]	25	20	32	+77	+4 ; +202
	Turning BM	7	4	10	+135	-17 ; +561
Left-turn crash	All crashes	614	548	589	+12 [b]	-7 ; +33 [b]
	MV and turning MV	334	299	334	+9 [b]	-16 ; +40 [b]
	Turning MV and BM	120	119	161	+48 [b]	+4 ; +110 [b]
	Turning MV and Ped	65	45	47	+1	-33 ; +53
	Turning BM	95	85	47	-41	-59 ; -15
Right-angle crash	All crashes	575	536	522	-1	-13 ; +11
Crash with parked MV	All crashes	217	182	142	-21	-36 ; -1
	MV and parked MV	123	105	96	-8	-30 ; +22
	BM and parked MV	94	78	46	-38	-57 ; -11
Crash with pedestrian from right	All crashes	296	220	244	+13	-5 ; +34
	MV and Ped	228	162	140	-10	-28 ; +11
	BM and Ped	68	58	104	+80	+30 ; +148
Crash with pedestrian from left	All crashes	123	83	85	+23 [b]	-25 ; +102 [b]
	MV and Ped	111	75	68	+5 [b]	-38 ; +78 [b]
	BM and Ped	12	9	17	+78	-15 ; +273
Crash with entering or exiting bus passenger		5	4	73	+519	+157 ; +1390
Other pedestrian crashes		32	25	41	+66	+3 ; +167

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model, [c] motor vehicle, [d] bicycle or moped, [e] pedestrian.

Several design features especially at intersections affect the safety effects. At signalized intersections, it has been found that the number of crashes with traffic from entry lanes with a shortened bicycle track ending before a right-turn lane, see Figure 2, fell statistically significant by 30 percent, whereas the number of injuries increased by 19 percent. Another design at signalized intersections is to end the bicycle track at the stop line, i.e. advanced bicycle tracks. This resulted in a statistically significant increase of 25 percent in crashes, whereas injuries only increased by 9 percent. Entry lanes with an advanced bicycle track and no turn lanes for motor vehicles resulted in statistically significant increases of 68 and 67 percent in crashes and injuries respectively. The figures for entry lanes with turn lanes and advanced bicycle track showed a 15 percent increase in crashes and a fall of 5 percent in injuries. A comparison shows that entry lanes with an advanced bicycle track without turn lanes for motor vehicles is the design, which is most unsafe. Shortened bicycle tracks and advanced bicycle tracks with turn lanes for motor vehicles are equally effective as far as safety goes. There is a difference, however, advanced bicycle tracks are best for pedestrians and bicyclists, whereas shortened bicycle tracks are best for motor vehicle occupants. Other results for e.g. non-signalized intersections and bus stops also shows significantly different safety effects for the various designs.

FIGURE 2 Photos of shortened bicycle track (left) and advanced bicycle track (right).

Bicycle Lanes

The marking of bicycle lanes resulted in an increase in crashes of 5 percent and 15 percent more injuries, see Table 5. These increases are not statistically significant. The decline in road safety can be seen both at intersections and on links. The worsening safety occurred especially amongst bicyclists and moped riders, where the increase in injuries is 49 percent.

In line with the study of bicycle tracks, there is a larger increase in injuries among women of 22 percent with the marking of bicycle lanes, whereas the figure for men was only 7 percent. There is a fall in injuries among children under 20 years of age and an increase among those aged 20-34.

TABLE 5 Safety Effects of Bicycle Lanes

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	95% CI [a]
Crashes	All	389	295	311	+5	-10 ; +23
	Injury	95	90	102	+14	-15 ; +52
	Property damage only	294	205	209	+1	-16 ; +21
Injuries	All	106	98	113	+15	-13 ; +52
	Fatal	3	3	0	+22	-15 ; +73
	Severe	72	48	59		
	Minor	31	47	54	+5	-36 ; +73
Intersections	All crashes	327	249	247	0	-16 ; +18
	All injuries	87	82	93	+14	-16 ; +54
Links	All crashes	62	47	64	+30	-9 ; +87
	All injuries	19	16	20	+27	-38 ; +160
Pedestrians, all injuries	Total	29	24	19	-17	-54 ; +49
	At intersections	23	20	18	-8	-51 ; +74
	On links	6	4	1	-53	-91 ; +154
Bicyclists and moped riders, all injuries	Total	41	39	60	+49	-1 ; +126
	At intersections	33	30	47	+57	-1 ; +150
	On links	8	9	13	+27	-48 ; +207
Motorists, all injuries	Total	36	35	34	+12	-34 ; +89
	At intersections	31	32	28	+1	-43 ; +79
	On links	5	3	6	+39 [b]	-98 ; +10753 [b]

[a] 95% confidence interval, [b] inhomogeneous i.e. results of random effects model.

The marking of bicycle lanes has a markedly different effect on the crash composition compared to the construction of bicycle tracks. Bicycle lanes did not apparently lead to an appreciable fall in rear-end crashes between motor vehicle and bicycle / moped or crashes involving left-turning bicycle / moped. Conversely, the marking of bicycle lanes did not apparently lead to an increase in crashes between bicycle/moped and pedestrians or crashes between left-turning motor vehicle and bicycle / moped.

There are however similarities. The number of crashes involving right-turning motor vehicles increased statistically significant by 73 percent with the marking of bicycle lanes. There was also a considerable increase in rear-end crashes between two bicycles / mopeds.

RESULTS OF BEFORE-AFTER TRAFFIC STUDY

The construction of bicycle tracks resulted in a 20 percent increase in bicycle/moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage on those roads, where bicycle tracks have been constructed, see Table 6. These effects are statistically significant. A considerable amount of these effects were already visible during the construction period, although the effects increased after road works were completed.

The marking of bicycle lanes resulted in a 5 percent increase in bicycle / moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage on those roads, where bicycle lanes have been marked. These effects are not statistically significant.

TABLE 6 Effects on Traffic of Construction of Bicycle Tracks and Marking Bicycle Lanes

		Traffic effect (percent)	
		Best estimate	95% CI [a]
Bicycle tracks	Bicycle / moped traffic mileage	+20	+11 ; +29
	Motor vehicle traffic mileage	-10	-14 ; -6
Bicycle lanes	Bicycle / moped traffic mileage	+5	-4 ; +14
	Motor vehicle traffic mileage	-1	-10 ; +8

[a] 95% confidence interval.

Bicycles comprise over 95 percent of bicycle / moped traffic. The effects are valid for bicycle traffic, but it is not known whether they are valid for moped traffic on its own.

DISCUSSION

The study is based on a second-best methodology. Corrections for changes in traffic volumes and road safety trends have been made. Despite methodological shortcomings, study results show systematic patterns. Several safety and traffic effects are statistically significant. The analyses point towards specific safety gains and flaws for different road user groups, crash situations and road and intersection designs. Overall, there is internal consistency in the changes of safety and traffic volumes, which indicate causality, and the causal direction seems clear.

The bicycle facilities effects on traffic volumes are rather large. We do not know for sure whether these effects are a result of changes of route choice or transport mode choice or both. The magnitude of the changes in traffic volumes on the reconstructed streets, and the traffic volumes on parallel streets, however, do indicate that thousands of travelers in total must have changed their choice of transport mode. We do not know who have shifted mode – children, middle-aged or elderly, women or men, beginners or experienced, etc. Another point is that the reduced motor vehicle traffic volumes may have resulted in traffic operation changes e.g. higher vehicular speed, increased crossing activity by pedestrians outside formal crossings, etc. Due to dramatic shifts, the corrections for changes in traffic volumes in the safety studies can be important to the safety effect findings.

If corrections for traffic volumes were not done at all, the expected number of crashes and injuries in the after period on the roads, where bicycle tracks were constructed, would be 2,758 and 875, respectively. The comparable figures found when corrections for traffic volumes were done, see Table 3, are 2-4 percent lower. This means that corrections for traffic volumes result in a small worsening of the overall safety effect, i.e. the effect would be about 6 percent instead of about 10 percent as shown in Table 3. However if corrections for traffic volumes were not done, the increase in bicycle-moped injuries would be 15 percent instead of the 10 percent when these corrections were done. Here the corrections actually improve the safety effect, because the bicycle traffic has increased. The difference in the safety effects calculated respectively with and without corrections for traffic volumes are rather small. Therefore, the results of the safety studies are not particular sensitive to the method for making corrections for traffic volumes.

Bicycle tracks and bicycle lanes separate bicycle traffic from motor vehicle traffic on links between intersections. Having these bicycle facilities is perceived to be safer and more satisfying by bicyclists compared to a mixed traffic situation (*18*). Seen in this perspective, the results of this study are somewhat controversial. Constructing bicycle tracks and marking bicycle lanes in urban areas resulted in an increase in crashes and injuries of approximately 10 percent in Copenhagen, Denmark. Bicyclists' safety has worsened due to these facilities.

On the other hand, making these bicycle facilities resulted in more cycling and less motor vehicle traffic. This must have contributed to benefits due to more physical activity, less air pollution, less traffic noise, less oil consumption, etc. A recent study shows that an extra pedal cycled kilometer in Copenhagen gives an average gain in health and production solely due to more physical activity of rather more than 5 DKK, which equals about 1 US$ (*19*). The positive benefits may well be much higher than the negative consequences caused by new safety problems. It will be reasonable to sum up costs and benefits in order to identify roadways that are relevant for implementing bicycle facilities.

Design of bicycle facilities clearly seems to have safety implications. The study has revealed a few points in relation to this. However, it remains unclear whether it is possible to design urban bicycle facilities so road safety is improved.

CONCLUSIONS

The main conclusions of the research reported in this paper can be summarized in the following points:

1. A before-after traffic, crash and injury study of constructing bicycle tracks and marking bicycle lanes has been completed taking into account changes in crash trends, traffic volumes and regression-to-the-mean effects in the before period. Bicycle facilities are predominantly made in order to provide bicyclists better travel conditions.

2. The weighted means or best estimates for safety effects of bicycle tracks in urban areas are an increase of about 10 percent in crashes and injuries. This is due to a large increase of 18 percent in intersections, which more than outweigh a small reduction on road links between intersections. Pedestrians, bicyclists and moped riders safety at intersections are significantly worsened. Results vary significantly from road to road.

3. One reason to this heterogeneity in safety effect between roads is that some bicycle track designs are safer than others. Roads with bicycle tracks and parking permitted are safer compared to roads with parking bans. Bicycle tracks than ends at the stop line at signalized intersections with no turn lanes for motor vehicles should be avoided due to major safety problems.

4. The best estimates for safety effects of bicycle lanes in urban areas are an increase of 5 percent in crashes and 15 percent in injuries. Safety is worsened both at intersections and on links. Bicyclists' safety has significantly worsened on the roads, where bicycle lanes have been marked. More detailed traffic and design conditions were not studied in relation to bicycle lanes.

5. The construction of bicycle tracks resulted in a 20 percent increase in bicycle/moped traffic mileage and a decrease of 10 percent in motor vehicle traffic mileage on those roads, where bicycle tracks have been constructed. The marking of bicycle lanes resulted in a 5

percent increase in bicycle/moped traffic mileage and a decrease of 1 percent in motor vehicle traffic mileage on those roads, where bicycle lanes have been marked. This must have contributed to benefits due to more physical activity, less air pollution, less traffic noise, less oil consumption, etc.

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