Safety Effects of Intersection Signalization: a Before-After Study

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ABSTRACT

This paper presents a before-after crash and injury study of intersection signalization in an urban area. Conversion from yield to signal control at 54 intersections in central Copenhagen, Denmark, is analyzed. Police recorded crashes, which occurred at converted intersections as well as crashes up to 500 meters away on roadways leading up to converted intersections, are included in the study. The method used accounts for general crash and injury trends, changes in traffic volumes, and also regression-to-the-mean effects in the before period. The best estimates for mean safety effects of intersection signalization are decreases in crashes and injuries of respectively 21 and 17 percent at 3-armed intersections, and 39 and 33 percent at 4-armed intersections. These findings are in line with previous studies. The safety benefits at converted intersections are primarily due to significant reductions in right-angle crashes. Safety is also improved on roadways up to 100 meters away from the center of the converted 3-armed intersections, and up to 200 meters away from converted 4-armed intersections. About 60 percent of the total safety improvement occurred on the roadways and only about 40 percent occurred at the converted intersections. In total, for converted intersections and roadways up to 200 meters away, the best estimates for mean safety effects of intersection signalization are decreases in crashes and injuries of respectively 19 and 21 percent near and at the 3-armed intersections, and 26 and 33 percent near and at the 4-armed intersections.

INTRODUCTION

Intersections are often signalized in urban areas in order to improve traffic operations, safety, perceived risk and signal coordination.

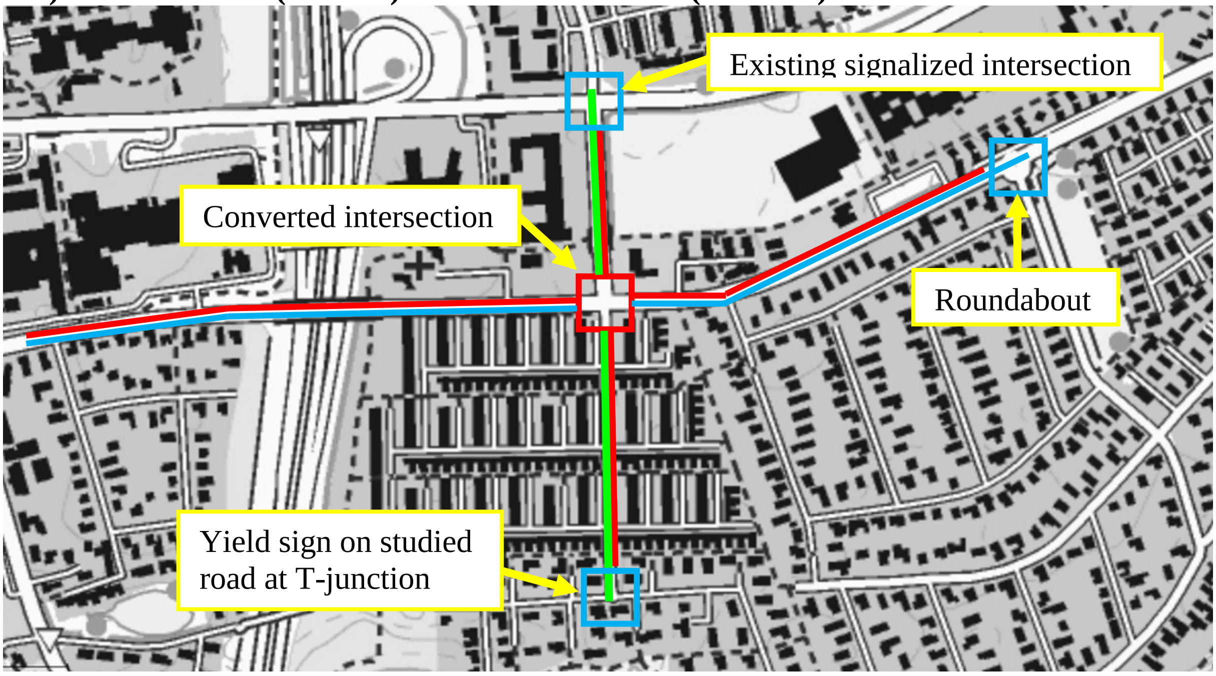
Many safety studies of intersection signalization have been undertaken worldwide. A meta-analysis of 28 studies published in 1967-1995 shows that signalization of 3-armed intersections reduces injury and property damage only (PDO) crashes by 15 percent, and signalization of 4-armed intersections reduces injury crashes by 30 percent and PDO crashes by 35 percent (*1*). A more recent North American study of signalization of 22 three-armed and 100 four-armed intersections in urban areas found that the number of injury crashes fell by 14 percent at 3-armed intersections and 23 percent at 4-armed intersections (*2*). A new American study of signalization of 6 three-armed and 39 four-armed intersections in rural areas found a reduction in crashes by 44 percent (*3*). Many studies state that intersection signalization reduce the number of right-angle crashes, whereas the number rear-end crashes increases, e.g. the recent American studies found reductions in right-angle crashes of 34-77 percent and a 38-58 percent increase in rear-end crashes (*1-3*). These effects are based on changes in the number of crashes at intersections or intersection-related crashes. It is unclear in many studies how far away from the intersection center an intersection-related crash may occur. It is also relatively unclear in these studies how intersections and signal-control were designed before and after the conversion. The recent American studies include intersections being converted from stop to signal control.

The before-after study, which is presented in the following, focus on safety effects of signalization of 54 intersections in central parts of Copenhagen, Denmark. The intersections were signalized in 1977-1999. The study includes one 5-armed, 35 four-armed and 18 three-armed intersections. Intersections were converted from yield (shark teeth) to signal control. Channelization was rare on minor roads both before and after conversion, but often present on major roads especially after conversion. Intersections were illuminated by street lighting both before and after conversion. All traffic signals operate pre-timed. There is typically 2-4 signal heads for through vehicular traffic for each direction with 1-3 signal heads placed on poles on the near side, 0-1 signal heads on span-wire close to intersection center and 1-3 signal heads on poles on the far side. Flashing yellow and right-turn on red is not allowed. Almost all signalized arms have pedestrian signals and zebra crossings.

The main purpose of the study is to identify safety effects of signalization both at converted intersections and roadways leading up to converted intersections. Police recorded crashes, which occurred at converted intersections as well as crashes on the roadways up to 500 meters (1,639 feet or 0.31 miles) away from the center of the converted intersection, are included in the study. Some of the studied roadways are shorter than 500 meters, because the roadway ends or traffic on the roadway faces a yield sign or signal-control. The studied roadways therefore sometimes end at existing signalized intersections, roundabouts or other yield controlled intersection (hereafter called end-crossroads), which are located less than 500 meters away from the converted intersection.

Crashes are split into crashes at converted intersections and crashes on roadways by using crash information. Police officers and crash records technicians judge whether or not the crash is intersection-related, and this judgment is used to make the split. Roadway crashes are split into whether they occurred on the road, which was respectively minor or major prior to signalization. Roadway crashes are also split into crashes on links and crashes at end-crossroads. The different locations of crashes are explained in Figure 1.

FIGURE 1 Explanation of Location of Crashes at Converted Intersection (red box) and Roadways. Roadways are split into Main Roads (blue line) and Minor Roads (green line) and also Links (red line) and End-crossroads (blue box).



METHODOLOGY

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 intersections and roadways 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 or injuries expected to occur in the after period if intersections were not signalized, A_{Before} is the number of crashes or 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 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 roadways had undergone more than one reconstruction or other scheme. Only “clean” schemes are studied, meaning that for the intersections being signalized and the roadways leading up to these intersections, no other scheme has been implemented in before and after periods and in the year when signals was installed.

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 both intersections and links between intersections, 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 the general comparison group and the studied intersections and roadways. Trends for different types of crashes and injuries of the general comparison group were compared. Crash trends for different types of intersections and links are very similar, hence no need for sub-grouping. However, trends for different crash or injury severities and transport modes exhibit rather different developments. It is 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 or Injuries 1976-2004)

	[a] Bicycle / moped	[b] Pedestrian	[c] Motor vehicle
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 or injuries in the sub-comparison group in the after period divided by the number of crashes or 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 at the studied intersection and roadways in the before period, $A_{Before,1}$, as part of Formula 1. C_{Trend} is only a two-point trend, where crashes in all years in the before period are summed and crashes in all years in the after period are summed. Due to this a yearly safety effect, e.g. safety effect in the first, second, … year after implementation, is not possible to describe.

The correction factor $C_{Traffic}$ is based on changes in traffic volumes at the studied intersections and roadways and in the general comparison group. The relationship between traffic flow and crashes or 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 or injuries, N is annual average daily traffic (AADT) on the link, N_{pri} and N_{sec} are the incoming motor vehicle daily traffic 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 for urban roads, which have been developed during the last decades in Denmark, whereas α varies between the different types of roads and intersections (*4-11*). Figures for α varies, because the level of safety depends on the type of road and intersection. In this case, bicycle / moped traffic is also known, and here the sparse number of crash prediction models indicate that bicycle / moped traffic only influence the number of crashes involving cyclists and moped riders. Formula 2 and 3 are then used to set up formulas for $C_{Traffic}$:

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

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

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

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

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

Traffic data from before and after periods are used, hence, increases and decreases in traffic volumes from before to after are accounted for. Traffic volumes from the comparison group is included in formula 4-7 in order to avoid "double accounting" for the general change in traffic volumes, since this is already accounted for once in C_{Trend}. Changes in traffic volumes are known for 43 of the 54 study sites. The change from before to after in motor vehicle traffic at the studied intersections and roadways varied from -19 percent to +65 percent, however, most changes were small and followed the changes in the general comparison group. $C_{Traffic,\ pmv}$ is on average 1.019. Similar, the change in bicycle-moped traffic was between -29 percent and +115 percent, but again most changes followed the general comparison group. $C_{Traffic,\ bike}$ is on average 1.034. Where changes in traffic volumes are unknown $C_{Traffic}$ has been set to 1, i.e. changes in traffic on the study site follows changes in traffic in the general comparison group.

The analysis of long-term crash trends is made in order to check for abnormally high crash or injury 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 signalization. The before-before period is chosen because it is prior to an eventual black spot identification period or other type of systematic crash investigation period that may have lead to signalization. This before-before period is then used to calculate an expected number of crashes and injuries in the before period of the studied intersections and roadways by making corrections for general 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 studied intersections and roadways.

Only for 20 of 54 study sites it is possible to make the calculation of C_{RTM}, because crash records only are available back to 1976 or other schemes were implemented at the studied intersections and roadways 6-12 years before signalization.

TABLE 2 Expected and Observed Crashes and Injuries in the Before-before and Before Period respectively for Studied Intersections and Roadways

		Observed BEFORE-BEFORE	Expected BEFORE	Observed BEFORE	Change in safety (percent)	
					Best estimate	[a] 95% CI
Intersections	All crashes	128	189	200	[b] +17	[b] -17 ; +65
	All injuries	55	57	76	+31	-10 ; +91
Roadways	All crashes	905	1,014	994	-1	-10 ; +9
	All injuries	446	332	334	[b] +1	[b] -20 ; +27

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

The results of the analyses of long-term crash trends are shown in Table 2. Meta-analyses have been used to calculate best estimates for safety changes and related confidence intervals. Table 2 shows no statistically significant changes. However, the number of injuries (and injury crashes) at the intersections is much higher than expected, actually 31 percent higher than expected. The correction factor, C_{RTM}, is therefore set to 1 / 1.31 = 0.76 for injuries and injury crashes at the intersections. Analyses indicate that the correction factor should rely on the severity of injury, but the numbers of respectively killed, severe injury and slight injury are relatively small, and it is not reasonable to create different correction factors for the different injury severity levels. Instead only changes in all injuries are shown in the results. Detailed analyses of potential regression-to-the-mean effects on the roadways show that the crash trends follow the trends in the general comparison group at any distance (10-500 meters away) from the intersection being signalized. For PDO crashes at the intersections and for both crashes and injuries on the roadways, C_{RTM} is set to 1, because the observed number of crashes and injuries in the before period is only respectively 0.6 percent higher, 1.0 percent lower and 0.5 percent higher than expected, i.e. the trends in these crashes and injuries follows almost perfectly the trends in the general comparison group. The results about the regression-to-the-mean effects fit well with statements from the city administration. They state that they convert from yield to signal control when many injury crashes or severe injury crashes occur at the intersection. In other words, the decision to install signals is not based on the number of PDO crashes at the intersection or crashes on roadways.

There are major differences in correction factors between study sites primarily due to general crash trends being different during the period 1976-2004. Due to the long analytical period, meta-analysis rather than simple sums of crashes and injuries is used in order to describe best estimates for mean safety effects and the variance of these effects. The meta-analysis methodology is described by Elvik (*12-13*). Below is a short description of the log odds method of meta-analysis applied in this study.

Each estimate of safety effect at an intersection or a roadway or alike was assigned a statistical weight inversely proportional to its variance. The variance of the logarithm of the odds ratio is:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D},$$

where A and B is the number of crashes at the studied site in respectively the before and after period, and C and D is the number of crashes in the general comparison group in respectively the before and after period. The statistical weight of each estimate in the fixed effects model of meta-analysis is:

$$w_i = \frac{1}{v_i}$$

The weighted mean safety effect based on a set of estimates of safety effects is:

$$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right),$$

where y_i is the logarithm of each estimate of safety effect and w_i is that statistical weight as describe above.

The fixed effects model of meta-analysis is based on the assumption that there is only random variation in findings between safety effects at the studied sites. To test the validity of this assumption, the following test statistic, Q, is estimated:

$$Q = \sum_{i=1}^{g} w_i y_i^2 - \frac{\left(\sum_{i=1}^{g} w_i y_i\right)^2}{\sum_{i=1}^{g} w_i}$$

This test statistic has a χ^2 distribution with g – 1 degrees of freedom, where g is the number of estimates of safety effect (number of studied sites) that have been combined. If this test statistic is statistically significant, a random effects model of analysis will be adopted. In this model, the statistical weight assigned to each safety effect is modified to include a component reflecting the systematic variation of estimated safety effects between studies sites. This component is estimated as follows:

$$\sigma_\theta^2 = \frac{[Q - (g - 1)]}{c},$$

where Q is the test statistic described above, g is the number of estimates and c is the following estimator:

$$c = \sum_{i=1}^{g} w_i - \frac{\sum_{i=1}^{g} w_i^2}{\sum_{i=1}^{g} w_i}$$

The variance of each modified safety effect now becomes:

$$v_i * = \sigma_\theta^2 + v_i$$

The corresponding modified statistical weight becomes:

$$w_i * = \frac{1}{v_i *}$$

A 95 percent confidence interval (95% CI) for the weighted mean estimate of safety effect is obtained according to the following expression:

$$95\%\ \mathrm{CI} = \exp\left[\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right) \pm 1.96 \cdot \frac{1}{\sqrt{\sum_{i=1}^{g} w_i}}\right]$$

The weights of this expression are either the fixed effects weights of the random effects, depending on the model of analysis adopted. Fixed effects models are used for homogeneous mean effects (Q is not statistical significant), i.e. only random variation in estimated effects. Random effects models are used for heterogeneous mean effects (Q is statistical significant on a 5 percent level).

When the number of crashes is zero at a studied site in the before or after period, i.e. when A or B is zero, then the log odds of meta-analysis does not work. The tradition in these situations is to add a half crash. In this study a half crash has been added number of crashes in the before period, and a half crash multiplied by the correction factors C_{Trend}, $C_{Traffic}$ and C_{RTM} has been added to respectively the number of expected crashes in the after period and the number of crashes in the after period. This works well when there are none or only few zero values. However, in this study the number of zero values are high, when crashes are split into different types, e.g. rear-end and right-angle crashes. Therefore simple sums of crashes instead of meta-analysis are used in order to estimate mean safety effects when crashes are split into different types.

RESULTS

The results of the study, i.e. safety effects of intersection signalization, are given in three parts respectively for converted intersections, roadways, and for converted intersections and roadways as a whole.

Safety Effects for Converted Intersections

Signalization of intersection has resulted in a statistically significant reduction of 36 percent in crashes and 26 percent in injuries, see Table 3. The 21 and 17 percent reductions estimated for 3-armed intersections are not significant, but are similar to results from other studies. The 39 and 33 percent reductions estimated for 4-armed intersections are statistically significant, and also close to results from other studies. The estimations for the 5-armed intersection are very different, because one crash in the after period has many injuries. Given that the crash number decreases significantly, signalization has most probably also improved safety at the 5-armed intersection.

TABLE 3 Estimated Mean Safety Effects for Converted Intersections of Intersection Signalization (Statistically Significant Results are Marked in Grey)

		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	[a] 95% CI
Crashes	All 54 intersections	454	404	236	[b] **-36**	[b] **-48 ; -21**
	3-armed intersections	141	121	83	[b] -21	[b] -48 ; +20
	4-armed intersections	297	267	149	**-39**	**-50 ; -25**
	5-armed intersection	16	16	4	**-75**	**-92 ; -25**
Injuries	All 54 intersections	223	127	80	**-26**	**-43 ; -2**
	3-armed intersections	67	39	26	-17	-50 ; +37
	4-armed intersections	151	85	48	**-33**	**-52 ; -6**
	5-armed intersection	5	4	6	+54	-54 ; +408

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

An analysis of relations between the safety effect and the distance between the converted intersection and existing signalized intersections on the main road indicates interesting relations for 4-armed intersections. As existing signalized intersections are located closer to the converted 4-armed intersections the higher the safety effect becomes, see Table 4. This relation can’t be documented for converted 3-armed intersections, due to a low number of intersections and a low diversity in location of existing signalized intersection. Another analysis of relations between the safety effect and motor vehicle traffic volumes on the main road also indicate interesting relations for converted 4-armed intersections. Table 4 shows that signalizing intersections on roads with low traffic volumes apparently results in better safety effects than on roads with high traffic volumes. This result is in line with results from a North American study, which also found that intersection signalization produces better safety effects with low AADT compared to high AADT (*2*). This relation can't be documented for converted 3-armed intersections. It seems that both location of existing signals and AADT influence the safety effect at the converted 4-armed intersections when these two independent variables are combined. The results for 4-armed intersections are only indications of relations, because the confidence interval for the safety effect of the different categories of location of existing signals and AADT overlaps each other. Effects on injuries are similar to the effects on crashes in Table 4, and therefore not shown.

TABLE 4 Estimated Mean Crash Effects for Converted 4-armed Intersections of Intersection Signalization split into Location of Existing Signalized Intersections and AADT on Main Road (Statistically Significant Results are Marked in Grey)

4-armed intersections, crashes		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	[a] 95% CI
Location of existing signals on main road	1-2 signals under 200 m away	96	87	39	**-48**	**-65 ; -22**
	1 signal 200-500 m away	62	64	35	**-41**	**-62 ; -8**
	2 signals 200-500 m away	101	84	52	**-34**	**-53 ; -7**
	Signal more than 500 m away	38	32	23	-28	-58 ; +21
AADT on main road	2,500-6,000	80	76	32	**-55**	**-70 ; -31**
	6,000-12,000	109	100	54	**-38**	**-56 ; -14**
	12,000-18,000	43	40	25	-29	-57 ; +17
	18,000-40,000	65	51	38	-24	-51 ; +18

[a] 95% confidence interval.

The safety effects for intersections have also been split into groups of crash types. As mentioned previously this split unable the use of meta-analysis due to many zero-values, and the safety effects are then base on simple sums of crashes and injuries. The effects on crashes shown in Table 5 (top half) are in line with findings in other studies. The numbers of right-angle crashes decreases significantly in 3-, 4- and 5-armed intersections by overall 84 percent. The numbers of single vehicle, rear-end, frontal, right- and left-turn crashes increases by about 35 percent. Pedestrian crashes fall by 16 percent. Effects on injuries are similar to the effects on crashes in Table 5, and therefore not shown.

Table 5 (lower half) also shows results for another split into groups of crash types as defined in Table 1. The results in Table 5 shows that bicycle/moped and motor vehicle only crashes fall significantly by respectively 30 and 50 percent, and pedestrian-motor vehicle crashes fall by 26 percent. These results indicate that all transport modes get safety benefits at the intersections due to signalization.

TABLE 5 Crash Effects for Converted Intersections of Intersection Signalization split into Different Types of Crashes (Statistically Significant Results are Marked in Grey)

Crashes	Effect on crashes Expected AFTER → Observed AFTER			
	All intersections	3-armed	4-armed	5-armed
Single vehicle crashes	+34 % 19 → 25	-17 % 10 → 8	+106 % 8 → 17	-100 % 1 → 0
Rear-end and frontal crashes	+37 % 28 → 38	+90 % 10 → 19	+1 % 8 → 8	+ % 0 → 1
Right- and left-turn crashes	+34 % 69 → 93	-2 % 32 → 31	**+65 %** **36 → 59**	+48 % 2 → 3
Right-angle crashes	**-84 %** **237 → 37**	**-75 %** **52 → 13**	**-86 %** **172 → 24**	**-100 %** **12 → 0**
Pedestrian crashes	-16 % 51 → 43	-29 % 17 → 12	-6 % 33 → 31	-100 % 1 → 0
Bicycle and moped crashes	**-30 %** **110 → 77**	-14 % 37 → 32	**-41 %** **72 → 43**	+221 % 1 → 2
Pedestrian-motor vehicle crashes	-26 % 46 → 34	-54 % 15 → 7	-9 % 30 → 27	-100 % 1 → 0
Motor vehicle only crashes	**-50 %** **248 → 125**	**-35 %** **68 → 44**	**-52 %** **165 → 79**	**-86 %** **14 → 2**

Safety Effects for Roadways

Results for roadways leading up to the converted intersections are given in this section. These roadways are up to 500 meters ((1,639 feet or 0.31 miles) long, but can be shorter. Studied roadways are split into main and minor roads, and also links and end-crossroads. An explanation of these terms was given in the introduction. Table 6 shows the mean effects on crashes based on meta-analyses for roadways, main and minor roads, and end-crossroads and links. Mean effects on injuries are similar to the effects on crashes in Table 6, and therefore not shown.

Crash numbers is statistically significant reduced by 10 percent on the roadways due to the intersection signalization. The meta-analyses indicate a crash effect, which is high and significant near the converted intersections and then vanish about 200 meters (656 feet) away from converted intersections, see Table 6. In absolute numbers, the crash effect on roadways (2,460 – 2,224 = 236) is actually greater than at converted intersections (404 – 236 = 168).

The crash effect is highly beneficial near the converted intersections and then becomes poorer further away both on main and minor roads and on links. None of the crash effects for end-crossroads are statistically significant, and the figures also indicates that no or only minor changes in safety have taken place here.

TABLE 6 Estimated Mean Crash Effects for Roadways, Main and Minor roads, and End-Crossroads and Links up to 500 meters away from Converted Intersections (Statistically Significant Results are Marked in Grey)

Crashes		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	^{a} 95% CI
Roadways	Up to 500 meters away	2,481	2,460	2,224	^{b} **-10**	^{b} **-17 ; -3**
	10-100 meters away	491	493	386	^{b} **-20**	^{b} **-33 ; -5**
	110-200 meters away	698	698	592	**-13**	**-22 ; -3**
	210-350 meters away	778	747	737	-0	-10 ; +11
	360-500 meters away	514	522	509	-1	-13 ; +12
Main roads	Up to 500 meters away	1,985	1,939	1,738	^{b} **-11**	^{b} **-18 ; -3**
	10-100 meters away	382	370	292	**-18**	**-30 ; -4**
	110-200 meters away	545	537	475	-7	-18 ; +5
	210-350 meters away	641	608	585	-3	-13 ; +9
	360-500 meters away	417	424	386	-8	-20 ; +6
Minor roads	Up to 500 meters away	496	521	486	-4	-16 ; +9
	10-100 meters away	109	123	94	-16	-37 ; +11
	110-200 meters away	153	161	117	**-25**	**-41 ; -3**
	210-350 meters away	137	139	152	+12	-12 ; +42
	360-500 meters away	97	98	123	+27	-3 ; +67
Links	Up to 500 meters away	1,612	1,582	1,360	^{b} **-15**	^{b} **-23 ; -6**
	10-100 meters away	472	471	371	^{b} **-20**	^{b} **-33 ; -4**
	110-200 meters away	524	524	422	**-16**	**-27 ; -5**
	210-350 meters away	409	391	354	-8	-20 ; +7
	360-500 meters away	207	196	213	+11	-9 ; +36
End-crossroads	80-500 meters away	869	878	864	-2	-13 ; +11
	80-200 meters away	193	196	185	-4	-22 ; +18
	210-350 meters away	369	356	383	+6	-9 ; +23
	360-500 meters away	307	326	296	-8	-22 ; +8

^{a} 95% confidence interval, ^{b} heterogeneous i.e. results of random effects model.

The roadways are split into study sites with respectively converted 3- and 4-armed intersections in Table 7. The number of crashes on roadways leading up to the converted 5-armed intersection is relatively few and not shown. Table 7 shows statistically significant beneficial mean safety effects on roadways up to 100 meters (328 feet) away from converted 3-armed intersections and up to 200 meters (656 feet) away from converted 4-armed intersections. More detailed analyses show that the beneficial safety effect practically vanishes about 100 meters away from converted 3-armed intersections and around 200 meters away from converted 4-armed intersections. The findings are somewhat in line with another Danish study, which showed that a beneficial safety effect from signalization of pedestrian crossings vanished about 120-150 meters away from the pedestrian crossing (*13*).

Analyses of relations between the safety effect on the first 200 meters of roadways closest to the converted intersections and respectively a) location of existing signalized intersections on the main road and b) AADT on the main road, indicate no relations when analyzing all 54 study sites and no relations for roadways leading up to respectively converted 3- and 4-armed intersections.

TABLE 7 Estimated Mean Crash Effects for Roadways up to 500 meters away from Converted 3- and 4-armed Intersections (Statistically Significant Results are Marked in Grey)

Crashes, roadways		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	[a] 95% CI
Near 3-armed intersections	Up to 500 meters away	883	853	812	[b] -5	[b] -19 ; +12
	10-100 meters away	170	168	133	**[b] -29**	**[b] -51 ; +3**
	110-200 meters away	207	198	190	-3	-21 ; +18
	210-350 meters away	373	350	345	[b] -1	[b] -21 ; +22
	360-500 meters away	133	138	144	+6	-17 ; +35
Near 4-armed intersections	Up to 500 meters away	1,570	1,577	1,379	**-12**	**-18 ; -5**
	10-100 meters away	316	320	242	**-24**	**-36 ; -10**
	110-200 meters away	481	490	391	**-18**	**-28 ; -6**
	210-350 meters away	396	388	385	+0	-13 ; +16
	360-500 meters away	377	380	361	-3	-16 ; +12

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

The crash effects for roadways have been split into groups of crash types in Table 8. As mentioned previously this split unable the use of meta-analysis due to many zero-values, and the safety effects are then based on simple sums of crashes. The crash effects in Table 8 (top half) shows that the numbers of rear-end and frontal crashes fall significantly by 18 percent and right-angle and pedestrian crashes by about 30 percent. These crash effects are almost the same on roadways near respectively converted 3- and 4-armed intersections. Table 8 (lower half) shows results for the split into groups of crash types as defined in Table 1. Numbers of bicycle / moped, pedestrian-motor vehicle and motor vehicle only crashes fall significantly by 19, 38 and 13 percent respectively. Again are crash effects almost the same on roadways near respectively converted 3- and 4-armed, however, bicycle / moped crashes do not fall near 3-armed intersections.

TABLE 8 Crash Effects for Roadways up to 200 meters away from Converted 3- and 4-armed Intersections split into Different Types of Crashes (Statistically Significant Results are Marked in Grey)

Crashes, roadways up to 200 m away from intersections being signalized	Effect on crashes Expected AFTER → Observed AFTER		
	Roadways near all 54 intersections	Near 3-armed intersections	Near 4-armed intersections
Single vehicle crashes	-3 % 262 → 253	+3 % 76 → 78	-8 % 184 → 169
Rear-end and frontal crashes	**-18 % 256 → 210**	-10 % 81 → 73	**-21 % 170 → 134**
Right- and left-turn crashes	-10 % 217 → 195	+1 % 76 → 77	-18 % 140 → 115
Right-angle crashes	**-28 % 275 → 197**	-25 % 79 → 59	**-32 % 192 → 130**
Pedestrian crashes	**-32 % 181 → 123**	-33 % 54 → 36	**-31 % 124 → 85**
Bicycle and moped crashes	**-19 % 342 → 278**	+4 % 108 → 113	**-30 % 231 → 161**
Pedestrian-motor vehicle crashes	**-38 % 154 → 96**	-35 % 40 → 26	**-38 % 112 → 69**
Motor vehicle only crashes	**-13 % 694 → 604**	-15 % 217 → 184	**-14 % 467 → 403**

Safety Effects for Converted Intersections and Roadways as a whole

Safety effects of intersection signalization for converted intersections and roadways up to 200 meters away from converted intersections are presented in this section. Roadways 210-500 meters from the intersections that were signalized are not included here, because the previous section showed that the safety effects for roadways at these distances were close to zero.

Results based on meta-analyses are given in Table 9. In total, the numbers of crashes and injuries fall by respectively 23 and 28 percent at converted intersections and on roadways up to 200 meters away from converted intersections due to intersection signalization. Near and at converted 3-armed intersections the corresponding figures are 19 and 21 percent, which is less than near and at converted 4-armed intersections, where crashes and injuries dropped by respectively 26 and 33 percent. All these figures are statistically significant.

The numbers of single vehicle, rear-end, frontal and right- and left-turn crashes do not seem to be affected significantly by intersection signalization. In other words, the increasing numbers of single vehicle, rear-end, frontal and right- and left-turn crashes that took place at the intersections have been counterbalanced by decreasing numbers of the same types of crashes on the roadways.

In total, right-angle crashes have decreased by 51 percent due to the signalization of the 54 intersections, and pedestrian crashes decreased 24 percent. These changes are almost the same near and at respectively converted 3- and 4-armed intersections. The decrease in right-angle crashes is slightly larger near and at converted 4-armed intersections (54 percent) compared to near and at converted 3-armed intersections (44 percent). These figures are statistically significant except for the change in pedestrian crashes near and at converted 3-armed intersections.

TABLE 9 Estimated Mean Safety Effects of Intersection Signalization for Converted Intersections and Roadways up to 200 Meters away from Converted Intersections (Statistically Significant Results are Marked in Grey)

Intersections and roadways as a whole		Observed BEFORE	Expected AFTER	Observed AFTER	Safety effect (percent)	
					Best estimate	[a] 95% CI
All crashes	Near/at all 54 intersec	1,643	1,595	1,214	**[b] -23**	**[b] -30 ; -16**
	Near/at 3-armed intersec	518	486	406	**[b] -19**	**[b] -34 ; -1**
	Near/at 4-armed intersec	1,094	1,077	782	**-26**	**-33 ; -19**
	Near/at 5-armed intersec	31	32	26	-19	-52 ; +37
All injuries	Near/at all 54 intersec	769	538	365	**-28**	**-36 ; -18**
	Near/at 3-armed intersec	233	164	123	**-21**	**-37 ; -1**
	Near/at 4-armed intersec	527	365	228	**-33**	**-43 ; -21**
	Near/at 5-armed intersec	9	8	14	+71	-27 ; +299
Single vehicle crashes	Near/at all 54 intersec	277	281	278	-3	-18 ; +16
	Near/at 3-armed intersec	91	86	86	+3	-25 ; +40
	Near/at 4-armed intersec	183	192	186	-7	-25 ; +15
Rear-end and frontal crashes	Near/at all 54 intersec	281	284	248	-11	-26 ; +6
	Near/at 3-armed intersec	93	91	92	+3	-24 ; +41
	Near/at 4-armed intersec	183	188	152	-17	-34 ; +3
Right- and left-turn crashes	Near/at all 54 intersec	287	286	288	+1	-14 ; +20
	Near/at 3-armed intersec	113	107	108	+0	-24 ; +32
	Near/at 4-armed intersec	171	176	174	+1	-19 ; +25
Right-angle crashes	Near/at all 54 intersec	520	512	234	**-51**	**-58 ; -42**
	Near/at 3-armed intersec	134	131	72	**-44**	**-59 ; -24**
	Near/at 4-armed intersec	370	364	154	**-54**	**-62 ; -44**
Pedestrian crashes	Near/at all 54 intersec	278	232	166	**-24**	**-38 ; -7**
	Near/at 3-armed intersec	87	71	48	-24	-47 ; +9
	Near/at 4-armed intersec	187	157	116	**-23**	**-40 ; -2**
Bicycle and moped crashes	Near/at all 54 intersec	483	453	355	**[b] -20**	**[b] -34 ; -3**
	Near/at 3-armed intersec	153	146	145	+3	-19 ; +31
	Near/at 4-armed intersec	326	304	204	**[b] -30**	**[b] -45 ; -10**
Pedestrian-motor vehicle crashes	Near/at all 54 intersec	244	200	130	**-30**	**-44 ; -12**
	Near/at 3-armed intersec	70	55	33	-32	-55 ; +2
	Near/at 4-armed intersec	171	141	96	**-28**	**-45 ; -6**
Motor vehicle only crashes	Near/at all 54 intersec	916	942	729	**-21**	**-29 ; -13**
	Near/at 3-armed intersec	295	285	228	**-18**	**-31 ; -2**
	Near/at 4-armed intersec	597	632	482	**-23**	**-32 ; -13**

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

Bicycle / moped, pedestrian-motor vehicle and motor vehicle only crashes have in total decreased by respectively 20, 30 and 21 percent. These figures are statistically significant. There is a major difference in the crash effects for bicycle / moped crashes, where the number of crashes has remained almost unchanged near and at converted 3-armed intersections, whereas there is a decrease of 30 percent near and at converted 4-armed intersections.

DISCUSSION

The presented safety effects of intersection signalization at the converted intersections are in line with previous studies. The safety effects at converted 4-armed intersections are better compared to the effects at converted 3-armed intersections. This is primarily because the right-angle crashes share of all crashes in the before period is higher at converted 4-armed intersections (64 percent) compared to at converted 3-armed intersections (44 percent). The safety effects of intersection signalization highly depend on right-angle crashes share of all crashes because signalization predominantly affects this crash type at the intersections.

The study documents significant safety improvements on roadways near converted intersections as a result of intersection signalization. The safety effects on roadways exhibit a dose-response relationship. The safety effect is high close to converted intersections then diminishes further away and vanishes about 200 meters away from converted intersections.

The study actually documents that about 60 percent of the total safety improvement due to intersection signalization occur on the roadways and only about 40 percent at the converted intersections. Thus traffic planners and safety engineers would hefty underestimate safety benefits of intersection signalization if they only predict safety consequences for the intersections they wish to signalize. It is likely that the split in safety improvement (60-40 percent) is different for intersection signalization in rural areas, and also in other countries due to differences in e.g. crash recording systems, geometric and signal-control design.

The large decreases in right-angle and pedestrian crashes on roadways indicate that it becomes safer to cross these roadways. Road users coming from side streets and driveways near the converted intersections seem to have benefited from a significant safety gain.

Another possible explanation regarding pedestrians might be that they in the after period to a higher extent cross the road at the converted intersection than they did prior to the signalization. Such change in behavior will lead to less crossing activity and probably fewer pedestrian crashes on roadways. However, the study does not include figures for pedestrian traffic volumes.

CONCLUSIONS

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

1. A before-after crash and injury study of intersections signalization taking into account general crash and injury trends, traffic volumes and regression-to-the-mean effects in the before period is presented. Intersection signalization is often done in order to improve traffic operations, safety, perceived risk and signal coordination.

2. The best estimates for mean safety effects of intersection signalization are decreases in crashes and injuries of respectively 21 and 17 percent at 3-armed intersections, and 39 and 33 percent at 4-armed intersections. These safety benefits are primarily due to significant reductions in right-angle crashes.

3. Safety is improved on roadways up to about 100 meters away from converted 3-armed intersections and up to approximately 200 meters away from converted 4-armed intersections. About 60 percent of the total safety improvement that took place due to intersection signalization occurred on roadways and only about 40 percent at converted intersections.

4. In total, for both converted intersections and roadways up to 200 meters away, the best estimates for safety effects of intersection signalization are decreases in crashes and injuries of respectively 19 and 21 percent near and at converted 3-armed intersections, and 26 and 33 percent near and at converted 4-armed intersections.

5. In total, for both converted intersections and roadways up to 200 meters away, pedestrian and right-angle crashes decrease significantly. Most road users gain safety benefits from intersection signalization, except bicyclists and moped riders near and at converted 3-armed intersections.

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