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Two-way Cycle Crossings at Non-signalized Intersections and Roundabouts

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ABSTRACT

Cycle paths running along roads may cross side roads near intersections. Some 776 sites where a two-way cycle path crosses a road close to a non-signalized intersection or roundabout have been used for accident modelling. Only cycle paths that run parallel and less than 15 meters from a road are included. A total of 384 accidents occurred at the 776 two-way cycle crossings including 188 injury accidents. Traffic counts of both path, road and intersection traffic were performed. Negative binomial accident models were estimated using traffic counts and design features as independent variables. On average accident rates are 0.09 accidents per million motor vehicles crossing cycle paths, 0.47 bicycle accidents per million cyclists crossing roads and 3.48 moped accidents per million moped riders crossing roads. Three types of cycle crossings have very different accident rates. No accidents occurred at 50 grade-separated crossings meaning that accident rates are zero and it is the safest type of crossing. At 152 sites path users have to yield to road users and here accident rates are 0.01 per million motor vehicles and 0.21 per million cyclists/moped riders. The 152 sites are many times safer than 539 sites where road users have to yield to path users and where accident rates are 0.18 per million motor vehicles and 0.86 per million cyclists/moped riders. The accident models indicate that signage and marking of the two-way cycle crossings influence safety at the crossings. Models also indicate that traffic volumes on roads parallel to paths, type and design of intersections, and the distance between intersections and two-way cycle crossings influence safety at the crossings.

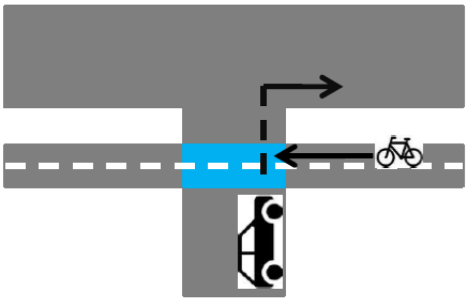
Keywords: cycle path, cycle crossing, crossing design, safety, accident model.

1 INTRODUCTION

This paper is based on a safety study of sites, where two-way cycle paths cross side roads near non-signalized intersections and roundabouts. Only cycle paths that run parallel and less than 15 meters from a road are included. The study was carried out by Trafitec for the Danish Road Directorate and the Danish Road Standard Organization. The purpose of the study was to estimate relations between safety and design of the cycle crossing. The study is inspired by and a further elaboration of a master thesis by Buch [1], which included a safety study and an observational study of two-way cycle crossings near non-signalized 3- and 4-armed intersections, where the cycle crossing crosses the side road and motor vehicles must yield to cyclists.

The master thesis' safety study included accidents between passenger cars/vans on side roads and cyclists/moped riders using the cycle paths. 75 % of the accidents involved a cyclist/moped rider riding against the traffic stream in the nearest drive lane on the parallel road and only about 25% were accidents with cyclists/moped riders on the cycle path riding with traffic in the nearest drive lane. The master thesis showed that the most common type of accident at the cycle crossings is situation 620, see Figure 1, and this finding is in line with foreign studies on this subject. The master thesis also showed that up to 20 % of the right-turning drivers from the side roads do not look to the right before turning into the main road. This share of drivers depended on the presence of traffic on the main road and site conditions.

Figure 1. Accident situation 620. Right turning vehicle colliding with oncoming vehicle from the right (in this case bicycle/moped on path).



The results in the master thesis were in line with previous results. Finnish studies based on accidents and observations have shown that cyclists riding against the traffic stream in the nearest drive lane on the parallel road are more often involved in accidents in the cycle crossing at side roads [2-5]. The studies included non-signalized intersections and roundabouts. Observational studies indicated that the prime reason was that right-turning motor vehicle drivers did not look to their right side before entering from a side road.

Schepers et al. studied safety in cycle crossings at non-signalized intersections [6]. The study showed a higher risk of bicycle accidents at two-way cycle crossings compared to one-way cycle crossings and no bicycle facilities. The results also indicated that a distance of 2-5 meters between bicycle facility and side of main carriageway leads to fewer crashes compared to bike lane or no facility. Finally the results indicated that coloured road markings – especially in connections with other road markings – increase the number of bicycle accidents. Several studies have shown that the number of accidents per cyclist decreases when the number of cyclists increases at intersections [6-9].

A Norwegian study of conflicts at a non-signalized intersection showed that the number of conflicts decreased during time [10]. Phillips et al. expected that the number of conflicts decreased because the road users improved their driving skills in this specific intersection due to experience.

The Danish Road Directorate and the Danish Road Standard Organization wanted to know how the design of the cycle crossings is related to safety. The study described in this paper uses accident rates and accident prediction models to describe relations between safety and cycle crossing design. The study was carried out by Buch and Jensen [11] and is published on www.trafitec.dk in Danish.

2 DATA AND METHODOLOGY

The study is based on police recorded accidents, traffic counts and data about design of cycle paths, cycle crossings, roads and nearby intersections/roundabouts. Using these data, accident rates are calculated and accident and injury prediction models are estimated.

2.1 Accident, traffic and design data

All cycle crossings where two-way cycle paths cross side roads near intersections or roundabouts were recorded in 17 Danish municipalities. Cycle paths that run parallel and less than 15 meters from a parallel road are included. Only cycle crossings where the side road is paved and has a street name or an Average Annual Daily Traffic (AADT) of more than 100 are included. The 17 municipalities are located in all regions of Denmark and each municipality has at least one cycle crossing with a minimum of 4 accidents in the period 2000-2011.

A total of 776 two-way cycle crossings were identified. Police recorded accidents in the period 2000-2011 at these cycle crossings involving at least one cyclist, moped rider or pedestrian that used the cycle path were extracted from the national accident database. A total of 384 accidents were extracted thereof 188 injury accidents. A cyclist was using the cycle path in 53 % of the accidents and a moped rider used the cycle path in 47 % of the accidents. Only 5 accidents involved a pedestrian and 2 of them were wheeling a bicycle. At 75 % of the cycle crossings there were no accidents recorded. The highest number of recorded accidents at one site is 9. The rather long accident period was chosen because the police record less than 100 accidents per year at two-way cycle crossings in Denmark.

The cycle crossings are located in rural areas, small towns, suburbs and central areas of medium and larger cities. 584 of the 776 cycle crossings are located near 3-armed non-signalized intersections, 87 near 4-armed non-signalized intersections and 105 near roundabouts. Using aerial photos and Google Street View the designs of cycle paths, cycle crossings, roads and nearby intersections/roundabouts were identified.

It was necessary to perform traffic counts at the sites as part of the study, because traffic counts at cycle paths are rare in Denmark. Normally, it is not recommended to perform traffic counts for less than four hours, and even with such counts an error of about 15 % for motor vehicles and 36 % for bicycles and mopeds can be expected [12]. Due to financial and time limitations it was not possible to count traffic at all 776 sites in at least four hours. It was chosen to count traffic in a relatively short time period at many sites instead of counting few sites in long time periods. Traffic counts of 30 minutes at 188 of 776 sites were done. This was the compromise between counting at as many sites as possible and getting a decent idea of traffic volumes at the counted sites. The sites were counted during May and June 2013. Locally, traffic volumes can have changed considerably between 2000 and 2013, but it has unfortunately not been possible to take that into account.

30 minutes traffic counts were converted to average daily traffic by using the official Danish factors for enumeration [12]. Factors according to time of the day, day of the week and week of the year were used, see Equation 1. For motor vehicles the factors depend on the expected type of traffic. 99 % of the intersections are characterised by residential/work, local or regional traffic. The factors for these 3 types of traffic are almost the same and an average is used. For bicycle/moped traffic the factors depend on location of sites in urban, rural or on the border between urban and rural zones.

$$ADT = f_{hour \rightarrow day} \cdot f_{day \rightarrow week} \cdot f_{week \rightarrow year} \cdot 2 \cdot counts(30\text{min}) \quad (1)$$

Traffic has been counted at all sites with 4 or more accidents, and traffic was counted at 50 % of sites with 2-3 accidents but only about 20 % of sites with 0-1 accidents. The added traffic volumes are most precise at the most important sites in the models, i.e. contributing with most accidents. Sites with 2-3 accidents were randomly grouped pairwise according to type of intersection (3-arm, 4-arm, roundabout) and zone (urban, rural). One site from each group was picked randomly for traffic counting and the counts were added to both sites in the group. Sites with 0-1 accidents were randomly grouped in groups of five according to type of intersection (3-arm, 4-arm, roundabout), zone (urban, rural) and design (channelization of side and parallel road). One site from each group was picked randomly for traffic counting and the counts were added to each of the five sites.

Motor vehicle traffic counts at about 20 sites were compared to previous traffic counts at the same sites. The error in 30 minutes counts differed between sites, but the error was less than 25 % at all sites. The traffic volumes have three major biases, which one should have in mind when reading the results:

- The time of the counts (2013, while accidents from 2000-2011)
- The length of the counts (30 minutes)
- Traffic volumes at sites with no traffic counts

2.2 Accident and injury prediction models

Accident rates have been calculated, i.e. bicycle accidents pr. million cyclists (from cycle path), moped accidents pr. million moped riders (from cycle path), bicycle/moped accident pr. million cyclists/moped riders (from cycle path), and bicycle/moped accident pr. million motor vehicles crossing the cycle path. Accident and injury prediction models where accident and injury density (UHT) are related to traffic volumes (N_i) and independent design variables (x_i):

$$UHT = a \cdot N_i^{P_i} \cdot \exp(\sum_{i=1}^{n} b_i \cdot x_i) \qquad (2)$$

where a, p_i and b_i are estimated constants. These models have a negative binomial distribution with a log-link function and are estimated using proc GENMOD in SAS version 9.2.

Accident and injury prediction models are based on two data sets. One data set is 332 sites where the design has remained unchanged during the period 2000-2011. At those sites a total of 191 accidents and 77 injuries have occurred. The other data set is 709 sites, where some 377 sites have been changed and only accidents and design recordings from the period with the longest existing design are used in the modelling. At those sites a total of 305 accidents and 140 injuries have occurred. Here data have been offset using the number of years and using weights representing the general accident and injury developments among cyclists and moped riders in Denmark in the period 2000-2011. The two offset methodologies result in almost identical models, but only models using weights are shown in this paper because these explain most of the systematic variation in accident figures. For both data sets grade-separated cycle crossings have been excluded because no accidents have been recorded at those sites.

The GENMOD procedure estimates the constants, standard errors and 95 % confidence intervals, but besides these we also calculate the models explanatory power using Elvik's index:

$$R_k^2 = 1 - \frac{k_{model}}{k_{mean}} \qquad (3)$$

where k_{model} is the dispersion parameter of the estimated accident prediction model, and k_{mean} is the dispersion parameter of the accident data for a model without any independent variables, i.e. only the mean - a constant is estimated. Elvik's index indicate how much of the systematic variation within the accident data that the model explains. Other goodness-of-fit statistics than Elvik's index such as Mean Prediction Bias, Mean Squared Prediction Error, Mean Absolute Deviation or Cure Plots have not been calculated.

Models have been developed in a "manual forward-stepwise" manner. First, 24 independent variables of which some are described in several ways are tested for their statistical relation to accident and injury density. Second, the statistical significant variable ($p \leq 0.05$) that reduces AIC (Akaike's Information Criterion) most enters the model. If two variables reduce AIC to the same extent then the variable that reduces the dispersion parameter or Elvik's index most is chosen. This second process is then repeated, and during these repetitions type 3 tests are performed in order to ensure that all variables in a model are statistical significant. If adding a variable to the model do not reduce AIC by more than 1-2 then the modelling development process is stopped. One should be careful interpreting an accident prediction model, because estimated constants do not represent causal relationships due to unrecorded accidents and missing independent variables.

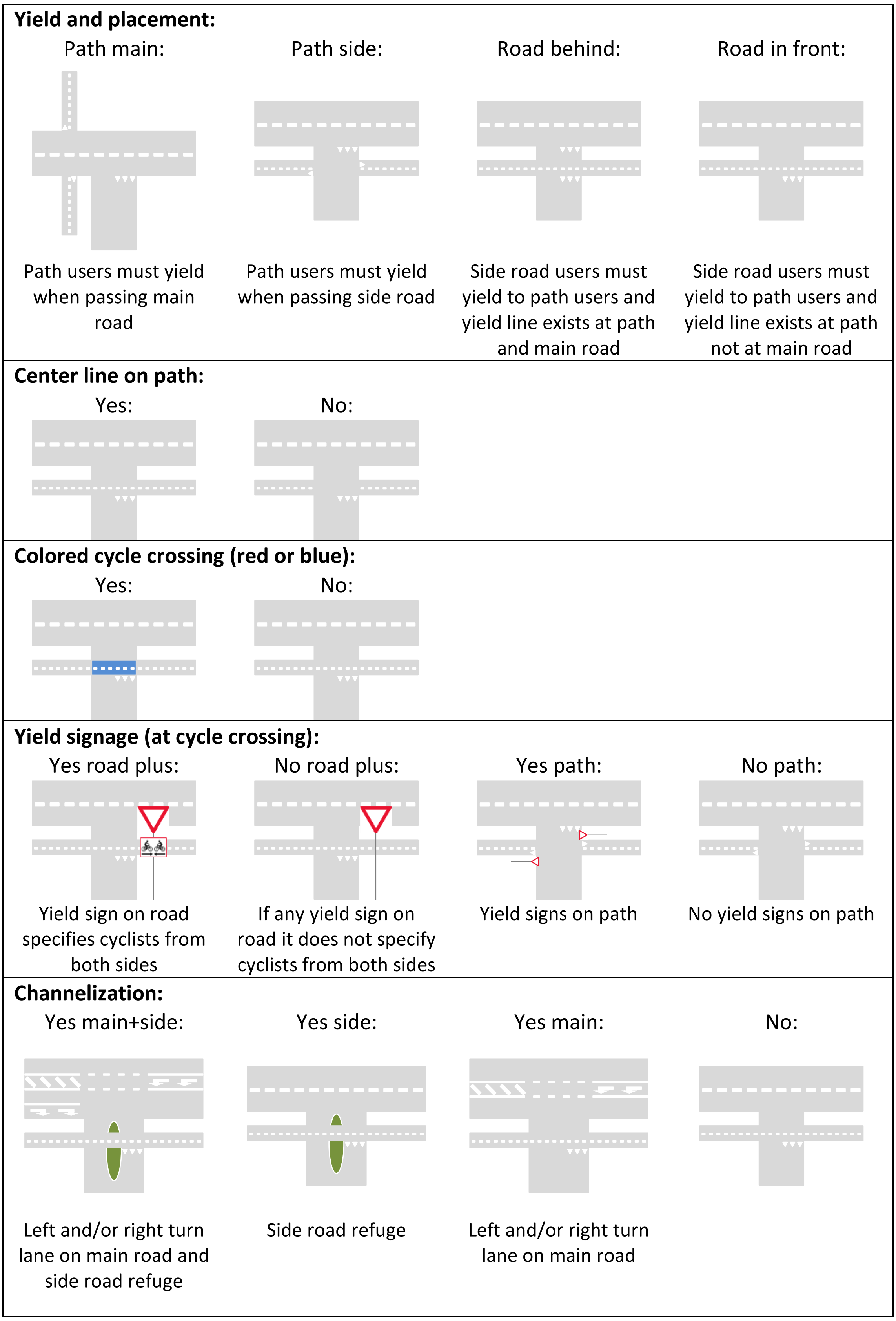
3 RESULTS

Two accident prediction models and two injury prediction models are shown in Table 1. Besides traffic volumes on the cycle path and the total number of incoming motor vehicles to the nearby intersection/roundabout, the models include five design variables. These five design variables are explained in Figure 2 on the next page.

Table 1. Accident and injury prediction models. Note: * significant on a 0.05 level.

Variable	Category	*Accidents, 332 sites*	*Accidents, 709 sites*	*Injuries, 332 sites*	*Injuries, 709 sites*
Ln(a)	-	*-5.2983**	*-5.9677**	*-3.1338**	*-4.2712**
Cycle path traffic (p_1)	-	*0.3383**	*0.3870**	*0.2331**	*0.3708**
Motor vehicle traffic (p_2)	-	*0.2740**	*0.3217**		
Yield and placement (b_1)	*Path main*	*-0.2556*	*-0.6058*	*-0.5214*	*-1.2090*
	Path side	*-0.8639*	*-0.6377*	*-0.9031*	*-1.5390**
	Road behind	*-1.0143**	*-0.7133**	*-2.2292**	*-0.9579**
	Road in front	*0.0000*	*0.0000*	*0.0000*	*0.0000*
Center line on path (b_2)	*Yes*	*0.6762**	*1.1172**	*0.7703**	*1.1673**
	No	*0.0000*	*0.0000*	*0.0000*	*0.0000*
Colored cycle crossing (b_3)	*Yes*	*0.5252**		*0.8020**	*0.5899**
	No	*0.0000*		*0.0000*	*0.0000*
Yield signage (b_4)	*Yes road plus*	*0.6867**	*0.1736*		
	Yes path				
	No road plus	*-0.1341*	*-0.8773**		
	No path				
Channelization (b_5)	*Yes main+side*				
	Yes side		*0.6830**		*1.0778**
	Yes main				
	No		*0.0000*		*0.0000*
Elvik's index		*0.66*	*0.54*	*0.77*	*0.59*

Figure 2. Illustration of five design variables that are included in the accident and injury prediction models.



A number of other variables like speed limit, zone (urban, rural), sight distances, distance between path and parallel road have been tried to relate to accident and injury densities, but these other variables are not significant. The models explain 54-77 % of the systematic variation in accident and injury figures. Each model includes the variable describing traffic volumes on cycle paths and four design variables. The two accident prediction models include the variable describing incoming motor vehicle traffic volumes at the intersections/roundabouts, whereas this variable is not part of the two injury prediction models.

A center line marked on the path in the cycle crossing increases the number of bicycle and moped accidents and injuries. Coloring of the cycle crossing also increases the number of bicycle and moped accidents and injuries. Adding a yield sign next to the path or specify bicycle traffic from both sides to the yield sign on the road increases the number of accidents with cyclists and moped riders. There have not been sufficient sites with the different types of yield signage and the different types have been mixed into two groups. At a few sites eventual yield signage was not possible to verify on Google Street View. Presence of turn lanes on the main road and/or side road refuges is also related to more bicycle and moped accidents and injuries. Where cyclists and moped riders on the path have to yield to motor vehicles on the road is found to be safer than a situation where motor vehicles have to yield to path users and there only is a yield line at the path and not a second yield line at the intersection or roundabout. Having only one yield line on the side road is typical where the path is located close to the parallel main road. Having two yield lines on the side road is safer than just having one, but at sites with two yield lines the path is typically also located further away from the main road.

Figure 3. Relative accident risk for cyclists and moped riders at six typical two-way cycle crossing designs in Denmark. Design A has a risk of 1 and the risk is increasing to 18 at design F. Based on the accident model with 332 sites.

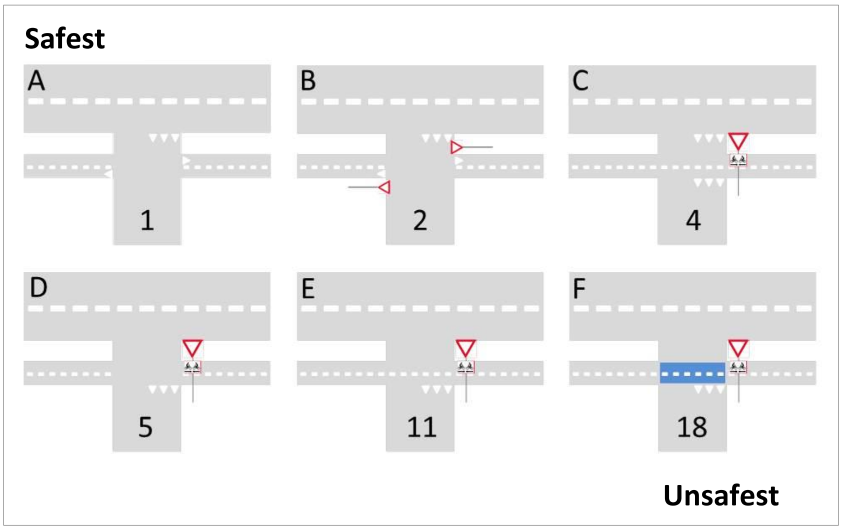


Figure 3 presents in an easy understandable way the accident prediction model based on the 332 sites that have remained unchanged for the period 2000-2011. Design F has about 18 times more bicycle and moped accidents than design A when traffic volumes on the path and the nearby intersection/roundabout are the same.

3.1 Traffic volumes

During the modeling process several variables for motor vehicle traffic volumes were tried to fit accident and injury data as best as possible. It is worth noticing that the total incoming motor vehicle traffic volumes at the nearby intersection/roundabout fits better to accident data than the motor vehicle traffic volumes crossing the path. This means that motor vehicle traffic on the main road (not entering the side road or exiting from the side road) influence safety on the cycle crossing even though these motor vehicles do not cross the cycle crossing. A possible explanation to this phenomenon is that drivers have increasing difficulty entering or exiting the side road as the traffic volume on the main road increase – and leaves those drivers with less time to interact with path users. However a doubling of motor vehicle traffic volumes only increases the number of cycle crossing accidents by 21-25 %.

The accident rates are based on the number of motor vehicles actually crossing the cycle paths and not the total number of motor vehicles in the nearby intersection. 0.09 accidents per million motor vehicles crossing the cycle path occurred at 764 sites.

Cycle paths with large traffic volumes are safer for the individual cyclist or moped rider than a path with low traffic volumes. A doubling of the cycle path traffic volume results in 26-31 % more cycle crossing accidents and 18-29 % more cycle crossing injuries. So the "Safety in numbers" phenomenon is present for path users. In total there have occurred 0.47 bicycle accidents at the crossings per million cyclists and 3.48 moped accidents per million moped riders at 764 sites.

3.2 Yield and placement

The safest solution is that the cycle path and side road is grade-separated. No cycle crossing accidents and no accidents on the cycle path have been recorded at the grade-separated solution, which is why that solution is not part of the accident and injury prediction models. The grade-separated solution must on the other hand be designed so the path users do not choose to use the roads instead of the cycle path.

As Figure 3 shows fewest accidents occur at cycle crossings in the same level as the roads when path users have to yield to motor vehicles on the side road. At cycle crossings next to roundabouts and 3-armed intersections where left turns are prohibited the safety is much better if the path users have to yield to motor vehicles on the side road. At 152 sites where path users have to yield to motor vehicles, the accident rate is 0.21 accidents per million path user. In comparison, 0.86 accidents per million path users have occurred at 539 sites where motor vehicles have to yield to path users. Measured in number of accidents per million motor vehicles crossing the cycle paths the rates are 0.01 and 0.18 respectively.

The distance between the cycle crossing and the nearby main road seems to have a considerable but different influence on safety depending on who have to yield at the cycle crossing, see Table 2 on the next page. This parameter was not used in the model due to lack of significance probably because of opposing tendencies depending on the "Yield and Placement" variable. Table 2 presents the calculated accident rates instead.

Table 2. Number of cycle crossing accidents per million path users depending on distance between cycle crossing and main road and who have to yield at cycle crossings. Based on 676 sites and 309 accidents.

Distance between cycle crossing and main road	*Path users have to yield to motor vehicles on side roads*	*Motor vehicles on side roads have to yield to path users*
0-3.0 meters	*0.35*	*0.69*
3.1-6.0 meters	*0.39*	*1.08*
6.1-12.0 meters	*0.12*	*1.33*
More than 12.0 meters	*0.16*	*1.14*

When path users have to yield to motor vehicles on side roads safety is best if the distance between cycle crossing and main road is more than 6 meters. This is very different compared to the situation where motor vehicles on side roads have to yield to path users. Then safety is best if the distance between cycle crossing and main road is 3 meters or less. However when motor vehicles on side roads have to yield to path users and two yield lines are marked on the side road – one at the cycle crossing and one at the intersection/roundabout – then it is best that the distance between cycle crossing and main road is somewhat longer than a passenger car, i.e. more than 6 meters.

3.3 Marking and signage

Figure 3 and the accident and injury prediction models show that marking and signage of the cycle crossings influence safety. A center line approximately doubles the number of cycle crossing accidents, and adding blue or red colour to the cycle crossing increases the number of cycle crossing accidents by about 60 %. A possible explanation to this might be that these types of markings may increase cyclists and moped riders speed through the cycle crossing and perhaps give a false sense of safety.

Yield signs at intersections have typically given a small improvement in safety [13]. However at cycle crossings the study shows that such signs are related to a significant worsening of safety. It is unclear why it is so, but these signs are typically placed at side roads with large motor vehicle traffic volumes. At the same time the signs are more often lacking in low-speed neighbourhoods.

It is possible that the variables describing marking and signage are endogenous. In other words it could be that center lines, blue cycle crossings and/or yield signs have been applied to sites that already had high accident rates due to other circumstances.

4 CONCLUSIONS

One should be careful interpreting an accident prediction model, because estimated constants do not represent causal relationships due to unrecorded accidents and missing independent variables. It is likely that some independent variables in the presented accident prediction models are endogenous and hence estimated constants are questionable. The conclusions of the research reported in this paper can only be indicative and can be summarized as follows:

- Grade-separated cycle crossings seem to be the safest solution where a two-way cycle path, which runs parallel to a main road, crosses a side road.

- If cycle path users have to yield to motor vehicles on a side road then it seems safest to place the cycle crossing more than 6 meters from the main road. If done so then this design is the second safest solution.

- If motor vehicles on a side road have to yield to cycle path users at the cycle crossing then it seems safest to place the cycle crossing more than 6 meters from the main road when a yield line is marked on the side road both at the cycle crossing and at the nearby intersection. If only one yield line is marked then it seems safest to place the cycle crossing less than 3 meters from the main road.

- Applying centre lines, colour and/or yield signs at crossings where a two-way cycle path, which runs parallel to a main road, crosses a side road seems to significantly increase the number of bicycle and moped accidents and injuries.

The safety effects of markings and signage identified in this paper are linked to a high degree of uncertainty. It is relevant to further study crossings of two-way cycle paths and roads. More reliable safety effects could be obtained through before-after safety evaluations of applying markings and signage, especially using experimental study designs.

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