Road factors and Bicycle–Motor vehicle crashes at unsignalized priority intersections

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Road factors and bicycle–motor vehicle crashes at unsignalized priority intersections**

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Abstract
In this study, the safety of cyclists at unsignalized priority intersections within built-up areas is investigated. The study focuses on the link between the characteristics of priority intersection design and bicycle–motor vehicle (BMV) crashes. Across 540 intersections that are involved in the study, the police recorded 339 failure-to-yield crashes with cyclists in four years. These BMV crashes are classified into two types based on the movements of the involved motorists and cyclists:

- type I: through bicycle related collisions where the cyclist has right of way (i.e. bicycle on the priority road);
- type II: through motor vehicle related collisions where the motorist has right of way (i.e. motorist on the priority road).

The probability of each crash type was related to its relative flows and to independent variables using negative binomial regression. The results show that more type I crashes occur at intersections with two-way bicycle tracks, well marked, and reddish coloured bicycle crossings. Type I crashes are negatively related to the presence of raised bicycle crossings (e.g. on a speed hump) and other speed reducing measures. The accident probability is also decreased at intersections where the cycle track approaches are deflected between two and five metres away from the main carriageway. No significant relationships are found between type II crashes and road factors such as the presence of a raised median.

Keywords: Road safety; Cyclists; Bicycle crossings; Unsignalized priority intersections; Accident prediction models; Negative binomial regression

1. Introduction

Collisions between bicycles and motor vehicles have caused severe life and property losses in many countries (Wang and Nihan, 2004). The Netherlands is one of the safest countries for cyclists, as crash risks for cyclists are lower in countries with higher bicycle use. In 2007, 34% of all trips up to 7.5 km were made by bicycle (Ministry of Transport, Public Works, and Water Management, 2009). In spite of this, the numbers of traffic deaths and in-patients among cyclists are substantial in the Netherlands (over twenty per cent of all recorded traffic deaths and in-patients). The majority of bicycle–motor vehicle (BMV) crashes occur within built-up areas at unsignalized priority intersections, such as where an arterial road intersects with a local road. Over ninety-five percent of these are failure-to-yield crashes.

This study was issued by the Dutch Ministry of Transport, Public Works, and Water Management in order to develop measures for road authorities. The study is therefore focused on the link between priority intersection design characteristics and BMV crashes. As small crash numbers limit the number of variables that can be included in regression analyses, only those road features were selected for which our literature research (see Section 1.1 and 1.2) revealed that they were potentially relevant for failure-to-yield crashes with cyclists. Furthermore, only design characteristics were included, e.g. speed humps, while non-design characteristics, like speed, were excluded.

BMV crashes are classified into two types depending on who had priority (i.e. the cyclist in the case of type I crashes; the motorist in the case of type II crashes). Separate analyses are conducted for both crash types as different traffic flows and road features influence each group. For instance, the number of type I crashes is directly related to the amount of motorized traffic on the side road (i.e. the volume of motorists entering or leaving the main road) and only indirectly to the volume of motorists on the main road. Furthermore, most road features affect specific traffic flows. For instance, painting a bicycle track along the main road may have an influence on cyclists on the main road and on motorists crossing the track when entering or leaving the main road. Therefore, this road feature may be related to type I crashes while a relationship with type II crashes is less likely.

1.1 Type I crashes and road factors

In type I crashes, the cyclist rides on the priority road and is hit by a vehicle that is leaving or entering the side road. Cyclists on the arterial road have priority over vehicular traffic. An in-depth study of bicycle-car collisions in four Finnish cities showed that cyclists most often noticed the driver before the accident and believed the driver would give way as required by law. However, only a small portion of the drivers noticed the cyclist before impact (Räsäsen and Summala, 1998).

Several priority intersection design characteristics that can be linked to type I crashes have been studied in the last decades. A lot of studies focused on safety effects of bicycle facilities along arterial roads. In their meta-analysis Elvik and Vaa (2009) found a significant increase of bicycle accident numbers due to bicycle tracks at junctions. It is suggested that the crash numbers increase at junctions with bicycle tracks because of a lack of attention due to the physical separation of cyclist and motor traffic. According to Herslund and Jørgensen (2003), drivers who search the road area for possible counterparts may focus their attention on the location where cars usually are. Welleman and Dijkstra (1988) studied the risks (numbers of crashes per passing cyclist) at crossroad branches of priority intersections with different bicycle facilities for cyclists on the main road. In this study, cycle lanes were found to be most risky for cyclists. Cycle paths and mixed traffic on the carriageway did not significantly differ from each other. The risk of bicycle crashes is found to be elevated at priority intersections with two-way cycle tracks along the arterial road, as drivers entering from the side road have difficulties in detecting cyclists from the right (Räsäsen and Summala, 1998; Schnüll et al., 1992; Wachtel and Lewiston, 1994). Summala et al. (1996) studied drivers' scanning behaviour at T-intersections. Drivers turning right from the minor road scanned the right leg of the T-intersection less frequently and later than those turning left. Drivers develop a scanning strategy, which concentrates on more frequent and major dangers but ignores and may even mask visual information on less frequent dangers.

A sight obstacle makes that situation even more hazardous, because drivers cannot even detect cyclists with peripheral vision (Räsäsen et al., 1999). On the contrary, Henson and Whelan (1992) suggested that good visibility at T-junctions was associated with a greater probability of bicycle crashes when a cyclist was riding among cars. They assume that a form of 'risk compensation' operates. When visibility is poor drivers behave cautiously at the junction, counteracting the obvious danger. A wider entry width of the minor road was associated with a decreased safety of cyclists riding on the main road. The extra space may invite vehicles to queue two abreast on the minor road. A left-turning vehicle could screen a cyclist from a vehicle waiting to turn right (Henson and Whelan, 1992).

The results of studies on the effect of markings are inconsistent. The city of Portland studied the effects of blue pavement markings in combination with a "Yield to Cyclist" sign for crossings where the cyclist travels straight and the motorist crosses the bicycle lane in order to exit a roadway, or merge onto a street from a ramp. Significantly higher numbers of motorists yielded to cyclists and slowed before entering the blue pavement areas. However, the blue pavement also resulted in fewer cyclists turning their heads to scan for traffic or using hand signals (Hunter et al., 2000). Jensen (2008) studied the safety effects of blue cycle crossings at signalized intersections. The safety effect depends on the number of blue cycle crossings at the junction. One blue cycle crossing reduces the number of junction crashes by ten percent, whereas marking of two and four blue cycle crossings increases the number of crashes by twenty-three and sixty percent, respectively. Schnüll et al. (1992) did not find bicycle crashes to be affected by the type of marking at priority intersections without traffic lights. Like Gårder et al. (1998), they did show that cyclists riding on the priority road are less at risk if they use raised bicycle crossings as compared to crossings delineated by white painted rectangles. Raising a bicycle crossing leads to somewhat increased bicycle speeds, but significantly reduced motor vehicle speeds (Gårder et al., 1998). A study of cyclist safety at minor priority junctions showed, moreover, that the establishment of speed reducing exit constructions leads to a fall in the number of bicycle crashes of up to fifty percent (Herrstedt, 1979).

To conclude, two intersection design characteristics seem to reduce the complexity of the driving task when giving way to cyclists on the main road, thereby improving cyclist safety. The addition of a left-turn lane or left-turn section on the main road was found to decrease type I crashes, but this is only studied at priority intersections outside built-up areas (CROW, 2002). It enables drivers leaving the main road to slow down and stop without hindering through traffic. Schnüll et al. (1992) studied the safety effect of the distance between the cycle track and the side of the arterial road. A clearance between two and four metres at priority intersections was found to be most favourable. According to Elvik and Vaa (2009), the aim of a bent-out crossing is to give drivers turning into the side road extra time to notice crossing cyclists, and to allow vehicles waiting to exit the side road to do so without blocking the crossing point.

In this Section, several factors have been mentioned on how intersection design characteristics affect the behaviour of cyclists and motorists and thereby cyclist safety: visual scanning strategies, risk compensation, and the complexity of the driving task. Drivers' scanning strategies are primarily focused on where motorists are and to a lesser extent on where cyclist are. Therefore, problems may arise if both are physically separated by bicycle tracks. Also, the visual scanning strategy of right-turning drivers who approach the main road is concentrated on the left leg of the intersection, while they may be confronted with cyclists from the right riding along a two way cycle track. Increasing the conspicuousness of a bicycle crossing by pavement markings or raising the crossing seems to increase cyclists' speed and reduce their visual scanning, while drivers decrease their speed and improve their visual scanning (i.e. risk compensation operates). Drivers also counteract the obvious danger of a poor visibility from the minor road due to sight obstacles as long as it does not hinder an already insufficient visual scanning behaviour. To conclude, it is suggested that left-turn sections and a clearance between two and four metres between the main road and bicycle tracks decrease the complexity of the driving task in that it offers drivers turning into the side road extra time to slow down and notice cyclists.

1.2 Type II crashes and road factors

In type II crashes the cyclist crosses the priority road and is hit by a through vehicle on the main carriageway. These crashes take place at both priority intersections and single separate bicycle crossings (i.e. where a solitary cycle track crosses the priority road). Less is known about these crashes as compared to type I crashes. An in-depth study of bicycle-car collisions in four Finnish cities showed that cyclists rarely did anything to avert these crashes, while drivers often did something. As compared to type I crashes the cyclist victims were more often unfamiliar with the accident location and under eighteen years of age. For cyclists, crossing a major road is more demanding than crossing a minor road (Räsäsen and Summala, 1998). The complexity of the traffic situation seems to play a role in these crashes.

Only a limited number of studies are focused on the link between intersection design characteristics and type II crashes. Therefore, we also looked at one thorough study on pedestrian crossing safety. Zegeer et al. (2001) studied the safety effects of two road factors related to the complexity of the traffic situation for pedestrians. Road factors found to be related to the frequency of pedestrian crashes (taking the average daily pedestrian and motor vehicle volumes into account) were the number of lanes of the main carriageway and the presence of a raised median or crossing island. The Dutch Design Manual for Bicycle Traffic (CROW, 2006) provides recommendations to avoid type II crashes, but no studies were found that confirmed the underlying assumptions. Middle islands that enable cyclist to cross in two phases are recommended for busy streets. The presence of middle islands often coincides with a left-turn section or lane (in between raised medians) on the main road for left-turning drivers and cyclists crossing the artery. In Dutch research on priority intersections outside urban areas, it was found that the addition of a left-turn lane reduced the number of type II crashes (CROW, 2002). Also, three-armed priority intersections are preferred over four-armed intersections. The type of junction may also effect the risk of type I crashes. A specific type of intersection where only type II crashes occur is a single separate bicycle crossing. Zegeer et al. (2001) did not find a significant difference in pedestrian crash rate between priority intersections and mid blocks.

1.3 Bicycle accident prediction models

The average daily numbers of motor vehicles and cyclists are important predictors of bicycle crashes. According to Brüde and Larsson (1993) it may be hard to decide whether additional factors that describe the design in greater detail influence the number of crashes, as traffic flows explain the systematic variation in accident frequency to such a large extent. Brüde and

Larsson (1993) developed bicycle and pedestrian accident prediction models for intersections of the following kind:

$$E(\mu) = \alpha N_M^{\beta_1} N_C^{\beta_2}$$

where $E(\mu)$ is the predicted annual number of bicycle crashes, N_M is the average daily number of incoming motor vehicles, N_C the average daily number of passing bicyclists, and α, $\beta 1$ and $\beta 2$ are estimated parameters. Coefficients β_1 and β_2 describe the shape of the relationship between traffic volume and the number of crashes. As shown by a lot of studies either coefficient often takes on a value between about 0.3 and 0.9 (Elvik, 2009). This means that the percentage increase of the number of crashes is less than the percentage increase of traffic volume. The more cyclists there are the lower is the risk faced by each cyclist (i.e. bicycle crashes per passing cyclist). This effect is sometimes called “safety in numbers”. Jensen (2008) used the above described accident prediction model to correct for changes in traffic volumes at treated junctions and a comparison group in a before-after accident study.

The above described model can be extended to the basic form of nearly all modern accident prediction models (Eenink et al., 2008):

$$E(\mu) = \alpha N_M^{\beta_1} N_C^{\beta_2} e^{\sum y_i x_i}$$

The estimated number of crashes, $E(\mu)$, is a function of traffic volumes and a set of risk factors, x_i (i = 1, 2, 3, …, n), i.e. the road factors under investigation. The effects of various risk factors that influence the probability of crashes, given exposure, is modelled as an exponential function, that is as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i, and values of the variables, x_i, denoting the presence of road factors. Poisson and negative binomial (NB) regression are suitable to estimate the model’s parameters. Poisson and NB models serve as statistical approximations to the crash process (Lord et al., 2005). The central assumptions underlying the Poisson distribution are independency of events and equality of mean and variance. The latter requirement is often violated due to overdispersion, i.e. the variance exceeds the mean.

To correct for the overdispersion problem for the Poisson model, Wedderburn (1974) suggested that one could inflate the variance μ_i to $\tau \mu_i$ where τ is referred to as ‘overdispersion parameter’ (and $\tau \geq 1$). It was also suggested that the overdispersion parameter τ could be estimated by $\chi^2/(n - k)$, where χ^2 is the Pearson’s chi-square statistic, n is the number of observations (i.e. the number of intersections), and k is the number of unknown regression parameters in the Poisson model. Miaou (1994) suggests that NB regression is used if the overdispersion of accident data is found to be moderate or high (e.g. when the overdispersion parameter exceeds 1.3).

2. Method

The present study uses a correlational design to study whether BMV crashes are related to intersection design characteristics. A problem in accident studies is the preponderance of “excess” zeros frequently observed in crash count data, i.e. many intersections without crashes in a given period of time. Lord et al. (2005) have shown that this arises from low exposure and/or inappropriate selection of time/space scales. The selection of intersections was based on the volumes of cyclist and motor vehicle traffic to limit this problem. Non-signalized intersections where the major road had a speed limit of 50km/h were selected if they were high on either or both of these volumes. Seven municipalities were contacted before the study to determine main cycle routes and busy arterial roads (ADT around 8,000 and higher). Half of the priority intersections were selected because they were part of a main cycle route and half because they were part of a busy arterial road. We considered a study period of four years (2005 through 2008) to be of adequate length to gather enough recorded crashes without running a high risk of changes in the infrastructure after 2005. Municipalities were contacted to ask which intersections were reconstructed in the study period so that these could be excluded.

Estimates of daily cyclist and motor vehicle volumes at each intersection were determined by volume counts in the second half of 2009, which were expanded to estimate daily volume counts based on hourly adjustment factors derived from the Dutch Mobility Study (survey on the travel behaviour of the Dutch population; SWOV 2009). Like in Henson and Whelan's (1992) study, counts were conducted for twenty minutes in the off-peak period and outside school vacation periods. Like in Wang and Nihan's study we distinguished different movements to relate each accident type to its relative flows. This means through cyclist traffic on the main road and motorized vehicles entering or leaving the major road for type I crashes, and through motorized traffic on the main carriageway and cyclists crossing the major road for type II crashes.

In this study, NB regression was used to examine the relationship between the number of crashes per intersection and the independent variables (see also section 3.1). The regression coefficients were estimated based on maximum likelihood estimation using Generalized Linear Models in SPSS. The significance of coefficients was checked using the method analogical to the t-test used in conventional regression analyses referred to as the Wald test (Agresti, 1996). The Wald test is a method by which the square of the ratio of a parameter estimate to its standard error is computed and tested with one degree of freedom to test the hypothesis that a certain parameter y_i, is zero. The following intersection design characteristics were selected to study type I crashes:

- type of bicycle facility: cycle lane, one-way bicycle path, two-way bicycle path, or no bicycle facility (i.e. cyclists mixed with other traffic);
- distance between the bicycle track and the side of the main carriageway: 0-2m, 2-5m, over 5m;
- visibility from the minor road: unrestricted view over 100m or more at 2m before the main road or it's adjacent cycle path, or restricted (i.e. worse visibility);
- marking and use of colours:
  - colour: reddish coloured crossing, or else;
  - quality of (other) markings (white painted rectangles to delineate cycle tracks; or white stripes or continuous lines to delineate cycle lanes): well-visible; hardly visible, or no marking;
- presence of a speed reducing measure for motorists that enter or leave the priority road (e.g. a raised bicycle crossing);
- number of lanes of the side road (i.e. entry width);
- presence of a left-turn lane or left-turn section on the main road;
- type of intersection: three-armed, or four-armed.

The following intersection design characteristics were selected to study type II crashes:

- number of lanes of the main road;
- presence of middle islands:
  - no raised middle islands;
  - raised middle islands that enclose a left-turn section, i.e. cyclist are enabled to cross the main road in two phases and share the space with left-turning motorists;
  - raised middle islands with a separate space for cyclists;
- presence of speed-reducing measures for through motor vehicles on the main road, e.g. speed humps;
- type of intersection: four-armed, three-armed, or single separate bicycle crossings (i.e. where a solitary cycle track crossed the priority road).

Examples are included in figure 1 and 2 to clarify the above-mentioned design characteristics.

Figure 1 Example of a well-marked, reddish coloured, raised bicycle crossing for through cyclists on a one-way cycle track with a distance of over five meters from the priority road; a raised middle island with a separate space for cyclists crossing the two-lane priority road**.**

Figure 2 Example of a reddish coloured bicycle lane for through cyclists; exit constructions at minor roads; raised middle islands that enclose a left-turn section for both cars and cyclists crossing the two-lane priority road**.**

The first two variables for type II crashes are combined into six categories as their effects may interact. BMV crash data in the Dutch National Road Crash Register are aggregated at the intersection level and without further classification into our two accident types. Consequently, we had to conduct additional data collection work to satisfy our specific study requirements. With the index numbers of the crashes at the priority intersections in our selection, we called up the original police records that include a brief description of the accident, and, in many cases, a collision site figure. This enabled us to assign crashes to one of the two accident types.

3. Results

In total, 540 priority intersections were included in this study, of which 490 were susceptible to type I crashes (type I crashes, by definition, cannot happen at single separate bicycle crossings) and 524 to type II crashes (i.e. type II crashes cannot happen at three-armed junctions with one two-way cycle path that crosses the side road, and at intersections where crossing the main road is forbidden). The figures are presented in Table 1. Type I crashes, where the cyclist has right of way, happen more often than type II crashes, where the driver has priority. However cyclists run a relatively higher risk of type II crashes per passing cyclist.

Crash Type	Number of inter-sections	Crash numbers 2005-2008	Crash variance	Number of intersections with # number of accidents										Average daily number of motorized vehicles[1]	Average daily number of cyclists[2]	Risk (per million passing cyclists)
				0	1	2	3	4	5	6	7	8	9			
I	490	183	0.66	371	78	27	10	2		1	1			2.200	1.500	0.17
II	524	156	0.65	417	82	16	5	1		1		1	1	7.000	850	0.24

[1] motorized vehicles entering or leaving the main road for type I crashes; through motorized traffic on the main carriageway for type II crashes
[2] through cyclist traffic on the main road for type I crashes; cyclists crossing the main carriageway for type II crashes

Table 1 Numbers of intersections, crashes, traffic volumes, and risks..

3.1 Type of analysis: Poisson or NB regression

When using Poisson regression, the variances of the estimated parameters are underestimated in case of overdispersion, resulting in invalid hypothesis testing. The overdispersion parameters (τ, estimated as described in section 1.3) were 1.50 for Type I and 1.44 for Type II crashes respectively, which indicates overdispersion (Miaou, 1994). The NB model seems to be a suitable alternative as it explicitly models overdispersion. To more formally test the appropriateness of the Poisson model against the NB alternative, we used the Likelihood Ratio test (LR test). The equality of mean and variance of the Poisson assumption is tested against the NB-alternative that explicitly models overdispersion. Given that the variance of the NB model alternative is equal to ($\mu + q\mu^2$), the NB model reduces to the Poisson model when q = 0 (i.e. H_0: q=0; H_1: q>0). The test statistic is given by: $LR = -2(L_r - L_u)$ where L_r is the log likelihood gained from the Poisson model, and L_u is the log likelihood from the NB model. The statistic is chi-square distributed with one degree of freedom (Irvine, 2004). The LR was 14.8 for type I crashes and 35.0 for type II crashes. Due to these very high LR values the Poisson null hypothesis of no overdispersion is rejected in both cases. Akaike's information criterion (AIC) also improves when explicitly modelling overdispersion using NB-regression. It is reduced from 722 to 708 for type I crashes and from 700 to 665 for type II crashes. To conclude, NB regression was chosen as the data exhibit overdispersion.

3.2 Results for type I crashes

Eight independent variables are selected for the type I accident risk model, using the total number of type I crashes per intersection between 2005 and 2008 as the dependent variable. The estimated regression coefficients and their significance levels shown by Wald statistics and corresponding *P*-values are presented in Table 2. For traffic volumes, positive coefficients indicate positive relationships with accident numbers. For intersection design characteristics, a factor level with a greater coefficient indicates a greater probability of crashes. The sign of a coefficient for a factor level is dependent upon that factor level's effect relative to the reference category. The exponential of the regression coefficient for categorical variables is included in the table as it is interpretable as relative risk (i.e. relative to the reference category). Ratios greater than one indicate that the presence of the characteristic in question increases the probability of an accident.

Besides traffic volumes, four road factors are significantly related to type I crashes (at the five percent level). The use of a red colour and high quality markings to delineate bicycle crossings are positively related to type I crashes while speed-reducing measures for vehicles entering or leaving the side road are negatively related to type I crashes. The type of bicycle facility and its clearance from the main road is also related to type I crashes. Significantly fewer crashes occur at intersections where the cycle path approaches are deflected two to five meters away from the main carriageway. The accident probability is almost the same for cycle lanes and cycle paths with a distance between the track and the side of the main road under two metres. More type I crashes occur at intersections with two-way cycle tracks. No significant link was found between visibility from the minor road, type of intersection and type I crashes. The number of intersections where the main road has no bicycle facility was too low to distinguish ‘no bicycle facility’ as a separate category in Table 2. This category was combined with cycle lanes because both lack a physical separation between cyclists and motorists. The category of cycle lanes is treated separately in Table 3, where shared roadways are excluded.

The use of colour and high quality markings seem to have an adverse effect on safety. An additional analysis was conducted to differentiate between cycle tracks and cycle lanes as the type of marking and layout are different (see for instance figure 1 and 2). The results are shown in Table 3. The directions of the effects are similar to those shown in Table 2. The use of red colour and high quality markings are related to an increase of type I crashes. However, the effect size is greater for cycle tracks than for cycle lanes and greater for the use of well visible markings than for the use of colour. Only the relationship between the use of well visible markings on bicycle tracks and type I crashes is significant.

Parameter	Number of intersections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.43 (-12.21 to -6.65)		44.22	<0.001
Volume of motorized vehicles entering or leaving the major road		0.73 (0.50 to 0.96)		38.30	<0.001
Volume of through cyclists		0.48 (0.24 to 0.73)		13.56	<0.001
Two-way versus one-way cycle track					
one-way cycle path or other provision	423	0 (reference)	1 (reference)		
two-way cycle path	67	0.56 (0.01 to 1.11)	1.75 (1.01 to 3.03)	4.00	0.046
Distance between the bicycle facility and the side of the main carriageway					
cycle lane or no cycle facility	232	0 (reference)	1 (reference)		
cycle track 0-2m	43	0.03 (-0.69 to 0.74)	1.03 (0.50 to 2.10)	0.01	0.944
cycle track 2-5m	127	-0.61 (-1.20 to -0.01)	0.55 (0.30 to 0.99)	4.01	0.045
cycle track over 5m	88	-0.07 (-0.71 to 0.57)	0.93 (0.49 to 1.76)	0.05	0.823
Use of a red colour and quality of markings for bicycle crossings					
none	137	0 (reference)	1 (reference)		
red colour	190	0.38 (-0.16 to 0.93)	1.47 (0.85 to 2.52)	1.93	0.165
high quality markings	80	0.55 (-0.13 to 1.24)	1.74 (0.88 to 3.45)	2.52	0.112
red colour and high quality marking	83	0.93 (0.33 to 1.53)	2.53 (1.39 to 4.60)	9.16	<0.01
Raised bicycle crossing or other speed reducing measure for vehicles entering or leaving the side road					
not present	277	0 (reference)	1 (reference)		
present	213	-0.70 (-1.15 to -0.26)	0.49 (0.32 to 0.77)	9.49	<0.01
Visibility from the minor road					
good	341	0 (reference)	1 (reference)		
restricted	115	0.32 (-0.15 to 0.78)	1.37 (0.86 to 2.19)	1.75	0.186
bad	34	-0.62 (-1.78 to 0.54)	0.54 (0.17 to 1.72)	1.09	0.297
Number of lanes of the side road					
one	22	0 (reference)	1 (reference)		
two	456	-0.89 (-1.84 to 0.06)	0.41 (0.16 to 1.07)	3.35	0.067
three	12	-0.76 (-2.21 to 0.68)	0.47 (0.11 to 1.98)	1.07	0.300
Left-turn lane or left-turn section on the main road					
not present	341	0 (reference)	1 (reference)		
present	149	0.11 (-0.33 to 0.56)	1.12 (0.72 to 1.74)	0.26	0.612
Type of intersection					
three-armed	314	0 (reference)	1 (reference)		
four-armed	176	-0.16 (-0.58 to 0.26)	0.56 (0.46 to 0.85)	0.56	1.295

Table 2 Estimation results for the type I accident risk model (Log likelihood is -337.55).

Parameter	Number of intersections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.63 (-12.63 to -6.62)		39.40	<0.001
Volume of motorized vehicles entering or leaving the major road		0.70 (0.47 to 0.94)		33.89	<0.001
Volume of through cyclists		0.44 (0.17 to 0.71)		10.40	<0.01
Type of bicycle facility					
cycle lane	193	0 (reference)	1 (reference)		
cycle path	258	-0.43 (-1.27 to 0.41)	0.65 (0.28 to 1.51)	1.01	0.315
Use of red pavement					
none	179	0 (reference)	1 (reference)		
reddish coloured cycle lane	131	0.28 (-0.41 to 0.97)	1.32 (0.66 to 2.64)	0.63	0.428
reddish coloured cycle path	141	0.27 (-0.32 to 0.85)	1.30 (0.73 to 2.34)	0.79	0.375
Use of markings for cycle tracks and cycle lanes					
no or low quality markings	292	0 (reference)	1 (reference)		
well visible markings on cycle lanes	31	0.46 (-0.29 to 1.21)	1.58 (0.75 to 3.37)	1.43	0.232
well visible markings on cycle tracks	128	0.76 (0.16 to 1.35)	2.13 (1.17 to 3.86)	6.19	0.013

Table 3 Estimation results for the type I accident risk model in relation to markings on cycle tracks and cycle lanes (Log likelihood is -329.33).

3.3 Results for type II crashes

Five independent variables are included in the type II accident risk model, using the number of type II crashes per intersection between 2005 and 2008 as the dependent variable. The results are shown in Table 4. Traffic volumes are significant predictors of type II crashes. No significant relationships were found between type II crashes and intersection design characteristics.

Given the small number of intersections with middle islands, we put together the two categories of middle islands. The analysis was repeated with four in stead of six categories (main roads with two, respectively, more than two lanes were still treated separately). Again, none of the results except the relationships between volumes and type II crashes, were found to be statistically significant. The signs of the parameters for middle islands did not change, i.e. intersections of two-lane main roads with middle islands were found to have a (non-significant) higher probability of type II crashes as compared to intersections without middle islands (Wald $\chi^2(1, 523)=2.53$; $P=0.11$). Like in Table 4, the relationship was reversed for intersections of main roads with more than two lanes (Wald $\chi^2(1, 523)=1.03$; $P=0.31$).

Parameter	Number of intersections	Regression parameter (95% Wald CI)	Exponential of the regression parameters (95% CI)	Wald χ^2	*P*-value
Constant		-9.48 (-12.52 to -6.43)		37.16	<0.001
Volume of through motorized vehicles		0.50 (0.20 to 0.79)		10.85	<0.001
Volume of cyclists crossing the major road		0.56 (0.36 to 0.76)		29.15	<0.001
Speed reducing measure for through motorized vehicles on the priority road					
not present	438	0 (reference)	1 (reference)		
speed hump or other measure	86	0.24 (-0.28 to 0.77)	1.28 (0.76 to 2.16)	0.83	0.361
Raised median and number of lanes of the priority road					
two lanes; no raised median	238	0 (reference)	1 (reference)		
two lanes; middle islands that enclose a left-turn section for both cars and cyclists	110	0.39 (-0.12 to 0.91)	1.48 (0.89 to 2.47)	2.24	0.134
two lanes; raised middle islands with a separate space for cyclists	83	0.36 (-0.28 to 0.99)	1.43 (0.76 to 2.70)	1.23	0.267
more than two lanes; no raised median	45	0.51 (-0.22 to 1.24)	1.67 (0.80 to 3.45)	1.89	0.169
more than two lanes; middle islands that enclose a left-turn section for both cars and cyclists	17	-0.04 (-1.16 to 1.09)	0.96 (0.31 to 2.96)	0.00	0.948
more than two lanes; raised middle islands with a separate space for cyclists	31	0.09 (-0.70 to 0.89)	1.10 (0.50 to 2.43)	0.05	0.815
Type of intersection					
single separate bicycle crossing	47	0 (reference)	1 (reference)		
four-armed intersection	175	0.25 (-0.52 to 1.02)	1.28 (0.59 to 2.78)	0.40	0.528
three-armed intersection	302	-0.19 (-0.95 to 0.58)	0.83 (0.39 to 1.78)	0.23	0.635

Table 4 Estimation results for the type II accident risk model (Log likelihood is -326.36).

4. Discussion

Several findings of this study are useful for the development of countermeasures to prevent type I crashes with through bicyclists on priority roads crossing a minor road at a non-signalized intersection within a built-up urban area. The most effective measure to improve the safety of cyclists is the use of speed-reducing measures for drivers leaving or entering the main road (e.g. a raised bicycle path and/or exit construction). It is suitable in most cases as it does not require additional space in contrast to the construction of a bicycle path or an increase of the clearance between a bicycle track and the side of the priority road. A one-way bicycle path with a clearance between two and five metres is safer than a cycle lane. Marking bicycle crossings with red coloured pavement or white rectangles seems to have an adverse effect of the safety of cyclists, particularly in the case of cycle tracks. Cyclists seem more at risk at intersections with two-way bicycle paths as compared to intersections with other facilities. In choosing between one-way and two-way cycle tracks practitioners have to take possible effects on the itinerary level into account. The advantage of one-way cycle tracks along an artery may be diminished if a large share of all cyclists has to make a detour by crossing the priority road two times or even chooses to ride against traffic at the left side of the main road. None of the investigated road factors showed a statistically significant correlation with type II crashes with cyclists crossing the main road. This may be partly due to small sample sizes and type II crash numbers but most effect sizes were also smaller for the type II accident prediction model as compared to the type I accident prediction model.

4.1 Bicycle crashes and traffic volumes

The coefficients of the accident prediction models (β_1 and β_2) were in the same range as reported by other researchers (i.e. between 0.3 and 0.9; Elvik and Vaa, 2009) and there were interesting differences between the models for type I and type II crashes. In the accident prediction model for type I crashes, the coefficient for the volume of motorized vehicles is higher than the coefficient for the volume of bicycles. A growth of x percent in motorized traffic entering or leaving the side road leads to a greater rise of type I crashes than an increase of x percent in through cyclist traffic. For type II crashes it is the other way around, although the difference is small and non-significant in this case. The relationship (i.e. the size of the coefficients) may be dependent on which party has to give priority to whom. Cyclists have priority over motorists in type I crashes; in the case of type II crashes it is the other way around. The party who has to give priority (often called the 'secondary direction' in the literature on Accident Prediction Models) seems to adapt his or her behaviour the most to the number of counterparts, i.e. the parameter for the secondary direction is higher than for the primary direction. On the contrary the parameter for the primary direction is often found to be the highest in other studies, although the results are inconsistent for unsignalized intersections (e.g. Reurings, et al., 2005).

4.2 Road factors and type I crashes

The findings on type I crashes are discussed in terms of visual scanning strategies, risk compensation, and the complexity of the driving task. We found that priority intersections with one-way cycle paths have the same or even less bicycle crashes than intersections with other or no bicycle facilities, while other researchers concluded that cycle tracks increase the number of cycle crashes at junctions (Elvik and Vaa, 2009). The difference may result from several causes. It is assumed that cycle tracks are less safe than cycle lanes because drivers' scanning strategies are primarily focused on where motorists are and thus less on physically separated bicycle tracks (Herslund and Jørgensen, 2003). Our study is conducted in the Netherlands, one of the countries with the highest level of cycling where most adults have grown up riding a bicycle. Drivers in countries with high levels of cycling may adapt their scanning routines. This may partly explain the "safety in numbers" effect, i.e. the risk faced by each cyclist declines as the number of cyclists increases (Elvik, 2009). Another explanation is methodological in that we have controlled for the volumes of motorists and cyclists. Most of the studies that Elvik and Vaa (2009) used in their meta-analysis have not controlled for the number of cyclists, i.e. the results refer to changes in the total numbers of crashes after cycle tracks were installed. Like us, Welleman and Dijkstra (1988) did control for the cyclist volumes and found that priority intersections with bicycle paths improved the safety of bicyclists as compared to intersections with bicycle lanes. Welleman and Dijkstra's study was also conducted in the Netherlands. Their results may be due to the high level of cycling in the Netherlands as well.

Two-way bicycle crossings decrease cyclist safety at unsignalized priority intersections. This is due to the visual scanning strategy of right-turning drivers from the minor road who scan the right leg of the T-intersection less frequently and later than those turning left (Summala et al., 1996). The visual scanning problem of right-turning drivers was recently confirmed by a study on visual scanning behaviour in Groningen, a Dutch city with an above average level of cycling (Van Haeften, 2010).

Like other researchers (e.g. Gårder et al., 1998; Herrstedt, 1979; Schnüll et al., 1992) we found that raised bicycle crossings and other speed-reducing measures are effective in reducing the number of bicycle crashes at priority intersections, while red coloured pavement and other markings seemed to deteriorate the safety of cyclists. In general, these road features seem to increase cyclists' speed and reduce their visual scanning, while drivers decrease their speed and improve their visual scanning (Hunter et al., 2000; Gårder, et al., 1998). A possible explanation for our results is that both marked crossings and raised bicycle crossings have an effect on cyclists' behaviour, while raised bicycle crossings have the largest effect on drivers' behaviour. This hypothesis could be tested in future research by comparing cyclists' and drivers' viewing behaviour and speed between crossings that are, or are not, raised, and that have pavement markings of varying quality.

We confirmed the finding by Schnüll et al. (1992) that a distance between the cycle track and the side of the arterial road between two and five metres is safest for cyclists. This distance may decrease the complexity of the driving task in that it offers drivers turning into the side road extra time to notice cyclists (Elvik and Vaa, 2009). A larger clearance may also prevent severe crashes with right-turning trucks. Niewöhner and Berg (2005) recommended to redirect bicycle paths away from the middle of the junction to keep cyclists out of the blind spot on the passenger side of trucks. Their findings seem to point in the same direction as ours.

4.2 Road factors and type II crashes

No significant relationships were found between type II crashes and the investigated intersection design characteristics. The amount of research and understanding of these crashes is limited compared to type I crashes. On the one hand the complexity of the traffic situation seems to play a role as was suggested by Räsänen and Summala (1998). At intersections where the main road has three or more lanes, less type II crashes occur if there are raised middle islands. The difference is not significant, but the sign of the effect has a plausible direction in accordance with our expectation. Enabling cyclists to cross in two phases might lower the demands and increase safety for roads with more than two lanes. On the other hand our findings suggest that 'risk compensation' or underestimation of the crossing task by cyclists plays a role as well. Raised middle islands seem to have an adverse effect on safety at intersections of two-lane roads, although this difference is not significant either. Another indication that risk compensation of cyclists might play a role is the relationship between type II crashes and the intensity of motorized traffic. The number of crashes rises less than proportionally to the numbers of motorized vehicles on the main road. Cyclists seem to be able to compensate to a certain extent for the increased demands of elevated traffic volumes on arterial roads.

4.3 Recommendations for practitioners

Two things should be taken into account by practitioners when applying the outcomes of this study. In the first place, the outcomes concern the intersection level, while decisions between one-way and two-way cycle tracks should be based on the effect on the itinerary level as well. The same applies to the choice between cycle tracks and cycle lanes, as the latter bicycle facility is more prone to crashes on road links (Welleman and Dijkstra, 1988). In the second place, this study is focused on bicycle crashes. Practitioners have to take all crashes into account. Of particular importance is the question of whether mopeds (with a maximum speed limit of 45 km/h in the Netherlands) are allowed to use cycle tracks as Welleman and Dijkstra (1988) found that bicycle paths have the highest moped crash rate. We expect that raised bicycle crossings have a positive safety effect for all road users due to the decreased speed of motorists. For instance, Gårder, et al. 1998 found a decreased number of pedestrian crashes. We have not found other relevant studies on the overall safety effects of unsignalized priority intersection design characteristics.

4.4 Recommendations for further research

We focused on the links between bicycle crashes and road factors. Intersection design characteristics may also influence accident severity, especially speed reducing measures. About eighteen percent of both type I and type II accident victims were hospitalised or killed in the crash. Crashes seemed to be less severe at intersections with speed-reducing measures. The number of deaths and in-patients were too small to include severity in the analyses. Further research could focus on the link between road features and crash severity. Also, a finer crash typology can be used in further research. However, distinguishing more crash types results in even fewer crashes per intersection. Possibly, different research approaches, like Zegeer et al.'s (2001) design where the rare crash sites were selected beforehand and augmented by near control sites, will be necessary for carrying out valid analyses on infrequent crash types. Given the ageing of the population, it would for instance be interesting to study how intersection design characteristics affect the risk of left-turning crashes in which older cyclists are often involved (Goldenbeld, 1992).

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