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Published in:
Transportation Research. Part F: Traffic Psychology and Behaviour

DOI (link to publication from Publisher):
10.1016/j.trf.2016.05.008

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Madsen, T. K. O., & Lahrmann, H. S. (2017). Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies. *Transportation Research. Part F: Traffic Psychology and Behaviour*, *46*(Part B), 438-450. https://doi.org/10.1016/j.trf.2016.05.008

Transportation Research Part F 46 (2017) 438–450

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 3 April 2016
Accepted 3 May 2016
Available online 30 June 2016

Keywords:
Cyclist
Bicycle facility
Road design
Signalized intersection
Traffic conflict
Relative risk

ABSTRACT

The purpose of this study is to compare the safety of cyclists in five bicycle facility layouts in signalized intersections at various traffic volumes in order to assess if some layouts are better than others with regards to cyclist safety and to develop methods to facilitate this comparison. The five layouts included two full-length bicycle tracks with and without separate right-turning lane, two truncated bicycle tracks – one in which cyclists and right-turning vehicles merge in the right-turning lane, one continued into a narrow bicycle lane – and a recessed bicycle track. Using two different definitions of traffic conflicts the safety of cyclists in each layout is calculated as the risk of a cyclist being involved in a conflict with left- and right-turning vehicles at low, medium and high vehicle volumes, respectively. In total, around 35,500 left-turning vehicles, 38,000 right-turning vehicles and 16,000 cyclists going straight ahead were observed, resulting in 12 left-hook and 25 right-hook traffic conflicts for the reaction-based indicator and 25 left-hook and 80 right-hook traffic conflicts for the time-based indicator. The results show that regardless of which of the two conflict indicators were used, the number of conflicts was too small to make firm conclusions about which layout is safest for cyclists at various traffic volumes, although the study was based on 80 h of video recordings from each of the five intersections. However, a recessed bicycle track seems to be safer than the other geometric layouts. In order to facilitate the detection of conflicts, we developed watchdog video analysis software to reduce the amount of video. This software compressed 400 h of video into 64 h, i.e. 16% of its original length. The use of this software is particularly important to provide enough conflicts for an analysis if even larger traffic conflict studies should be carried out.

1. Introduction

In some countries and in particular in some cities, cycling is a frequently used mode of transportation. For instance, in Copenhagen and Amsterdam the bicycle share is higher than 30% (DTU Transport, 2014). However, travelling relatively unprotected, cyclists run a high risk if they are involved in accidents. In 2014, more than 2000 cyclist fatalities were registered in Europe (European Commission, 2015).

Bicycle facilities such as bicycle tracks (separated from the road with curbs) and bicycle lanes (separated from the road with painted lines) have frequently been constructed in Denmark as a means of improving the safety of cyclists and the sense of security to promote cycling. However, studies have shown that bicycle tracks do not improve the safety of cyclists.

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http://dx.doi.org/10.1016/j.trf.2016.05.008
1369-8478/

Although the number of bicycle accidents decreases on road sections with bicycle tracks, more accidents occur in intersections (Agerholm, Caspersen, Madsen, & Lahrmann, 2006; Bach, Rosbach, & Jørgensen, 1985; Gårder, Leden, & Thedéen, 1994; Jensen, 2006; Jørgensen & Rabani, 1969; Linderholm, 1992; Wegman & Dijkstra, 1988). The increase is composed of a higher amount of turning accidents compared to intersections without bicycle tracks (Jensen, 2006; Jørgensen & Rabani, 1969) and is particularly high in signalized intersections (Jensen, 2006). Bicycle lanes are less safe for cyclists on road sections compared to both bicycle tracks and no bicycle facility, but the bicycle lanes seem to have no influence on the number of injured cyclists in intersections compared to no bicycle facility (Nielsen, Andersen, & Lei, 1996; Wegman & Dijkstra, 1988). However, Jensen (2006) found an increase (statistically insignificant) in the number of injured cyclists and moped riders in intersections as well as on road sections after the construction of bicycle lanes.

The differences in the safety effects of bicycle tracks and bicycle lanes suggest that, although bicycle facilities result in more accidents involving cyclists in intersections, some layouts may be safer than others. Previous studies have primarily compared various geometric layouts of bicycle facilities in signalized intersections under the assumption that the best layout is safer for cyclists independently of the traffic volume and thus compared layouts with different traffic volumes by controlling for these differences (see e.g. Buch & Jensen, 2012; Herrstedt, 1979). So far, only a few studies have assessed the risk of cyclists for different bicycle facilities using varying traffic volumes, an example is Linderholm (1992). However, it has been indicated that the best layout of bicycle facilities depends on the traffic volume in the intersection (Vejregelrådet, 2010). Though, it is still unknown at which traffic volume the various bicycle facilities should be used in order to construct cycling crossings that are as safe as possible. The purpose of this study is to compare the safety of cyclists for commonly used Danish bicycle facility layouts in signalized intersections to assess which layout is better at various traffic volumes and to develop methods to facilitate this comparison. The study is carried out as a traffic conflict study based on video recordings from five intersection arms with different designs of bicycle tracks.

2. Background

Various studies have evaluated the safety effects of different geometric layouts (illustrated in Fig. 1) in signalized intersections to assess which layout is safest for the cyclists. Based on comparisons of the safety of bicycle tracks and lanes in intersections, the suggestion was terminating the bicycle track 20–30 m before the intersection and force the road users to drive closer to each other to improve the visibility of the cyclist (Herrstedt, 1979). Two layouts were tested against a full-length bicycle track for the remaining section leading up to the intersection from where the bicycle track was

Fig. 1. Different geometric layouts of bicycle facilities. Image of rumble stripes: Google.

terminated: (1) Truncated bicycle track followed by a right-turning lane in which cyclists merged with the right-turning vehicles. There was no difference in the number of cyclist accidents, while moped riders experienced significantly fewer right-hook and left-hook accidents (turning vehicle against straight-going road user) compared to a full-length bicycle track (Herrstedt, 1979) and (2) Truncated bicycle track followed by a narrow bicycle lane and markings of the lane inside the intersection with dotted stripes or as a blue lane. The conclusion was that the safety of cyclists had improved but that the markings inside the intersection did not influence the road user behaviour (Herrstedt et al., 1994). A later study of blue bicycle markings in signalized intersections showed that blue markings reduce the number of accidents and injuries in cases where only one crossing of a four-armed intersection is marked (Jensen, 2008). However, blue markings should be used sparsely as they tend to attract too much focus to the pavement and crossing cyclists at the expense of other road users and traffic lights, thus resulting in more rear-end collisions and red light running accidents when two or four crossings are blue (Jensen, 2008). A simulator study of the effect on the frequency of traffic conflicts shows that dotted bicycle markings and green bicycle markings reduce the occurrence of traffic conflicts (Hurwitz, Jannat, Warner, Monsere, & Razmpa, 2015).

Rumble stripes on the right side of the bicycle lane, forcing cyclists to drive closer to the vehicles, seem to improve the safety of cyclists by reducing the number of right-hook accidents (Jensen & Nielsen, 1999; Nielsen, 1994b). In addition to the rumble stripes, the stop line was moved five metres further back from the intersection to increase the visibility of the cyclists to particularly right-turning vehicles when both have stopped for red light. However, studies of staggered stop lines yield to different conclusions. Linderholm (1992) and Herrstedt et al. (1994) conclude that staggered stop lines improve the safety of cyclists in signalized intersections. Similarly, advanced stop lines, i.e. a bike box placed in front of the staggered stop line, improve the safety of cyclists (Dill, Monsere, & McNeil, 2012; Linderholm, 1992; Weigand, 2008). Buch and Jensen (2012) found that the effect of the staggered stop lines depends on the number of lanes and the type of lane before the intersection. If the intersection had one or two lanes, fewer accidents than expected occurred, while more accidents than expected occurred in intersections with three or more lanes. Separate right-turning lanes resulted in a limited impact of staggered stop lines on the number of right-hook accidents, whereas shared lanes for straight-going and right-turning vehicles caused the number of accidents to increase significantly.

Separated bicycle crossings, in which the bicycle track is recessed from the parallel road in the intersection, can be used to gather vulnerable road users (cyclists, pedestrians) in one spot and increase the visibility of cyclists by moving their stop line forward compared to that of motorized vehicles. When approaching the intersection, the bicycle track is either separated from the road (Gårder et al., 1994) or placed near the road (Vestergaard, 2013). In the intersection, the bicycle crossing is located just to the left of the zebra crossing, creating a space to the left of the bicycle lane where right-turning vehicles can stop and wait for crossing cyclists and pedestrians without pressure from vehicles coming from behind on the primary road (Gårder et al., 1994). In a simulator study, the separation of the bicycle crossing from the road had no consistent effects on the frequency of traffic conflicts (Hurwitz et al., 2015).

3. Method

3.1. Study design

The study applies traffic conflicts as an alternative to accidents. Traffic conflicts are situations with two or more road users being so close to each other in time and space that they will collide if their speeds and directions remain unchanged. However, the collision is prevented in time because at least one of the road users performs an evasive manoeuvre (Hydén, 1987; Kraay, 1982). This approach was chosen because only a small percentage of all cyclist accidents in Denmark are recorded by the police. The police register around 5% of the total number of cyclists treated at the hospital or emergency room after an accident (Statistics Denmark, 2014). Thus, conclusions from accident studies are typically based on only a few of the accidents that have actually occurred. As opposed to this, traffic conflict studies comprise all safety critical situations. If the recorded accidents are not representative for all accidents, results of accident studies may yield to conclusions that differ from results of traffic conflict studies. Furthermore, when conducting the study as a conflict study, it is possible to give a better estimation of the traffic volume at the time of the conflict. Accurate traffic counts for motorized vehicles and cyclists are essential in order to relate the safety of cyclists in different layouts of crossing facilities to the traffic volume. However, in most intersections, available traffic counts for vehicles are either out-dated or non-existent since they are usually conducted manually and thus not collected on a regular basis. Cyclist counts are particularly rare. Add to this the fact that traffic patterns and volumes may have changed significantly during the time span of several years used for an accident analysis and that the changes in a particular intersection may not correspond to the general trend. Therefore, it is difficult to collect new traffic counts and convert to the time of the accident. As traffic conflicts occur more frequently than accidents (Hydén, 1987), enough data can be collected within a short period of time, allowing traffic counts and conflict data to be collected simultaneously.

Traditionally, traffic conflict studies were carried out using trained observers in the field. As this approach involves a risk of missing or misjudging conflicts without providing an option to look through it again, video recordings of the sites are often collected. However, a manual analysis of the video footage is often very time-consuming. Researchers have thus developed video analysis software for an automated tracking of road users to identify traffic conflicts automatically in order to reduce the time spent on analysing the video footage (see e.g. Laureshyn, 2010; Saunier & Sayed, 2007). Typically, the performance of such systems decreases as the complexity of the video increases, e.g. by rapidly changing weather and light conditions, occlusion, shadows and complex traffic scenes with multiple road user groups sharing the same space (Buch, Velastin, & Orwell, 2011). A human-in-the-loop is, therefore, still necessary for assessment of the findings from the video analysis, especially for complex tasks such as detecting traffic conflicts. Therefore, the main purpose of video analysis software should be reducing the amount of video data that has to be assessed manually. In this study, we developed video analysis software (Bahnsen, Madsen, Jørgensen, Lahrmann, & Moeslund, 2014) which had two purposes: (1) to reduce the amount of video material needing manual analysis in order to identify traffic conflicts and (2) to perform an automatic traffic count of left-turning vehicles, right-turning vehicles and straight-going cyclists, respectively. Bahnsen and Moeslund (2015) give a technical description of the software. The tool is a so-called watchdog system that detects events that should be investigated further while discarding the parts of the video with no activity of interest. This study carried out the reduction of the video data by identifying and extracting events that had the potential of becoming traffic conflicts. Since traffic conflicts occur only if two road users have been close to each other in time and space, a potential conflict was defined as an event with simultaneous arrival of a turning vehicle and a crossing cyclist. A simultaneous arrival had occurred if the cyclist arrived at the conflict area up to 2.5 s after the vehicle has left the area or when the cyclist had left the area up to 1.0 s before the vehicle arrived at the same area (Nielsen, 1994a).

Two types of conflicts were of main interest in the study: conflicts between cyclists and right-turning vehicles and conflicts between cyclists and left-turning vehicles. These conflict types were chosen since this kind of interaction leads to the two most frequent accident types between cyclists and vehicles according to the police records. Accident records from the Danish police for 2010–2014 show that 16.5% of the cycling injury accidents involved a right-turning vehicle and a straight-going cyclist, whereas 13.0% involved a left-turning vehicle and a straight-going cyclist (Vejdirektoratet, 2015). In one of the studied layouts cyclists and right-turning vehicles merged before the intersection. The study included merging conflicts in this intersection as it was expected that most conflicts between right-turning vehicles and cyclists would occur in the right-turning lane before the intersection. Fig. 2 illustrates the conflict types included in this study.

3.2. Bicycle facility layouts

This study included examination of four signalized intersections with typical Danish layouts (*a*-*d*), which are recommended in the Danish guidelines (Vejregelrådet, 2010), and one signalized intersection with an, at least in Denmark, experimental design (*e*) of bicycle facilities in signalized intersections. Layout *e* requires special permission before construction and only exists in a few locations in Denmark (Vestergaard, 2013). The layouts were as follows:

(a) Full-length bicycle track combined with separate right-turning lane.
(b) Truncated bicycle track followed by a separate right-turning lane in which cyclists and vehicles merge.
(c) Full-length bicycle track combined with a shared lane for straight traffic and right-turning vehicles.
(d) Truncated bicycle track followed by a narrow bicycle lane combined with shared lane for straight traffic and right-turning vehicles.
(e) Recessed bicycle track combined with a shared lane for straight traffic and right-turning vehicles.

Fig. 3 shows the bicycle facilities. The specific locations were selected based on high traffic volumes of cyclists and turning vehicles. None of the five bicycle facilities had high numbers of accidents according to the police records. No accidents of the types included in this analysis (see Fig. 2) were registered in any of the layouts *b*, *d* and *e* during the period 2004–2013. Two accidents were registered in layouts *a* and *c* – one right-hook and one left-hook accident in each intersection.

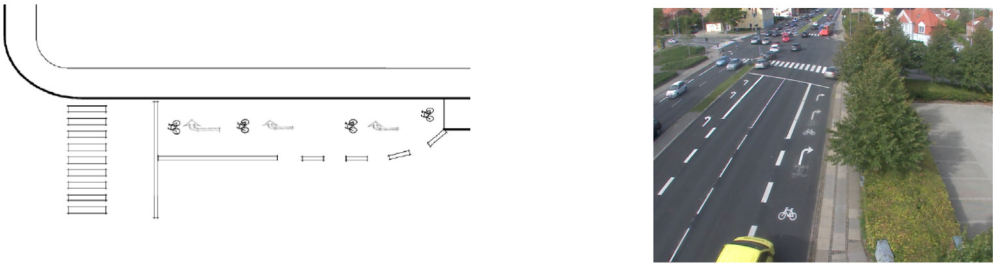
In all layouts, the bicycle facility is one-way with cyclists following the general direction of traffic (i.e. right-hand driving) and thus riding to the right of vehicles driving in the same direction. Motorized vehicles must yield to cyclists before turning.

In layouts with bicycle tracks, the track is elevated above the road and separated with a curb. The bicycle track is discontinued at the stop line just before the intersection and continues at the same level as the road inside the intersection.

(1) Right turn in front of a cyclist (2) Left turn in front of a cyclist (3) Merging to the right in front of a cyclist

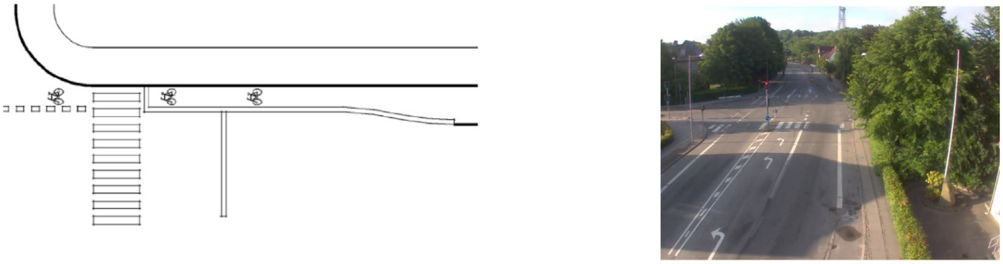
Fig. 2. Types of traffic conflicts included in the study.

(a) Full-length bicycle track combined with separate right-turning lane.

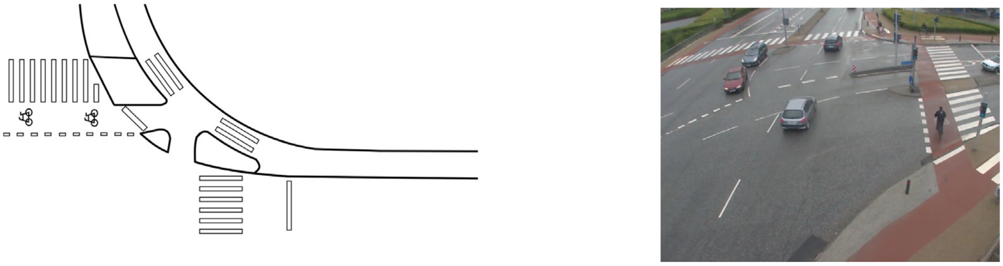


(b) Truncated bicycle track followed by a right-turning lane.

(c) Full-length bicycle track combined with a shared lane foor straight traffic and right-turning vehicles.



(d) Truncated bicycle track followed by a narrow bicycle lane combined with a shared lane for straight traffic and right-turning vehicles.



(e) Full-length recessed bicycle track combined with a shared lane for straight traffic andright-turning vehicles.

Fig. 3. Schematic overview of geometric layouts of bicycle facilities (left) and overview photos of intersections (right). Schematics a-d adapted from (Vejregelrådet, 2010).

A bicycle lane is at the same level as the road and separated by a 30 cm wide white marking. Some of the layouts have staggered stop lines (*a*, *d* and *e*) by which the motor vehicles are stopped 5 m or more behind the cyclists. In two layouts, the bicycle lane inside the intersection has coloured marking (*a*: blue, *e*: red). In addition, one intersection (*a*) had an exclusive green phase for right-turning vehicles before the initiation of the green phase for all road users in that direction. Except for one intersection (*e*), cyclists are not permitted to turn right on red, i.e. without complying with the traffic lights.

Due to a long separate right-turning lane in layout *b* (46 m), the camera view could not capture the intersection point where the bicycle track stops and the right-turning lane begins. This point is located approximately 18 m upstream the camera view. There is a risk that some merging conflicts have occurred outside the camera view. However, observations from the video recordings show that many right-turning vehicles change lane rather late in this intersection.

3.3. Data collection

Video recordings in the five intersections were collected in May, June and September 2013. The study was based on recordings from five days (Monday-Friday) from 5 a.m. to 9 p.m. in each intersection, i.e. 80 h per intersection. The layouts were filmed with a video camera mounted on lampposts near the intersections. The camera was connected to a netbook and powered by car batteries that were locked into a box beneath the lamppost.

3.4. Data processing

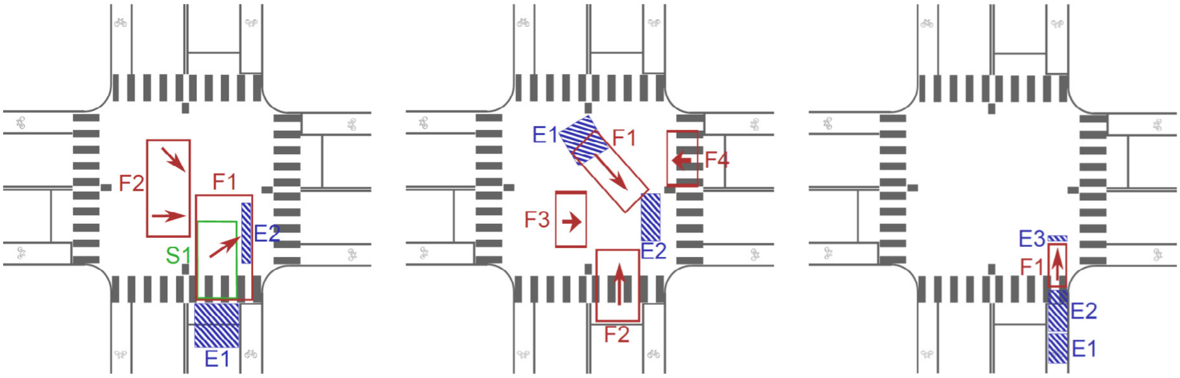
Two types of data were extracted using video analysis software: (1) traffic conflicts and (2) traffic counts.

3.4.1. Identifying traffic conflicts using the watchdog method

The video recordings were processed in multiple steps. First, the recordings were analysed with the watchdog software (Bahnsen et al., 2014). The watchdog software detected road users based on motion in the image. Multiple fields were created on top of the video in areas of the intersections where the road users of interest were present. Motion was only registered inside the fields. Three different types of fields could be used in order to detect road users if they passed the field in any direction, passed the field in a particular direction or were stationary inside the field. In order to detect road users and discard noise from shadows, shaking trees, bad weather etc. in the recordings, the sensitivity of the fields towards changes in the image was adjusted. Given that urban intersections are complex due to many road users and modes of transportation sharing the same space, sequences of multiple fields were created in order to increase the accuracy of the detection of a certain traffic stream. Fig. 4 illustrates the detection of road users via multiple fields. To be detected as a straight-going cyclist, left-turning vehicle or right-turning vehicle, the fields should be triggered in the right order corresponding to how the road users would cross the intersection. For instance, a right-turning vehicle must first be detected near the stop line, then move in a right-going direction and finally cross the bicycle lane at the right arm of the intersection. The last field in the sequence was located in the area where the trajectories of the turning vehicle and the cyclist intersect. Every time this field was triggered, a timestamp was written into a log. This approach enabled an estimation of the time interval of two road users crossing each other's trajectories and thus served as a means to identify events with simultaneous arrival of a cyclist and a turning vehicle.

The watchdog software reduced the video recordings from each intersection from 80 h to 3–25 h per intersection depending on the complexity of the recordings and the number of potential conflicts. In total, the data was reduced from 400 h to 64 h of video material.

A manual assessment of the reduced video data was conducted to determine which of the events should be further analysed in order to decide if they were actual traffic conflicts. Events with one or both road users performing an evasive manoeuvre (braking, swerving, accelerating) and events with high potential of resulting in an accident due to short distances



(1) Right-turning motorized vehicles (2) Left-turning motorized vehicles (3) Straight-going cyclists

Fig. 4. Schematic diagrams of the detection of road users in the software (Bahnsen et al., 2014). Three different types of fields are combined to detect when the road users pass a field in any direction (E/blue), move in a particular direction (F/red) or are stationary inside a field (S/green).

(time and/or space) between the road users were selected for further analysis. To identify traffic conflicts, an analysis was conducted in the semi-automatic video analysis tool T-Analyst (Trafvid, 2014). In the software, calibration is made to convert video coordinates to real-world coordinates, which allows extracting trajectory data by manually placing bounding boxes around the road users at regular intervals, e.g. at every fourth frame. Based on the positions of the bounding boxes and timestamps for the video frames, trajectories are created for each of the two road users that are assumed to be involved in a traffic conflict. By combining trajectories of the two road users, various traffic conflict indicators are calculated.

The risk of cyclists was studied using two different definitions of a traffic conflict: one based on the time interval between two crossing road users and one based on an assessment of the reactions of the road users. For the time-based measure, a combination of the Time-to-Collision (TTC) and T_2 was used as an indicator for conflicts. The TTC describes the time remaining to avoid a collision in cases where the road users are on a collision course. If the minimum TTC ($\text{TTC}_{\min}$) is above 0, a collision has not occurred. Events without collision course may involve a high potential for a collision if the speed and/or direction of the road users should change only little to bring the road users on a collision course. Therefore, the study included events in which the second road user has short time to respond to changes. This was done through the T_2 value. The T_2 describes the time remaining for the second road user to avoid a collision if changes in speed and/or direction of the two road users will bring them on a collision course (Laureshyn, 2010). This project defines a conflict as an event where a straight-going cyclist and a turning vehicle are on collision course with $\text{TTC}_{\min} \leqslant 2.0$ s or on crossing course with $T_{2,\min} \leqslant 0.5$ s.

The challenge of using a time-based conflict indicator is to determine which value should define the boundary between conflicts and non-conflicts. If the value has been set too high, events with an effective traffic flow may be selected. If the value has been set too low, some conflicts are omitted. Therefore, this study examines an additional definition of conflicts. This indicator was based on the presence of an evasive manoeuvre performed near the conflict area as this suggests that at least one of the road users would not voluntarily be exposed to the danger of the incident. The definition is thus similar to the approach of the Swedish Traffic Conflict Technique (Hydén, 1987) and DOCTOR (van der Horst & Kraay, 1986) except that this study bases the indicator exclusively on the presence of the evasive manoeuvre whereas no classification of severity of the conflict was carried out. In the second conflict indicator of this project, a conflict was defined as an event in which at least one of the road users clearly showed that he considered the event dangerous and, as a result, reacts near the conflict point, e.g. by using gestures, braking or changing direction. To discard events with a low probability of conflicts occurring, the assessment is conducted only for events with $\text{TTC}_{\min} \leqslant 2.0$ s or $T_{2,\min} \leqslant 1.0$ s.

3.4.2. Traffic counts

From the watchdog software, traffic counts for the road users were collected automatically. The traffic counts were divided into intervals of 15 min. In some periods during the recordings, bad weather conditions (e.g. heavy rain or shadows) influenced the quality of the automatic traffic count. To take this into account, the traffic volume in a particular quarter was estimated as the median of the traffic counts for each of the five days. For instance, in the software 37, 34, 28, 37 and 39 right-turning vehicles were registered from Monday to Friday between 7:30 a.m. and 7:45 a.m. in one of the intersections. The median (37) was used as an approximation of the intensity of right-turning vehicles in that particular intersection. Despite the daily variation in the traffic volume, this method was considered sufficiently accurate for the study. Table 1 shows the traffic counts for motorized vehicles and Table 2 shows the traffic counts for cyclists.

The traffic counts were used to split the recordings into groups with various traffic volumes and as an exposure measure to estimate the risk of being involved in a traffic conflict as a cyclist. As there are always two road users involved in a traffic conflict, the question is thus how to combine the traffic volumes of the two conflicting streams in order to describe the exposure to the conflict in terms of the potential of being involved in a conflict. Similar to the approach of Linderholm (1992), this study uses the number of cyclists crossing the intersection as exposure measure while the number of turning vehicles was

Table 1

Number of turning vehicles that have passed the intersection within the study period of five days during low, medium and high traffic intensities (low: 0–15 turning vehicles per 15 min, medium: 16–35 turning vehicles per 15 min, high: >35 turning vehicles per 15 min). AADT estimates are given in round brackets and the number of intervals of 15 min in square brackets.

Layout	Total	Low vehicle intensity	Medium vehicle intensity	High vehicle intensity
Right-turning vehicles				
a	16,015 (3000)	130 [15]	2120 [85]	13,765 [220]
b	3240 (600)	1735 [265]	1015 [45]	490 [10]
c	6625 (1400)	860 [115]	4335 [170]	1430 [35]
d	4685 (900)	2025 [205]	2465 [110]	195 [5]
e	7360 (1500)	610 [70]	6165 [235]	585 [15]
Left-turning vehicles				
a	8075 (1600)	610 [80]	4150 [170]	3315 [70]
b	6545 (1200)	720 [80]	4740 [215]	1085 [25]
c	7825 (1600)	820 [90]	4945 [180]	2060 [50]
d	6525 (1300)	730 [90]	5205 [215]	590 [15]
e	6510 (1400)	1010 [100]	5500 [220]	0 [0]

Table 2
Number of crossing cyclists that have passed the intersection within the study period of five days during low, medium and high traffic intensities of turning vehicles (low: 0–15 turning vehicles per 15 min, medium: 16–35 turning vehicles per 15 min, high: >35 turning vehicles per 15 min).

Layout	Total	Low vehicle intensity	Medium vehicle intensity	High vehicle intensity
Cyclists relative to right-turning vehicles				
a	3115	15	405	2695
b	3670	2700	660	310
c	3975	970	2590	415
d	3145	1460	1500	185
e	2055	260	1525	270
Cyclists relative to left-turning vehicles				
a	3115	250	1650	1215
b	3670	545	2655	470
c	3975	630	2605	740
d	3145	465	2465	215
e	2055	360	1695	0

taken into consideration by means of a subdivision into groups with similar traffic intensities of motorized vehicles within one group.

The volumes of left- and right-turning motorized vehicles were divided into three groups, representing low, medium and high traffic intensities. Based on the automatic traffic counts of turning motor vehicles, each interval of 15 min of the day was assigned to one of three groups: low intensity (0–15 turning vehicles per 15 min), medium intensity (16–35 turning vehicles per 15 min) and high intensity (>35 turning vehicles per 15 min). As the traffic intensities of the two turning directions can differ, each quarter was assigned to one of the three groups separately for right-turning and left-turning vehicles. For instance, if 12 left-turning vehicles cross the intersection in 15 min and 25 right-turning vehicles pass in the same time period, the cyclists for this particular quarter are assigned to the low traffic intensity for left-turning vehicles and medium traffic intensity for right-turning vehicles. Table 1 shows the total exposure of turning vehicles in each of the three groups and Table 2 the number of cyclists who crossed the intersections in time periods with low, medium and high vehicle intensities.

3.5. Data analysis

The five geometric layouts of bicycle facilities were compared based on the relative risk of the cyclists (e.g. the number of conflicts between a right-turning vehicle and a straight going cyclist divided by the number of straight going cyclists) for each of the three traffic intensities (low, medium, high).

4. Results

4.1. Risk of cyclists against right-turning vehicles

Table 3 shows the relative risk of a cyclist being involved in a traffic conflict with a right-turning vehicle for each of the five geometric layouts of bicycle facilities in signalized intersections. Layout *a* (full-length bicycle track combined with separate right-turning lane) had a high number of right-hook conflicts for a high traffic intensity using both conflict indicators. However, the relative risk was the second lowest for the reaction-based conflict measure but the second highest for the time-

Table 3
Risk of cyclists being involved in right-hook conflicts for various traffic intensities (low = 0–15 turning vehicles per 15 min, medium = 16–35 turning vehicles per 15 min, high = >35 turning vehicles per 15 min). The risk is indicated as the number of conflicts per 1000 cyclists. The number of conflicts is shown in brackets. Cells with a dash (–) denotes that the total number of cyclists for that particular traffic intensity was below 100 or that no motor vehicles have been registered.

Layout	Low vehicle intensity	Medium vehicle intensity	High vehicle intensity
Reaction-based conflict measure			
a	–	0.0 (0)	4.5 (12)
b	0.4 (1)	0.0 (0)	6.5 (2)
c	0.0 (0)	0.8 (2)	4.8 (2)
d	0.7 (1)	1.3 (2)	5.4 (1)
e	0.0 (0)	1.3 (2)	0.0 (0)
Time-based conflict measure			
a	–	2.5 (1)	10.4 (28)
b	6.7 (18)	4.5 (3)	16.1 (5)
c	1.0 (1)	3.1 (8)	7.2 (3)
d	2.1 (3)	5.3 (8)	5.4 (1)
e	0.0 (0)	0.7 (1)	0.0 (0)

based measure at high vehicle intensities. Apart from layout *a* at high vehicle intensities, only a few conflicts (0–2) were found for each layout using the reaction-based indicator of traffic conflicts. For the time-based measure, layout *b* (truncated bicycle track followed by a separate right-turning lane in which cyclists and vehicles merge) had many conflicts and a high relative risk for cyclists at low and high vehicle intensities. The same applies for layout *c* (full-length bicycle track combined with a shared lane for straight traffic and right-turning vehicles) and *d* (truncated bicycle track followed by a narrow bicycle lane combined with shared lane for straight traffic and right-turning vehicles) at medium vehicle intensity. Layout *e* (full-length recessed bicycle track combined with a shared lane for straight traffic and right-turning vehicles) resulted in few conflicts and had a low relative risk of cyclists except at medium traffic intensity when using the reaction-based conflict measure. Generally, the results indicate that the risk is higher for high vehicle intensity than for low or medium intensities of the motorized traffic. Furthermore, the time-based conflict measure includes more conflicts and thus indicates higher risks of cyclists than the reaction-based measure. However, in one case the number of conflicts is higher for the reaction-based measure than for the time-based measure: layout *e* at medium vehicle intensity.

Due to the low number of conflicts, only one pairwise comparison of the layouts for each of the three traffic intensities was statistically significant at the 5% level; layout *e* had significantly fewer right-hook conflicts compared to layout *d* at medium traffic intensity when using a time-based measure. Furthermore, there is a tendency showing (*Z*-test, $p < 0.10$) that layout *b* has more right-hook conflicts compared to layouts *c* and *d* at low traffic intensity and *e* at medium traffic intensity when using a time-based measure.

4.2. Risk of cyclists against left-turning vehicles

Table 4 shows the relative risk of a cyclist being involved in a traffic conflict with a left-turning vehicle for each of the five geometric layouts of bicycle facilities in signalized intersections. Generally, the risk of a cyclist being involved in a conflict with a left-turning vehicle was lower than with a right-turning vehicle. Apart from layouts *b* (truncated bicycle track followed by a separate right-turning lane in which cyclists and vehicles merge), *c* (full-length bicycle track combined with shared lane for straight traffic and right-turning vehicles) and *d* (truncated bicycle track followed by a narrow bicycle lane combined with shared lane for straight traffic and right-turning vehicles) at medium traffic intensity, there were only a few conflicts (0–2) for each layout. The relative risk of cyclists is higher for layout *d* at medium traffic intensity than for all other layouts.

Due to the low number of conflicts at each intersection, only one pairwise comparison of the relative risk of cyclists was statistically significant (*Z*-test, $p < 0.05$); layout *c* had significantly fewer left-hook conflicts than layout *d* at medium traffic intensity when using the time-based measure. Additionally, there is a tendency (*Z*-test, $p < 0.10$) pointing towards layout *d* having more left-hook conflicts than layouts *a* and *c* when using the time-based measure.

5. Discussion

5.1. Relative risk of cyclists for different geometric layouts of bicycle facilities

5.1.1. Layout e seems to be the safest

This study evaluates five geometric layouts of bicycle facilities in signalized intersections in order to assess if one layout is safer than others at various vehicle intensities. The results indicate that layout *e* appears to be safer than the other layouts. It should be noted that the number of cyclists was lower for this intersection than for the others (Table 2). This should, however, not influence the fact that layout *e* seems to be the safest layout of the studied facilities. In case of a safety-in-numbers effect, i.e. that the relative risk of a cyclist decreases as the total number of cyclists increases (Elvik, 2009), layout *e* can be

Table 4

Risk of cyclists being involved in left-hook conflicts for various traffic intensities (low = 0–15 turning vehicles per 15 min, medium = 16–35 turning vehicles per 15 min, high = >35 turning vehicles per 15 min). The risk is indicated as the number of conflicts per 1000 cyclists. The number of conflicts is shown in brackets. Cells with a dash (–) denotes that the total number of cyclists for that particular traffic intensity was below 100 or that no vehicles have been registered.

Layout	Low vehicle intensity	Medium vehicle intensity	High vehicle intensity
Reaction-based conflict measure			
a	0.0 (0)	0.0 (0)	0.8 (1)
b	0.0 (0)	0.8 (2)	2.1 (1)
c	1.6 (1)	0.0 (0)	0.0 (0)
d	0.0 (0)	2.4 (6)	0.0 (0)
e	0.0 (0)	0.6 (1)	–
Time-based conflict measure			
a	0.0 (0)	0.6 (1)	1.6 (2)
b	0.0 (0)	1.9 (5)	2.1 (1)
c	1.6 (1)	1.2 (3)	0.0 (0)
d	0.0 (0)	4.5 (11)	0.0 (0)
e	0.0 (0)	0.6 (1)	–

assumed to be safer than the other layouts even if the number of cyclists had been higher. As opposed to previous studies concluding that the safety of cyclists is improved when cyclists and right-turning vehicles drive closer to each other than usual (Herrstedt et al., 1994; Jensen & Nielsen, 1999; Nielsen, 1994b), these results show that moving the bicycle track further away from the road seems to improve the safety of cyclists. A possible explanation may be that when increasing the distance between the road and the bicycle track enough to allow vehicles to stop before the bicycle track after making the turn, the driver is placed perpendicular to the bicycle track before passing it, which facilitates the detection of a cyclist because the driver would turn his head less to notice the cyclist. The use of a staggered stop line may further contribute to the low occurrence of right-hook conflicts similar to previous findings (Herrstedt et al., 1994; Linderholm, 1992).

5.1.2. Effects of separate right-turning lanes and staggered stop lines

In most cases, layout *a* has a lower risk than layout *c*, although the difference is small. However, layout *a* has a higher absolute number of conflicts at high traffic intensity. The two layouts differ from each other by layout *a* having a separate right-turning lane, staggered stop line and blue bicycle marking whereas layout *c* has a shared lane for right-turning and straight going vehicles and neither staggered stop line nor bicycle marking. The results are similar to the findings of Buch and Jensen (2012) who found that more accidents occur in intersections with separate right-turning lanes compared to shared lanes for straight-going and right-turning traffic. An explanation is that separate right-turning lanes are constructed in intersections with many right-turning vehicles which then results in a relatively low risk. Previous studies have come to different conclusions on the effect of staggered stop lines. Buch and Jensen (2012) found that there was a limited effect on the safety of staggered stop lines when constructed in intersections with separate right-turning lanes. Linderholm (1992) and Herrstedt et al. (1994) both conclude that staggered stop lines improve the safety of cyclists but both studies were relatively small. Similarly, this study cannot conclude whether staggered stop lines improve or deteriorate the safety of cyclists in terms of being involved in traffic conflicts with right-turning vehicles due to a small number of conflicts. Hurwitz et al. (2015) found that the safety of cyclists is improved by coloured bicycle markings. The difference in the risk level between the two layouts may, therefore, result from the presence of the blue bicycle marking.

This study suggests that layout *d* with a narrow bicycle lane and a staggered stop line is less safe for cyclists than layout *c*, which has a bicycle track and no staggered stop line. This finding contradicts with the results of Herrstedt et al. (1994) who concluded that a truncated bicycle track followed by a narrow bicycle lane improved the cyclist safety when compared to a full-length bicycle track. However, this may be explained by the small number of conflicts in our study.

5.1.3. High risk of layout b due to merging

Truncated bicycle tracks which continue into a separate right-turning lane in which cyclists and right-turning vehicles merge (layout *b*) seem to involve a higher risk for cyclists compared to a bicycle track (layout *a*). It is even likely that some merging conflicts may have occurred outside the camera view in layout *b* and thus that the number of traffic conflicts has been underestimated in this layout. However, it should be noted that the number of conflicts was generally high for the time-based measure and much lower for the reaction-based measure, except for layout *a* at high traffic volumes. An explanation may be that merging between cyclists and right-turning vehicles often result in the road users driving close to each other in a controlled manner, which is thus not detected as a traffic conflict in the reaction-based indicator but only in the time-based indicator.

5.1.4. Implications of large traffic volumes

A high number of right-hook conflicts occur in layout *a* at high traffic volumes. This intersection had a remarkably high number of right-turning vehicles compared to the other intersections. Around 16,000 right-turning vehicles entered the intersection during the five days of the study, which is more than twice as much as the second busiest intersection and five times as much as in the intersection with the lowest traffic volume, see Table 1. As a result, the majority of all cyclists pass during time periods with high vehicle intensity, and thus most conflicts occur at high volumes. The risk of a cyclist being involved in a right-hook conflict is, therefore, relatively similar to that of the other layouts. It should be noted that layout *a* has an exclusive green phase for right-turning vehicles prior to the ordinary green phase. This solution ensures a temporal separation of some of the right-turning traffic and the cyclists and is common in intersections with high turning traffic volumes. When the traffic volumes are so high that not all right-turning traffic can pass during the exclusive green phase, the right of way suddenly changes from the vehicle to the cyclists when all road users from that direction have green light. This may have contributed to some conflicts that would probably not have occurred if the exclusive green phase and the traffic passing in it had not existed. On the other hand, an exclusive green phase may improve the safety of cyclists if the traffic volume is low enough to ensure that all right-turning vehicles pass during this phase. The effect of an exclusive green phase for vehicles on cyclist safety has not been evaluated in this project but should be subject to further research.

5.1.5. Left-turning road users may overlook cyclists hidden behind vehicles

Cyclists run a high risk of conflicts with left-turning vehicles when passing the intersection with a narrow bicycle lane (layout *d*) at medium traffic volume. This may be due to a low capacity of left-turning vehicles, forcing them to cross the intersection even at small time gaps. Thus, they risk overlooking cyclists that may have been hidden behind a straight-going vehicle.

5.2. Conflict indicators

In order to compare the risk of cyclists for the geometric bicycle facility layouts, the analysis included two traffic conflicts indicators. Generally, the reaction-based conflict indicator includes fewer conflicts than the time-based indicator. However, in most cases the two indicators show the same patterns of the safety in each layout. In four cases, the number of right-hook conflicts is much higher for the time-based indicator than for the reaction-based indicator: layout *b* (low vehicle intensity), layout *c* (medium vehicle intensity), layout *d* (medium vehicle intensity) and layout *a* (high vehicle intensity), which thus results in higher risks than reflected by the reaction-based indicator.

For layout *b*, in which the cyclists and right-turning vehicles merge before the intersection, the number of conflicts was 1 for the reaction-based measure and 18 for the time-based measure. An analysis of the conflicts shows that merging between the road users often implies that the road users drive close to each other but that the action seems to be under control. This suggests that the time-based indicator used in this study is not suitable to identify conflicts in merging situations because the events reflect normal behaviour with the roads users being aware of each other. Those events may, of course, entail a higher risk of conflicts and thus accidents in cases where the road users fail to detect each other in time.

A further analysis of the conflicts for layout *a*, *b* and *c* suggests that the difference in the number of conflicts and thus the risk of cyclists is caused by the inclusion of events where the right-turning vehicle and the cyclist were on a collision course but where the driver seemed to be aware of the cyclist and stopped to yield to the cyclist before crossing the bicycle lane soon after the cyclists have passed. This indicates that the TTC value was set too high in the time-based measure.

In one case, more right-hook conflicts were detected with the reaction-based measure than with the time-based measure. This occurred for layout *e* (medium vehicle intensity). In the recordings of the situation, there were signs of lacking trust (hesitation and braking) from one or both road users. However, the reaction happened too early to be included in the time-based measure.

Both indicators used in this study have advantages and disadvantages. The reaction-based indicator represents events where the interaction between the road users did not work properly, which could have resulted in a collision if they had not reacted to the danger. This approach thus uses some of the principles from other established traffic conflict techniques (Hydén, 1987; van der Horst & Kraay, 1986). Using a strict conflict measure, however, may reduce the number of conflicts significantly and even for studies of several days there is a risk that no conflicts are found at all. Therefore, Laureshyn, Ardö, Svensson, and Jonsson (2009) used a less strict conflict definition in a study where no serious conflicts were found using the Swedish Traffic Conflict Technique. In our study, we used a similar approach by introducing the time-based indicator which included situations with road users not being at collision course. Although more events are classified as conflicts and situations with a high risk of collision are included despite of the road users not reacting to the potential danger, the results from this study show that if the threshold value has been set too high, events with an effective traffic flow where the road users cross each other in a controlled manner will be selected. On the other hand, if the value has been set too low, some conflicts are omitted and we may experience the same issues with few conflicts as with the reaction-based indicator. Therefore, even if the time-based measure is used, we should consider performing a manual (subjective) assessment of the identified conflicts. Furthermore, when taking the time consumption of the data analysis into account, it may be better to increase the amount of video recordings and use the reaction-based conflict indicator exclusively as the time-based indicator requires a manual registration of the trajectories of the road users. This registration is rather time-consuming. However, it is still unclear which conflict indicator to use in order to reflect the safety as good as possible and this should be subject to further research.

5.3. Exposure

In this study, the number of cyclists was used as an exposure measure. Although easy to collect, this approach has some shortcomings, because it usually does not reflect the real exposure well. The problem is that although there are many road users, a potential collision is only imminent if two road users are close to each other in time and space. The traffic counts alone cannot determine if this is the case. Attempts have been made to convert traffic counts in order to better reflect the number of possible events that may lead to a conflict. Examples are to use the square root of the product of the two conflicting streams (Linderholm, 1992), negative binomial models (Dill et al., 2012) or to estimate the number of meeting possibilities based on a Poisson distribution containing the traffic volumes and the time it takes for one of the road users to pass the conflict area (Linderholm, 1992). The latter method is, however, not valid in signalized intersections. Although these methods have shown a good relationship with the real number of potential conflicts, they are just estimates and will not always yield reliable results. For instance, the square root of the products yields the same exposure (i.e. 10) in case of 10 road users in each conflicting stream as in case of 100 and 1 in the two streams. However, it is clear that in the latter case only one conflict can happen. Thus, in some cases, it may be just as good to use the traffic counts directly.

An alternative to traffic counts is to use an event-based exposure measure (e.g. simultaneous arrivals, interaction between two road users, braking events) (Elvik, 2015). The advantage of this kind of measure is that it directly relates to the actual potential of being involved in a conflict since the prerequisite for a conflict to happen is that a simultaneous arrival has occurred. For each simultaneous arrival, there are only two possible outcomes: either it develops into a conflict or it does not. In the study, we developed video analysis software to detect potential conflicts between two road users. The number of simultaneous arrivals corresponds to the total number of situations which may potentially result in a collision. As there was a lot of false positives among the simultaneous arrivals due to inaccurate measurements of the time interval between the road users, traffic counts were used instead because they were easier to count accurately. Due to technical limitations of the software, two road users will be counted as one if they drive close to each other. This issue is particularly the case for traffic counts of cyclists as they often ride with a shorter distance to other cyclists compared to the distance between two vehicles. Thus, this may have contributed to a better estimate of the risk of cyclists compared to if all cyclists had been counted since it comes closer to the total number of possible collisions between a turning vehicle and the cyclist in an intersection.

5.4. The watchdog method

To facilitate the identification of conflicts from the video recordings, we developed watchdog video analysis software to reduce the amount of video recordings that had to be analysed manually. With this software, we were able to reduce the video recordings from 80 h per intersection to 3–25 h per intersection and in total from 400 h to 64 h. Especially in intersections with low traffic volumes, the watchdog is capable of reducing the proportion of video that should be analysed manually to a few percent of the total length. Even in intersections with heavy traffic and a complex traffic environment, e.g. due to merging between road users and bad weather conditions, the recordings in this study were reduced by 69%. To improve the accuracy of the software and reduce the amount of video even further, further research should consider the use of multiple sensor types, e.g. by combining RGB and thermal cameras, see e.g. (Bahnsen & Moeslund, 2015).

However, a risk of using software to identify potential conflicts is that some conflicts are missed. In order to reduce this risk, we chose to register events in which the road users passed each other with a greater distance than they would probably have had if they were involved in a conflict. Following this decision, more events without conflicts had to be discarded manually. Thus, the amount of video after using the watchdog can be reduced even more than in this study if accepting a higher risk of missing conflicts. We have no reason to believe that there is a systematic bias in which conflicts that may potentially be missed, but further research is needed to clarify whether or not this is the case.

6. Conclusion

This study indicates that cyclist safety in signalized intersections can be improved by choosing the right geometric layout of the bicycle facility. Out of the five layouts evaluated in this study, a recessed bicycle track seemed to provide the highest level of safety for cyclists. Although a large amount of video recordings were analysed – 80 h per intersection – there were too few conflicts to offer a conclusive answer to the question of which layout of bicycle facilities in signalized intersections is safest for cyclists at various traffic volumes. However, the study does show that the number of conflicts is small regardless of which of the two conflict indicators is used – a strict reaction-based or a less strict time-based – which suggests that the amount of data should be increased. In order to do so, video analysis software is deemed necessary as the amount of data will exceed what can possibly be analysed manually. In the study, we developed watchdog video analysis software and applied it successfully to reduce the amount of video to 16% of its original duration. Further developments of the software may result in more accurate detections of potential conflicts and thus lead to even larger reductions of the video data.

Acknowledgements

The study was funded by the Danish Road Directorate. The watchdog software used in this study was developed by Chris Bahnsen, Anders Jørgensen and Thomas B. Moeslund, Visual Analysis of People Lab, Aalborg University. The authors would like to thank Aliaksei Laureshyn and Åse Svensson, Lund University, for guidance and support during the collection and analysis of data.

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