Voorrangsgedrag en veiligheid op fietsoversteekplaatsen op bypasses

De invloed van de voorrangsregeling

Wouter van Haperen, Stijn Daniels, Tim De Ceunynck

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Wetenschapspark 5 bus 6 | 3590 Diepenbeek

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Samenvatting

Bypasses bij verkeerslichtengeregelde kruispunten zijn een ingreep om de verkeersdoorstroming te verbeteren, aangezien rechts afslaand verkeer de verkeerslichten kan vermijden en enkel volledig dient te stoppen wanneer dit noodzakelijk is. Vaak zijn hierop oversteekvoorzieningen voor voetgangers en (brom)fietsers voorzien. De internationale literatuur toont aan dat bypasses de algehele veiligheid verhogen, maar suggereert dat er met betrekking tot kwetsbare weggebruikers verhoogde veiligheidsrisico's bestaan: bestuurders van motorvoertuigen focussen voornamelijk op andere motorvoertuigen en letten minder op de eventuele aanwezigheid van (brom)fietsers en voetgangers. In Vlaanderen bestaan er geen harde richtlijnen voor het ontwerp van bypasses en de bijbehorende fietsoversteekplaatsen, wat geresulteerd heeft in een verscheidenheid aan toepassingen. De meest voorkomende vorm van bypass-ontwerp heeft een fietsoversteek voorziening centraal op de bypass, waarop fietsers in beide richtingen kunnen oversteken. Met betrekking tot de voorrangsregeling is er echter geen uniformiteit, wat kan leiden tot onduidelijke en verwarrende situaties. Daarom wordt in dit onderzoek getracht een beter inzicht te verkrijgen in de manier waarop het interactieproces tussen (brom)fietsers en bestuurders van motorvoertuigen op bypasses verloopt. Bijkomend wordt er een verkeersveiligheidsanalyse uitgevoerd, waarbij de invloed van de voorrangsregeling op de veiligheid van de fietsers wordt getoetst. Ook werd gekeken naar de invloed van de aanwezigheid van een zebrapad op de veiligheid van fietsers, maar geen significante effect kon gevonden worden. Vier locaties in de provincies Antwerpen en Limburg werden geselecteerd voor een week continue video observatie. Op twee locaties waren de fietsers in de voorrang, op de andere twee de bestuurders van motorvoertuigen. In totaal werden 1366 interacties geanalyseerd.

Vier types van voorrangsgedrag werden gedefinieerd, gebaseerd op welke weggebruiker eerst ging en wie het initiatief nam. De videodata laten zien dat er tussen de twee voorrangsregelingen (ofwel (brom)fietsers ofwel bestuurders van motorvoertuigen mogen eerst) geen aanzienlijke verschillen bestaan. Voor beide regelingen is te zien dat het de (brom)fietser is die in meer dan 70% van de gevallen als eerste oversteekt en dat dit meestal op een defensieve manier gebeurt. Aangezien de oversteekrichting van links naar rechts (vanuit het oogpunt van de bestuurder van het motorvoertuig) het meest voorkomend was, werd de analyse verder opgesplitst in oversteekrichting. Hierbij werd opgemerkt dat op één van de locaties de meerderheid (68%) van de fietsers die van rechts naar links overstak, bij de oversteekvoorziening arriveerde in een niet toegelaten richting. Dit verklaart mogelijk dat op deze locatie voor deze oversteekrichting (brom)fietsers minder vaak als eerste overstaken en zij hogere percentages defensief gedrag vertoonden. Een binaire logistische regressieanalyse werd uitgevoerd om te achterhalen welke aspecten de oversteekvolgorde bepalen. Er werd bevonden dat het feit een fietser en niet een bromfietser te zijn en van links (vanuit het oogpunt van de bestuurder van het motorvoertuig) te arriveren de kans vergroot voor de kwetsbare weggebruiker om als eerste over te steken. Indien één van beide weggebruikers vertraagt, verkleint deze weggebruiker zijn/haar kans om als eerste over te steken.

De veiligheidsevaluatie werd gebaseerd op conflictobservatie en gebruikte de minimale waarde van de Time-to-Collision en de waarde van de Time-to-Accident. De correlatie tussen de twee indicatoren was hoog ($r^2 > 0.83$), wat er op duidt dat beide veiligheidsindicatoren in grote mate overeenstemmen. We vonden geen significante invloed van de voorrangsregeling op de veiligheid van (brom)fietsers. De beschrijvende statistiek van beide indicatoren suggereerde wel dat de voorrangsregeling wel van invloed kan zijn wanneer de fietser rechts naar links oversteekt, aangezien voor deze situaties locaties met voorrang voor bestuurders van motorvoertuigen meer potentieel kritieke situaties opleverde.

Gebaseerd op de waarnemingen dat het de fietser is die, ongeacht de voorrangsregeling, in meer dan 80% van de gevallen als eerste oversteekt en dat de veiligheidsevaluatie geen significante invloed van de voorrangsregeling kon aantonen, kan er geen conclusie getrokken over welke voorrangsregeling de voorkeur verdient. Daarnaast is het niet duidelijk of het hoge percentage 'vrijwillig afstaan' van de voorrang door bestuurders van motorvoertuigen het gevolg is van een algemeen voorzichtige houding tegenover kwetsbare weggebruikers of van onzekerheid met betrekking tot het voorgeschreven gedrag. Meer uniformiteit in de voorrangsregeling en consistentie in de vormgeving hiervan leidt mogelijk tot meer duidelijkheid en minder onveilige situaties.

1 Inleiding

Om de verkeersdoorstroming op kruispunten met verkeerslichten te verbeteren, kunnen bypasses worden aangelegd (AWV, 2009). Deze stroken voor rechts afslaand verkeer stellen bestuurders van motorvoertuigen in staat om de verkeerslichten te vermijden en enkel te stoppen wanneer dit noodzakelijk is. Vaak zijn er oversteekvoorzieningen voor fietsers en voetgangers voorzien, maar de vormgeving verschilt per locatie. Twee types bypassdesigns kunnen onderscheiden worden: bypasses waar fietsoversteekplaatsen bij de in- en uitgang zijn aangelegd, waarbij de oversteken meestal enkelrichting zijn, en bypasses waar de (meestal dubbelrichting) fietsoversteekplaats centraal op de bypass geplaatst is (Figuur 1, links en rechts respectievelijk). Strikte regels voor de vormgeving en de voorrangsregeling bestaan momenteel niet in Vlaanderen of België.

Figuur 1: De twee types van bypass-ontwerp, gebaseerd op de aanbevelingen van het AWV (2009).

Huidig onderzoek in de internationale literatuur heeft zich voornamelijk gericht op de veiligheidsaspecten van bestuurders van motorvoertuigen, waarbij notie gemaakt werd van mogelijke veiligheidsproblemen met betrekking tot zwakke weggebruikers (Fitzpatrick et al., 2006; Polders et al., 2015; Potts et al., 2011; 2013). Echter, diepgaand onderzoek naar de gedragingsprocessen tussen (brom)fietsers en bestuurders van motorvoertuigen tijdens het interactieproces op bypasses met een centrale fietsoversteekplaats ontbreekt. Het primaire doel van de studie is om de huidige kennis over de veiligheid van fietsers op bypasses uit te breiden, waarbij gefocust wordt op de invloed van de voorrangsregeling. Ook de invloed van een zebrapad direct voor de fietsoversteek op de veiligheid van de fietsers werd in het onderzoek opgenomen. Hiervoor werd een gedragsobservatie en een conflictanalyse uitgevoerd.

2 Opzet

Via het Agentschap Wegen en Verkeer werd een database met ruim 300 locaties van kruispunten met bypasses verkregen. Gebaseerd op categorisering per configuratie (Figuur 1) en verschillende ontwerpelementen (oversteekrichting, zebrapad, verkeersplateau) werd het meest voorkomende bypass-design geselecteerd voor evaluatie. Vier locaties werden geselecteerd voor een week continue video-observatie (Figuur 2). De geselecteerde kruispunten in Diepenbeek (Verbindingslaan en Grendelbaan), Beringen (Kasteletsingel en Paalsesteenweg) en Geel (Grote steenweg en Westerloseweg, Westelijke Ring en Eikenstraat) hebben allemaal een dubbelrichting fietsoversteek, roodlichtcamera’s, een voorsorteerstrook voor de bypass en geen invoegstrook aan het einde van de bypass. De data tussen 11 en 17 juni 2015, telkens tussen 06:00 en 21:00, werden geanalyseerd. In de rest van het rapport zijn de locaties benoemd aan de hand van de voorrangsregeling (‘Fietser’ voor fietsers in de voorrang, ‘Auto’ voor bestuurders van motorvoertuigen) en de aanwezigheid van een zebrapad (Z).

Fietser (Zebrapad) Fietser Auto (Zebrapad) Auto

Figuur 2: Screenshots van de camera’s bij de oversteekvoorzieningen op de bypasses.

2.1 Verkeerssituaties

Tijdens de videodata collectie deden zich verschillende verkeerssituaties voor (Figuur 3, links). De verschillende situaties kunnen als volgt omschreven worden:

- De ‘*alle verkeerssituaties*’ categorie weerspiegelt alle situaties waarin minimaal één weggebruiker op de oversteekvoorziening van de bypass aanwezig is.
- Situaties van de ‘alle verkeerssituaties’ waarbij minimaal twee weggebruikers gelijktijdig aanwezig zijn bij de oversteekvoorziening, zijn gelabeld als ‘*passages*’. Tijdens deze events is het niet noodzakelijk dat de fietser ook daadwerkelijk van de oversteek gebruik maakt (‘*geen-oversteek events*’).
- Alle passages waarin de fietser en het motorvoertuig elkaar kruisen zijn gelabeld als ‘*interacties*’. Tijdens deze events zijn beide weggebruikers gelijktijdig op de oversteekvoorziening en dienen zij op elkaar te reageren om veilig over te kunnen steken.
- *‘Conflicten*’ zijn interacties die voldoen aan de definitie voorgesteld door Amundsen en Hydén (1977): *“Een observeerbare situatie in welke twee of meer weggebruikers elkaar zodanig naderen in ruimte en tijd dat een botsing zal plaatsvinden indien hun beweging onveranderd blijft.”*
- *´Ongevallen*’ zijn conflicten die resulteren in een botsing tussen twee of meer weggebruikers.

Figuur 3: Links, de types events gedefinieerd in deze studie. De pyramides geven niet de proporties weer, maar een schematische indicatie. Rechts, de aankomstrichtingen van de fietsers.

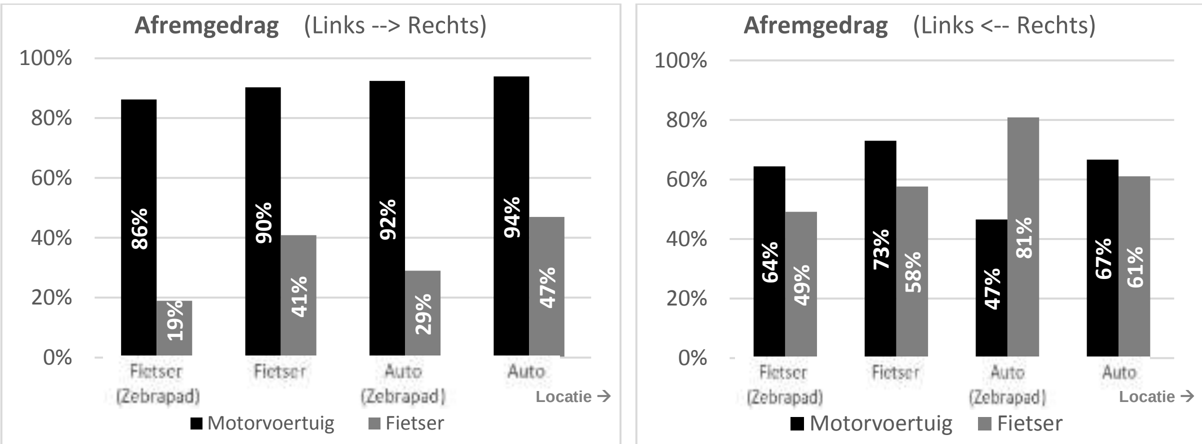
Figuur 3 (rechts) geeft een overzicht van de mogelijke richtingen waaruit fietsers de oversteekvoorziening kunnen naderen. Buiten de fietsoversteek zelf zijn op alle locaties de fietspaden enkelrichting, met uitzondering van locatie ‘Fietser (Zebrapad)’, waar een fietspad in richting ‘1’ ontbreekt en alle fietsers de oversteekvoorziening naderen en verlaten via ‘2’. Alhoewel het naderen van de fietsoversteek vanuit richtingen ‘2’ (met uitzondering van Fietser (Zebrapad)) en ‘3’ niet is toegestaan, werd dit wel geobserveerd.

3 Voorrangsgedrag

3.1.1 Afremgedrag

Het verminderen van de snelheid tijdens de aankomst werd als objectieve maat gebruikt om na te gaan of de weggebruiker bereid was (gewillig of geforceerd) om de ander voor te laten gaan. Hiervoor werden alle ‘interacties’ geanalyseerd, waarbij een onderscheid gemaakt werd in de oversteekrichting. Aan de hand van χ^2-toetsen werd getest of er met 95% betrouwbaarheid verschillen tussen de voorrangsregelingen bestaan. Figuur 4 geeft de percentages van het aantal interacties weer in welke de weggebruikers afremde. De belangrijkste observaties zijn als volgt:

- Bestuurders van motorvoertuigen
  - remmen vaker af dan fietsers, ongeacht de voorrangsregeling (χ^2 = 222.030, df= 1, p = .000);
  - remmen relatief gezien vaker af als de fietser van links naar rechts (vanuit het oogpunt van de aankomende bestuurder) oversteekt in vergelijk met wanneer de fietser van rechts naar links oversteekt (χ^2 = 162.203, df= 1, p = .000).
- Fietsers remmen vaker af als ze van rechts naar links oversteken dan andersom (χ^2 = 105.818, df= 1, p = .000).
- De voorrangsregeling heeft geen significante invloed op het afremgedrag (χ^2 = 0.068, df= 1, p = .418 voor fietsers en χ^2 = 0.013, df= 1, p = .482 voor bestuurders van motorvoertuigen).



Figuur 4: Percentage weggebruikers die afremmen op de vier locaties met een onderscheid in oversteekrichting.

3.1.2 Oversteekgedrag

Alle interacties werden geanalyseerd en gebaseerd op de verkeersregels – gaat de weggebruiker die voorrang heeft eerst – en de manier van oversteken – neemt de weggebruiker die eerst gaat initiatief – werden de volgende vier types oversteekgedrag gedefinieerd (Tabel 1):

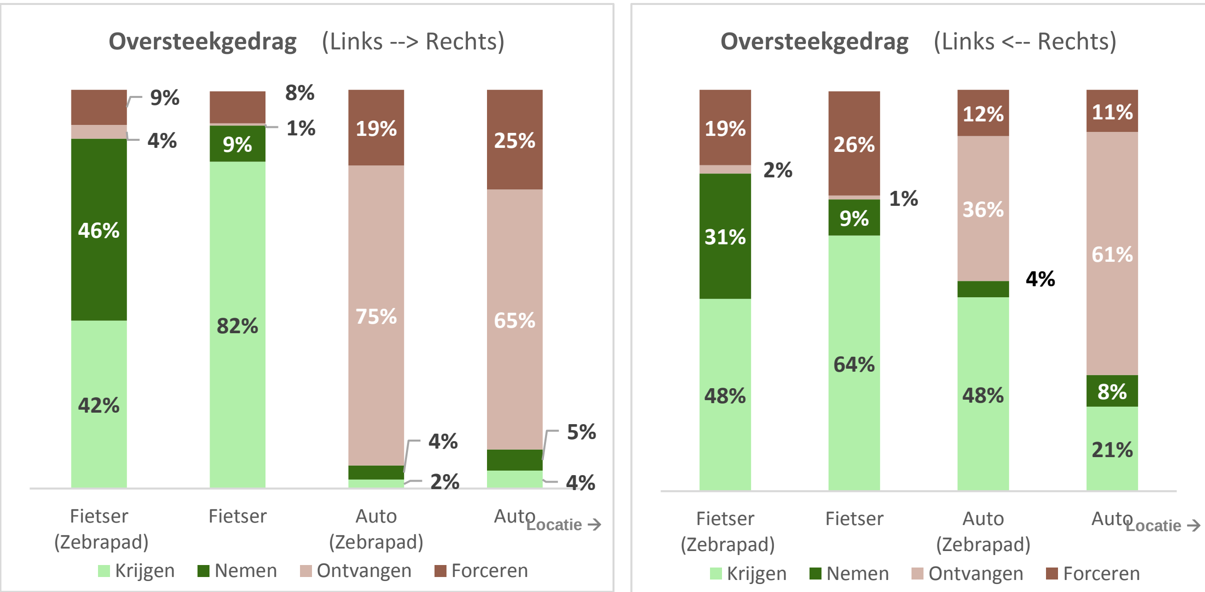
- *Nemen*: De weggebruiker die voorrang heeft, gaat eerst en dwingt zijn voorrangsrecht af.
- *Krijgen*: De weggebruiker die voorrang heeft, steekt als eerste over zonder zijn recht op voorrang af te hoeven dwingen.
- *Forceren*: De weggebruiker die voorrang dient te verlenen dwingt de andere weggebruiker om te stoppen of stopt niet wanneer de weggebruiker met voorrang aan de oversteekvoorziening staat te wachten op een veilig moment om over te steken.
- *Ontvangen*: De weggebruiker met voorrang staat zijn recht om als eerste over te steken gewillig af. Voorbeelden om dit gedrag te herkennen zijn het signaleren met groot licht door bestuurders van motorvoertuigen of fietsers die gebaren dat de motorvoertuigen eerst kunnen gaan. Ook al is dit gedrag defensief, in deze situaties wordt de voorrangsregeling niet nageleefd.

Tabel 1: De vier types van voorrangsgedrag gedefinieerd in dit onderzoek.

↓ Voorrangsregeling opgevolgd \ Stijl →	*Offensief*	*Defensief*
Ja	Nemen	Krijgen
Nee	Forceren	Ontvangen

Op locaties met fietsers in de voorrang gaat in 84% van de gevallen de fietser eerst. Opmerkelijk is dat op locaties met voorrang voor bestuurders van motorvoertuigen dit percentage gelijkaardig is (82%). Daarnaast is de verdeling tussen offensief en defensief gedrag van de fietsers wanneer zij als eerste oversteken gelijk bij beide voorrangsregelingen (13% en 87% respectievelijk). Figuur 5 geeft de resultaten weer wanneer een onderscheid gemaakt wordt in de oversteekrichting. De kleuren duiden aan dat de voorrangsregeling wel (groen) of niet (rood) gerespecteerd werd, de tinten of dit defensief (lichter) of offensief (donkerder) gebeurde. De volgende observaties gemaakt worden:

- Fietsers
    - gaan eerst in de meerderheid van de gevallen, ongeacht de voorrangsregeling;
    - gaan vaker eerst als ze van links naar rechts oversteken;
    - vertonen vaker defensief dan offensief gedrag als ze als eerste oversteken (met uitzondering van locatie ‘Fietser’ in de richting van links naar rechts).



Figuur 5: De types van oversteekgedrag op de vier locaties.

3.1.3 Richting van aankomst

De bevindingen van zowel het afremgedrag als het oversteekgedrag suggereren dat de resultaten van de locatie ‘Auto (Zebrapad)’ enigszins afwijken wanneer de oversteekrichting van rechts naar links overwogen wordt, aangezien hier de bestuurders van motorvoertuigen in de meerderheid van de gevallen als eerste oversteken. Een mogelijk verklaring hiervoor is dat ruim 68% van de fietsers die in deze richting oversteekt de oversteekvoorziening vanuit richting ‘3’ (Figuur 3, rechts) nadert. Dit percentage is hoger in vergelijking met de andere locaties (27%, 17% en 0%). Bestuurders van motorvoertuigen verwachten mogelijk niet dat fietsers uit deze richting kunnen arriveren en zoeken daarom niet actief naar hun mogelijke aanwezigheid. In minder dan de helft van de gevallen remmen zij zichtbaar af om de fietser eventueel eerst over te laten steken. Fietsers daarentegen naderen de fietsoversteekplaats veel voorzichtiger (ruim 80 procent remt af), mogelijk zich bewust van het feit dat ze over het hoofd gezien worden door aankomende automobilisten. In bijna alle gevallen dat de automobilisten eerst gaan, verlenen de fietsers dan ook (correct) voorrang.

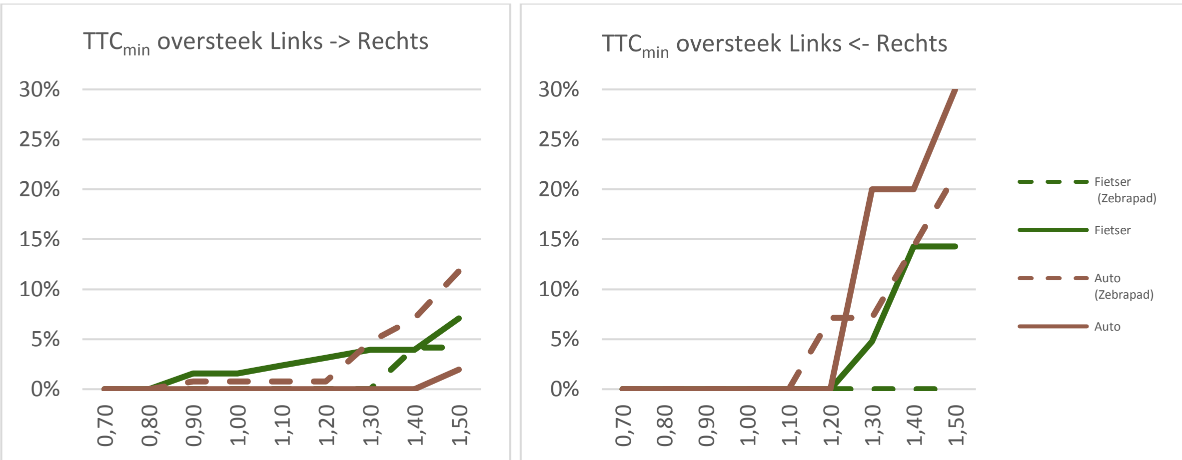
3.2 Verkeersconflicten analyse

De verkeersveiligheidsevaluatie maakt gebruik van twee indicatoren die gebaseerd zijn op de *'Time-to-Collision'* (TTC). De TTC geeft de tijd weer die overblijft totdat twee weggebruikers met elkaar zullen botsen, indien hun snelheid en richting onveranderd blijft (Hayward, 1972). De TTC is een continue waarde zolang beide weggebruikers zich op een botskoers bevinden. De twee meest voorkomende methodieken om de relevante waarde te selecteren zijn als volgt:

- *TTC_{min}*: De DOCTOR techniek gebruikt de minimale waarde van de TTC om de conflicternst vast te stellen (Kraay et al., 2013). Binnen de stedelijke omgeving wordt een waarde van minder dan 1.50 seconden als kritiek beschouwd.
- *Time-to-Accident (TA-waarde)*: De Zweedse Verkeersconflicttechniek (Hydén, 1987) is gebaseerd op de TTC-waarde op het moment dat de weggebruikers een ontwijkende actie uitvoeren. De conflicternst wordt bepaald aan de hand van de TTC-waarde en de snelheid op het moment van de start van de ontwijkende actie, waarbij een ernst-level wordt toegekend (Svensson, 1998). In dit onderzoek is level 24 als grens tussen ernstige en niet ernstige conflicten aangehouden (een hogere waarde betekent een ernstiger conflict).

3.2.1 TTC_{min}

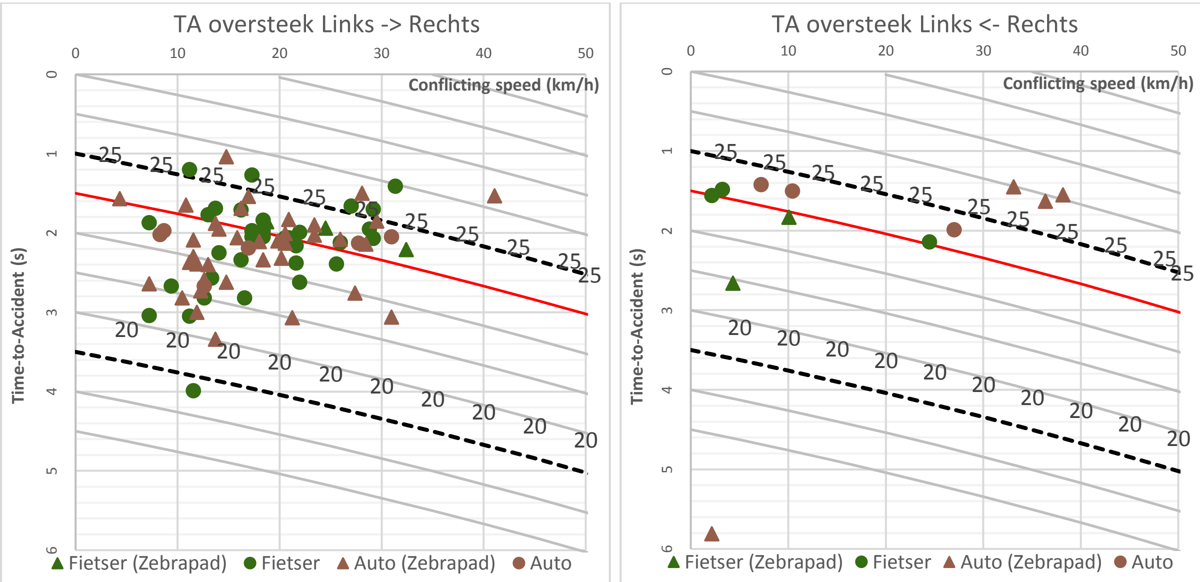
Van de in totaal 1366 interacties kon voor 387 situaties een TTC-waarde berekend worden (in de overige 979 situaties bevonden de weggebruikers zich niet op een botskoers). Het aantal ernstige conflicten (TTC_{min} < 1.50 secondes) was lager dan 15% op alle locaties en bedroeg 23 in totaal. Een effect van de voorrangsregeling op de veiligheid van fietsers werd enkel zichtbaar indien de oversteekrichting in beschouwing werd genomen. Het percentage ernstige conflicten voor de richting van rechts naar links was hoger voor locaties met voorrang voor bestuurders van motorvoertuigen (Figuur 6). Voor de oversteekrichting van links naar rechts werd geen invloed van de voorrangsregeling gevonden.



Figuur 6: De cumulatieve distributies van de conflicten geïdentificeerd door de TTC_{min} indicator. De figuren laten enkel het bereik van de kritieke waarden zien (TTC_{min} < 1.50 seconden).

3.2.2 Time-to-Accident

Van de 387 conflicten kon voor 93 events (24%) een ontwijkende actie van één van de weggebruikers vastgesteld worden. Figuur 7 geeft de conflicten gebaseerd op oversteekrichting weer, waarbij de rode lijn het grensniveau tussen lichte en serieuze conflicten aangeeft (level 24). Conflicten boven deze lijn zijn gedefinieerd als 'ernstig'. Het totaal aantal conflicten is vele malen lager dan het aantal conflicten dat geïdentificeerd werd door de TTC_{min} indicator. Dit is waarschijnlijk te wijten aan het feit dat in vele gevallen de bestuurder van het motorvoertuig voor de bocht en de invoegmanoeuvre zijn snelheid diende te verminderen, in plaats van het uitvoeren van een ontwijkende actie om een aanrijding met de fietser te voorkomen. Ongeveer de helft (N = 43) van de TA-conflicten werd als ernstig bestempeld (level ≥ 24). De drie meest ernstige conflicten (level 26) werden gevonden op locaties met voorrang voor bestuurders van motorvoertuigen. In lijn met de bevindingen van de TTC_{min} werd ook hier vastgesteld dat het percentage ernstige conflicten in de oversteekrichting van rechts naar links voor locaties met voorrang voor bestuurders van motorvoertuigen het hoogste was.



Figuur 7: Conflicten op de vier locaties geïdentificeerd door de TA-waarde.

4 Conclusies en aanbevelingen

4.1 Bevindingen

Deze studie onderzocht het voorrangsgedrag tussen fietsers en bestuurders van motorvoertuigen op fietsoversteekplaatsen op bypasses aan verkeerslichtengeregelde kruispunten. De resultaten laten zien dat, ongeacht de voorrangsregeling, fietsers in de ruime meerderheid van de gevallen als eerste oversteken wanneer zij gelijktijdig aankomen met bestuurders van motorvoertuigen (> 82%). Deze bevinding lijkt in lijn met het onderzoek van De Ceunynck e.a. (2015), die een vergelijkbare trend observeerden bij fietsoversteekplaatsen op rotondes. Het hoge aantal interacties waarbij bestuurders van motorvoertuigen hun recht om als eerste over te steken vrijwillig afstaan (> 70%) suggereert dat er mogelijk een informele voorrangsregeling op fietsoversteekplaatsen op bypasses wordt toegepast, waarbij de fietser ongeacht de geldende regels meestal als eerste mag oversteken. Hoe deze informele voorrangsregeling tot stand is gekomen, is niet duidelijk. Er kan sprake zijn van een algemeen voorzichtige houding tegenover kwetsbare weggebruikers of zelfs van hoffelijkheid van bestuurders, maar mogelijk spelen ook onzekerheid of een gebrek aan kennis over de geldende voorrangsregels een rol. Allicht wordt deze onzekerheid versterkt doordat de voorrangsregels of de manier waarop deze worden aangeduid verschillen van kruispunt tot kruispunt.

4.2 Dienstorder AWV 17 oktober 2014

Op 17 oktober 2014 werd er door het AWV een dienstorder uitgevaardigd met betrekking op de markering van fietsoversteekplaatsen op gewestwegen (AWV, 2014). Het dienstorder stelt dat op fietsoversteekplaatsen op bypasses geen blokmarkeringen toegepast mogen worden indien er zich direct naast de oversteekvoorziening een zebrapad bevindt. Daarnaast bepaalt het dienstorder dat een blokmarkering voor een fietsoversteekplaats nooit met een rode kleur mag worden ingekleurd en dat als fietsers in de voorrang zijn, het fietspad zowel voor en na de fietsoversteek één aaneengesloten geheel moet vormen. Volgens dit dienstorder voldoen drie van de vier testlocaties niet aan de basisprincipes die daarin werden vastgelegd.

4.3 Aanbeveling

De veiligheidsevaluatie kon niet concluderen dat het ene type voorrangsregeling (fietsers voorrang bij het oversteken) veiliger is voor fietsers dan de andere regeling waarbij het afslaande gemotoriseerde verkeer voorrang heeft. Uit de verkregen resultaten blijkt wel dat fietsers het vaakst als eerste oversteken, ongeacht de geldende voorrangsregel. Het is mogelijk dat hier sprake is van hoffelijkheid van bestuurders van motorvoertuigen, maar het gebrek aan consistentie in vormgeving en uniformiteit in de toepassing van de voorrangsregeling kan ook tot verkeerde verwachtingen leiden. Het is belangrijk dat de betrokken weggebruikers weten welk gedrag van hen verwacht wordt om te voorkomen dat beiden erop rekenen dat de ander zal afremmen of stoppen, wat tot gevaarlijke situaties kan leiden. Om onzekerheid bij weggebruikers zoveel mogelijk te beperken bevelen we aan om de voorrangsregeling op bypasses en kruispunten in het algemeen zo gelijk mogelijk te maken: of fietsers of bestuurders van motorvoertuigen in de voorrang in plaats van afwisselende voorrangsregelingen tussen locaties. Onze resultaten lieten niet toe om te stellen welke regeling de voorkeur verdient. Regelgevers en ontwerpers moeten beseffen dat het feitelijke voorrangsgedrag bij fietsoversteken relatief los lijkt te staan van de formele, ter plaatse geldende, voorrangsregels. Om de onzekerheid bij weggebruikers verder te beperken, bevelen we ook aan om de huidige regelgeving met betrekking tot markering, inclusief het AWV-dienstorder van 17 oktober 2014, consequent toe te passen op zowel bestaande als toekomstige kruispunten.

Yielding behavior and traffic conflicts at cyclist crossing facilities on channelized right-turn lanes (extended version of the Dutch report)

Summary

Channelized right-turn lanes (CRTLs) are a means of improving traffic flow efficiency, enabling right-turning drivers to bypass traffic lights at signalised intersections (for right-hand drive countries). In many cases, crossing facilities for pedestrians and cyclists are placed on these right-turn lanes. Previous studies examining the safety performance of CRTLs indicate that they increase overall safety levels but hint that certain issues regarding vulnerable road users may still exist. This study investigated these safety issues through site-based observations of yielding behaviour and the effect of the priority rule on cyclists' safety in two CRTL designs. Four locations in Belgium were selected: two where the priority rule favoured cyclists and two where motorists had priority.

The four locations were videotaped unobtrusively over one week. With regard to yielding, four types of crossing behaviour were identified and defined. The video data shows that, independent of the priority rule, cyclists crossed the conflict zone first in most interactions using a defensive crossing style. A model was developed, which indicates that when a cyclist, rather than a moped rider (allowed at cycling infrastructure in Belgium), arrives from the left at the cyclist crossing, it will be more likely that the cyclist crosses first. Road users who slow down have a lower probability of crossing first. A safety evaluation was performed using two traffic conflict indicators (TTC_{min} and the TA value). High correlations between the two indicators were found ($r^2 > 0.83$), but no conclusions about the safest priority rule for cyclists could be drawn. The results hinted, however, that locations with motorist priority and crossings from right to left (from the driver's point of view) yielded the highest number of safety critical events.

1 Introduction

Several right-turn treatments exist to improve traffic flow efficiency at signalised intersections. Examples include exclusive right-turn lanes, right-turn-on-red rules and channelized right-turn lanes (CRTLs) (AASHTO, 2011). The latter offers drivers a more comfortable right-turn movement by allowing them to bypass traffic lights and stop only when it is really necessary. In many cases, these treatments include crossing facilities for cyclists as well, but their design varies between intersections. In general, two types of cyclist crossings at CRTLs can be distinguished, one where cyclist crossings are located at the entrance and the exit of the CRTL and another where the cyclist crossings is at the centre of the CRTL (Figure 1). The main difference between the two configurations is that when there are crossings at both the entrance and exit, these are usually unidirectional, while a crossing facility at the centre of the turning lane allows cyclists and mopeds to cross in both directions. CTRL design guidelines and regulations are not clear as to which configuration should be used in which situations, and clear rules are lacking regarding how priority rules in centre-crossing designs should be applied. As a result, there is no uniformity in CRTL design; this creates unclear and possibly unsafe situations for cyclists and motorists. To our knowledge, no international literature has investigated the influence of priority rules on yielding behaviour and cyclists' safety at cyclist crossings in CRTLs. Therefore, and on request of the Flemish Road Agency, this research aims to determine which priority rule for the centre-crossing design is safest for cyclists.

According to Potts et al. (2013), many transportation agencies perceive CRTLS improve traffic safety levels, but quantitative data supporting this statement is limited. Most studies investigating the safety performance of CRTLs have focused on motorists and the comparison of right-turn treatments. For example, Dixon et al. (1999) compared intersections with shared through lanes (one lane accommodating traffic both going straight and turning right) and right-turn lanes with and without raised islands in Georgia (USA) and found that the presence of traffic islands decreased the number of right-angle crashes. Fitzpatrick et al. (2006) conducted a similar study in Texas (USA) and concluded that shared through lanes experienced fewer crashes than right-turn lanes. A Belgian study evaluated 1,295 crashes at 87 signalised intersections and concluded that intersections with CRTLs are less prone to accidents (Polders et al., 2015). However, an increase in the number of rear-end collisions was found; this was attributed to yielding behaviour towards vulnerable road users and searching behaviour for an appropriate gap to merge into the traffic stream. Autey et al. (2012) compared two types of CRTL designs in Canada and concluded, based on traffic conflict observations, that sharper turning angles at the convergence point yield increasingly severe potential dangerous situations.

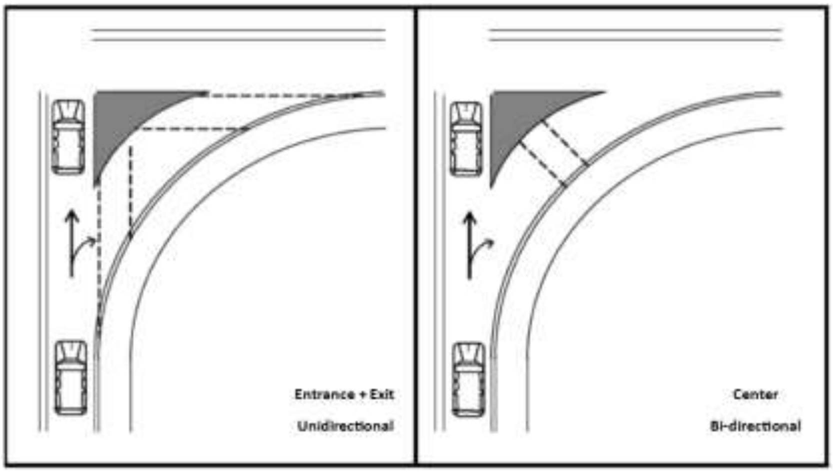


Figure 1: The two configuration types of accommodating vulnerable road users on CRTLs (modified from Potts et al., 2011). Although these diagrams were created for pedestrian crossings, they apply to cyclist facilities as well.

Scientific research focusing on cyclists' and pedestrians' safety issues in CRTLs is limited. Several studies suggest that conflicts between motorists and vulnerable road users may occur because drivers focus mainly on motorists driving on the road that they are about to turn onto rather than on pedestrians and cyclists (Fitzpatrick et al., 2006; Polders et al., 2015; Potts et al., 2011; 2013). In these cases, drivers may see approaching vulnerable road users but are unable to detect them, succumbing to the "looked-but-failed-to-see" error (Herslund & Jørgensen, 2003). Additional problems occur on bidirectional crossings because drivers might not expect cyclists to arrive from their right-hand side. Potts et al. (2013) compared conventional right-turn lanes, share through lanes and CRTLs and found that conventional right-turn lanes experienced 70-80% more pedestrian crashes; however, no differences were found between the other two right-turn treatment types. Sayed et al. (2013) conducted a video observation study in Canada that investigated both motorists' and cyclists' safety and found that cyclists' safety was mostly threatened by motorists ignoring yield signs and blocking the cyclist crossing facility.

2 Objective

Previous studies have focused on the road safety performance of channelized right-turn lanes with regard to motorised road users. However, little is known about safety issues for vulnerable road users. The present study is designed to identify the behavioural responses of drivers and cyclists during the yielding process at CRTLs. The main objective of this study is to improve understanding of cyclists' safety in this type of infrastructure, focusing specifically on the priority rule. For this purpose, real-world observations were conducted to assess yielding behaviour and to study traffic conflicts dependent on the priority rule. For brevity, when we refer to cyclists, this group also includes moped riders unless otherwise stated.

3 Methodology

Although accident data is natural and the most commonly used source for safety evaluation, it has several recognised disadvantages, underreporting being a very important one. Particularly with regard to pedestrian and cyclist crashes, there is a larger underreporting rate compared to crashes involving other modes of transport (OECD, 1998). Furthermore, because accidents are rare in occurrence, a proper safety evaluation requires many years of accident data in order to (paradoxically) prevent accidents from happening, and this data may not always be available. Therefore, traffic conflict techniques and other surrogate measures of safety have been used to evaluate traffic safety based on events that precede accidents, are observable and occur more frequently. These traffic conflicts are defined as situations in which two or more road users will collide *'if their movements remain unchanged*' (Amundsen and Hydén, 1977). Although the validity of traffic conflict techniques has not yet been fully determined, empirical evidence suggests a statistically significant correlation between the frequency of traffic conflicts and accidents (e.g., Hydén, 1987; Svensson, 1998; Sayed and Zein, 1999; El-Basyouny and Sayed, 2013). Furthermore, Autey et al. (2012) and Sayed et al. (2013) have demonstrated the usefulness of traffic conflict observations for safety evaluations at CRTLs (but focused on motorised road users). For these reasons, traffic conflict observation was chosen as a means of safety evaluation.

A database containing the locations of around 300 intersections constructed with at least one CRTL was made available by the Flemish Road Agency (AWV). By considering the configurations (Figure 1) and design elements (intersection crossing angle, form of the curve, speed limits, raised platforms, zebra crossings), four locations were selected for a cross-sectional research design, all containing a bidirectional cyclist crossing facility. All locations had no raised platforms and accommodated cyclists crossing in both directions. Two locations included a zebra crossing, where pedestrians are required to cross the CRTL (for locations without a zebra crossing, pedestrians have to use the cyclist crossing facility). For both pairs (with a zebra crossing and without), one gave cyclists priority and the other gave motorists priority using yielding signs and shark's teeth yielding lines. Two intersections were located in the municipality of Geel (province of Antwerp) and the other two in Beringen and Diepenbeek (province of Limburg). At each location, two video cameras were used to observe yielding behaviour. One of the cameras was located at the approaching leg, approximately 50 meters from the cyclist crossing; this enabled the capture of relevant road users' approaching behaviour. The second camera was mounted closer to the crossing facility in order to gather accurate distance and speed measurements (Figure 2). Data was collected between the 11th and 17th of June 2015 during daytime hours (06:00 – 21:00), covering five working days and one weekend.

C (Z) | C | M (Z) | M

Figure 2: Screenshots from the cameras closest to the crossing facilities at the four locations. Locations are named based on priority rule (cyclists (C) or motorists (M) have the right-of-way) and the presence of a zebra crossing (Z).

The video data was manually reviewed and then processed using the semi-automated video analysis tool T-Analyst (Laureshyn, 2014), developed at Lund University. This software transforms image coordinates of pixels to road plane coordinates, lets the user manually annotate the road users' trajectories, which enables the accurate calculation of speeds and distances. From these, the software calculated the traffic conflict indicators in an accurate and objective manner based on motion prediction at constant speed and direction.

3.1 Traffic Events

With regard to traffic events, the classification depicted in Figure 3 is taken from the road safety hierarchy popularised by Hydén (1987). The figure provides a schematic overview of the relative frequency in which these different events occur, but it does not represent accurate proportions. The different event types can be described as follows:

- The '*all traffic events*' category represents all situations in which at least one road user is present at the CRTL crossing facility.
- Situations in the 'all traffic events' category in which two road users were simultaneously present near the crossing facility were labelled *'passages'*. 'Simultaneously' in this study is defined as the motorist being captured on the camera closest to the crossing facility and the cyclist being within 10 meters of the centre of the crossing facility at the time of the motorist's approach. This event type includes situations in which the cyclist crossed the projected path of the motor vehicle (defined as *'interactions'* and described below), as well as situations in which the cyclist did not cross the path of the motor vehicle ('*no crossing' events,* the dashed arrow in Figure 3, right). The inclusion of 'no crossing' events allowed the examination of situations in which approaching drivers unnecessarily (intend to) yield to cyclists that do not cross.
- All 'passages' in which cyclists and motorists cross at the crossing facility simultaneously are labelled *'interactions'* (the solid arrow in Figure 3, right). During these events, drivers and cyclists need to react to and/or communicate with each other in order to cross safely.
- *'Conflicts'* are interactions that comply with the general international definition proposed by Amundsen and Hydén (1977): *'An observable situation in which two or more road-users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged'*.
- *'Accidents'* are conflicts that result in the collision of two or more road users.

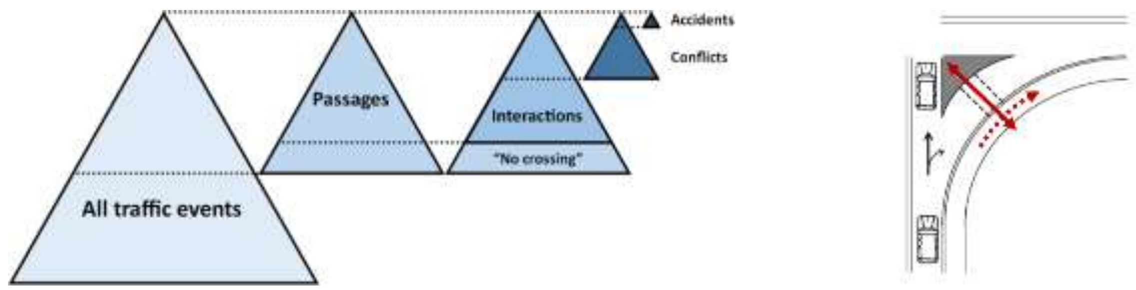


Figure 3: On the left, the types of traffic events defined in this study. The pyramids do not represent actual proportions, but merely provide a schematic indication of relative frequency. On the right, the difference between 'interactions' (solid arrow) and "no crossing" (dashed arrow) (modified from Potts et al., 2011).

3.2 Yielding Behavior

Yielding behaviour was analysed using two approaches. The first approach focused on the slowing down behaviour of the involved road users, which was considered as an indication that one or both road users were prepared (either willingly or forcibly) to let the other road user cross first. The second approach focused on the crossing style used by the road user that crossed first, based on priority rule compliance and the approaching behaviour of the road users involved. The following provides a short description of the two methods:

- *Slowing down behaviour*: All passages were used to determine which road user slows down during their approach to the crossing facility at the CRTL. The analysis distinguished between 'no crossing' events and interactions because these are two different types of events. During 'no crossing' events, cyclists and motorists are not on a collision course and will therefore never collide as long as they continue on their planned path. In contrast, the risk of a collision is present during interactions. 'No crossing' events, however, can provide an indication as to whether approaching drivers anticipate the possibility that a cyclist will cross and therefore proceed with increased caution.

- *Crossing behaviour*: Because crossing is a prerequisite for the analysis of crossing behaviour, interactions rather than passages were analysed. The classification of yielding behaviour proposed by Van Minnen and Braimaister (1994) was used and modified to describe crossing behaviour. Based on rule compliance (*'Does the road user that has priority go first?')* and crossing style (*'Does the road user that went first take the initiative?')*, the following four types of yielding behaviour are defined (Table 1):
    - *Taking*: The road user that has priority goes first while forcing the other road user to let them go first. Two types of this behaviour can be distinguished:
        - Both road users will arrive at the crossing facility simultaneously if they maintain their approaching speed. The prioritised road user is not slowing down, forcing the other road user to reduce their speed.
        - The prioritised road user arrives at the crossing facility and stops for some reason. The road user then decides to cross by starting to move again while another road user is approaching.
    - *Getting*: The road user that has priority goes first without forcing right-of-way. This type of defensive crossing occurs in the following situations:
        - The road user that should yield has time to pass the crossing facility before the prioritised road user arrives but slows down and/or stops to yield anyway.
        - Both road users will arrive at the same time at the crossing facility, and the road user that should yield slows down and/or stops willingly. In order to distinguish between 'getting' and 'taking', the difference between willingly or forcibly stopping was defined by the moment when the motorist passed the start of the (right-turn) curve (if slowing down happened before this point, it was defined as willingly yielding).
        - The road user that has priority is waiting at the crossing facility for an opportunity to cross. The approaching road user that should yield reduces speed and/or stops to yield.
    - *Forcing*: The road user that should yield does not slow down or stop to yield, either forcing the other road user to stop or failing to stop when the prioritised road user is waiting for a safe opportunity to cross. This type of crossing behaviour is considered to be offensive.
    - *Receiving*: The road user that has priority willingly gives it away. Examples of indicating this behaviour include the flashing of headlights by drivers or a cyclist waving a driver to pass first. Although this crossing type is considered defensive, it violates the priority rule.

Table 1: The four types and characteristics of yielding defined in this research

↓ Rule compliance \ Style →	***Offensive***	***Defensive***
Yes	Taking	Getting
No	Forcing	Receiving

3.3 Traffic Conflict Analysis

Two conflict indicators were used to determine cyclists' safety at CRTL crossing facilities. Both indicators were applied for all identified conflicts and compared afterwards. The indicators included in the comparison are based on the time-to-collision:

- *Time-To-Collision*: Based on the assumption that two or more road users are on a collision course (i.e., they will collide if their movements remain unchanged), the time-to-collision (TTC) represents the time that is left until a collision will occur if all involved road users maintain their current speed and direction (Hydén, 1997). The TTC is a continuous variable as long as road users are on a collision course. The two most common methodologies for selecting a relevant TTC-value for a conflict are:
    - TTC_{min}: The DOCTOR technique proposes using the minimum value of the TTC as a measure for conflict severity. Within urban environments, TTC_{min} values less than 1.50 seconds represent safety critical situations according to this method (Kraay et al., 2013).
    - *Time-To-Accident (TA value)*: The Swedish Traffic Conflict Technique (Hydén, 1987) is based on the TTC-value at the moment that road users perform evasive actions in order to avoid a collision. Conflict severity is determined by allocating a severity level, based on the conflicting speed, at the same moment, and the identified TTC value. The thresholds between safety levels are formed by braking curves. Svensson and Hydén (2006) proposed the categorisation of conflicts into highest severity (> 25), fairly high severity (20-25) and lower severity (< 19). However, they also indicated that for conflicts involving vulnerable road users, a lower threshold could be used because vulnerable road users have lower speeds and are often the first to take evasive action, resulting in systematically lower scores (Svensson, 1998; Laureshyn et al., forthcoming). Therefore, conflicts with a severity of level 24 or higher are considered serious in this research.

4 Results

4.1 Yielding Behavior

4.1.1 Slowing down behavior

The reduction of speed was taken as an objective measure to determine if a road user was prepared, either willingly or forcibly, to let the other road user go first. All passages were observed in order to determine which road user slowed down. Because at three locations the majority of the cyclists crossed from left to right (from the perspective of the approaching driver), this was labelled as the dominant crossing direction. To analyse slowing down behaviour, the following three types of situations were assessed separately:

- 'No crossing' events (according to the description in section 3.1)
- Cyclists and mopeds crossing from left to right (dominant crossing direction)
- Cyclists and mopeds crossing from right to left (secondary crossing direction)

During conflicts in which motorists crossed first, it was not clear if the approaching driver reduced their speed to negotiate the curve of the CRTL, to carefully merge with other traffic at the end of the lane or because they noticed the cyclist. Therefore, speed profiles (based on a measurement every 0.2 seconds) were examined visually. If drivers showed a sudden rather than smooth increase in speed reduction at a certain point during their braking manoeuvre, they were categorised as slowing down for the approaching cyclist.

Table 2 provides an overview of the sample sizes at the different locations with regard to the amount of 'no crossing' events and interactions (see description under 3.1). 'No crossing' events were rare at two of the four locations (four events or less). It seems, however, that drivers approach the cyclist crossing facility with more caution in case cyclists are in priority (52% versus 28% of precautionary yielding situations).

Table 2: Descriptive analyses of the possible yielding events and the distribution of crossing directions

Location	"No crossing" events		Interactions		
			Crossing direction		Total
	Total (#)	Unnecessary yield (#)	L → R (#)	L ← R (#)	
C (Z)	4	3	58	59	117
C	103	54 [52%]	330	225	555
M (Z)	385	109 [28%]	397	145	542
M	2	2	116	36	152
Total (n)	494	168	901	465	1366

Slowing down behaviour during all interactions is presented in Figure 4. The graph illustrates which percentage of interactions the drivers and cyclists reduced their speed for each other. The χ^2 test of independence was used for the following important observations:

- The proportion of drivers who slowed down was significantly higher than those of cyclists (dominant crossing direction: χ^2 = 83.105, df = 1, p = .000; secondary crossing direction: χ^2 = 77.464, df = 1, p = .000).
- A higher proportion of drivers slowing down was found in events where cyclists crossed in the dominant direction compared to events in which cyclists arrived from the right side (χ^2 = 162.203, df = 1, p = .000).

- Cyclists reduced their speed more often when crossing in the secondary direction compared to the dominant crossing direction (χ^2 = 105.818, df = 1, p = .000).
- The proportion of road users that reduced their speed appeared to be independent of the priority rule (χ^2 = 0.068, df= 1, p = .418 for cyclists slowing down and χ^2 = 0.013, df= 1, p = .482 for motorists slowing down).
- The M (Z) location yielded very different results when cyclist crossings occurred in the secondary direction. The proportion of cyclists slowing down was higher than in the other locations and in comparison to the proportion of motorists slowing down. This might be explained by the fact that in 68 % of the interactions in which cyclists crossed from right to left, the cyclist arrived at the crossing facility while cycling in the opposite (and illegal) direction. Drivers might not expect cyclists to arrive from that direction and therefore may not actively look for them. At the same time, because they cycle in this illegal direction, cyclists might approach with more caution, resulting in more frequent slowing down behaviour.

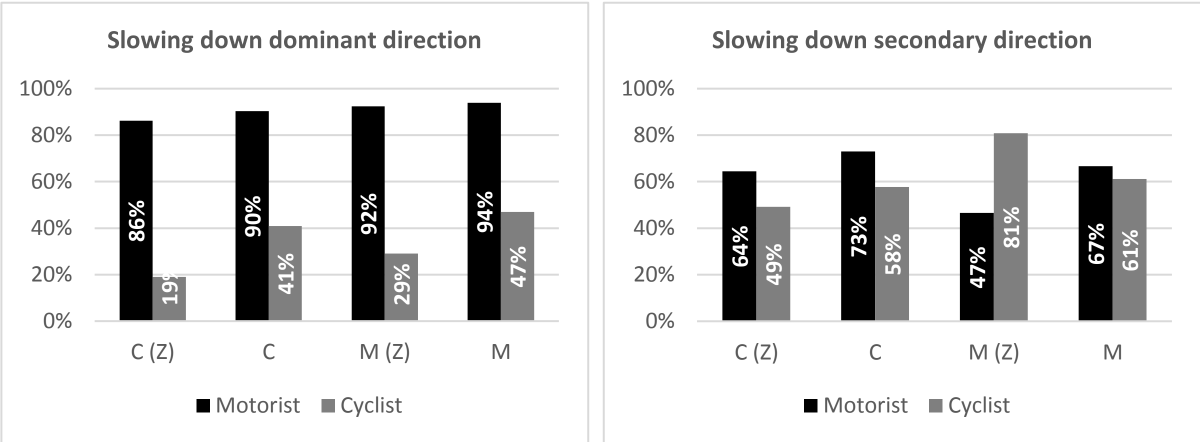


Figure 4: The slowing down rates for all locations, distinguished in crossing direction (dominant: left -> right and secondary: left <- right)

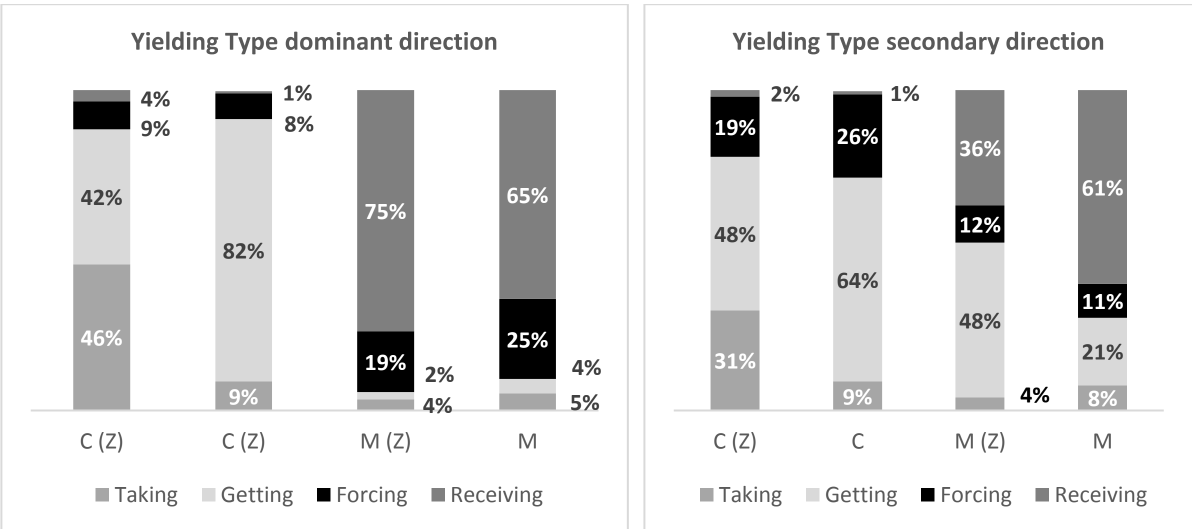


Figure 5: The yielding types for all locations. 'Taking' and 'getting' align with the priority rule

4.1.2 Crossing behavior

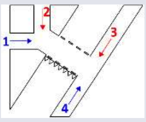
The type of crossing behaviour was analysed for all interactions based on the definitions formulated in section 3.2. Again, a distinction in crossing direction was made. The results of the analysis can be found in Figure 5. The following important observations were made:

- Independent of the priority rule or the crossing direction, cyclists crossed first in the majority of cases ('taking' and 'getting' for the C (Z) and C locations, 'forcing' and 'receiving' for the M (Z) and M locations), except for the M (Z) location.
- When crossings occurred in the dominant direction, cyclists crossed first more often than in situations in which they crossed in the secondary direction (χ^2 = 158.875, df = 1, p = .000).
- The proportions of cyclists' offensive crossing behaviour was higher when cyclists crossed in the dominant direction (χ^2 = 19.779, df = 1, p = .000).
- For three locations, cyclists used a defensive crossing style during events in which they crossed first.
- When cyclists crossed in the secondary direction, motorists forced priority (at C(Z) and Z) more often compared to cases when cyclists crossed in the dominant direction.
- The M (Z) location showed clearly different results when cyclists crossed in the secondary direction. The same issues that were discussed in the previous section may apply.

4.1.3 Model development

The χ^2 statistics were computed in order to determine which factors influenced the order of crossing. Because the descriptive statistics hinted that the direction from which the cyclist arrived at the crossing facility influenced who crossed first, the variable 'crossing direction' was transformed into 'direction of arrival'; four possible directions of arrival were identified. Table 3 provides an overview of the variables that were included in the analysis and whether or not they were found to be influential in a bivariate test. The priority rule, road-user types and cyclists crossing in a group or alone were not found to be associated with crossing order when considered separately.

Table 3: The chi square statistics of variables possibly influencing crossing order

Variable	Labels	Pearson χ^2	p-value
Priority	0 = Motorist, 1 = Cyclist	.0118	.9133
Zebra crossing	0 = no, 1 = yes	5.6814	.0171*
Arrival direction at the crossing facility (red indicates a violation of the traffic regulations)		214.4595	< .0001**
Motorists slows down	0 = no, 1 = yes	1096.2676	< .0001**
Cyclist slows down	0 = no, 1 = yes	263.7309	< .0001**
Cyclist in group	0 = no, 1 = yes	2.6646	.1026
Cyclist type	0 = moped, 1 = cyclist	2.3329	.1267
Motorist type	0 = car/suv, 1 = van/truck, 2 = other	1.6298	.4427

* p < 0.05 (significant at 95% CI), ** p < 0.01 (significant at 99% CI) level, n = 1362

Table 4: The binary logistic regression results for crossing order of cyclists and motorists at crossing facilities on channelized right-turn lanes. The model predicts the chance that the cyclist will cross first

Variables[a]	Estimate	Odds ratio	p-value
Intercept	-2.3335		0.0005***
Cyclists' arrival direction at crossing facility			0.0001
1: Left	1.4372	4.209	0.0008***
2: Top left	-0.6113	0.543	0.2556
3: Top right	1.0493	2.856	0.0528*
4: Bottom Right	Reference		
Motorist slows down			< 0.0001***
Yes	6.4853	655.463	
No	Reference		
Cyclist slows down			< 0.0001***
Yes	-2.7987	0.061	
No	Reference		
Cyclist type			0.0132**
Pedal cyclist	1.1479	3.152	
Moped	Reference		
Hosmer and Lemeshow test[b]	5.2003 (df = 5, p = 0.3919)		
Nagelkerke R^2[c]	0.8591		

***p < 0.01 (significant at 99% CI); **p < 0.05 (significant at 95% CI); *p < 0.10 (significant at 90% CI)
[a] Values present the parameter estimates of the logistic regression model. For categorical variables, the reference category is indicated.
[b] The Hosmer and Lemeshow goodness-of-fit test indicates a good fit for the developed model.
[c] The statistic indicates the error reduction of the model in percentages; e.g., 0.8591 is equal to an error reduction of 85.91%.

A binary logistic regression model was developed in order to predict which road user would cross first (1 was used for cyclists crossing first). Logistic regression models are used to predict the probability of a certain value of a categorical dependent variable. A backward stepwise procedure was utilised in SAS 9.4 statistical software and provided the results presented in Table 4. The final model indicates that in the majority of cases, slowing down behaviour by both types of road users significantly influenced crossing order. As expected, the probability for cyclists to cross first increased substantially if an approaching driver slowed down (odds ratio = 655.463), while he probability decreased if the cyclist reduced speed. With regard to the direction of approach, it was found that a cyclist had the highest probability of crossing first if they arrived from the left (highest odds ratio in comparison with the other directions). Furthermore, cyclists crossing from direction 3 were also more likely to cross first (odds ratio = 2.856).

4.2 Traffic Conflict analysis

4.2.1 TTC_{min}

A TTC value was calculated for a total of 387 events. For each conflict, the minimum value of the TTC was registered and then grouped into increments of 0.10 seconds. For all locations, the proportion of serious conflicts (based on a threshold level of 1.50 seconds) did not exceed 15 % of all conflicts and amounted to 23 events in total. Cumulative distributions were plotted but only revealed differences when there was a distinction in the crossing direction (Figure 6). Serious conflicts occurred more often when cyclists crossed in the secondary direction, but the most critical values were found for the dominant crossing direction (the lowest values found were 0.91 and 0.97 compared to 1.23 for the secondary crossing direction). The results suggest that when crossing occurred in the secondary direction, the proportion of serious conflicts was higher for situations in which cyclists should yield (more than 20%) compared to situations in which they have the right-of-way (less than 15%). However, this observation did not prove to be statistically significant ($\chi^2 = 0.774$, df = 1, p = .379) and is therefore only indicative.

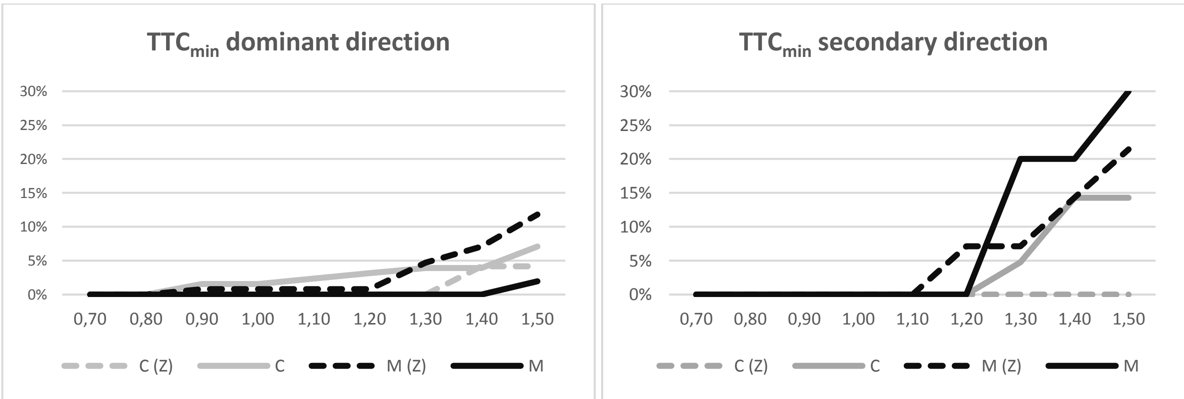


Figure 6: The cumulative distributions of the conflicts identified by the TTCmin indicator. The figures only show the cumulative distributions covering the serious conflicts (TTCmin < 1.50 seconds)

4.2.2 Time-To-Accident

In total, evasive actions for 93 conflicts were identified; the resulting conflicting speed and TA severity levels are plotted in Figure 7. In many cases, both road users performed an evasive action. For these situations, the severity level of the road user that produced the least severe conflict (the relevant road user) was selected (Shbeeb, 2000, p28). For half of the cases, the cyclist was identified as the relevant road user, with the exception of location C (30%). Roughly 50% of the observed conflicts had a severity level of at least 24, resulting in 43 serious conflicts in total. The most critical safety level found was 26, which occurred three times at a location where cyclists should yield. Similar to the findings of the TTC_{min} indicator, it was observed that the proportion of serious conflicts for the secondary crossing direction was higher compared to the dominant crossing direction (67% (9 out of 12) vs 43% (35 out of 81)), but that this difference was not significant ($\chi^2 = 2.313$, df = 1, p = .128). Higher proportions of serious conflicts for the secondary crossing direction were also found when only events with a severity level of at least 25 and 26 were considered (25% vs 10% and 17% vs 1%, respectively). It was also observed that with regard to the secondary crossing direction, only three serious conflicts were found for locations where cyclists have priority and six for locations where motorists have the right-of-way.

4.2.3 Comparison between conflict indicators

Due to their differing characteristics, the number of conflicts identified by the two indicators differed. The TTC_{min} can be calculated for every situation in which road users were (at some point) on a collision course, while the TA value can only be determined if at least one of the involved road users performed an evasive action. As a consequence, all conflicts with a TA value also had a TTC_{min} value, but the reverse was not true. In total, 93 out of the 387 events contained values for both indicators. The overlapping conflicts were examined in more detail in order to examine the relationship between the TA value and the TTC_{min} indicator. Figure 8 (left) presents a scatterplot containing the 93 conflicts and their corresponding TTC_{min} and TA values. Only five conflicts had identical values for both indicators; the remaining 88 conflicts had higher TA values (by an average of 0.23 s). This is expected (the minimum is smaller than the other TTC values, including TA): when an evasive action is taken, the involved road users still approach each other in both space and time. The effect of the evasive action is that the TTC value will reduce at a lower rate until a certain minimum is reached, and the TTC value will increase and eventually cease to exist when the collision course has been eliminated. Linear regression equations were created for both priority rules, showing high correlations between the two indicators ($r^2 > 0.83$).

Because the TA value does not directly relate to conflict severity (severity level is determined by the combination of the TA value and the driving speed at the start of the evasive manoeuvre), a second scatterplot showing the severity levels was created (Figure 8, right). In general, lower TTCmin values corresponded to higher severity levels, but the relationship between the two indicators is not entirely linear for the most critical safety events. Simple linear regression also indicated strong correlations between severity level and TTCmin values for both cyclist priority (r2 > 0.60) and motorist priority (r2 > 0.78).

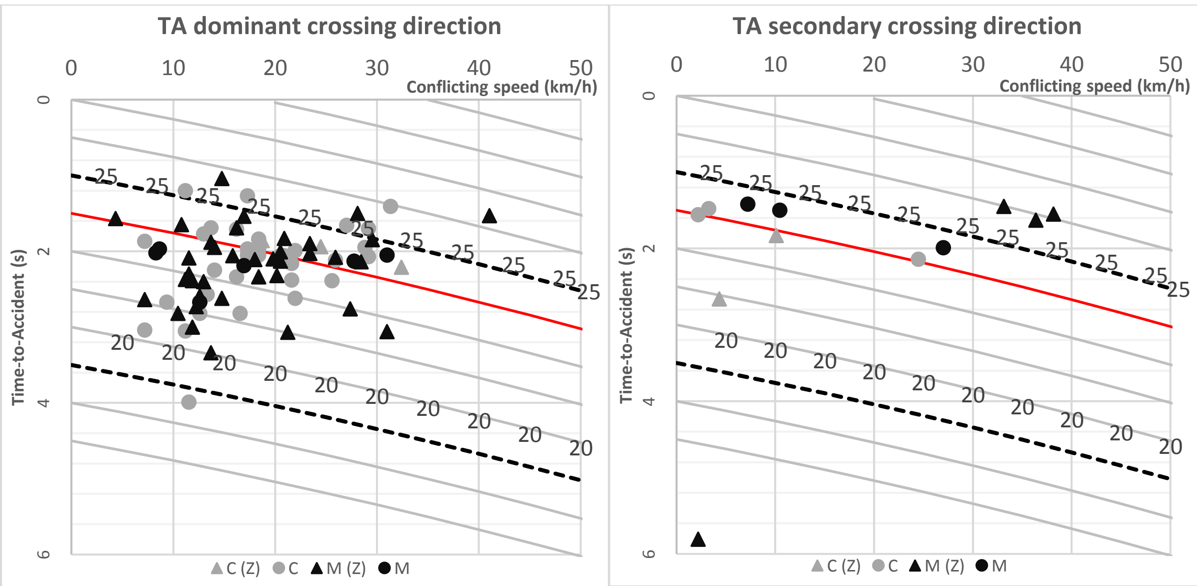


Figure 7: Conflicts identified by the TA-value, based on crossing direction. The red line indicates the threshold level between slight and serious conflicts (level 24)

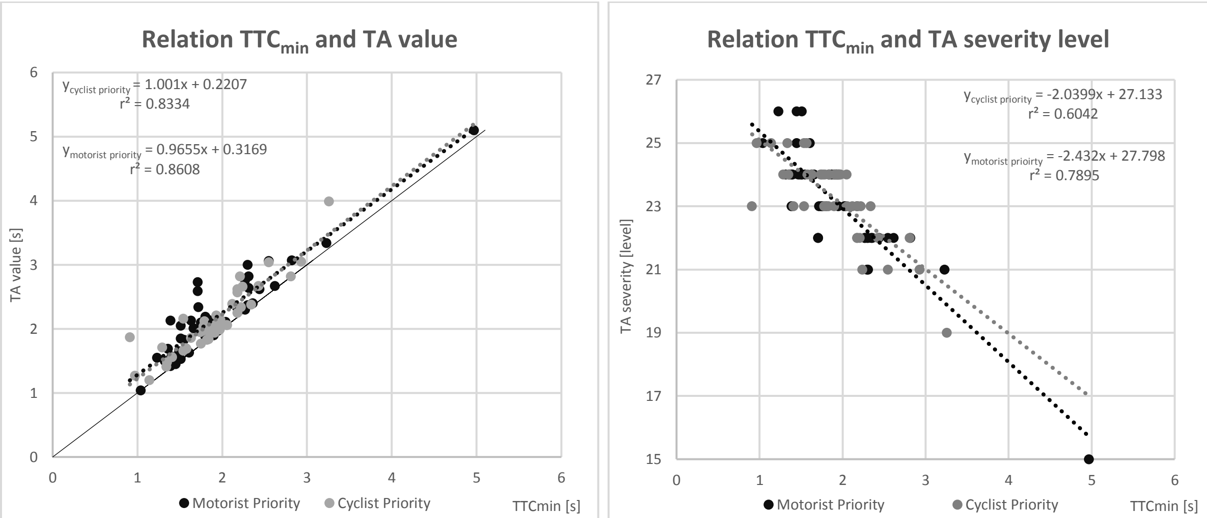


Figure 8: The values of the conflicts with the two indicators are compared (n = 93). TTCmin is compared with TA on the left and with the severity level on the right. Distinctions between motorist and cyclist priority is made and linear regression models are plotted. The equations for the models are depicted in the left and right corners of the graphs

4.2.4 Safety effect of priority ruling

The regression equations suggest that for the conflict events for which both indicators were calculated, high correlations between the TTC_{min} and TA value exist. Therefore, in order to evaluate the effect of the priority rule on cyclists' safety, a student t-test was performed. A statistically significant lower mean for locations with motorist priority at the 0.10 level was found ($t = -1.677$, $p = 0.094$), indicating that these locations yield more critical conflicts. A comparable analysis was run for the TA value, but no statistically significant influence was found ($F = 0.477$, $p = 0.635$).

5 Discussion

5.1 Yielding Behavior

The results show that cyclists cross first in the majority of cases, using a defensive crossing style. Even when motorists have the right-of-way, they willingly let the cyclist cross first. This observation is in line with the results of a Flemish study investigating yielding behaviour at roundabouts (De Ceunynck et al., 2015). Studies in the scientific literature regarding the yielding of motorists for cyclists at crossings where motorists have priority were not found; this limited the opportunity to determine if these high 'courtesy' yielding rates are only part of the Flemish driving culture or are common in other countries, as well. With regard to the observations of yielding behaviour at CRTLs with cyclist priority, no comparable studies were found. Sayed et al. (2012) identified the main safety issue for cyclists as motorists ignoring the yield sign, but this conclusion was based on the analysis of traffic conflicts only. No figures of interactions with (in)correct yielding behaviour were provided. A logistic regression model indicated that only the reduction in speed by the involved road users and being a cyclist or moped rider influenced the crossing order. Our finding that the probability of crossing first decreases when the road user reduces their speed is in line with the findings of other studies (e.g., De Ceunynck et al., 2012; Björklund & Åberg, 2005).

5.2 Safety evaluation

This study used the TTC_{min} and Swedish Traffic Conflict Technique to evaluate cyclists' safety at CTRL crossing facilities. The following aspects must be considered:

- The severity threshold selected to distinguish between slight and serious conflicts determines the number of serious conflicts identified. With regard to the Swedish Traffic Conflict Technique, the literature is not clear as to which severity level should be selected as the threshold level. Furthermore, most reported traffic conflict studies have focused on interactions between motorised road users, while vulnerable road users (including cyclists) have other capabilities to perform evasive actions. Shbeeb (2000), for example, pointed out that pedestrians can stop almost instantaneously, while motorised vehicles cannot. Pedestrians and cyclists are far more manoeuvrable and therefore are better able to avoid collisions. However, lowering the severity threshold from level 26 (suggested by Svensson and Hydén (2006)) to level 24 might mitigate the systematically lower severity scores created by the evasive actions of vulnerable road users (Svensson, 1998; Laureshyn et al., forthcoming). Comparable to a study of Laureshyn et al (forthcoming), a severity level 24 was selected as the threshold. It should be noted, however, that no other studies found by the authors used this severity level to distinguish between severe and slight conflicts. Therefore, caution is needed when our results are compared with other studies.
- Both safety indicators evaluate safety levels based on the involved road users being on a collision course. However, the occurrence of a collision course can be the result of the following situations (listed from the perspective of the driver, but also applicable from the perspective of the cyclist):
    1. The involved road users are on a collision course throughout their entire approach, resulting in the need for at least one of them to take an evasive action to avoid a collision.
    2. During the beginning of their approach, the involved road users are on a collision course. Because the driver has to take the right-turn curve and needs to (carefully) merge with traffic at the end of the right-turn lane, the driver reduces speed and thereby transforms the collision course into a crossing course well in advance of the crossing facility. In these cases, the initial speed reduction is not caused by the presence of the cyclist but by the curve and/or merging manoeuvre at the end of the right-turn lane. As a result, no evasive action is required of either road user.
    3. During the beginning of their approach, the involved road users are on a crossing course. Because the driver has to take the right-turn curve and needs to (carefully)

merge with traffic at the end of the right-turn lane, the driver reduces speed and thereby transforms the crossing course into a collision course. Presumably because he notices the cyclist, the driver continues to gradually reduce speed to let the cyclist pass first. In these situations, the evasive braking manoeuvre is not initiated but continued. The exact moment when braking becomes an evasive action is difficult to determine.

4. During the beginning of their approach, the involved road users are on a crossing course. Because the driver has to take the right-turn curve and needs to (carefully) merge with traffic at the end of the right-turn lane, the driver reduces speed and thereby transforms the crossing course into a collision course. In order to avoid collision, an evasive action by (one of) the road users becomes necessary (e.g. increasing rather than continuing braking force).

- One could argue that the TTC value is only relevant for situations 1, 3 and 4 because during these situations road users are on a collision course as part of their 'planned' movement through the CRTL. The avoidance of a possible collision in situation 2 is the result of the speed reduction needed for motorists to drive safely through the curve and merge with traffic at the end of the turning lane and not a reaction to the presence of the cyclist. With regard to the Swedish Traffic Conflict Technique, situation 3 poses difficulties because it is nearly impossible to determine the exact moment the approaching driver reacts to the cyclist by continuing the braking manoeuvre. However, one could raise the question here whether these 'type 3' events should be labelled as slight conflicts in any case because the 'start' of the evasive action was not influenced by the (detection of) the cyclist and no new (sudden) evasive action is commenced.
- The TTC_{min} indicator can be determined for all situations in which road users are (at some point) on a collision course, while the TA value requires evasive manoeuvres to detect and classify conflicts. As described in the previous point, evasive actions can only be detected in situations 1 and 4. This might explain why for only 93 out of 387 TTC_{min} events a TA value could be calculated.
- The TTC value evaluates what would have happened if both road users maintained their speed and direction. For many events in our safety evaluation, the selected TTC value (either TTC_{min} or TA) was selected when the road user was reducing its speed. Therefore, the TTC at this instant may over represent the overall severity.

5.3 Influence of Priority Ruling

Based on the findings, this study could not conclude which priority rule is safer for cyclists at crossing facilities at CRTLs. The study did show that yielding behaviour in the majority of cases occurred in a defensive manner and that for all locations the cyclist or moped rider crossed first in the majority of the cases, independent of the priority rule at that location. For situations in which cyclists crossed in the dominant direction (from left to right from the perspective of the approaching driver), motorists gave their priority away willingly. These high levels of courtesy yielding suggest that drivers tend to approach the crossing facility cautiously, possibly due to the complex nature of the infrastructure itself, where motorists not only need to check for the presence of other road users but also need to select an acceptable gap to merge with the traffic stream at the end of the right-turn lane. Another possible explanation for these high rates of courtesy yielding might be that motorists are driving at a relatively low speed and due to a lack of uniformity in the application of the priority rule decide to yield to vulnerable road users anyway. The relationship between speed and yielding has previously been suggested by Bertulis and Dulaski (2014), who found that lower speeds resulted in higher yielding rates (75% yielded at 32 km/h, only 40% yielded at 50 km/h).

5.4 Strengths, limitations and further research

Further development is needed for the definitions of yielding types. Most researchers only define yielding behaviour in terms of which road user crosses first (e.g., Sakshaug et al., 2010). However, such categorisation does not consider the full yielding process in which the involved road users need to interact with each other. Van Minnen and Braimaister (1994) also considered the manner of crossing in terms of taking and getting priority. They acknowledged that such definitions are only useful if the difference between taking and getting can be objectively identified. However, in these definitions 'taking' and 'getting' do not align with the priority rule. Therefore, in section 3.1, their definitions of yielding types were further developed. The difference between 'taking' and 'getting' priority was established on the basis of the motorist's location. Further research is needed to determine if distance is a reliable objective measurement in this regard.This research used semi-automated video analysis software to analyze road user behavior. Although this is still a rather time consuming process, it allows for accurate, reliable and objective analyses of revealed road user behavior at micro-level. Other and more conventional techniques (e.g. human observers or inductive loops) do not enable to analyze the data at the same level of detail achieved in this study.

This research used semi-automated video analysis software to analyse road user behaviour. Although this is still a rather time consuming process, it allows for accurate, reliable and objective analyses of road user behaviour at the micro level. Other more conventional techniques (e.g., human observers or inductive loops) do not enable data analysis at the same level of detail achieved in this study.

The analysis of yielding behaviour showed that the location with motorist priority and a zebra crossing had deviating results when the secondary crossing direction was considered. A high proportion of incorrect cycling behaviour was observed at this location; in 68% of cases, the cyclist arrived at the crossing facility while cycling in the opposite (illegal) direction. This percentage was much lower for the other locations (27%, 17% and 0%). The findings indicate that drivers might not expect cyclists to approach from this direction, which is reflected by a lower proportion of drivers' speed reduction. However, the privacy legislation did not allow us to film inside the car, making it impossible to examine if searching behaviour was an influence.

The safety evaluation showed that for 93 out of 1,366 (<7 %) interactions, a TA value could be calculated, of which 43 (3%) were labelled serious conflicts (based on a threshold level of 24 in the Swedish Traffic Conflict Technique). For the TTC_{min} indicator, the percentage of serious conflicts was even lower: only 2 % (n = 23) based on a threshold value of 1.50 seconds. Linear regression models for both indicators revealed that the priority rule had no statistically significant influence on cyclists' safety at the 0.05 level. However, the TTC_{min} indicator found lower values for locations with motorist priority (p = 0.094), hinting that these locations might experience more safety critical values. The descriptive analysis indicated that cases where motorists had priority and cyclists crossed in the secondary direction (from the viewpoint of the driver) resulted in more serious conflicts (although this could not be confirmed at the 5% significance level). Further research and more data and testing sites might confirm that locations with motorist priority yield more safety critical events.

6 Conclusions

The most important findings of this research are:

- Independent of the priority rule, cyclists cross first in the majority of cases.
- During most interactions at locations where cyclists should yield, drivers give their priority away willingly.
- Being a cyclist rather than a moped rider and arriving from the left at the cyclist crossing facility increases the probability of the cyclist crossing first. Slowing down behaviour by either road user decreases the probability of crossing first.
- Although the TTC_{min} and TA indicator measure different conflict characteristics, strong correlations were found between them ($r^2 > 0.83$ when TA values are considered and $r^2 > 0.60$ when TA severity levels are taken into account).
- No statistically significant influence of the priority rule on conflict severity was found.
- The two safety indicators both suggested that the priority rule favouring motorists yields more serious conflicts when cyclists cross from right to left (from the perspective of the approaching driver)..

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