Road Safety Differences Between Priority-Controlled Intersections and Right-Hand Priority Intersections: a Behavioral Analysis of Vehicle-Vehicle Interactions

Authors:

Tim De Ceunynck, Evelien Polders, Stijn Daniels, Elke Hermans, Tom Brijs and Geert Wets (corresponding author)
Transportation Research Institute (IMOB), Hasselt University
Wetenschapspark 5/6, 3590 Diepenbeek, Belgium
Fax: +32(0)11 26 91 99
Tel.: +32(0)11 26 91 -- {18; 44; 56; 41; 55; 58}
E-mail: {tim.deceunynck; evelien.polders; stijn.daniels; elke.hermans; tom.brijs; geert.wets}@uhasselt.be

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ABSTRACT

This study analyzes interactions between two vehicles at right-hand priority intersections and priority-controlled intersections, which will help to gain a better insight in safety differences between both types of intersections. Data about yielding, looking behavior, drivers' age and gender, approaching behavior, type of manoeuvre, order of arrival and communication between road users are collected by on-site observations. Logistic regression models are built to identify variables that affect the probability that a violation against the priority rules occurs, and the probability that a driver looks to the sides when entering the intersection.

The number of right-of-way violations is significantly higher at the observed right-hand priority intersection (27% of all interactions) than at the priority-controlled intersection (8%). Furthermore, at the right-hand priority intersection the behavior of drivers on the lower volume road is more cautious than the behavior of drivers on the higher volume road, and violations are more likely when the driver from the lower volume road has priority, indicating that the higher volume road is considered as an implicit main road.

At both intersection types, there is a higher probability of a right-of-way violation when the no-priority vehicle arrives first, indicating that yielding is partly a matter of "first come, first served". For both intersections, the way a driver approaches the intersection (i.e., stopping, decelerating or holding the same speed) is highly relevant for the occurrence of a right-of-way violation and the probability that the driver looks to the sides on his approach to the intersection.

KEYWORDS

Safety hierarchy, right-of-way violations, looking behavior

INTRODUCTION

Intersections are complex locations with many different movements, resulting in a wide range of possible interactions among road users. To facilitate these interactions, different types of right-of-way rules are in place. The level of control these types of right-of-way rules exert on interactions ranges from strongly controlled (e.g. signalized intersections) to little controlled (e.g. right-hand priority intersections).

The proper level of control for unsignalized intersections in urban areas is often the subject of debate because various factors may be taken into account, such as traffic volumes, surrounding environment and safety considerations *(1)*. In urban areas, priority-controlled intersections and right-hand priority intersections are the most common types. These intersection types exert the lowest level of control over road user interactions. At priority-controlled intersections, drivers arriving from the secondary road have to yield to drivers coming from the primary road. At right-hand priority intersections, all arriving roads are considered equivalent, and all arriving drivers need to yield to drivers coming from their right-hand side.

Unfortunately, scientific literature is inconclusive about which of both intersection types should be preferred in which situations from a safety point of view. Generally, no significant difference in the number of crashes is found when transforming right-hand priority intersections to priority-controlled intersections, which indicates that a higher level of control does not guarantee an improvement in safety *(2)*. Since the low level of control at both intersection types necessitates a lot of interaction between road users, a better insight in these interactions can lead to a better understanding of the safety issues at these types of locations.

Therefore, this study analyzes road users' interactions at a micro-level by using structured on-site behavioral observations to explore the way these interactions take place, and how they differ between both types of intersections.

BACKGROUND

Overall Traffic Safety at Priority-Controlled and Right-hand Priority Intersections

Priority-controlled intersections are often assumed to have an important safety advantage over right-hand priority intersections. The higher level of control at these intersections is less ambiguous for road users and leads to more consistent yielding behavior compared to right-hand priority intersections *(2)*.

However, an overview based on 14 studies *(2)* concludes that the number of injury crashes is generally only reduced by 3% (95% CI [-9; +3]) when converting right-hand priority intersections to priority-controlled intersections. Elvik et al. *(2)* mention that some studies even indicate an increase in the number of crashes, for instance in case of low traffic volumes on the secondary road *(3-5)*. This may seem surprising, but the counterbalancing factor is that driving speeds on the primary road of priority-controlled intersections tend to be higher *(2)*. At right-hand priority intersections, all vehicles are required to approach the intersection with greater caution because they may need to yield to another vehicle, while vehicles on the primary road of a priority-controlled intersection do not need to yield to other vehicles, leading to higher approach speeds. Therefore, the crash severity is generally higher at priority-controlled intersections *(6)*.

Road User Behavior

Drivers' behavior in intersections is influenced by the right-of-way rules that apply, the intersection design, and other road users' expected and actual behavior *(7-10)*. Interacting with other road users would be impractical without formal rules. These rules describe how a driver should behave in different traffic situations, and provide information about the intentions and behaviors that can be expected from other road users *(10)*. However, violations of the formal rules are common in practice.

Violations can be committed deliberately (e.g. to reduce driving time) or because of driver errors (lack of knowledge about the rules, misjudgment,…) *(11)*. Behavioral, personal and environmental elements can have an influence on the occurrence of violations. When behavior that is in contradiction with formal rules becomes common in particular situations, this indicates that an informal rule has developed *(10)*. In the case of an interaction between two road users, a dangerous situation can occur when one of the road users complies with formal priority rules while the other road user applies an informal rule.

Yielding behavior

Research indicates that failure to yield is one of the primary factors leading to crashes at unsignalized intersections *(12;13)*.

Formal priority rules are respected quite well at priority-controlled intersections, but not at right-hand priority intersections *(2;7)*. Helmers and Åberg *(7)*, cited by *(10)*, indicate that the right-hand priority rule is violated most often when the vehicle coming from the right is on a connector road, which can be considered as an "implicit minor road", although both approaching roads are technically equally important. This is the result of a combination of drivers on the "main road" behaving as if they have priority, and drivers on the "minor road" behaving as if they do not have priority *(7)*. The study indicates lower compliance with the right-hand priority rule at three-leg intersections compared to four-leg intersections. Johannessen *(8)*, cited in *(10)*, indicates that on average 75% of all drivers comply with the right-hand priority rule at four-leg intersections, and 56% of the drivers at three-leg intersections.

Communication

Communication between interacting road users is an aspect of behavior that may help to make one's own intentions clear to other road users, and to predict the behavior that the other road user will execute. This way, it can benefit road safety. Communication may include using direction indicators, which is an official form of communication, or hand gestures, flashing the headlights, sounding the horn or other forms of non-official communication.

However, most communication signals can be ambiguous and may therefore also lead to dangerous situations when misinterpreted *(14)*.

Approach behavior

The speed of another approaching vehicle is an important factor for a driver's decision to give way or not *(15)*. The approach speed can implicitly indicate the driver's intentions in the interaction. Slowing down or stopping can indicate an intention to yield, while holding the same speed or accelerating can indicate an intention not to yield. Drivers state that they yield more often when another driver maintains his speed than when the other driver slows down *(10)*.

Looking behavior

Detection errors (i.e. not seeing another road user) are an important cause of collisions, and failure to look errors are the most common detection error *(13;16)*. When drivers expect that drivers coming from the side roads will yield to them, they tend not to look to the sides *(7;9)*. Kulmala *(9)* indicates that 80% of drivers who enter right-hand priority intersections look to the right by turning their head. Drivers who look to the right do this at lower approach speeds than other drivers. Looking behavior can also be a form of communication, for instance not looking to a driver coming from a side road may express that one has no intention to yield.

Influence of Driver Age and Gender

For all age groups, failure to yield is one of the strongest primary contributing circumstances in crashes *(17)*. However, the relative fraction of failure to yield crashes increases with age *(17;18)*. Search and detection errors and evaluation errors have the highest contribution to intersection crashes for all age groups *(18)*. Keskinen et al. *(19)* indicate that there are no differences in looking behavior between different ages.

Young drivers have a general crash rate that exceeds the risk of any other age group *(20)*. In failure to yield crashes, younger drivers are especially overrepresented in "passive" crashes (i.e. someone violates the young driver's right-of-way), most likely due to a combination of speeding, slow hazard perception and a firmness to enforce their right-of-way *(18)*. Middle-aged drivers are also less likely to be at-fault in failure to yield crashes *(21)*.

Older drivers are overrepresented in most types of intersection crashes *(19)*. At unsignalized intersections, failure to yield crashes are most common *(18;22)*. The main issue is that the complexity of the driving task conflicts with age-related impairments such as declining vision, perception, cognitive functioning and physical abilities *(22)*. Older drivers have difficulties in selecting safe gaps in conflicting traffic, mainly because they are less able to correctly estimate the speed of approaching vehicles *(22)*. They overestimate the speed of vehicles driving at slow speeds, and underestimate the speed of vehicles driving at higher speeds *(23)*. Older drivers tend to drive and accelerate slower than other drivers, which might lead to dangerous situations when interacting at unsignalized intersections because other drivers might incorrectly interpret the slower speeds as an intention to give way *(19)*.

Gender differences in driving behavior also influence interactions between road users. Generally, women have more cautious driving habits than men, resulting in a lower overall crash involvement, even when corrected for exposure *(24)*. Men are significantly more often involved in crashes involving right-of-way violations than women *(24)*. Kulmala *(9)* indicates that women enter right-hand priority intersections on average 3-4 km/h slower than men.

Status

It can be concluded that a number of elements affecting interactions between road users have been explored in previous research, but the number of studies is limited. Moreover, variables that are potentially important have sometimes not been explored in an integrated way, and most studies date from a long time ago. Furthermore, priority-controlled and right-hand priority intersections have rarely been compared based on elements other than the number of right-of-way violations. Therefore, the understanding of interactions between drivers at these intersections is limited. More precisely, elements that have an influence on yielding behavior and elements that influence drivers' looking behavior seem to be important aspects to investigate more profoundly. This study collects these behavioral elements in an integrated way, and focuses on examining which elements have an influence on yielding behavior and drivers' looking behavior.

METHODOLOGY

Study Design

This study aims to further explore the way drivers interact with each other at priority-controlled and right-hand priority intersections. The design of the study is cross-sectional, indicating that two intersections have been selected that are as comparable as possible, except for the difference in right-of-way rules. The study focuses on side interactions between two vehicles. Observable elements of interactions that are potentially relevant to road safety are collected, including yielding, looking and approaching behavior, communication, gender and age of the involved drivers.

Selection of study locations

One priority-controlled intersection and one right-hand priority intersection are selected in the province of Limburg (Belgium) for extensive observation. At the priority-controlled intersection, the right-of-way is indicated by yield signs and pavement markings. When no yield signs or pavement markings are present, the right-hand priority rule applies by default. This is the case for the selected right-hand priority intersection.

The intention of this study is to investigate the influence of the type of priority control on vehicle-vehicle interactions. Therefore, interactions should be as unguided by specific intersection characteristics other than the type of priority control as possible. For that reason, two "basic" intersections are chosen that have no geometrical particularities such as bicycle paths, crossings, speed reducing measures etc. that may influence the way interactions between drivers take place. The road widths are the same for both intersections and for all approaching branches to avoid an influence from the fact that drivers tend to yield less to drivers coming from a narrower road *(10)*. Four-leg intersections have been chosen because three-leg intersections influence yielding behavior. The intersections are located in a residential area and have a speed limit of 50 km/h on all branches. The intersections have relatively low traffic volumes because intersections with higher volumes tend to be equipped with additional geometric properties such as bicycle paths. Both intersections have similar traffic volumes, with a higher volume on one of the roads. The priority-controlled intersection has an approaching traffic volume (7a.m. till 6p.m. period) of 2441 pce (passenger car equivalent) on the primary (in-priority) road and 278 pce on the secondary road, the right-hand priority intersection has traffic volumes of 2648 pce and 289 pce respectively. For reasons of brevity, we refer to the higher volume road at the right-hand priority intersection also as the "primary road" and the lower volume road as the "secondary road", although the terms do not indicate a hierarchy here.

Definition and operationalization of the concept "interaction"

A first crucial element is what is to be considered an "interaction". We define an interaction as a situation in which two road users arrive at the intersection with such closeness in time and space that the presence of one road user can have an influence on the behavior of the other. An interaction between two road users is an elementary event in the traffic process that has the potential to end up in a collision *(25)*. Interactions are the lowest (least severe) level of a safety hierarchy in which relations exist between the lower severity levels and the highest severity level, i.e. a crash *(26-28)*.

To facilitate and objectify the observations, this definition is operationalized as a geographical space around the intersection. The limits of this space are at both intersections 50m away from the intersection plane on both sides of the primary road, and 25m on both sides of the secondary road. The choice for two different distances is based on speed measurements that indicate a significantly higher driving speed for vehicles approaching the intersection from the primary road. The average approach speeds on the secondary roads are similar for both intersection types, while the approach speeds on the primary roads are on average slightly higher (±3 km/h) at the priority-controlled intersection compared to the right-hand priority intersection. The distances are chosen based on pilot tests that have indicated that this is in most occurring situations a good cut-off value to distinguish between vehicles that have an influence on each other and vehicles that do not.

Observation protocol

Each intersection is observed for 30 hours during the period November 24^{th} till December 5^{th} 2011. All observations have taken place in dry weather conditions during daytime because of the need to look inside vehicles to collect information about drivers' gender, age and looking behavior. Twilight, night and rainy conditions do not allow this. The observations are done in blocks of 2-3 hours, spread evenly throughout the hours of the day and days of the week (including weekends) for both intersections to avoid possible biases. All observations have been executed by one observer using a standardized observation form. All variables have been objectified and standardized as binary or categorical variables to allow quantitative analyses of the interactions.

Ensuring and Assessing the Reliability of the Data Collection

A second observer has examined the same interactions for part of the observation period to perform an intercoder reliability assessment. Intercoder reliability is the extent to which independent observers reach the same conclusion when evaluating the same situation using the same method *(29)*. A high level of agreement between coders is considered as a sign of theoretical solidity of the applied method and a good training of the observers, while large differences among coders suggest weaknesses in the research methods, such as poor operational definitions or training of the observers *(29-31)*.

Furthermore, all interactions are recorded, which allows to validate most of the variables. Therefore, the data about these variables should be virtually 100% correct, irrespective of their intercoder reliability. Drivers' gender, age and looking behavior could not be verified this way.

Analysis of the Collected Behavioral Data

The data are analyzed using logistic regression models, which can be used to predict the probability of a certain event when the dependent variable is dichotomous *(32)*. Firth's penalized maximum likelihood is applied because it avoids the problem of quasi-complete separation, which is the most common convergence failure in logistic regression *(32;33)*.

Models are built using a stepwise procedure. The Akaike Information Criterion is used to assess the models. The measure indicates the relative goodness-of-fit of the model, but penalizes larger numbers of parameters, providing a tradeoff between accuracy and complexity of the model *(34)*. Variance inflation factors (VIF's) are used to check for multicollinearity (i.e. a high correlation between two or more independent variables). VIF's higher than 4 indicate a high correlation *(35)*. All variables in the end models have VIF's lower than 2, so there are no multicollinearity issues in the presented models.

RESULTS AND DISCUSSION

Intercoder Reliability

An extensive intercoder reliability assessment is performed based on 113 of the 483 interactions (23% of all data). The intercoder reliability is assessed by using two measures: Cohen's κ and percent agreement. Percent agreement is the simplest intercoder reliability measure and expresses the percentage of cases for which the observers agree. Cohen's κ is a measure that corrects percent agreement for agreement by chance, and is therefore generally considered to be a more favorable intercoder reliability measure than percent agreement *(29)*. However, percent agreement is calculated as well because some of the calculations suffer from the so-called "κ paradox". These are situations where the Cohen's κ incorrectly yields a low reliability estimate because the distribution over the data categories is strongly skewed

(36;37). In these situations, the use of percent agreement is recommended since this measure is not susceptible to the κ paradox *(37)*.

A κ-value of 0.70 is considered satisfactory for exploratory studies, a value of 0.80 is acceptable in most studies *(29)*. All variables that have a reliable κ-value exceed the 0.70 threshold for Cohen's κ, and all-but-one (i.e. gender of the driver on the primary road) even exceed the stricter criterion of 0.80. All variables (including those with an unreliable κ-value) have a percent agreement of 0.85 or higher. Most importantly, the agreement on which situations are considered "interactions" and which ones are not is 100%. The differences in reliability between both intersection types are minimal. In conclusion, the intercoder reliability values are high and quite stable across all variables and intersections.

Descriptive Statistics

Descriptive statistics are presented in table 1. At the priority-controlled intersection, the vehicle on the primary road is always the vehicle that has priority. However, the situation at the right-hand priority intersection is not as clear. Vehicles entering the intersection from each intersection leg may either be the in-priority vehicle and the no-priority vehicle, depending on which leg the other interacting vehicle is coming from.

The variables "Approach prim" and "Approach sec" indicate that drivers on the secondary road of the right-hand priority intersection stop and decelerate more often when approaching the intersection, while drivers on the primary road often hold their speed. Also, the looking behavior variables indicate that drivers on the secondary road nearly always look to the sides, while drivers on the primary road do not. Therefore, drivers on the secondary road seem to approach the intersection more cautiously than drivers on the primary road, which indicates that road users may consider the primary road as an implicit main road. The high number of right-of-way violations is another element that stresses the presence of an informal priority rule *(10)*. The higher traffic volume on the primary road is likely to contribute to the occurrence of this informal priority rule. Driver interactions are influenced by expectations based on prior experience *(38)*. Therefore, especially drivers who are familiar with the intersection may not expect drivers arriving from the secondary road, and therefore approach the intersection incautiously, leading to violations of the priority rule.

Therefore, there are two possibilities of coding the data from the right-hand priority intersection: either distinguishing between in-priority vehicles and no-priority vehicles, or distinguishing between vehicles on the primary road and vehicles on the secondary road. Therefore, it is decided to analyze the data according to both possibilities to check whether the results differ. The variables recoded according to the distinction in-priority and no-priority are indicated in italics.

Drivers comply with the right-hand rule in only 73% of the interactions (147 out of 201), which is very similar to *(8)*, which indicates 75% compliance. The compliance at the priority-controlled intersection (92%) is significantly higher than at the right-hand priority intersection ($X^2(1,N=483)=22.46$, $p<0.001$), which is in line with *(7)*.

TABLE 1 Descriptive statistics.

Variable name and description – Distinction prim/sec *Distinction in-priority/no-priority*	Priority-controlled intersection (N=182)	Right-hand priority intersection (N=201) (distinction prim/sec)	Right-hand priority intersection (N=201) – (distinction driver in-priority vs. no-priority)
Data about yielding			
ViolationPriority – right-of-way rule is violated	Yes:15 ; No:167	Yes:54 ; No:147	
HasPriority prim – vehicle on primary road has priority *HasPriority VP – in-priority vehicle has priority*	Yes:182 ; No:0	Yes:86 ; No:115	*Yes:201 ; No:0*
HasPriority sec – vehicle of secondary road has priority *HasPriority VNP – no-priority vehicle has priority*	Yes:0 ; No:182	Yes:115 ; No:86	*Yes:0 ; No:201*
GetPriority prim – vehicle on primary road gets priority *GetPriority VP – in-priority vehicle gets priority*	Yes:167 ; No:15	Yes:124 ; No:77	*Yes:147 ; No:54*
GetPriority sec – vehicle of secondary road gets priority *GetPriority VNP – no-priority vehicle gets priority*	Yes:15 ; No:167	Yes:77 ; No:124	*Yes:54 ; No:147*
Demographic variables			
Gender prim – gender of driver on primary road *Gender VP – gender of in-priority driver* M = male; F = female	M: 125 ; F: 57	M:138 ; F: 63	*M:121 ; F: 80*
Gender sec – gender of driver on secondary road *Gender VNP – gender of no-priority driver* M = male; F = female	M: 104 ; F: 78	M:108 ; F: 93	*M:125 ; F: 76*
Age prim – age of driver on primary road *Age VP – age of in-priority driver* Y = young driver; M = middle-age driver; O = older driver	Y: 5 ; M:159 ; O:18	Y:5 ; M:186 ; O:10	*Y:4 ; M:174 ; O:23*
Age sec – age of driver on secondary road *Age VNP – age of no-priority driver* Y = young driver; M = middle-age driver; O = older driver	Y: 3 ; M:150; O:29	Y:6 ; M:166; O:29	*Y:7 ; M:178 ; O:16*
Approaching behavior			
Prim arrives first – vehicle on primary road reaches junction plane first *VP arrives first – in-priority vehicle reaches junction plane first*	Yes:15 ; No:167	Yes:58 ; No:143	*Yes:77 ; No:124*
Sec arrives first – vehicle on secondary road reaches junction plane first *VNP arrives first – no-priority vehicle reaches junction plane first*	Yes:112 ; No:70	Yes:90 ; No:111	*Yes:71 ; No:130*
Arrive same time – vehicle on primary and secondary road reach junction plane at the same time *Same time –in-priority and no-priority vehicle reach junction plane at the same time*	Yes:55 ; No:127	Yes:53 ; No:148	
Approach prim – approach behavior of vehicle on primary road at junction plane *Approach VP – approach behavior of in-priority vehicle at junction plane* Stop = stops completely; Dec. = decelerates; Hold= holds same speed; Acc. = accelerates	Stop: 1 ; Dec.: 24 ; Hold: 157 ; Acc.: 0	Stop:40 ; Dec.:53 ; Hold:106 ; Acc.:2	*Stop:52 ; Dec.:64 ; Hold:84 ; Acc.:1*

TABLE 1 Descriptive statistics [cont.].

Approach sec – approach behavior of vehicle on secondary road at junction plane *Approach VNP – approach behavior of no-priority vehicle at junction plane* Stop = stops completely; Dec. = decelerates; Hold = holds same speed; Acc. = accelerates	Stop:179 ; Dec.:1 ; Hold:2 ; Acc.:0	Stop:110 ; Dec.:69 ; Hold:22 ; Acc.:0	*Stop:98 ;* *Dec.:58 ;* *Hold:44 ;* *Acc.:1*
Drivers' looking behavior			
LookLeft prim – driver on primary road looks left *LookLeft VP – in-priority driver looks left*	Yes:21 ; No:161	Yes:22 ; No:179	*Yes: 123 ; No: 78*
LookRight prim – driver on primary road looks right *LookRight VP – in-priority driver looks right*	Yes:10 ; No:172	Yes:90 ; No:111	*Yes:128 ; No:73*
DontLook prim – driver on primary road does not look right or left *DontLook VP – in-priority driver does not look right or left*	Yes:155 ; No:27	Yes:107 ; No:94	*Yes:160 ; No:41*
LookLeft sec – driver on secondary road looks left *LookLeft VNP – no-priority driver looks left*	Yes:182 ; No:0	Yes:198 ; No:3	*Yes:97 ; No:104*
LookRight sec – driver on secondary road looks right *LookLeft VNP – no-priority driver looks right*	Yes:181 ; No:1	Yes:198 ; No:3	*Yes:66 ; No:135*
DontLook sec – driver on secondary road does not look right or left *DontLook VNP – no-priority driver does not look right or left*	Yes:0 ; No:182	Yes:0 ; No:201	*Yes:41 ; No:160*
Manoeuvre			
TurnLeft prim – vehicle on primary road turns left *TurnLeft VP – in-priority vehicle turns left*	Yes:14 ; No:168	Yes:9 ; No:192	*Yes:85 ; No:116*
TurnRight prim – vehicle on primary road turns right *TurnRight VP – in-priority vehicle turns right*	Yes:0 ; No:182	Yes:2 ; No:199	*Yes:28 ; No:173*
DontTurn prim – vehicle on primary road does not turn *DontTurn VP – in-priority vehicle does not turn*	Yes:168 ; No:14	Yes:190 ; No:11	*Yes:88 ; No:113*
TurnLeft sec – vehicle on secondary road turns left *TurnLeft VNP – no-priority vehicle turns left*	Yes:83 ; No:99	Yes:144 ; No:57	*Yes:68 ; No:133*
TurnRight sec – vehicle on secondary road turns right *TurnRight VNP – no-priority vehicle turns right*	Yes:58 ; No:124	Yes:29 ; No:172	*Yes:3 ; No:198*
DontTurn sec – vehicle on secondary road does not turn *DontTurn VNP – no-priority vehicle does not turn*	Yes:41 ; No:141	Yes:28 ; No:173	*Yes:130 ; No:71*
Communication data			
Direction prim – driver on primary road uses directional lights *Direction VP – in-priority driver uses directional lights*	Yes:168 ; No:14	Yes:11 ; No:190	*Yes:99 ; No:102*
Direction sec – driver on secondary road uses directional lights Direction VNP – no-priority driver uses directional lights	Yes:116 ; No:66	Yes:153 ; No:48	*Yes:65 ; No:136*
Gesture prim – driver on primary road uses horn, hand gesture or flash of headlights to communicate *Gesture VP – in-priority driver uses horn, hand gesture or flash of headlights to communicate*	Yes:1 ; No:181	Yes:1 ; No:200	*Yes:8 ; No:193*
Gesture sec – driver on secondary road uses horn, hand gesture or lights to communicate *Gesture VNP – no-priority driver uses horn, hand gesture or flash of headlights to communicate*	Yes:0 ; No:182	Yes:8 ; No:193	*Yes:1 ; No:200*

Priority Violation Models

The models in table 2 indicate the variables that influence the probability that the right-of-way rule is violated. Since the logistic regression models the logistic transformation of the dependent variable (i.e., the natural logarithm of the odds of the dependent variable), *e* should be raised to the power of the variable estimate to obtain the influence of the variable on the probability that a priority violation takes place. For example, in the priority-controlled intersection model, the estimate of "Sec arrives first" is 1.5265, which implies that the odds of a priority violation are $e^{1.5265} = 4.6$ times higher when the vehicle on the secondary road arrives at the intersection first than when the vehicle on the secondary road does not arrive first.

The priority-controlled intersection model shows three significant variables. "Sec arrives first" indicates that a violation is significantly more likely when the vehicle on the secondary road (i.e. the vehicle that should give way) arrives first at the intersection. "Approach sec" indicates that a violation is less likely when the vehicle on the secondary road comes to a full stop compared to when it only slows down. Perhaps the most remarkable finding is that the probability of a right-of-way violation is significantly (99% CI) higher when the driver on the primary road looks to the right. There are a number of possible explanations. The most likely explanation is that drivers who look to the right while entering an intersection do this at a lower speed than other drivers. This explanation would be in line with Kulmala's *(9)* findings, although his observations only apply to right-hand priority intersections. This way, looking to the right could be a proxy for a cautious driving style of the driver on the primary road, with the side effect that the vehicle on the secondary road either sees this as implicit communication indicating that the driver on the primary road may give way *(14)*, or as an opportunity to infringe on the primary road driver's right-of-way with a low perceived personal risk. Another possibility is that the driver on the secondary road directly observes that the driver on the primary road is looking to the right, with the same possible side effects (i.e. implicit communication or opportunity to infringe).

Right-hand priority intersection model A includes "HasPriority sec", "Sec arrives first" and "DontLook prim". The first two variables indicate a higher probability of a right-of-way violation when the secondary road has priority, and a lower probability of a violation in case the vehicle on the secondary road arrives first. Both variables seem to confirm that the primary road is indeed considered as a higher-order road, resulting in a higher number of right-of-way violations committed by the drivers on this road. "DontLook prim" indicates a higher probability of a violation when the driver on the primary road does not look to either side. As in the priority intersection model, this can either indicate that these drivers approach the intersection at higher speeds (in line with *(9)*), this way discouraging the driver on the secondary road to enforce his right-of-way for safety reasons, or as an implicit way of communicating a lack of intention to give way.

Right-hand priority intersection model B includes "VNP arrives first", "approach VP" and "approach VNP". "VNP arrives first" indicates a higher chance of a right-of-way violation when the no-priority vehicle arrives first at the intersection. "Approach VP" indicates the highest chance of a priority violation in case the in-priority vehicle comes to a full stop.

"Approach VNP" indicates a significantly higher chance of violation when the no-priority vehicle maintains its speed, and a significantly lower chance when the no-priority vehicle comes to a stop.

TABLE 2 Factors influencing the probability of a right-of-way violation.

Variables	Priority-controlled intersection	Right-hand priority intersection (distinction prim/sec) ("model A")	Right-hand priority intersection – (distinction VP/VNP)[1] ("model B")
Intercept	0.027 (p=0.980)°	-1.591 (p<0.001)***	*-0.765 (p=0.365)°*
HasPriority sec		1.281 (p<0.001)	
Sec arrives first *VNP arrives first*	1.5265 (p=0.034)**	-0.473 (p=0.013)**	 *1.198 (p<0.001)****
Approach VP			*Stop: 2.153 (p=0.004)**** *Dec.: 0* *Hold: -1.009 (p=0.150)°* *Acc.: -1.134 (p=0.526)°* *(p<0.001)****
Approach sec *Approach VNP*	Stop: -2.653 (p=0.017)** Dec.: 0 Hold: 1.154 (p=0.451)° (p=0.050)**		 *Stop: -1.823 (p=0.007)**** *Dec.: 0* *Hold: 1.544 (p=0.023)*** *Acc.: 0.677 (p=0.702)°* *(p<0.001)****
LookRight prim	1.098 (p=0.009)***		
DontLook prim		0.771 (p<0.001)***	

[1] VP= in-priority vehicle; VNP = no-priority vehicle
*** p≤0.01 (significant at 99% CI)
** p≤0.05 (significant at 95% CI)
* p≤0.10 (significant at 90% CI)
° p>0.10 (not significant at 90% CI)

Two general patterns are observed for both intersections. The presence of "Sec arrives first/VNP arrives first" in the model of the priority-controlled intersection and model B of the right-hand priority intersection indicates that the chance of a right-of-way violation is significantly higher when the no-priority vehicle arrives first at the intersection. This indicates that the priority behavior of road users is partly a matter of "first come, first served". Another possibility is that the no-priority drivers are more likely to make mistakes in estimating the approaching vehicles' time and/or speed when they arrive first at the intersection. When the in-priority vehicle arrives at the same time or even before the no-priority vehicle, these mistakes are much less likely.

"Approach sec/Approach VNP" is also present in the priority-controlled intersection model and right-hand priority model B. The variable indicates that the probability of a violation significantly reduces when the no-priority vehicle stops, compared to the reference category of only decelerating. This indicates that, once road users have completely stopped, they are much less likely to commit a right-of-way violation than in other situations. Furthermore, at the right-hand priority intersection, the chance of a violation is higher when the no-priority vehicle holds its speed. This finding is also confirmed by “Approach VP”, which shows the reverse pattern for the in-priority vehicle, i.e. a significantly higher probability of a violation when the in-priority vehicle stops, and a lower (although not significant) probability in case the in-priority vehicle maintains its speed.

Looking Behavior Models

Table 3 presents the factors that influence drivers’ looking behavior. Only the looking behavior of drivers on the primary roads could be modeled, since virtually all drivers from the secondary roads look to the sides. For right-hand priority intersection model B, both the looking behavior of in-priority and no-priority drivers could be modeled. The models present variables that influence the chance that the driver looks to at least one of the sides.

The priority-controlled intersection model only includes “Prim arrives first” and “Turn prim”. “Prim arrives first” indicates a higher probability that the driver on the primary road looks to the sides in case he arrives first, but the estimate is not significant. There is a significantly higher probability that the driver looks to the sides in case he makes a turn, which is expected; making a turning manoeuvre without looking to the side is quite difficult.

Right-hand priority model A indicates that “GetsPriority sec”, “Approach prim”, and “Turn prim” influence the looking behavior of the driver on the primary road. “GetsPriority sec” indicates a higher chance that drivers on the primary road look to the sides when the vehicle on the secondary road gets priority. “Approach prim” indicates that drivers have a significantly higher probability of looking to the sides when they come to a full stop, and a lower probability when they hold their speed. “Turn prim” indicates a (non-significantly) higher probability of looking to the sides in case a turning manoeuvre is executed.

Right-hand priority intersection model B1 indicates that “GetsPriority VNP”, “VP arrives first”, “gender VP” and “age VP” have an influence on the looking behavior of the in-priority driver. “GetsPriority VNP” indicates a higher probability that the in-priority vehicle looks to the sides when the no-priority vehicle gets priority. The in-priority driver is also more likely to look to the sides when he arrives at the intersection first. Furthermore, in-priority male drivers tend to look less to the sides than female drivers, although the difference is not significant. “Age VP” indicates that older in-priority drivers look to the sides more often than other age categories.

Right-hand priority intersection model B2 indicates a significant influence of “GetsPriority VP” and “Approach VNP” on the no-priority drivers’ looking behavior. “GetsPriority VP” indicates that the no-priority drivers are more likely to look to the sides when they yield to the in-priority drivers. “Approach VNP” indicates that no-priority drivers are more likely to look to the sides when they come to a full stop, and less likely when they hold their approach speed.

At the right-hand priority intersection, drivers are generally more likely to look to the sides in case they yield to the other road user. However, the causality in this relationship is likely to be the other way around: because road users look to the sides, they are more likely to yield to the other road user. This is the case for both in-priority and no-priority drivers. In-priority drivers are also more likely to look to the sides when they arrive first at the intersection. Furthermore, two right-hand priority intersection models indicate a significantly higher probability of looking to the sides when the driver comes to a full stop, while this probability is significantly lower when the driver holds his speed.

TABLE 3 Factors influencing the likelihood that a driver looks to the sides on approach to the intersection.

Variables	Priority-controlled intersection – Driver primary road	Right-hand priority (distinction prim/sec) – model A – Driver primary road	Right-hand priority intersection – (distinction VP/VNP) – model B1 – in-priority driver	Right-hand priority intersection – (distinction VP/VNP) – model B2 – no-priority driver
Intercept	0.0292 (p=0.951)°	1.368 (p=0.028)**	2.260 (p<0.001)***	1.570 (p=0.013)**
GetsPriority sec *GetsPriority VNP*		0.5124 (p=0.036)**	*1.262 (p<0.001)****	
GetsPriority VP				*0.561 (p=0.052)**
Prim arrives first *VP arrives first*	0.502 (p=0.171)°		*0.4649 (p=0.008)****	
Approach prim		Stop: 2.056 (p=0.006)*** Dec.: 0 Hold: -2.218 (p<0.001)*** Acc.: -0.200 (p=0.856)° (p<0.001)***		
Approach VNP				Stop: 2.173 (p=0.013)** Dec.: 0 Hold: -2.472 (p<0.001)*** Acc.: 0.090 (p=0.960)° (p<0.001)***
Turn prim	1.904 (p<0.001)***	0.655 (p=0.185)°		
Gender VP			F: 0 M: -0.287 (p=0.101)°	
Age VP			Y: -0.529 (p=0.528)° M: 0 O: 1.248 (p=0.081)* (p=0.095)*	

[1] VP= vehicle in priority; VNP = vehicle no-priority
*** p≤0.01 (significant at 99% CI)
** p≤0.05 (significant at 95% CI)
* p≤0.10 (significant at 90% CI)
° p>0.10 (not significant at 90% CI)

STUDY LIMITATIONS AND FURTHER RESEARCH

As this study is based on observations on two intersections, the possibilities to draw generalized conclusions are limited. This is a common limitation of studies focusing on the lower severity levels of the traffic safety hierarchy (i.e. interactions or conflicts) *(27;28;39-41)*. Nevertheless, the study can be considered as a pilot project that tests a standardized observation protocol and reveals some interesting hypotheses and topics for further research. Research should investigate the generalizability of the study results, and the influence of particular design elements (e.g. bicycle paths, crossing facilities,…) on interactions. This study can be a good base case to compare with, since the chosen intersections do not have such specific characteristics. Furthermore, the link between road user interactions and the higher levels of the safety hierarchy, i.e. conflicts and crashes, should be further investigated. This should reveal to what extent the lower levels of the safety hierarchy can be used to make predictions about the safety level of particular locations; at this point these links are still insufficiently clear.

Another limitation is that the study does not analyze all types of interactions. Observations in reduced visibility conditions, such as rain, twilight or night were not possible. Data about interactions between vehicles approaching each other from opposite roads have been collected, but they were too sparse to analyze quantitatively. Interactions between more than two road users were too complex to handle within the scope of this study.

The actual driving speed of the interacting vehicles would be a useful additional variable to collect since it might help to interpret the influence of the looking behavior on the occurrence of right-of-way violations. At this point, it is often unclear whether looking to the side is a proxy for a lower approach speed, as suggested by literature *(9)*, or a directly influencing factor.

CONCLUSIONS

The number of priority violations appears to be significantly higher at the right-hand priority intersection compared with the priority-controlled intersection.

Concerning right-of-way violations, it appears that at both intersections the chance for a violation is significantly higher when the no-priority vehicle arrives at the intersection first, indicating a “first come, first served” tendency. Furthermore, approach behavior is significantly predictive of right-of-way violations. The lowest chance of a violation is when the no-priority driver comes to a full stop, while the chance of a violation is highest when the no-priority driver holds his speed. Explicit communication, gender and age do not significantly influence drivers’ yielding behavior at either intersection.

At the priority-controlled intersection, there is also a higher probability of a violation in case the driver on the primary road looks to his right side when entering the intersection.

At the right-hand priority intersection there is a lower probability of a right-of-way violation when the secondary road vehicle arrives first, despite the general “first come, first served” tendency. Combined with the finding that there is a significantly higher chance of a right-of-way violation when the secondary road driver has priority, this indicates that drivers on the secondary road are much less likely to enforce their right-of-way or to infringe on the right-of-way of a vehicle on the primary road, indicating that the primary road is implicitly considered as a main road by drivers. The probability of a violation of the right-hand priority rule is higher when the driver on the primary road does not look to the sides.

Regarding looking behavior, few conclusions can be drawn for the priority-controlled intersection. At the right-hand priority intersection, drivers who look to the sides are more likely to give way to other road users. In-priority drivers are more likely to look to the sides when they arrive first at the intersection. The probability of looking to the sides is highest when drivers come to a full stop, and lowest when drivers hold their approach speed. The latter combination (holding speed and not looking to the sides) can be considered as dangerous behavior as both factors increase the probability of a right-of-way violation, and therefore may increase the probability of getting involved in a crash. Since right-of-way violations are identified as one of the main factors that contribute to crashes, this merits further research.

In summary, the results suggest a general “first come, first served” tendency in yielding behavior, a higher number of violations at the right-hand priority intersection and an informal right-of-way at the right-hand priority intersection that leads to a higher number of violations against drivers on the secondary road.

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