Road Safety Differences Between Priority-Controlled Intersections and Right-Hand Priority Intersections

Behavioral Analysis of Vehicle–Vehicle Interactions

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This study analyzes interactions between two vehicles at right-hand priority intersections and priority-controlled intersections and will help to gain a better insight into safety differences between both types of intersections. Data about yielding, looking behavior, drivers' age and gender, approaching behavior, type of maneuver, 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 will occur and the probability that a driver will look to the side 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. This situation indicates 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: this condition indicates 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 will look to the sides on his or her approach to the intersection.

Intersections are complex locations with many different movements, resulting in a wide range of possible interactions between 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, the scientific literature is inconclusive about which of the two 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 right-hand priority intersections are transformed into 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 into 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 in the two 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 with right-hand priority intersections (*2*).

However, an overview based on 14 studies concludes that the number of injury crashes is generally reduced only by 3% [95% confidence interval (CI) (−9, +3)] when right-hand priority intersections are converted to priority-controlled intersections (*2*). Elvik et al. (*2*) mention that some studies even indicate an increase in the number of crashes, for instance, in the 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*).

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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, etc.) (*11*). Behavioral, personal, and environmental elements can have an influence on the occurrence of violations. Behavior that is in contradiction to formal rules but has become common in particular situations 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 Björklund and Åberg (*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 the two 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 with four-leg intersections. Johannessen (*8*), cited in Björklund and Åberg (*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. In that 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 nonofficial 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 in 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 or her 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 indicates that 80% of drivers who enter right-hand priority intersections look to the right by turning their heads (*9*). 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 toward 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 are the highest contributors to intersection crashes for all age groups (*18*). Keskinen et al. indicate that there are no differences in looking behavior between different ages (*19*).

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 the result of a combination of speeding, slow hazard perception, and a firmness to enforce their right-of-way (*18*). Middle-aged drivers are 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 difficulty 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 more slowly than other drivers, which might lead to dangerous situations when they are 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 are women (*24*). Kulmala indicates that women enter right-hand priority intersections on average 3 to 4 km/h slower than men (*9*).

Status

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 on the basis of 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 the right-of-way rules. The study focuses on side interactions between two vehicles. Observable elements of interactions that are potentially relevant to road safety were 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 were 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. That 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 as possible by specific intersection characteristics, other than the type of priority control. For that reason, two "basic" intersections are chosen that have no geometrical particularities such as bicycle paths, crossings, or speed-reducing measures 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 (7 a.m. to 6 p.m. period) of 2,441 passenger car equivalents (PCEs) on the primary (in-priority) road and 278 PCEs on the secondary road; the right-hand priority intersection has traffic volumes of 2,648 PCEs and 289 PCEs, respectively. For reasons of brevity, the higher-volume road at the right-hand priority intersection is also referred to as the "primary road" and the lower-volume road as the "secondary road." The terms, however, do not indicate a hierarchy here.

Definition and Application of the Concept "Interaction"

A first crucial element is what is to be considered an "interaction." An interaction is defined 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 in a collision (*25*). Interactions are the lowest (least severe) level of a safety hierarchy in which relationships exist between the lower severity levels and the highest severity level, that is, a crash (*26–28*).

To facilitate and objectify the observations, this definition is applied in a geographic space around the intersection. At both types of intersections the limits of this space are 50 m away from the intersection plane on both sides of the primary road and 25 m on both sides of the secondary road. The choice for two 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 with the right-hand priority intersection. The distances are chosen on the basis of pilot tests that have indicated that this is in most situations a good cutoff value to distinguish between vehicles that have an influence on each other and vehicles that do not.

Observation Protocol

Each intersection was observed for 30 h during the November 24 through December 5, 2011, period. All observations took place in dry weather conditions during the daytime because of the need to look inside the vehicles to collect information about the drivers' gender, age, and looking behavior. Twilight, night, and rainy conditions did not allow this. The observations were done in blocks of 2 to 3 h, spread evenly throughout the hours of the day and days of the week (including weekends) for both intersections, to avoid possible biases. All observations were executed by one observer using a standardized observation form. All variables were 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 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 to be a sign of theoretical solidity of the applied method and the good training of the observers, while large differences among coders suggest weaknesses in the research methods, such as poor operational definitions or poor training of the observers (*29–31*).

Furthermore, all interactions were recorded, which allowed validation of 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 with 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 with a stepwise procedure. The Akaike information criterion is used to assess the models. The measure indicates the model's relative goodness-of-fit, but penalizes larger numbers of parameters, providing a trade-off between accuracy and complexity of the model (*34*). Variance inflation factors (VIFs) are used to check for multicollinearity (i.e., a high correlation between two or more independent variables). VIFs higher than 4 indicate a high correlation (*35*). All variables in the end models have VIFs lower than 2, so there are no multicollinearity issues in the presented models.

RESULTS AND DISCUSSION

Intercoder Reliability

An extensive intercoder reliability assessment based on 113 of the 483 interactions (23% of all data) was performed. The intercoder reliability was assessed by 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 was calculated as well because some of the calculations suffered from the so-called κ paradox. These are situations in which 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 because 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 had a reliable κ-value exceeded the 0.70 threshold for Cohen's κ, and all but one (i.e., gender of the driver on the primary road) exceeded even the stricter criterion of 0.80. All variables (including those with an unreliable κ-value) had a percent agreement of 0.85 or higher. Most important, the agreement on which situations are considered interactions and which ones are not was 100%. The differences in reliability between both intersection types were minimal. In conclusion, the intercoder reliability values were 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 be either the in-priority vehicle or 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 they are 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 previous experience (*38*). Therefore, drivers who are familiar with the intersection may be especially likely not to expect drivers arriving from the secondary road, and therefore they 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. It was decided that the data would be analyzed 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); this is similar to the finding of Johannessen, which indicates 75% compliance (*8*). The compliance at the priority-controlled intersection (92%) is significantly higher than at the right-hand priority intersection ($X^2(1, N = 483) = 22.46, p < .001$), which is in line with Helmers and Åberg (*7*).

Priority Violation Models

The models in Table 2 show 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 first at the intersection 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"

TABLE 1 Descriptive Statistics

Variable Name	Variable Description	Priority-Controlled Intersection (*N* = 182)	Right-Hand Priority Intersection (*N* = 201): Distinction = Primary or Secondary	Right-Hand Priority Intersection (*N* = 201): Distinction = In-Priority Versus No-Priority Driver
Data About Yielding				
ViolationPriority	Right-of-way rule is violated	Yes = 15, No = 167	Yes = 54, No = 147	Yes = 54, No = 147
HasPriority prim	Vehicle on primary road has priority	Yes = 182, No = 0	Yes = 86, No = 115	—
HasPriority VP	*In-priority vehicle has priority*	—	—	*Yes = 201, No = 0*
HasPriority sec	Vehicle of secondary road has priority	Yes = 0, No = 182	Yes = 115, No = 86	—
HasPriority VNP	*No-priority vehicle has priority*	—	—	*Yes = 0, No = 201*
GetPriority prim	Vehicle on primary road gets priority	Yes = 167, No = 15	Yes = 124, No = 77	—
GetPriority VP	*In-priority vehicle gets priority*	—	—	*Yes = 147, No = 54*
GetPriority sec	Vehicle of secondary road gets priority	Yes = 15, No = 167	Yes = 77, No = 124	—
GetPriority VNP	*No-priority vehicle gets priority*	—	—	*Yes = 54, No = 147*
Demographic Variables				
Gender prim	Gender of driver on primary road	M = 125, F = 57	M = 138, F = 63	—
Gender VP	*Gender of in-priority driver*	—	—	*M = 121, F = 80*
Gender sec	Gender of driver on secondary road	M = 104, F = 78	M = 108, F = 93	—
Gender VNP	*Gender of no-priority driver*	—	—	*M = 125, F = 76*
Age prim	Age of driver on primary road	Y = 5, MA = 59, O = 18	Y = 5, MA = 186, O = 10	—
Age VP	*Age of in-priority driver*	—	—	*Y = 4, MA = 174, O = 23*
Age sec	Age of driver on secondary road	Y = 3, MA = 150, O = 29	Y = 6, MA = 166, O = 29	—
Age VNP	*Age of no-priority driver*	—	—	*Y = 7, MA = 178, O = 16*
Approaching Behavior				
Prim arrives first	Vehicle on primary road reaches junction plane first	Yes = 15, No = 167	Yes = 58, No = 143	—
VP arrives first	*In-priority vehicle reaches junction plane first*	—	—	*Yes = 77, No = 124*
Sec arrives first	Vehicle on secondary road reaches junction plane first	Yes = 112, No = 70	Yes = 90, No = 111	—
VNP arrives first	*No-priority vehicle reaches junction plane first*	—	—	*Yes = 71, No = 130*
Arrive same time	Vehicle on primary and secondary road reach junction plane at the same time	Yes = 55, No = 127	Yes = 53, No = 148	Yes = 53, No = 148
Same time	*In-priority and no-priority vehicle reach junction plane at the same time*	—	—	—
Approach prim	Approach behavior of vehicle on primary road at junction plane	Stop = 1, Dec. = 24, Hold = 157, Acc. = 0	Stop = 40, Dec. = 53, Hold = 106, Acc. = 2	—
Approach VP	*Approach behavior of in-priority vehicle at junction plane*	—	—	*Stop = 52, Dec. = 64, Hold = 84, Acc. = 1*
Approach sec	Approach behavior of vehicle on secondary road at junction plane	Stop = 179, Dec. = 1, Hold = 2, Acc. = 0	Stop = 110, Dec. = 69, Hold = 22, Acc. = 0	—
Approach VNP	*Approach behavior of no-priority vehicle at junction plane*	—	—	*Stop = 98, Dec. = 58, Hold = 44, Acc. = 1*
Looking Behavior				
LookLeft prim	Driver on primary road looks left	Yes = 21, No = 161	Yes = 22, No = 179	—
LookLeft VP	*In-priority driver looks left*	—	—	*Yes = 123, No = 78*
LookRight prim	Driver on primary road looks right	Yes = 10, No = 172	Yes = 90, No = 111	—
LookRight VP	*In-priority driver looks right*	—	—	*Yes = 128, No = 73*
DontLook prim	Driver on primary road does not look right or left	Yes = 155, No = 27	Yes = 107, No = 94	—
DontLook VP	*In-priority driver does not look right or left*	—	—	*Yes = 160, No = 41*
LookLeft sec	Driver on secondary road looks left	Yes = 182, No = 0	Yes = 198, No = 3	—
LookLeft VNP	*No-priority driver looks left*	—	—	*Yes = 97, No = 104*
LookRight sec	Driver on secondary road looks right	Yes = 181, No = 1	Yes = 198, No = 3	—
LookLeft VNP	*No-priority driver looks right*	—	—	*Yes = 66, No = 135*
DontLook sec	Driver on secondary road does not look right or left	Yes = 0, No = 182	Yes = 0, No = 201	—
DontLook VNP	*No-priority driver does not look right or left*	—	—	*Yes = 41, No = 160*
Maneuver				
TurnLeft prim	Vehicle on primary road turns left	Yes = 14, No = 168	Yes = 9, No = 192	—
TurnLeft VP	*In-priority vehicle turns left*	—	—	*Yes = 85, No = 116*
TurnRight prim	Vehicle on primary road turns right	Yes = 0, No = 182	Yes = 2, No = 199	—
TurnRight VP	*In-priority vehicle turns right*	—	—	*Yes = 28, No = 173*

(continued on next page)

TABLE 1 *(continued)* **Descriptive Statistics**

Variable Name	Variable Description	Priority-Controlled Intersection ($N = 182$)	Right-Hand Priority Intersection ($N = 201$): Distinction = Primary or Secondary	Right-Hand Priority Intersection ($N = 201$): Distinction = In-Priority Versus No-Priority Driver
DontTurn prim	Vehicle on primary road does not turn	Yes = 168, No = 14	Yes = 190, No = 11	—
DontTurn VP	*In-priority vehicle does not turn*	—	—	*Yes = 88, No = 113*
TurnLeft sec	Vehicle on secondary road turns left	Yes = 83, No = 99	Yes = 144, No = 57	—
TurnLeft VNP	*No-priority vehicle turns left*	—	—	*Yes = 68, No = 133*
TurnRight sec	Vehicle on secondary road turns right	Yes = 58, No = 124	Yes = 29, No = 172	—
TurnRight VNP	*No-priority vehicle turns right*	—	—	*Yes = 3, No = 198*
DontTurn sec	Vehicle on secondary road does not turn	Yes = 41, No = 141	Yes = 28, No = 173	—
DontTurn VNP	*No-priority vehicle does not turn*	—	—	*Yes = 130, No = 71*
Communication Data				
Direction prim	Driver on primary road uses directional lights	Yes = 168, No = 14	Yes = 11, No = 190	—
Direction VP	*In-priority driver uses directional lights*	—	—	*Yes = 99, No = 102*
Direction sec	Driver on secondary road uses directional lights	Yes = 116, No = 66	Yes = 153, No = 48	—
Direction VNP	*No-priority driver uses directional lights*	—	—	*Yes = 65, No = 136*
Gesture prim	Driver on primary road uses horn, hand gesture, or flash of headlights to communicate	Yes = 1, No = 181	Yes = 1, No = 200	—
Gesture VP	*In-priority driver uses horn, hand gesture, or flash of headlights to communicate*	—	—	*Yes = 8, No = 193*
Gesture sec	Driver on secondary road uses horn, hand gesture, or flash of headlights to communicate	Yes = 0, No = 182	Yes = 8, No = 193	—
Gesture VNP	*No-priority driver uses horn, hand gesture, or flash of headlights to communicate*	—	—	*Yes = 1, No = 200*

NOTE: Variables coded for distinction between vehicles on primary (prim) road and those on secondary (sec) road are in roman. Variables coded for distinction between in-priority vehicles and no-priority vehicles are in italic. — = not applicable; M = male; F = female; Y = young driver; MA = middle-aged driver; O = older driver; stop = stops completely; dec. = decelerates; hold = holds same speed; acc. = accelerates.

TABLE 2 Factors Influencing Probability of Right-of-Way Violation

Variable	Priority-Controlled Intersection	Right-Hand Priority Intersection (distinction prim/sec) (Model A)	Right-Hand Priority Intersection (distinction VP/VNP) (Model B)
Intercept	0.027 ($p = .980$)°	−1.591 ($p < .001$)***	*−0.765 ($p = .365$)°*
HasPriority sec		1.281 ($p < .001$)	
Sec arrives first	1.5265 ($p = .034$)**	−0.473 ($p = .013$)**	
VNP arrives first			*1.198 ($p < .001$)****
Approach VP			*Stop = 2.153 ($p = .004$)**** *Dec. = 0* *Hold = −1.009 ($p = .150$)°* *Acc. = −1.134 ($p = .526$)°* *($p < .001$)****
Approach sec	Stop = −2.653 ($p = .017$)** Dec. = 0 Hold = 1.154 ($p = .451$)° ($p = .050$)**		
Approach VNP			*Stop = −1.823 ($p = .007$)**** *Dec. = 0* *Hold = 1.544 ($p = .023$)*** *Acc. = 0.677 ($p = .702$)°* *($p < .001$)****
LookRight prim	1.098 ($p = .009$)***		
DontLook prim		0.771 ($p < .001$)***	

NOTE: VP = in-priority vehicle; VNP = no-priority vehicle.
°$p > .10$ (not significant at 90% CI); *$p \le .10$ (significant at 90% CI); **$p \le .05$ (significant at 95% CI); and ***$p \le .01$ (significant at 99% CI).

indicates that a violation is less likely when the vehicle on the secondary road comes to a full stop compared with 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 findings, although his observations apply only to right-hand priority intersections (*9*). 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 sees this either as implicit communication indicating that the driver on the primary road may give way or as an opportunity to infringe on the primary road driver's right-of-way with a low perceived personal risk (*14*). 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 when the vehicle on the secondary road arrives first. Both variables seem to confirm that the primary road is indeed considered to be 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 situation can indicate that these drivers approach the intersection at higher speeds [in line with Kulmala (*9*)], in that way discouraging the driver on the secondary road from enforcing his or her right-of-way for safety reasons, or it can indicate 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 the case in which 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.

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 finding 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, speed, or both 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 is significantly reduced when the no-priority vehicle stops, compared with the reference category of only decelerating. This finding 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, that is, a significantly higher probability of a violation when the in-priority vehicle stops and a lower (although not significant) probability in the case in which 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, 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 includes only "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 the case in which the driver arrives first, but the result is not significant. There is a significantly higher probability that the driver looks to the sides in the case in which the driver makes a turn, which is expected; making a turning maneuver 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 (nonsignificantly) higher probability of looking to the sides in the case in which a turning maneuver 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 driver 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 or she 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 instances in which 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

TABLE 3 Factors Influencing Likelihood That Driver Will Look to Sides on Approach to Intersection

Variable	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 = .951)°	1.368 (p = .028)**	2.260 (p < .001)***	1.570 (p = .013)**
GetsPriority sec		0.5124 (p = .036)**		
GetsPriority VNP			*1.262 (p < .001)****	
GetsPriority VP				*0.561 (p = .052)**
Prim arrives first	0.502 (p = .171)°			
VP arrives first			*0.4649 (p = .008)****	
Approach prim		Stop = 2.056 (p = .006)*** Dec. = 0 Hold = –2.218 (p < .001)*** Acc. = –0.200 (p = .856)° (p < .001)***		
Approach VNP				Stop = 2.173 (p = .013)** Dec. = 0 Hold = –2.472 (p < .001)*** Acc. = 0.090 (p = .960)° (p < .001)***
Turn prim	1.904 (p < .001)***	0.655 (p = .185)°		
Gender VP			F = 0 M = –0.287 (p = .101)°	
Age VP			Y = –0.529 (p = .528)° M = 0 O = 1.248 (p = .081)* (p = .095)*	

°p > .10 (not significant at 90% CI); *p ≤ .10 (significant at 90% CI); **p ≤ .05 (significant at 95% CI); and ***p ≤ .01 (significant at 99% CI).

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 the driver looking to the sides when the driver comes to a full stop, while this probability is significantly lower when the driver holds his or her speed.

STUDY LIMITATIONS AND FURTHER RESEARCH

Because 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) (*26, 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 against 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, that is, conflicts and crashes, should be further investigated. That investigation 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 was often unclear whether looking to the side is a proxy for a lower approach speed, as suggested by the literature, or a directly influencing factor (*9*).

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 the case in which the driver on the primary road looks to his or her 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, the indication is 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 to be 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.

Concerning 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 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, further research is merited.

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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