



Caught in the blind spot of a truck: A choice model on driver glance behavior towards cyclists at intersections

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ABSTRACT

Vulnerable road users (VRUs) constitute an increasing proportion of the annual road fatalities across Europe. One of the crash types involved in these fatalities are blind spot crashes between trucks and bicyclists. Despite the presence of mandatory blind spot mirrors, truck drivers are often reported to have overlooked the presence of a bicyclist. This raises the question if and when truck drivers check their blind spot mirrors for the presence of bicyclists, and which factors contribute to such glance behavior. The current study presents the results of an analysis of naturalistic glance behavior by 39 truck drivers in 1,903 right-turning maneuvers at urban intersections, where in each maneuver there was a chance of crossing the path of a bicyclist. The descriptive analysis revealed that most often truck drivers did not cast a glance upon their blind spot mirrors as recommended by the examination guidelines. Furthermore, a choice model was developed with the main factors that have an impact on glance behavior. Drivers were more likely to glance with a priority regulation that allowed conflicts, with lower speed limits, with zebra crossings, without cyclist facilities, without a lead vehicle making the same maneuver, in presence of VRUs, without adverse sight conditions, in lower age groups, without certain non-driving related activities, when driving a truck with more direct vision on VRUs, and without a camera providing a view on the blind spot, and with less time between a standstill and starting the maneuver. Three factors did not significantly improve the choice model and were therefore left out, despite showing significant effects in bivariate tests: intersection layout (e.g., three vs. four legs), presence of advanced stopping lanes, and visual obstruction. Implications of the choice model are discussed for driver education (in terms of timely glances, reducing inattention, and hazard anticipation) and vehicle design (in terms of direct vision).

1. Introduction

The World Health Organization (2018) estimated that vulnerable road users (VRUs; pedestrians, bicyclists, and motorcyclists) represent more than half of all global road deaths in 2016, which highlights the importance to investigate crashes with VRUs. Trucks are one of the most dangerous collision opponents bicyclists can encounter at an intersection (Nieuwoehner & Berg, 2005). Trucks have rear-quarter blind spots: areas on the road which cannot be seen while looking forward, or through the rear-view and side mirrors. The large blind spots of trucks can only be viewed through dedicated blind spot mirrors, or by means of cameras aimed these locations. A failure of truck drivers to scan these mirrors before making a turn on an intersection can lead to serious crashes with vulnerable road users, such as cyclists and pedestrians

aiming at travelling straight ahead. In 2007, the European Union estimated that 400 people are killed in blind spot crashes in Europe every year, most of them being VRUs (European Union, 2007). Since then, several European studies have described blind spot crashes. An analysis of 7967 bicyclist-motorist crashes in Denmark by Kaplan and Prato (2013) showed that motorists turning right at urban intersections accounted for 33% of the crashes, at which the authors suggested that the problem could be related to blind spots. Talbot et al. (2014) analyzed police collision files in London involving bicyclists. They found that of the 53 fatalities and seriously injured in the sample, 27 (51%) had a truck as collision opponent, of which 16 (30%) concerned the blind spot scenario with a truck turning left (i.e., the nearside in Great Britain) across the path of the bicyclist. A study by SWOV (2015) found that on average 9 bicyclists lose their lives in a blind spot crash with a truck

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every year in the Netherlands. Finally, in a Norwegian study by Pokorný et al. (2017), trucks turning right into a bicyclist's path proved to be the most frequently occurring fatal truck-bicycle accident type in urban areas. Most blind spot crashes between trucks and bicyclists appear to occur at urban intersections (Pokorný et al., 2017; Schoon, 2006; International Road Transport Union, 2007). Furthermore, Schoon (2006) found that blind spot crashes typically occur when a right-turning maneuver by a truck is preceded by a full stop (e.g., due to waiting for a traffic light). In those circumstances, trucks are likely undertaken by bicyclist due to their low acceleration (Frings et al., 2012).

Since 2007, new trucks have been equipped with several blind spot mirrors to assist the driver, or with cameras and displays offering a similar view (European Union, 2003). Wide-angle exterior mirrors (i.e., Class IV) cover a wide area behind the cabin. Close-proximity exterior mirrors (Class V) cover an area immediately adjacent to the vehicle cab on the passenger's side. Finally, front mirrors (Class VI) cover the area in front of the cabin that cannot be seen from the driving position. The theoretical and practical exams in the Netherlands include the use of blind spot mirrors in relation to VRUs. The Dutch driving license authority (CBR, 2020) states that truck drivers should acquire an awareness of the presence of other road users at an intersection, as well as an awareness of its infrastructure and priority regulation, as early as possible. Furthermore, truck drivers should check if other road users are present just before and upon entering the intersection, and in case of making a turn, additional attention is prescribed for other road users in the blind spots of the vehicle during the maneuver, because they may undertake the truck. These instructions imply that truck drivers should cast a glance upon their blind spot mirrors at least once before a right turning maneuver is initiated, and at least once during the maneuver (but before crossing the bicyclist's path). Despite these instructions, drivers have been found failing to identify VRUs in the blind spot of their truck in the majority of the fatal and serious crashes (Talbot et al., 2014).

Why do truck drivers involved in blind spot crashes not see a bicyclist? Talbot et al. (2014) mention three potential causes. First, the driver may have looked in the direction of the bicyclist, but failed to see the bicyclist. Second, the driver may not have looked at the mirrors, for example because the driver's attention was captured by the presence of road users elsewhere, in line with a study on car drivers by Summala et al. (1996). Third, the driver may have checked the blind spot mirrors, but not at the moment during which the bicyclist was visible in the corresponding mirror. Talbot et al. (2014) argue that the European regulations on the field of view using mirrors is based on research with stationary trucks and stationary other road users. This implies that blind spot mirrors provide the best view on the traffic situations at a junction before moving off, but not when a truck and/or a VRU are already moving.

Several studies have mentioned visibility problems as a risk factor in crashes between cyclists and trucks.

Reduced visibility has been related to obstructed view (Pokorný et al., 2017; Nicaj et al., 2009; Eilert-Petersson and Schelp, 1997; Dozza and Werneke, 2014), inadequacy of street lighting (Hoque, 1990), dark clothing worn by cyclists (Pokorný et al., 2017), as well as weather conditions, such as rain and snow (Pokorný et al., 2017), and darkness (Hagel et al., 2014; Hamann et al., 2015). Driver inattention has also been coined as a risk factor for crashes between trucks and cyclists. Nicaj et al. (2009) found that most bicyclist fatalities occurred at intersections, and that most fatal crashes involved driver and/or bicyclist inattention. A Canadian study on fatal bicycle crashes reported that of the crashes involving a motorist, 34% were due to bicyclist inattention and 37% due to motorist inattention (Gaudet et al., 2015).

Aside from factors that may negatively influence glance behavior, there are also factors with a potential positive influence. From a behavioral perspective, bicyclists are advised not to stop directly next to a truck to ensure they are visible to the driver (Fiettersbond, 2022). When VRUs are visibly present for the driver, their presence may prime truck drivers early on to exhibit more cautious behavior (Garay-Vega

and Fisher, 2005; Crundall and Underwood, 2001), especially when many VRUs are present (Jacobsen, 2003). From an infrastructural perspective, Schoon (2012) argues that the greater the distance between a cycle lane or pavement (if present) and the main road, the better the driver's view on the presence of VRUs. Thomas and DeRobertis (2013) report that the use of physically separated bicycle tracks decreases the odds of a collision between a bicyclist and a motorized vehicle on busy streets. However, Vandenbulcke et al. (2014) have found that if physically separated cycle tracks are in close vicinity to the motorized traffic lane, there is actually an increased risk of collision, which indicates that physical separation alone is not enough to prevent such collisions.

So far we have presented several potential explanations for truck driver glance behavior in blind spot crashes. However, the suggestions by Talbot et al. (2014) are not based on empirical data, and the other factors (i.e., visibility, driver inattention, VRU presence, bicyclist infrastructure) are based on studies examining crashes in a variety of situations. The specific contribution of these factors to glance behavior in blind spot crashes is yet unknown. Knowledge on if and when truck drivers scan their mirrors for cyclists prior to blind spot crashes may help to prevent blind spot crashes in the future, but glance data is rarely collected in crashes. Behavioral studies provide an opportunity to interpret the findings from analysis of truck-bicyclist crashes (Pokorný and Pitera, 2019). To date, however, only a few on-road studies have been performed to examine glance behavior in blind spot interactions. Kircher and Ahlström (2020) instructed truck drivers to drive a fixed route and used an eye-tracker to investigate driver glance behavior towards a bicyclist at three intersections, of which one was regulated by traffic lights. Drivers were more likely to glance at a right mirror in one of the unregulated intersections, compared to the other two intersections, suggesting that the infrastructure design influences glance behavior. A generalized influence of infrastructure layout could not be determined, due to a low number of intersections in the sample. Furthermore, Kircher and Ahlström did not account for the presence of other road users, nor the presence of a bicyclist (who was always present, typically from at least 150 m before the intersection). Schindler and Bianchi Piccinini (2021) addressed the latter limitation by manipulating the presence of a bicyclist or pedestrian dummy in a test-track experiment, and found that such presence was associated with lower driving speeds and coming to a full stop further away from the intersection. Analysis of glance behavior revealed that truck drivers looked more often to the front right and right (i.e., where the mirrors are located) when a bicyclist was present. Schindler and Bianchi Piccinini reckon that their results are based on artificial interactions at a single intersection and advocate additional research on a larger variety of scenarios in a naturalistic setting. To our knowledge, the only naturalistic driving study on glance behavior by truck drivers at intersections was a pilot analysis performed by Jansen (2017), who found that truck drivers checked their close proximity exterior mirror in 19% of the maneuvers on average. However, this study has some important limitations. First, a separate study by Jansen et al. (2021) found that glances towards individual mirrors on the right side of a truck are often confused with glances towards other locations. Second, the dataset was not screened on the possibility that trucks crossed a bicyclist path during their maneuver, which means certain mirror checks may not have been necessary. Third, the algorithm with which right-turning maneuvers were identified excluded maneuvers involving a full stop; a scenario that may occur when the truck encounters a bicyclist. Due to these limitations, the findings of Jansen (2017) likely do not represent actual glance behavior in relevant maneuvers.

1.1. Research goal & paradigm

All in all, there appears to be little knowledge on glance behavior by truck drivers performing a right-turning maneuver, let alone which factors influence glance behavior. Previous studies are limited due to data collection (e.g., using a test track or driving a predetermined route),

data processing (e.g., selecting events without a potential collision path, annotating glances with low accuracy), and/or the scope of the analysis (e.g., considering few factors). Therefore, the goal of the present study is to explore which factors best explain glance behavior of truck drivers before and during right-turning maneuvers at urban intersections. Glance behavior has been collected using naturalistic driving data, and the impact of several factors on glance behavior has been studied by means of a choice model (see below). Due to its high prevalence in blind spot crashes, the present study focuses on maneuvers preceded by a full stop.

Previous studies recommend research on the actual use of blind spot mirrors using Naturalistic Driving (ND) data (Schoon, 2012; Schindler and Bianchi Piccinini, 2021). An advantage of ND data is that it offers a view on everyday driving routines from the perspective of the truck driver (Van Nes et al., 2019). In contrast, the manipulations typically found in experimental studies (such as the one performed by Kircher and Ahlström, 2020) may influence the natural behavior of truck drivers, whereas site-based observation, while essentially naturalistic, introduces a bias with regard to location and does not provide a detailed view of driver glance behavior and engagement in non-driving tasks. The UDRIVE naturalistic driving dataset (Van Nes et al., 2019) provides an opportunity to study the right turn maneuvers by truck drivers in an everyday, real-life driving context.

The instructions of CBR (2020) on desirable glance behavior at right-turning maneuvers do not specify explicitly when and in which order the (blind spot) mirrors should be checked. Implicitly, they do imply that truck drivers should cast a glance upon their mirrors at least once before a right turning maneuver is initiated, and at least once during the maneuver (but before crossing the bicyclist's path). The present study takes a novel approach to assess glance behavior, whereby a right turning 'event' is described in terms of two phases: before the maneuver and during the maneuver.

2. Method

The UDRIVE database features more than 38.000 h of naturalistic driving data with instrumented trucks driving in the Netherlands (Van Nes et al., 2019). Right turn maneuvers have been automatically extracted, and the resulting events have been coded to analyze the main factors influencing glance behavior.

2.1. Truck drivers

Truck drivers were recruited at four Dutch transport companies. The UDRIVE database included 47 Dutch truck drivers (46 males, 1 female), with ages between 21 and 71 years ($M = 49.09$, $SD = 11.12$). The truck driver sample is representative of the Dutch truck driver population in terms of gender and age, and the participating fleet owners are representative of the average fleet owner in the Netherlands. After screening candidate events (see video annotation below), the sample consisted of 39 truck drivers (38 males, 1 female), aged between 22 and 71 years ($M = 48.41$, $SD = 11.52$).

2.2. Vehicles and data acquisition system

The UDRIVE truck database involved Volvo FL and Volvo FM distribution trucks, both of which were equipped with all mandatory (blind spot) mirrors. For this study, we assume the mirrors were properly adjusted for the individual drivers. In addition, Volvo FL trucks feature a window in the lower section of the passenger door. By looking through this window, the driver can obtain a partial view of what the right pedestrian (Class V blind spot) mirror offers. Volvo FM trucks do not feature this extra window.

A Data Acquisition System (DAS) was installed in each truck (see Van Nes et al., 2019), which registered, amongst others, six camera views (see Fig. 1), CAN bus data (e.g., vehicle speed, sampled at 10 Hz), and GPS position data (sampled at 1 Hz). The GPS data were enriched with a map matching procedure, yielding information on the presence of

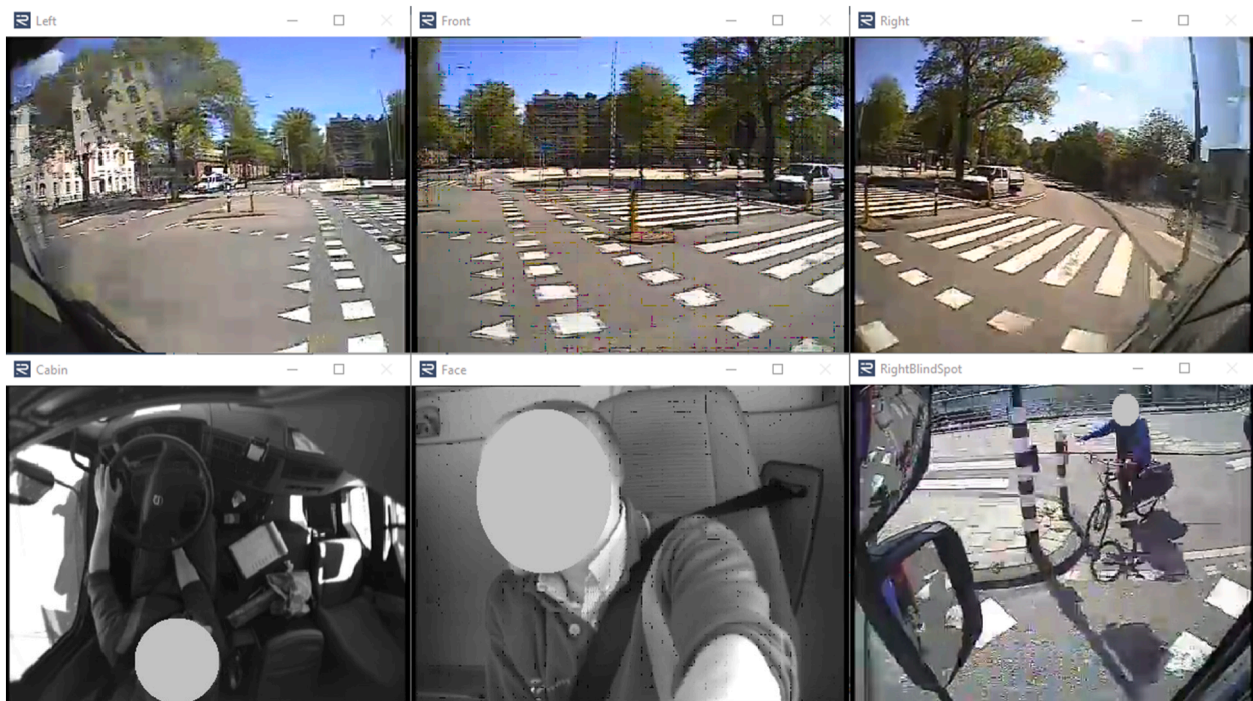


Fig. 1. Right-turn maneuver at a signalized intersection with a bicyclist in the right blind spot, viewed through six UDRIVE truck camera perspectives: front left, front center, front right, cabin view, driver face, and right blind spot. Faces have been anonymized to respect the privacy of the participating driver, as well as other road users.

intersections and roundabouts, local speed limits, as well as speed and heading direction (i.e., a value between 0 and 360 degrees). Recording started and ended when the truck key was switched. Given that colleagues of the participating drivers made use of the same trucks, only trips with drivers who signed informed consent have been included in the project database.

Manual review of video footage revealed that some trucks were equipped with a display on the mid console, switching on at driving speeds below approximately 20 km/h. In some trucks, the associated camera provided a view in front of the truck, whereas in other truck it provided a view next to the truck. These views could not be established for all trucks, in part due to limited resolution and contrast of the cabin camera installed for the present study, and in part because the displays were sometimes shut off throughout the entire trip. It is not known whether trucks were equipped with an auditory blind spot warning system.

2.3. Time windows for glance behavior

A right turning ‘event’ is described in terms of two phases: before the maneuver and during the maneuver. The time windows of these phases are operationalized as follows. According to PIARC (2016), an average driver needs up to six seconds to adapt to a new driving environment. We interpret the phase before the maneuver as an adaptation period lasting six seconds until the maneuver onset (operationalized as the first moment of steering). Following the maneuver onset, the phase during the maneuver runs until the last moment the driver may cast a glance upon the blind spot mirrors to prevent a collision with a bicyclist, which depends on driver hazard perception time, driver reaction time, vehicle reaction time, and vehicle brake time. Based on Velichkovsky et al. (2002), drivers will need at least 0.2 s to identify a hazard. Once a hazard has been detected, the driver will need to react by pressing the brake pedal. According to Green (2000) the average brake reaction time of drivers ranges between 0.75 s and 1.5 s, depending on whether drivers anticipate on braking or whether they are surprised, respectively. Seeing that the professional drivers in the present study should be trained on the potential presence of VRUs in the blind spot, a brake reaction time of 1.0 s has been assumed. The brake discs do not respond immediately to

the brake pedal. Here, a brake lag of 0.4 s has been assumed (Yukon Government, 2018). Finally, it takes time for the truck to come to a full stop. The average speed at the maneuver onset in the final dataset of the present study was $M = 12.21$ km/h ($SD = 4.66$). Assuming a linear deceleration of 5 m/s^2 (a minimum based on UN/ECE, 2016), the brake duration is 0.7 s. In sum, the last moment at which the driver can initiate a glance to prevent a potential collision is at 2.3 s before the truck reaches the zone where the truck and a bicyclist would have collided if they had both occupied the same space (hereafter: encroachment zone).

Fig. 2 illustrates the two event phases, each during which a glance upon the blind spot mirrors should be cast. As shown in Fig. 2.a, drivers will have more time to cast a sideways glance in the ‘during’ phase as the distance to a bicyclist increases (here shown by means of a physically separated cycle track), and especially if a full stop is made during the maneuver (e.g., to stop for a VRU, or in case of stop-and-go traffic). Vice versa, the duration of the ‘during’ phase decreases when the separation between truck and bicyclist decreases, for example in case of a marked cycle lane. Fig. 2.b shows the scenario where the driver has just enough time to glance during the maneuver. Had the encroachment zone been closer to the maneuver onset, then there would not have been a possibility to glance in time to stop the truck. For this reason, the availability of the ‘during’ phase is incorporated as binary variable in the discrete choice models.

2.4. Glance choice as dependent variable

Glance behavior of truck drivers in the UDRIVE database can be inferred from video footage collected by two cameras. One camera is mounted in the left A-pillar and pointed at the driver’s face. The other camera is mounted at the ceiling of the truck cabin, providing a top view of the driver (see Fig. 1). In the ideal world these camera perspectives provide enough information to accurately identify glances of the driver towards specific (blind spot) mirrors. A study by Jansen et al. (2021) using the same camera perspectives investigated the accuracy with which known driver glance locations in a truck can be coded. Individual mirrors on the passenger side of the truck were coded accordingly in at most 26% of the video stimuli (these mirrors were mostly confused with each other). The front blind spot mirror was coded with an average

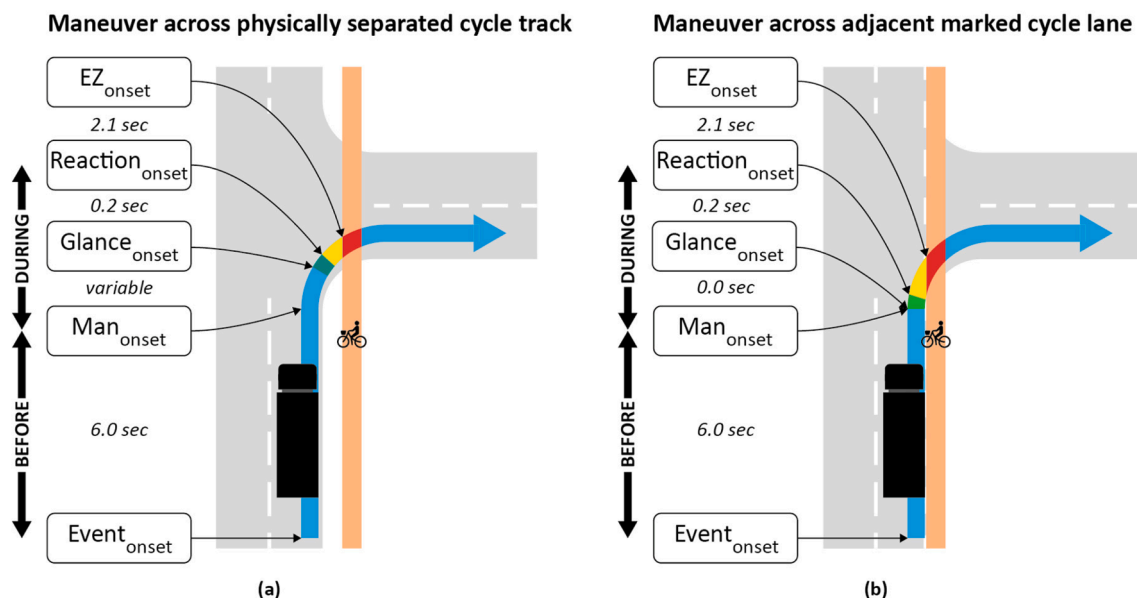


Fig. 2. Phases of a maneuver by a truck turning right into a physically separated cycle track (a) and an adjacent marked cycle lane (b). The ‘before’ phase starts at 6.0 s before the maneuver (Man) onset. The ‘during’ phase runs from the maneuver onset to the encroachment zone (EZ) onset. Glance onset corresponds with the last moment at which a driver can cast a glance upon the blind spot mirrors to prevent a collision with a bicyclist. The reaction time is comprised of the driver’s reaction time (1.0 s), the vehicle’s brake lag (0.4 s) and the brake duration (0.7 s) based on an average speed of 12.2 km/h at the maneuver onset.

accuracy of 3%, and typically confused with glances to the passenger side (62%) or glances through the right part of the windshield (33%). If all glance locations on the passenger side are grouped (i.e., right window, right side mirror, right blind spot mirror, right pedestrian mirror, right door lower window), then the resulting glance category 'Right' yields an average accuracy of approximately 90%. The authors argue that studies on blind spot crashes should focus on the presence or absence of sideways glances on the passenger side when using a camera setup similar to the one used in UDRIVE. This means that when a driver looks sideways, the driver has potentially looked at one of the mirrors (and if so, potentially saw a VRU), but this cannot be known for sure. If the driver does not look sideways, then by definition none of the blind spot mirrors on the passenger side have been checked (and no VRUs were seen). In the present study, we therefore discern between two glance categories: the driver looks to the right, or the driver looks elsewhere. This operationalization of glance behavior means that the findings are not only relevant for current truck cabin designs (i.e., with a low degree of direct vision), but also for future truck cabin designs where the driver has a direct view on VRUs when looking sideways. The present study does not focus on glances to the front blind spot mirror, due to the low accuracy level reported in Jansen et al. (2021).

If truck drivers should glance upon their mirrors at least once before a right turning maneuver is initiated, and at least once during the maneuver, then glance choice could be operationalized as a binary dependent variable (i.e., the driver did or did not look in both maneuver phases). However, the 'during' phase may not always be applicable, for example in case of a marked cycle lane (see Fig. 2.b). Moreover, if drivers do not cast a glance in both maneuver phases, then from a safety perspective it is still relevant to know whether a glance was cast either before or during the maneuver. Therefore, glance behavior is operationalized as a categorical variable (hereafter: 'glance choice') with four levels: 'N' (the driver did not cast any glances to the right), 'B' (the driver cast at least one glance to the right before the maneuver, but not during the maneuver), 'D' (the driver cast at least one glance to the right during the maneuver, but not before), and 'BD' (the driver cast at least one glance before the maneuver, and at least one glance during the maneuver). Following Velichkovsky et al. (2002) on hazard perception time, the minimum glance duration considered is 200 ms. Glances of at least 200 ms starting before the maneuver and ending after the maneuver are allocated to both maneuver phases.

2.5. Maneuver identification

Two signals served the identification of right turn maneuvers on urban intersections: GPS position data and CAN speed data. The CAN speed data in the UDRIVE truck database have incidentally shown perfect linear increases and decreases with durations over several seconds. Seeing that such speed profiles are unlikely to occur in reality, and given that video footage occasionally revealed standstills, it is more likely that missing data during pre-processing has resulted in linear interpolation between adjacent 'known' data points. Therefore, an R-script was developed, which tagged segments of CAN speed data as 'valid' when the absolute value of jerk (calculated as the second derivative of speed with respect to time) was not below 0.02 m/s^3 for a duration longer than 1 s, unless the vehicle was stopped (based on GPS data, with a tolerance of 15 m to compensate for drift). A total of 8.32% of the speed data was marked as 'invalid' and excluded from subsequent analysis.

Another R-script was developed to obtain the actual maneuvers. Based on empirical validation, sequences of data points were tagged as candidate maneuvers when the yaw rate (calculated as the first derivative of GPS heading with respect to cumulative distance) exceeded 0.4 deg/m with a minimum total heading change of 25 degrees, given that the duration of each maneuver was at least 2 s and driven in a forward gear (to exclude driving backwards). These thresholds were deliberately set low to reduce the chance of missing events. Next, a time window was drawn six seconds before the onset of the candidate maneuvers, and

three seconds following their offset. Candidate events (i.e., time windows including the maneuvers) were identified using the following criteria: the heading change was positive (a negative change corresponds with a left turn maneuver), throughout the entire time window CAN speed was valid and the speed limit was at or below 50 km/h, a full stop (i.e., a CAN speed of 0 km/h) preceded the maneuver onset, there was an overlap with an intersection according to the enriched GPS data, and there was no other left or right turn maneuver overlapping within the time window (such that subsequent annotation is unambiguously related to a single maneuver). All candidate events resulting from this script were assessed manually by human annotators to remove false positives due to, e.g., map matching errors, thus selecting only true right turn maneuvers on urban intersections.

2.6. Video annotation procedure

Four video raters (hereafter: annotators) manually validated and coded the candidate events in two annotation phases, supported by a dedicated codebook (see Appendix A and B for a description of the annotated variables). Screening in phase 1 served to select which candidate events were subjected to additional annotation in phase 2. Candidate events had to meet four criteria to pass the screening in phase 1. First, driver and traffic conditions had to be visible throughout the entire event through six camera perspectives (driver face, cabin, front left, front center, front right, and right blind spot). Second, the maneuver onset based on kinematics (i.e., the moment at which the jaw rate threshold is exceeded) and the maneuver onset based on video data (i.e., the moment at which the driver starts to steer) had to be within a tolerance margin of 1 s. Third, the candidate event had to feature a right-turning maneuver at an intersection (as opposed to, e.g., taking a curve in absence of an intersection). Fourth, the infrastructure had to provide an opportunity for cyclists to cross the trajectory of a right-turning truck (i.e., a bicyclist encroachment zone).

Annotation phase 2 comprised in-depth annotation on several variables. Infrastructural variables concerned priority regulation, pedestrian facilities, bicyclist facilities, and the presence of visual obstructions, in addition to intersection type (which had already been annotated in phase 1). Situational variables concerned traffic flow, the presence of vulnerable road users from several directions (same direction as the truck, opposite direction, passing in front) at the maneuver onset and on the right side of the truck during the first three seconds of the event, and adverse sight conditions. Finally, behavioral variables concerned engagement in non-driving related tasks (NDRTs) and glance direction over time. Varotto et al. (2021) found a low interrater reliability when all NDRT types (e.g., using a phone, reading, writing, eating, drinking, smoking) were considered simultaneously (i.e., resulting in one variable to denote NDRT engagement). Therefore, NDRT engagement, as defined in the UDRIVE codebook (Carsten et al., 2017), was annotated individually for each NDRT type in the present study. Glance direction was operationalized as looking to the right side of the cabin (i.e., right window, right side mirror, right blind spot mirror, right pedestrian mirror, or the lower window of the right door), or elsewhere. All annotators were participants in the former study of Jansen et al. (2020), as a result of which they were familiar with the glance directions operationalized in the present study.

Annotation was performed with a dedicated toolbox developed in Microsoft Visual Studio 2017, which restricted playback of the videos to the selected event. Annotation phase 1 started with a training session with 30 randomly selected events, followed by an interrater reliability test session on 20 randomly selected events. For each variable that did not meet the criteria for interrater reliability (hereafter: IRR, see next section), the individual ratings were discussed with the first author in a plenary session, until consensus was reached. Next, the events were randomly distributed across the annotators in batches of approximately 125 events. Phase two followed for events that met the criteria for follow-up annotation (typically resulting in smaller batches), and two

additional IRR tests were performed. One IRR test took place before the annotators were allowed to process their batches. The other IRR test was taken at the end of phase two to evaluate if the level of agreement across the annotators was consistent throughout the annotation process. An R-script was developed to verify that all variables within a batch were filled out. Consequently, there were no missing data.

2.7. Data analysis

All analyses were performed in R, and statistical tests were performed against a significant of $p = .05$.

2.7.1. Interrater reliability

The interrater reliability of the annotation was assessed based on the statistical measures and criteria as described in Varotto et al. (2021), meaning a Krippendorff's Alpha of at least 0.67, or in case of a significantly skewed distribution, a percentage agreement of at least 80%. When annotated variables initially did not meet the criteria, we examined whether grouping two or more levels within these variable could improve the interrater reliability.

The interrater reliability of glance behavior, the only variable coded frame-by-frame, was assessed based on two derived measures. First, the proportion of time glancing sideways within an event was used to evaluate whether annotators agreed on the glance direction. Second, the number of switches between glancing sideways and glancing elsewhere within an event was calculated as an indicator of the sensitivity of the annotators for dynamics in glance behavior.

2.7.2. Bivariate tests

We explored the relationship between the glance choice and the explanatory variables using descriptive statistics and statistical tests. We compared the empirical distribution functions of the continuous variables when the different glance choices were observed. The similarity of the distributions between groups were tested using two-sample Kolmogorov-Smirnov tests. To assess the relation between categorical independent variables and glance choices, Chi-square tests were performed. Groups that had <5 observations were merged with other groups based on a similar meaning.

2.7.3. Choice model

The main factors influencing glance behavior are analyzed in a choice model. Choice models allow to investigate the impact of multiple explanatory variables on the responses of drivers capturing explicitly unobserved correlations between similar alternatives (Gates et al., 2014) and by the individual driver (Farah et al., 2019; Ghasemzadeh and Ahmed, 2019; Paschalidis et al., 2018; Varotto et al., 2017, 2018). In this study, the choice model is a logit model. The utility functions U for driver n at time t are given by equations (1)-(4):

$$U_n^B(t) = \alpha^B + \beta^B \bullet X_n^B(t) + \gamma^B \bullet v_n^B + \varepsilon_n^B(t) \quad (1)$$

$$U_n^D(t) = \alpha^D + \beta^D \bullet X_n^D(t) + \gamma^D \bullet v_n^D + \varepsilon_n^D(t) \quad (2)$$

$$U_n^{BD}(t) = \alpha^{BD} + \beta^{BD} \bullet X_n^{BD}(t) + \gamma^B \bullet v_n^B + \gamma^D \bullet v_n^D + \varepsilon_n^{BD}(t) \quad (3)$$

$$U_n^N(t) = 0 + \varepsilon_n^N(t) \quad (4)$$

where α^B, α^D and α^{BD} are the constants, β^B, β^D and β^{BD} are the vectors of parameters associated with the explanatory variables $X_n^B(t), X_n^D(t)$ and $X_n^{BD}(t)$, γ^B and γ^D are the parameters associated with the driver-specific error terms $v_n^B \sim N(0,1)$ and $v_n^D \sim N(0,1)$, and $\varepsilon_n^B(t), \varepsilon_n^D(t), \varepsilon_n^{BD}(t)$ and $\varepsilon_n^N(t)$ are i.i.d extreme value error terms. Relevant explanatory variables are the driver behavior characteristics of the subject vehicle, the environment characteristics, the presence of other road users, the vehicle type, and the characteristics and the state of the driver. The probability of choosing the alternative $k \in C_i$ with $C_i = \{B, D, BD, N\}$ is

presented in equation (5):

$$P(Y_n(t) = k | \hat{I}_n(t), v_n^B, v_n^D) = \frac{Z_n^k(t) \bullet e^{V_n^k(t)}}{\sum_{i=1}^4 Z_n^i(t) \bullet e^{V_n^i(t)}} \quad (5)$$

where $Z_n^i(t)$ assumes a value equal to one when the alternative i is available for driver n at time t and zero otherwise and $V_n^i(t)$ indicates the part of the utility functions in equations (1)-(4) excluding the error term $\varepsilon_n^i(t)$. The model parameters α, β, ξ and γ were estimated using the R-package 'Apollo' (Hess & Palma, 2019). This package permits to define which alternatives are available for each observations and to capture correlations between and within individual drivers when the model is estimated. The model estimated can be used to forecast the glance choices of the drivers when the explanatory variables change.

Explanatory variables were considered for the choice model if the corresponding bivariate tests yielded statistical significance (see Appendix C). The explanatory variables were included one by one in the model. We included first the variables that showed a large impact on glance choice based on the descriptive statistics and the statistical tests. In this study, the order was as follows: 1) infrastructure characteristics, 2) traffic conditions and road users, and 3) driver and vehicle characteristics. Continuous variables were centered in the mean value. For categorical variables, the most frequent category was fixed as reference category. The likelihood ratio test was used to compare different model specifications and determine whether adding an explanatory variable or an error term significantly improved the model. We included separately in the model variables that had a very similar meaning and we examined the correlation matrix of the estimates each time. Following this procedure, we identified potential cases of multicollinearity between explanatory variables. Possible indicators of collinearity considered were a significant likelihood ratio test when several variables resulted to be non-significant, and large changes in the parameters estimated when a new variable was included. We tested variables that had a very similar meaning against each other and merged them when their impact on the glance choice was similar. We excluded one by one explanatory variables that did not have a significant impact. Error components capturing unobserved correlations among alternatives (Train, 2009) did not result in a significant improvement in the model fit and thus were not considered in the final model.

3. Results

3.1. Data reduction & sample description

An initial sample of 4,648 candidate events was subjected to assessment in the first annotation round, of which a total of 2,745 candidate events were excluded from analysis (see Fig. 3). The annotators were instructed to use a comment field whenever they were unsure about their rating and when an observed phenomenon did not fit any of the listed categories. Examples include not being able to see what the driver was holding (which is relevant for variables on secondary task involvement), and road markings that were covered by snow or foliage (required for annotating bicyclist facilities). The first author manually corrected these annotations by inspecting the videos prior to and after the events (which was not possible for the annotators). For 5 events tagged with 'unsure' or 'other' the correct annotation could not be resolved. After the data reduction steps, a final dataset of 1,903 events was obtained, consisting of 39 drivers with a median of 16 maneuvers per driver (minimum = 1, maximum = 366). For drivers with very few maneuvers, we do not know if the observed glance behavior is their default behavior, or driven by the circumstances. Therefore, we have chosen to include these drivers in the sample.

As per the selection criteria, all events included a full stop prior to the maneuver onset. In 1717 events (90.23%), the truck was already stopped at the beginning of the 6 s time window before the maneuver onset. Usually, there was only one full stop prior to the maneuver onset.

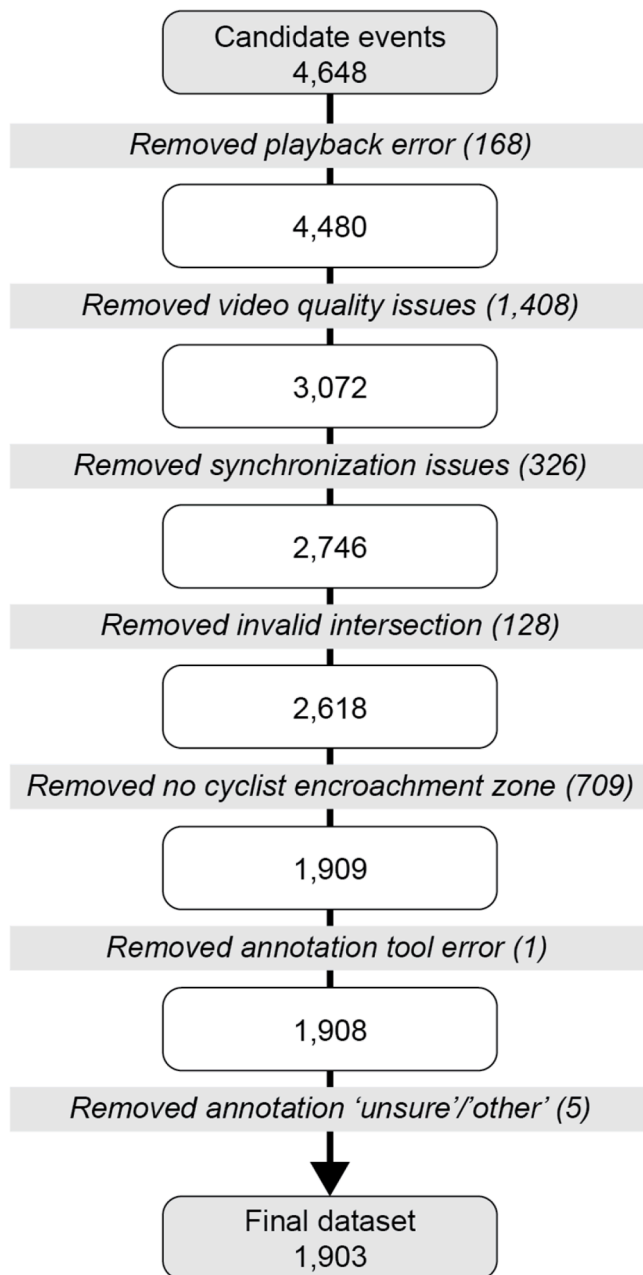


Fig. 3. Data reduction from 4,648 candidate events to a final dataset consisting of 1,903 events.

There were 10 events with two full stops, and 2 events with 3 full stops prior to the maneuver onset. Across the 1903 events, the average time spent waiting prior to the maneuver onset was 2.31 s ($SD = 1.41$), or 38.47% of the time ($SD = 23.42$). On average, the trucks started driving again at 3.60 s seconds before the maneuver onset ($SD = 1.52$), resulting in an average speed of 12.21 km/h ($SD = 4.66$) at the maneuver onset.

The average duration of the time window between the maneuver onset and the encroachment zone onset was 3.08 s ($SD = 1.99$, minimum = 0, maximum = 45.9). Manual inspection of a sample of the videos showed that short durations were often found when the encroachment zone was on a marked cycle lane, whereas long durations were typically found when multiple cyclists passed the subject vehicle on the right side, causing the truck to wait. In total, there were 145 events (7.62%) with a full stop during the maneuver (137 events with one full stop, 5 events with 2 full stops, and 3 events with three full stops). The mean time spent waiting during the maneuver was 1.29 s

($SD = 2.97$).

In 506 events (26.59%) the encroachment zone onset followed within 2.3 s after the maneuver onset, as a result of which no right-side glances of at least 0.2 s could have been cast in time during the maneuver to prevent a potential collision. As shown in Table 1, drivers failed to cast a glance throughout the entire event in 29% of the events where a glance could have been made during the maneuver, and in 51% of the events where glances during the maneuver were not applicable. In terms of following the guidelines for correct glance behavior, drivers cast a glance to the right side in both phases of the maneuver (i.e., before and during) in 33% of the events where a glance during the maneuver was applicable. If such glances were not applicable, drivers looked before the maneuver in 49% of the events.

3.2. Interrater reliability

The variables analyzed in subsequent analyses of section 3 proved to be eligible based on the reliability criteria. Two variables required merging of one or more underlying categories to meet the reliability criteria. For bicyclist facilities, a plenary discussion of events in which disagreement was found revealed that the annotators experienced difficulties in distinguishing between one-way and two-way cycle tracks. Grouping the cycle track categories yielded an interrater reliability level that met the criteria. Likewise, annotators experienced difficulties to distinguish between drivers using a mobile phone and drivers using an electronic device, resulting in sub-par agreement on secondary task involvement. Merging these categories resulted in a variable that met the criteria.

Annotators were in agreement on visual obstructions prior to the start of annotation phase 2 (agreement: 80%), but not by the time annotation was finished (agreement: 75%). Disagreement was mainly found between categories 'No obstruction' and 'Building/Billboard', indicating that annotators may have experienced difficulties to identify whether an obstacle was large enough to obscure a pedestrian or a bicyclist for the truck driver. Given that the reliability criteria were initially met, the decrement on percentage agreement was small, and a joint category based on the conflicting categories has no obvious meaning, we have chosen to include visual obstruction in subsequent analyses without grouping any of its categories.

3.3. Effect of continuous independent variables on glance choice

Fig. 4 compares the empirical cumulative distribution functions (CDFs) of the driver behavior characteristics when different glance choices were made. Fig. 4.a suggests that the driving speed at the maneuver onset was higher when drivers did not cast a right-side glance (category: 'N') compared to the other glance categories. Likewise, Fig. 4. b suggests that the time between the last stop and the maneuver onset was higher when drivers did not cast a right-side glance compared to the other glance categories. In addition, this duration was shorter when drivers looked only during the maneuver, compared to when they looked only before the maneuver and when they looked in both

Table 1

Distribution of glance choices as a function of whether a glance during the maneuver was applicable (i.e., starting ultimately 2.3 s prior to the maneuver onset). N.A. = glance choice not applicable.

Glance choice	Glance during maneuver applicable		Glance during maneuver not applicable	
	N	%	N	%
None	409	29.28	256	50.59
Before	186	13.31	250	49.41
During	341	24.41	N.A.	N.A.
Before + During	461	33.00	N.A.	N.A.
Total	1397	100.00	506	100.00

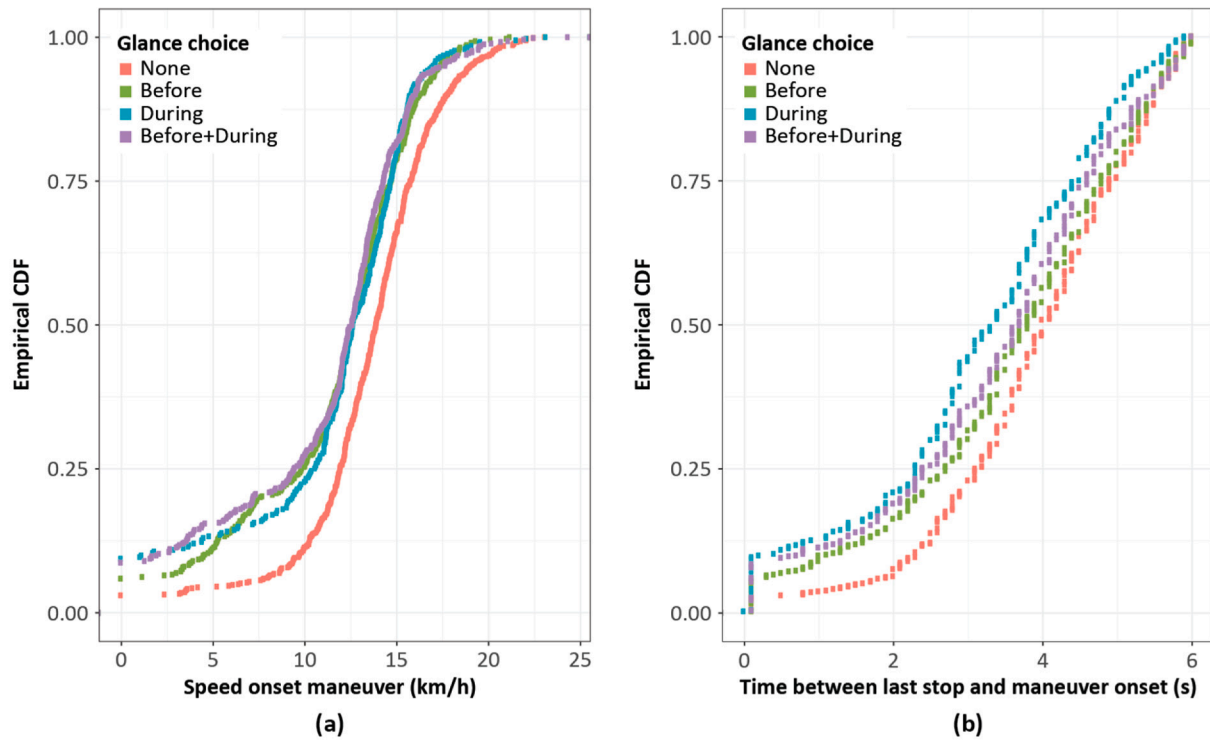


Fig. 4. Empirical cumulative distribution functions for (a) speed at the maneuver onset, and (b) time between the last stop and the maneuver onset (rounded to 0.1 s) as function of glance choice.

maneuver phases. The two-sample Kolmogorov-Smirnov tests revealed that the corresponding distributions were significantly different (see Table 2). The speed at the maneuver onset and the time since the last stop are significantly positively correlated ($\rho(1901) = 0.74, p < .001$), indicating that drivers have reached a higher speed if they had more time to accelerate.

3.4. Effect of categorical independent variables on glance choice

In this section, we discuss the explanatory variables that had a significant impact on glance choice based on the Chi-square test results. All interpretations of individual cells are related to situation where the driver did not cast a glance at all (i.e., glance choice 'none'), in line with the reference category for glance choice in the choice model discussed below. The overview of cell counts, the variables grouped due to low cell counts, and the Chi-square test results are presented in Appendix C. In addition to the variables described below, several other variables with a minimum cell count of 5 were tested but failed to reach a significant effect on the Chi-square test result. These variables were: any type of NDRT engagement during the maneuver, eating and/or drinking before the maneuver, presence of VRUs (separately or combined) moving sideways at the maneuver onset, presence of cyclists or pedestrians moving in the truck's direction at the maneuver onset, and presence of pedestrians on the right side in the first three seconds of the event.

Table 2

Statistics on the driver behavior characteristics at maneuver onset as a function of glance choice (N = No glances cast; B = Before the maneuver; D = During the maneuver; BD = Before and during the maneuver).

Variable	Mean and standard deviation				Two-sample Kolmogorov-Smirnov Test: p-value					
	N	B	D	BD	N vs. B	N vs. D	N vs. BD	B vs. D	B vs. BD	D vs. BD
Speed (km/h)	13.58 (3.91)	11.62 (4.63)	11.6 (4.9)	11.24 (5.05)	6.23×10^{-8}	2.59×10^{-6}	1.20×10^{-11}	0.85	0.442	0.163
Time since the last stop (s)	3.92 (1.32)	3.6 (1.57)	3.18 (1.57)	3.43 (1.61)	9.28×10^{-3}	1.83×10^{-10}	5.63×10^{-5}	6.55×10^{-4}	0.305	0.0238

limit). In both cases a lower speed limit was associated with more glances of categories 'B' and 'BD', and vice versa for a speed limit of 50 km/h.

Visual obstruction prior to the maneuver mostly concerned buildings and billboards, and to a lesser degree trees and vegetation. Visual obstruction was associated with more glances before the maneuver.

3.4.2. Traffic conditions and road users

Traffic flow was examined in terms of (lead) vehicles sharing (a part of) the trajectory of the truck. In presence of a right-turning lead vehicle (i.e., the subject vehicle follows the same path), drivers were less likely to look only before, only during and in both maneuver phases. A lead vehicle moving elsewhere (e.g., turning left or moving straight-ahead) and vehicles originating from other intersection legs merging into the subject vehicle's path were both associated with more glances in categories 'B' and 'BD'. With free flow, more glances were found in categories 'D' and 'BD'.

Effects on the presence of VRUs were examined through four variables. The first variable concerned the time window from 6 s before the maneuver onset (i.e., the start of the event) until 3 s before the maneuver onset. Here, the presence of a bicyclist and/or a PTW on the right side of the truck was associated with more 'B' and 'BD' glances. The remaining three variables dealt with VRU presence at the maneuver onset. The presence of any VRU (i.e., pedestrian, bicyclist, PTW) moving in the same direction of the truck was associated with more 'B' and 'BD' glances and fewer 'D' glances. Moving in the opposite direction of the truck, the presence of any VRU was associated with more 'D' and 'BD' glances. The presence of VRUs (separately or combined) moving sideways in front of the truck did not yield significant Chi-square test results.

The presence of one or more full stops during the maneuver (e.g., due to queues or crossing VRUs) was associated with more glances during the maneuver and in both maneuver phases. In case of adverse sight conditions at the maneuver onset (e.g., low sunlight), drivers were less likely to cast glances before the maneuver only.

3.4.3. Driver and vehicle characteristics

Four types of NDRT engagement prior to the maneuver onset yielded significant Chi-square tests: phone or electronic device use, phone or electronic device use combined with reading and/or writing, and smoking. The former two types involve at least a visual interaction, whereas the latter type involves at least a manual interaction. In case of phone or electronic device use drivers less often glanced before the maneuver. Grouping reading and/or writing with phone or electronic device use also resulted in fewer glances before the maneuver. Smoking was associated with a reduction in all glance categories.

Driver age was divided across three groups with equal sizes ($n = 13$ each). Drivers in the age group 21–43 years were more likely to cast a glance only before the maneuver and in both maneuver phases, and drivers in the age group 44–55 years were more likely to cast a glance only before the maneuver. In contrast, drivers in the age group 56–71 years were less likely to cast a glance only before and in both maneuver phases.

In Volvo FL trucks, which featured a window in the lower part of the passenger door, drivers more often cast glances in both maneuver phases. Volvo FM trucks do not feature a window in the lower part of the passenger door, and were associated with fewer glances in both maneuver phases. Irrespective of truck type, some trucks were equipped with a display on the mid console, at times providing a view on the blind spots next to or in front of the cabin (note: the status of the displays could not be reliably verified). The presence of a display was strongly negatively associated with right-side glances cast before the maneuver and during both maneuver phases.

3.5. Choice model

The choice model predicting glance behavior is the result of the

model selection procedure described in section 2.7.3. All categorical and continuous explanatory variables were tested in the model one by one. The ordinal variables were tested following the order in which they are presented in Appendix C. The next sections describe the variables that had a significant impact and the direction of these impacts. The utility functions of the final choice model are presented in Appendix D. The goodness of fit measures are presented in Table 3 and the estimation results are presented in Table 4. All parameters estimated are statistically significant at the 5% level. The alternative specific constant of casting a glance only before the maneuver was significant and negative indicating that, everything else being equal, drivers were less likely to cast a glance only before the maneuver than not to cast a glance. The constants of gazing only during the maneuver and in both maneuver phases were non-significant.

3.5.1. Infrastructure characteristics

The priority regulations at the intersection had a significant impact on glance choices. Drivers were more likely to look in one or both the maneuver phases than not to cast a right side glance at all when the priority was regulated by law. The effect of priority regulations by law on glances only before the maneuver and in both phases was similar and was significantly larger than on glances only during the maneuver. When the priority regulations were defined by traffic signs and markings, drivers were more likely to look only before the maneuver and in both phases while the effect on only during the maneuver was non-significant. Drivers were more likely to cast a glance in one or both maneuver phases when the priority at the intersection was regulated by traffic lights with potential conflicts. The effect differed across maneuver phases: the impact on both maneuver phases was larger than on only one phase, and the impact on only before the maneuver was larger than on only during. When there were traffic lights and potential conflicts were unknown (i.e., they could not be verified based on the video material), drivers were more likely to look only before the maneuver and in both phases while the effect on only during the maneuver was non-significant.

Certain bicyclist and pedestrian facilities had a significant impact on glance choices. Drivers were more likely to glance only before the maneuver when no bicyclist facilities were present close to the truck. A marked bicyclist lane close to the truck did not have a significant impact. Bicyclist facilities close to the truck did not have a significant impact on glances only during the maneuver and in both phases. An advanced stopping lane for cyclists in front of the truck did not have a significant effect. Drivers were less likely to cast glances in each maneuver phase when pedestrian facilities were either absent or did not include a zebra crossing (regardless of traffic lights, which were already accounted for with priority regulation). A pedestrian pavement without zebras and pedestrian facilities absent did not differ significantly. The impact on casting a glance only before, only during, and in both maneuver phases was similar.

Drivers were more likely to cast a glance in both maneuver phases when the minimum speed limit between the two intersection legs was lower than 50 km/h. The minimum speed limit did not have an impact on glances only before and only during the maneuver. Controlled for the minimum speed limit, the maximum speed limit between the two

Table 3
Statistics of the choice model predicting glance behavior.

Statistics	
Number of parameters associated with the explanatory variables (K)	23
Number of drivers	39
Number of observations	1903
Constant log likelihood $L(c)$	– 2239
Final log likelihood $L(\hat{\beta})$	– 2009
Adjusted likelihood ratio index (rho-bar-squared) $\bar{\rho}^2 = 1 - \frac{(L(\hat{\beta}) - K)}{L(c)}$	0.0924

Table 4

Estimation results of the choice model predicting glance behavior.

Variable	Description	Parameters	Estimate	Rob. t-ratio	Rob. p-value
–	Alternative specific constant	α^B	– 0.643	– 4.26	$2.07 \bullet 10^{-5}$
–	Alternative specific constant	α^D	0.149	1.47	0.142
–	Alternative specific constant	α^{BD}	– 0.189	– 0.99	0.322
Law	Binary variable equal to one when the priority regulation is by law	$\beta_{Law}^{B, BD}$	2.13	6.97	$3.14 \bullet 10^{-12}$
Law	Binary variable equal to one when the priority regulation is by law	β_{Law}^D	0.991	3.21	0.00135
Signs	Binary variable equal to one when the priority regulation is with traffic signs	$\beta_{Signs}^{B, BD}$	1.37	6.15	$7.59 \bullet 10^{-10}$
Lights Con	Binary variable equal to one when the priority regulation is traffic lights with conflicts	$\beta_{LightsCon}^B$	1.13	7.61	$2.71 \bullet 10^{-14}$
Lights Con	Binary variable equal to one when the priority regulation is traffic lights with conflicts	$\beta_{LightsCon}^D$	0.688	4.42	$9.83 \bullet 10^{-6}$
Lights Con	Binary variable equal to one when the priority regulation is traffic lights with conflicts	$\beta_{LightsCon}^{BD}$	1.38	9.64	$< 1 \bullet 10^{-22}$
Lights Unknown	Binary variable equal to one when the priority regulation is traffic lights with unknown conflicts	$\beta_{LightsUnknown}^{B, BD}$	0.374	2.35	0.0190
NoCycFac	Binary variable equal to one when there are no bicyclist facilities	$\beta_{NoCycFac}^B$	0.434	3.27	0.00106
MinSpeed Lim < 50	Binary variable equal to one when the speed limit of at least one leg was lower than 50 km/h	$\beta_{MinSpeedLim < 50}^{BD}$	0.860	4.64	$3.54 \bullet 10^{-6}$
NoPedZebra	Binary variable equal to one when the pedestrian facilities do not include a zebra crossing	$\beta_{NoPedZebra}^B$	– 0.558	– 5.29	$1.21 \bullet 10^{-7}$
LeadPath	Binary variable equal to one when a lead vehicle is in path	$\beta_{LeadPath}^B$	– 0.742	– 4.45	$8.51 \bullet 10^{-6}$
VRU OppDir	Binary variable equal to one when vulnerable road users are in the opposite direction at the maneuver onset	$\beta_{VRU_OppDir}^B$	0.450	2.12	0.0341
VRU OwnDir	Binary variable equal to one when vulnerable road users are in the direction of the truck at the maneuver onset	$\beta_{VRU_OwnDir}^{B, BD}$	0.303	3.28	0.00103
CycPTW EarlyRight	Binary variable equal to one when bicyclists and/or powered two wheelers are early visible on the right	$\beta_{CycPTW_EarlyRight}^B$	0.563	3.58	$3.50 \bullet 10^{-4}$
PedSide	Binary variable equal to one when pedestrians are moving sideways in front of the truck at the maneuver onset	$\beta_{PedSide}^{D, BD}$	0.429	2.35	0.0187
AdSight	Binary variable equal to one when the sight conditions are adverse	$\beta_{AdSight}^B$	– 0.838	– 2.13	0.0335
Age56–71	Binary variable equal to one when the age of the driver is between 56 and 71 years	$\beta_{Age56-71}^B$	– 0.335	– 2.06	0.0395
PhoneDevReadWri	Binary variable equal to one when the driver uses a phone or electronic device, reads or writes before the maneuver	$\beta_{PhoneDevReadWri}^B$	– 0.746	– 2.60	0.00933
TruckFM	Binary variable equal to one when the truck type is a Volvo FM (as opposed to Volvo FL)	$\beta_{TruckFM}^{BD}$	– 0.392	– 2.22	0.0263
NoCamIn	Binary variable equal to one when there is no camera installed in the truck	$\beta_{NoCamIn}^{BD}$	0.428	3.22	0.00129
Time LastStop	Time between the last stop and the maneuver onset	$\beta_{TimeLastStop}^D$	– 0.202	– 4.21	$2.58 \bullet 10^{-5}$
v_n^B	Driver specific error term	γ^B	0.350	3.12	0.00180
v_n^D	Driver specific error term	γ^D	– 0.279	– 4.04	$5.26 \bullet 10^{-5}$

intersection legs ($r_s = 0.43$) did not have a significant impact. The intersection layout and visual obstruction did not have a significant effect.

3.5.2. Traffic conditions and road users

Certain types of road users had a significant impact on glance choices. In presence of a right-turning lead vehicle, drivers were less likely to look only before, only during and in both maneuver phases. The effect was similar across the different alternatives. A lead vehicle turning left or moving straight-ahead, and vehicles originating from other intersection legs and moving into the same leg as the right-turning truck did not have a significant effect on glance choice. Drivers were more likely to glance only before, only during and in both maneuver phases when a VRU was moving towards the truck coming from the opposite direction at the maneuver onset. When a VRU was moving in the direction of the truck at the maneuver onset, drivers were more likely to glance only before the maneuver and in both maneuver phases. Different types of VRUs present on the right side of the truck in the first three seconds of the event had a different impact on glance choices. Drivers were more likely to glance in each maneuver phase when a bicyclist or a PTW was present on the right side. Pedestrians on the right side in those first three seconds did not have an impact. When a pedestrian was moving or about to move sideways at the maneuver onset, drivers were more likely to glance only during and in both maneuver phases. Pedestrian sideways did not have an impact on glances only before the maneuver. Finally, drivers were less likely to cast glances only before the maneuver in case of adverse sight conditions at the maneuver onset (e. g., low sunlight). The sight conditions did not have a significant impact

on glances only during the maneuver and in both phases.

3.5.3. Driver and vehicle characteristics

Certain states and characteristics of drivers had a significant effect on glance choices. Drivers were less likely to glance only before the maneuver when they were holding a phone or electronic device, reading or writing before the maneuver. The impact of these NDRTs were similar, and they did not have a significant effect on gazing only during the maneuver and in both maneuver phases. Smoking and grooming did not have a significant impact on glance behavior. Drivers aged 56–71 years were less likely to cast a glance in each maneuver phase compared to the reference group with drivers aged 44–54 years. The impact on gazing only before, only during, and in both maneuver phases was similar. Drivers aged 21–43 years did not have a significant impact on glance choices.

Certain vehicle characteristics and certain driver behavior characteristics had a significant impact on glance choice. Drivers were more likely to glance in both maneuver phases when the mid console did not include a display (which could have offered a view on a blind spot by means of a camera). The absence of such a display did not have a significant impact on glances in only one maneuver phase. When the truck type was a Volvo FM (i.e., without a window in the lower part of the passenger door), drivers were less likely to cast a glance in both maneuver phases. The truck type did not have an effect on glances cast in only one maneuver phase. With an increased time window between the last stop and the maneuver onset, drivers were less likely to glance only during the maneuver. The magnitude of this time window did not have an impact on glances only before the maneuver and in both phases.

Controlled for the time after the last stop, the presence of one or more full stops during the maneuver and the speed at the maneuver onset did not have a significant effect on glance choices.

The driver specific error terms lead to a significant improvement in goodness of fit. These error terms indicate that certain drivers were more likely to glance only before and in both phases, while other drivers were more likely to glance only during and in both phases. Introducing two different driver specific error terms resulted in a significant improvement in goodness of fit compared to introducing only one driver specific error term. Different error components were tested and there was no evidence of unobserved factors that influenced glances in one phase only or in both phases in a similar way.

When we compare the magnitude of the different parameters estimated, we notice that the priority regulations at the intersection have the largest impact on glance behavior. Drivers have the highest probability to cast a glance in one or both maneuver phases when the intersection is regulated by law only. Intersection regulated by signs only or by traffic lights with conflicts have also a large impact on the probability that drivers cast a glance in one or in both phases. Controlled for the priority regulations, speed limits lower than 50 km/h, absence of a lead vehicle in path, favorable sight conditions, lack of engagement in non-driving tasks, and the driver-specific error terms have a large impact on the probability that drivers glance in certain maneuver phases.

4. Discussion

In this study we used naturalistic driving data of 39 truck drivers to explore which factors best explain their glance behavior towards blind spot mirrors when turning right at urban intersections. With this work, we hope to better understand why truck drivers frequently fail to see vulnerable road users travelling straight ahead, resulting in the classical blind spot crash scenario. We elaborate first on the main findings of the choice model, followed by implications, limitations and recommendations for follow-up research.

4.1. Main findings

Findings from the choice model are presented according to the magnitude of their impact on the dependent variable. The choice model revealed that infrastructure characteristics were the main factors influencing glance behavior. More specifically, the priority regulations at intersection had the largest impact on glance choice. Drivers were more likely to cast glances in one or both maneuver phases in case of regulations by law only, by signs only, and by traffic lights with unprotected maneuvers than in case of regulations by traffic lights with protected maneuvers. These results can be interpreted as a form of compensatory behavior: drivers are more likely to glance when the priority regulations offer less protection from potential conflicts. When the intersection is regulated by traffic lights without conflict, drivers do not expect potential conflicts and are therefore less likely to cast a glance. The impact of priority regulation differed across glance choices: the largest impact was observed when the glance was cast both before and during the maneuver, whereas the smallest impact was observed when the glance was cast exclusively during the maneuver. Possibly, glances in both phases had a larger impact, because drivers could recognize the priority regulations while approaching an intersection, whereas glances during the maneuver only might have been influenced by situational factors, resulting in a smaller impact. Another infrastructure characteristic that had a large impact on glance behavior was the speed limit in both intersection legs. When at least one intersection leg had a speed limit lower than 50 km/h, drivers were more likely to look in both maneuver phases than to not look at all. This behavior can be linked to the infrastructure characteristics in the locations where lower speed limits are enforced. Lower speed limits are typically implemented in residential areas, where vulnerable road users can be expected and where the view on other traffic is limited compared to arterial roads.

Certain traffic conditions and road users had a large impact on glance choice. When a lead vehicle was in path, drivers were less likely to glance in any maneuver phase. The result mirrors a previous finding in a driving simulator experiment showing that the presence of other road users was associated with fewer glances towards the blind spot (Hurwitz et al., 2015). A possible explanation could be that drivers do not look at the blind spot because they focus on keeping a safe distance headway to the vehicle in front of them. Another explanation could be that drivers do not cast a glance because they trust that the driver in front has already checked for any potential conflicts. Drivers were less likely to glance only before the maneuver in case of adverse sight conditions at the maneuver onset (e.g., low sunlight). An explanation could be that drivers do not glance only before the maneuver because, at that time, they cannot have a clear vision of the whole traffic situation (e.g., they are temporarily blinded by the low sunlight). This finding may explain how adverse weather conditions could materialize as risk factors in previous studies (e.g., Pokorny et al., 2017; Hagel et al., 2014; Hamann et al., 2015).

Certain driver states and driver characteristics had a large impact on glance choice. Drivers were less likely to glance only before the maneuver when they were holding a phone or electronic device, reading or writing before the maneuver. Previous naturalistic driving studies report that car drivers are more likely to be engaged in visual-manual phone activities during standstill and less likely during a turning maneuver (Tivesten and Dozza, 2015; Christoph et al., 2019). If such self-regulating behavior is similar for truck drivers, this would explain why the effect of NDRT engagement on glance behavior was only found before the maneuver and not during the maneuver (or in both phases). There were also large differences between drivers, which can indicate different glance strategies between individuals. Certain drivers were more likely to glance only before or in both phases whereas other drivers glanced only during or in both phases.

Bicyclist and pedestrian facilities had a medium effect on glance choice. Drivers were less likely to glance only before the maneuver when a physically separated track was present next to the truck, compared to when no bicyclist facilities were present. A likely cause is the fact that the visibility of bicyclists through the blind spot mirrors becomes limited or even impossible with a greater lateral separation. This would also explain why the effect of bicyclist facilities on glance behavior was only found before the maneuver, and not during (because by that time the lateral separation is smaller and the blind spot mirrors do offer a view on bicyclists). In addition, drivers were less likely to cast glances in each maneuver phase when pedestrian facilities were either absent or did not include a zebra crossing. A possible explanation could be that drivers do not expect pedestrians to be present in absence of the facilities.

The presence of VRUs had a small to medium effect on glance choice. Drivers were more likely to glance in each maneuver phase when a bicyclist or a PTW was present on the right side at the beginning of the event or when a VRU was moving towards the truck coming from the opposite direction. In these circumstances, drivers might expect the VRU to be in the blind spot during the maneuver. When a VRU was moving in the same initial direction as the truck, drivers were more likely to glance only before the maneuver and in both maneuver phases. Different impacts based on the VRU types and locations might be explained by the different speeds (e.g., bicyclists and PTWs move faster than pedestrians) and expected timing of potential conflicts. When a pedestrian was moving or about to move sideways, drivers were more likely to glance during the maneuver and in both maneuver phases. This result does not seem to be directly linked to checking the blind spot. A possible explanation could be that drivers either expect other VRUs to be present in the blind spot or that they are actually looking at the pedestrian sideways and not at the mirrors. A similar result was found in a driving simulator study, in which drivers' attention was drawn towards pedestrians in front of the vehicle instead of towards the cyclists approaching the truck in the blind spot (Hurwitz et al., 2015).

Certain vehicle and driver characteristics had a medium or small

effect on glance choices. Drivers were more likely to cast a glance only during the maneuver than not to cast a glance shortly after the last stop. Possibly, truck drivers tended to look elsewhere before the maneuver, because the time window between the last stop prior to the maneuver onset and the maneuver onset itself was too short to pay attention to all required directions. To compensate, they looked right-ways (only) during the maneuver. Drivers were also less likely to glance in both phases when the mid console includes a display, at times providing a view on the blind spot. The camera could be used by the drivers to check the traffic situation instead of looking at the blind spot mirrors. Furthermore, drivers were more likely to glance in each phase when driving in a Volvo FL truck, compared to a Volvo FM truck. The former truck type contains a window in the lower half of the passenger door. The additional movement of objects in the periphery of the driver's field of view may have attracted the driver's attention (e.g., [Post & Johnson, 1986](#)). Older drivers were less likely to cast a glance in each phase. Possible explanations could be that they are more experienced in detecting hazards with less glances or that they received a different type of training.

Several variables did not significantly improve the choice model and were therefore left out, even though some of them did yield a significant Chi-square test result when tested individually. In terms of intersection design, X-intersections were associated with fewer glances before the maneuver. Seeing that X-intersections feature a larger number of conflict interactions than T-intersections, drivers may have been inclined to attend the many potential conflicts in front of the truck at the cost of the relatively few conflicts at the right side of the truck. Advanced stopping lanes are designed to offer bicyclists a proper turning position in front of motorized vehicles, and were associated with more glances before the maneuver. Advanced stopping lanes may have primed drivers to scan for bicyclist, similar to the effect of pedestrian facilities described above. However, we cannot exclude the possibility that drivers actually glanced into the front blind spot mirror (offering a view in front of the truck), but (some of) those glances were coded as 'looking right'. Finally, the finding that visual obstruction was associated with more glances before the maneuver can be explained by the fact that more glances are required if there is a high chance that a VRU is (temporarily) masked by an object.

4.2. Implications

Failure to check blind spot locations using mirrors or other means (e.g., cameras) is one of the risk factors mentioned in previous studies on blind spot crashes between trucks and bicyclists (e.g., [McCarthy and Gilbert, 1996](#); [Talbot et al., 2014](#)). In the present study, drivers frequently failed to cast any glance towards the right side throughout an event, thus neglecting the blind spot mirrors offering a view on the passenger side of the truck. Although drivers did glance more often when certain VRUs were present, absence of VRUs does not justify truck drivers to omit glances to the blind spot mirrors. Our findings may help to understand how everyday glance behavior of truck drivers could have been at the basis of blind spot crashes where bicyclists were hit by the side of the truck. In the early 2000 s, the impact location at the side of the truck concerned 25% ([International Road Transport Union, 2007](#)) to 38% ([Schoon et al., 2008](#)) of the blind spot crashes, the other location being in front of the truck. It is not known if this distribution still holds at present.

Several findings should result in follow-up actions to improve adequate glance behavior. Drivers tend to look less often when priority regulations offer more protection from conflicts, suggesting that they do not expect VRUs to cross by trusting the traffic lights. A violation of the priority rules (in particular red light negation) could thus be a very dangerous situation for VRUs ([International Road Transport Union, 2007](#); [Prati et al., 2018](#)). Therefore, truck drivers may require education to adjust their glance behavior to the possibility that VRUs will not always respect the traffic lights. The presence of a lead vehicle appears to

draw attention away from the blind spot mirrors. More research is needed to understand if this is due to avoiding a rear-end crash, or due to trusting the lead vehicle to make a correct judgment. In case of the former, a larger headway provides more time to (also) pay attention to the blind spot mirrors and may therefore be a viable strategy to educate. Previous studies on fatal blind spot crashes between trucks and bicyclists show that truck drivers are frequently distracted by NDRTs ([Stimpson et al., 2013](#); [Nica et al., 2009](#); [Gaudet et al., 2015](#)). In the present study such behavior occurred frequently and was associated with significantly fewer glances before a maneuver. Therefore, drivers should be prohibited to engage in NDRTs, or if NDRT-involvement is work-related, the work circumstances (e.g., time pressure) may require improvement. Finally, findings from the Chi-square model indicate that drivers tend to prioritize potential hazards in front of the truck at the expense of attending blind spot hazards when the complexity of an intersection increases (e.g., from T-intersection to X-intersection). Drivers may need to (learn how to) adjust their visual scanning strategy towards all potential conflict interactions, including those in the blind spot.

We explored whether drivers glanced more often towards the right side when it was in fact too late to stop the truck before entering the bicyclist encroachment zone. For example, drivers may have underestimated their reaction time and/or the truck's brake lag time. The impact of two alternative time windows on the proportion of glance choices in the 'none' category were examined. In the first scenario, the time window to cast a glance was extended from 2.3 s to 1.65 s before entering the encroachment zone. The proportion of events in which drivers failed to cast a glance decreased from 29% to 20% for events with a during phase, and from 51% to 34% for events without a during phase. In the second scenario, the time window was extended to 0.9 s before entering the encroachment zone (i.e., assuming an instant driver reaction time and no brake lag). The result was a further reduction of glance in the 'None' category (to 13% and 20%, respectively). This exploration suggests that many glances were cast too shortly before entering the encroachment zone. Therefore, drivers may need to receive more explicit education and/or assistance on timely glances towards the blind spot mirrors when making a right-turn, in addition to the suggestions made above.

An open question is which measures are effective to change driver (glance) behavior. Campaigns on, e.g., driver inattention may increase risk awareness, but it has been found that they do not necessarily change actual driver behavior ([van der Kint and Mons, 2019](#)). A review by [Vlakveld et al. \(2014\)](#) reports that drivers drive more safely if their employers have improved the safety culture of their organization, for example by group discussions on hazard perception. Such discussions may help to better deal with hazards of red light negation by VRUs, the effect of a lead vehicle on glance behavior, and to glance in time such that the truck can still be stopped before entering the encroachment zone. However, the underlying studies in [Vlakveld et al. \(2014\)](#) do not make clear to which extent NDRT-engagement is part of group discussions about safety or training of risk perception, which means the effect of such discussions on reducing driver inattention is unknown. Furthermore, professional truck drivers in the Netherlands are obliged to take part in refresher courses every five years. Awareness of blind spot risks is part of the curriculum, but participation is not guaranteed, because drivers are free to choose which course they follow. Therefore, additional research is needed to find effective measures to improve glance behavior by truck drivers.

Our investigation into NDRT involvement also yielded a methodological implication concerning the complexity of annotation. The present study differed from a former naturalistic driving study in terms of annotating NDRT involvement. [Varotto et al. \(2021\)](#) offered a single binary variable for annotators to denote any type of NDRT involvement and found a low interrater reliability. In contrast, we here implemented a separate binary variable for each NDRT type, which resulted in an adequate interrater reliability. The takeaway message is to minimize the amount of information in short-term memory required to annotate a

single variable, at least regarding NDRT involvement, but possibly also for other variables.

Implications for vehicle design can be based on findings related to truck type and presence of a blind spot display. The additional view provided by the lower window in the passenger door of Volvo FL trucks is, in essence, a reduction of the blind spot size. Our finding that a higher degree of direct vision is associated with more right-side glances supports the idea that a Direct Vision Standard policy (Summerskill et al., 2019; Transport for London, 2018; European Union, 2019) yields safer right-turn glance behavior by truck drivers. Mole and Wilkie (2017) argue that a direct view through the windscreen results in a shorter temporal blind spot (less time is needed to shift attention from one location to another) and a faster reaction time, compared to an indirect view. Despite the advantages of a direct view through the lower passenger door, drivers instead appear to be drawn to an indirect view provided by the blind spot display (Buck Consultants, 2007). The presence of a blind spot display at the center console was associated with fewer right-side glances, controlling for the presence of a lower right window in the passenger door. We cannot conclude whether drivers looked at the display instead (a more refined glance coding scheme would have been needed), but assuming this was the case, drivers may have trusted that the display provided an adequate view on the blind spot, and that a direct view through the lower right window in the passenger door was not necessary. Further research is needed to find out if a larger direct vision area is associated with a reduction of glances at a blind spot display.

4.3. Limitations & recommendations for future research

In terms of generalization, the present study sought to collect a meaningful naturalistic driving dataset with respect to blind spot crashes (cf. Knipling, 2015). First, a focus on intersections was chosen, because previous research has indicated that this is where most blind spot crashes occur (Pokorny et al., 2017; Schoon, 2006). Second, the scenario of a stopped truck prior to the maneuver was chosen, due to the risk of a bicyclist undertaking the truck (Frings et al., 2012), combined with reduced visibility (Kircher and Ahlström, 2020). The external validity of our dataset is likely higher than in previous studies on blind spot glance behavior. First, a naturalistic driving methodology was used, in which drivers interacted with real-life traffic (as opposed to simulator studies, e.g. Hurwitz et al., 2015), and in which drivers were free to manage their driving task as well as NDRT-engagement (in contrast with on-road experiments with explicit instructions, e.g., Kircher and Ahlström, 2020). Second, there was a wide selection of intersections (compared to three intersections located on a fixed route in Kircher and Ahlström, 2020). Notwithstanding our attempt to create a meaningful dataset, more research is needed to understand if glance behavior in the events surveyed here (in particular events where the driver failed to look) is representative for glance behavior in actual blind spot crashes.

From a methodological perspective, the camera positions in the instrumented trucks did not allow for accurate identification of individual mirror glances (Jansen et al., 2021; and see above). For this reason, a dichotomous classification of glance behavior was made, i.e., looking right versus looking elsewhere. Jansen et al. (2021) found that glances through the right part of the windshield were more often confused with glances through the right window (or any of the mirrors on the right side) than confusions the other way around (i.e., evidence of a perceptual overshoot effect). Thus, inaccuracy in coding may have resulted in an overestimation of right-side glances, and, consequently, an underestimation of the number of events where the driver did not cast a right-side glance at all. Seeing that the annotators were instructed to base their judgment on head and eyes orientation, as opposed to the traffic scene, we expect that inaccuracy in glance coding is randomly distributed across the events.

A more detailed understanding of glance behavior in blind spot scenarios could be obtained with accurate differentiation between

glances towards individual (blind spot) mirrors and looking outside the right window. Of particular interest are glances towards the front blind spot mirror during a maneuver, a location relevant for blind spot crashes where the impact location is in front of the truck (Schoon et al., 2008; Schoon, 2012), and to understand the impact of advanced stopping lanes on glance behavior. Future studies are therefore advised to install an additional camera in the right A-pillar, located close to the mirrors and providing a view on the driver's face. A camera at such a position may also result in fewer excluded events. In the present study, a large part of the candidate events had to be excluded because the face camera was turned off or misaligned. Some of the non-participating truck drivers may have rotated the cameras to avoid being filmed, despite information that their footage would be deleted. In the end, all participating drivers had excluded events due to video quality issues with the face camera, so a bias towards certain drivers within the sample is unlikely.

The present study used a fixed brake duration of 0.7 s, based on the average speed at the maneuver onset. Approximately half of the events featured a lower speed, which would have necessitated a shorter brake duration, and which would have allowed the driver more time to cast a right-side glance. As illustrated above, drivers appear to often look very late during the maneuver. Before adding the random components, we tested the model with shorter time windows (i.e., 0.9 s and 1.65 s instead of 2.3 s). The fixed effects were still significant, suggesting that the model is robust for changes in the time window.

Finally, the choice model developed in the present study predicted 9.24% of the variability in glance direction compared to a baseline model which included only the constants, which indicates that a large part of the variability is still unaccounted for. There could be other variables that influence glance behavior. In a driving simulator study by Warner et al. (2017) passenger car drivers looked more often at their side mirror when a sign was present that warned right-turning drivers to yield to bikes. Additional research is needed to examine how the presence of such signs influences glance behavior of truck drivers in real traffic. Furthermore, two significant driver specific error terms warrant further research into driver attitudes, into the development of driving assistance systems that are driver specific (e.g., Ribeiro et al., 2021), and, seeing that drivers frequently returned to their headquarters, into route familiarity (e.g., Intini et al., 2019).

5. Conclusion

This study explored which factors best explain glance behavior of truck drivers before and during right-turning maneuvers at urban intersections. To this end, naturalistic glance behavior by 39 truck drivers in 1,903 right-turning maneuvers was analyzed. Most often truck drivers did not cast a glance upon their blind spot mirrors before as well as during their maneuvers at the intersection, despite recommendations by the Dutch CBR examination guidelines. A choice model identified the main factors that influence truck driver glance behavior, including priority regulation, speed limits, facilities for vulnerable road users, presence of vulnerable road users and other traffic, sight conditions, truck design, driver age, and driver inattention. In line with previous studies on blind spot crashes between trucks and vulnerable road users, our findings demonstrate the relevance of investigating glance behavior at intersections and developing guidelines to improve the glance behavior of truck drivers.

CRediT authorship contribution statement

Reinier J. Jansen: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Silvia F. Varotto:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A–E. Supplementary data

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