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Truck drivers' behavior in encounters with vulnerable road users at intersections: Results from a test-track experiment

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ABSTRACT

Crashes involving cyclists and pedestrians in Europe cause the deaths of about 7600 persons every year. Both cyclists and pedestrians are especially exposed in crashes with motorized vehicles and collisions with trucks can lead to severe injury outcomes. The two most frequent crash scenarios between trucks and these vulnerable road users (VRU) are: a) when the truck wants to turn right at an intersection, with a cyclist riding parallel and planning to cross the intersection and b) when a pedestrian crosses in front of the truck in perpendicular direction to the movement of the truck. Advanced Driver Assistance Systems (ADAS)—that are expected to prevent or mitigate these crashes—benefit from detailed information about the behavior of truck drivers. This study is a first exploration of this research area, with the aim to assess how drivers negotiate the encounters with VRUs in the two scenarios described above. Thirteen participants drove an instrumented truck on a test-track. After some baseline recordings, the drivers experienced two laps where they encountered a cyclist target and a pedestrian target crossing their path. The results show that the truck drivers adapted their kinematic and visual behavior in the laps where the VRU targets were crossing the intersection, compared to the baseline laps. The speed profiles of the drivers diverged approximately 30 m from the intersection and glances were directed more often towards front right and right, during the scenario with the cyclist in comparison to baseline laps. For the scenario with the pedestrian crossing, the drivers changed their speed about 14 m from the intersection and glances were directed more often towards the front center, compared to baseline laps. As a result, both the speed and distance from the intersection at the end of the maneuver were significantly different between VRU and baseline laps. Overall, the findings provide valuable information for the design of ADAS that warn the drivers about the presence of a cyclist travelling in parallel direction or that intervene to avoid a collision with a cyclist or pedestrian.

1. Introduction

In 2016, 2064 cyclists and 5527 pedestrians were fatally injured on European roads (European Road Safety Observatory, 2018). These fatalities have decreased by 27% for cyclists and by 39% for pedestrians between 2007 and 2016. However, these reductions are lower than the average decrease for all modes of transportation (42%) and for motorized vehicles such as mopeds (57%), cars (44%) or busses (53%) in particular. As a result, the corresponding share of cyclist and pedestrian fatalities increased from 7% to 8%, between 2007 and 2015. Although most crashes involving cyclists are single-vehicle crashes (i.e., there is no other vehicle involved) (Stutts and Hunter, 1999; Thulin and Niska, 2009; Schepers et al., 2015), both cyclists and pedestrians are especially exposed in collisions with motorized vehicles (Richards, 2010), since these vulnerable road users (VRU) do not have a protective shell around them.

In Europe, minimum pedestrian protection requirements for cars have been established by law makers as well as consumer rating agencies since the early 2000s. Modern cars are equipped with passive safety equipment such as deployable hoods, absorbing front bumpers and even hood airbags, to mitigate the injury outcome. These measures have proven effective in reducing pedestrian and cyclist injuries (Fredriksson et al., 2014). Furthermore, in recent years, an increasing number of Advanced Driver Assistance Systems (ADAS) have been introduced, and through the advance of passive and active safety systems together, the goal is to further protect VRUs from the severe outcomes in crashes with cars. Test scenarios have also been developed to simulate the injuries in crashes with cyclists and pedestrians (e.g., EuroNCAP) and Strandroth et al. (2014) have found a significant correlation between injury outcome in real-traffic crashes and EuroNCAP

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pedestrian score, proving the effectiveness of the test scenarios. However, similar trends, especially the advancements through consumer rating agencies such as EuroNCAP, are lagging behind for trucks, both for light and heavy goods vehicles. This represents a concern, since the risk of severe injuries for pedestrians and cyclists is further increased in crashes that involve heavy goods vehicles (Frings et al., 2012; Seiniger et al., 2015; Pokorny et al., 2017; Malczyk and Bende, 2019).

In order to develop ADAS that address truck to VRU crashes, the first step is to identify the most frequent and critical target scenarios. For this reason, it is essential to gain an understanding of the most frequent conflict situations in real-world traffic (Fredriksson et al., 2014). Based on their analysis of data from the German In-Depth Accident Study (GIDAS), several national crash databases as well as the Community database on road accidents (CARE), Schindler et al. (2020) identified the two most frequent conflict situations between HGVs and VRUs: a) when the HGV wants to turn right at an intersection, with a cyclist riding parallel and planning to cross the intersection and b) when a pedestrian crosses in perpendicular direction to the HGV, which is travelling straight. In scenario a), the collision speeds are generally low (average of 13 km/h, maximum of around 30 km/h) and the impact point between the cyclist and the truck is located within the first 2 m of the length of the truck, i.e., the tractor and not the trailer. This scenario has also been identified by Pokorny et al. (2017) as the most frequent truck-to-cyclist crash type, especially in intersections with right-hand-rule and traffic signs, in the presence of wet road surfaces. In scenario b), collision speeds seem related to whether the pedestrian is overrun by the truck—in those cases where they are overrun, collision speeds are low (around 5 km/h), but the injury outcomes severe (fatal most of the time).

Once the scenarios have been defined, the development of ADAS benefits from a deep understanding of the contributing factors to the crashes and of the behavior of all road users before and after the initiation of the conflict (Najm et al., 2007; Bianchi Piccinini et al., 2017). Schindler et al. (2020) identified drivers' inattention and/or visual scanning mismatches as the most common contributing factor for the above-mentioned scenario a), due to the cyclist being hidden by parts of the vehicle. They also reported the mismatch between pedestrians' expectations and truck drivers' actions (i.e., moving forward) and pedestrians' inattention and/or visual scanning mismatches as the most common contributing factors for scenario b). However, like in the previous scenario, also drivers' inattention and/or visual scanning mismatches contributed to the crash, given that the pedestrian is often concealed by the vehicle body. Prati et al. (2018) performed a detailed literature review on bicycle-to-motorized-vehicle collisions and identified violations and errors of both parties as contributing factors to crashes: examples of violations included not respecting traffic signals or not yielding at intersections by both cyclists and drivers, while errors encompassed drivers' failure to see the cyclist. Although their research did not expressly focus on heavy vehicles, the authors reported that previous studies showed a risk effect of 2 for "large vehicles" and "HGV blind spot when turning". Adminaite et al. (2015) looked at crashes involving pedestrians and cyclists in Europe and concluded that the presence of large blind spots is one of the predominant contributing factors—due to the high seating position of truck drivers—in crashes between heavy goods vehicles and VRUs. Furthermore, Pokorny et al. (2017) examined official police data in Norway and found that 12% of crashes between trucks and cyclists were classified as blind spot crashes. These crashes had a higher average severity compared to other types of crashes involving trucks and cyclists. Silla et al. (2017) reported that information about the incidence of blind spot crashes is limited, but previous studies indicated that about 41% of truck-to-cyclist crashes in the Netherlands could be classified as blind spot crashes. Although trucks are equipped with mirrors to reduce the blind spots, Mole and Wilkie (2017) have shown that it takes about 4 s for drivers to check all mirrors. Hence, while increasing the number of mirrors might reduce spatial blind spots, the increased number introduces a temporal blind spot (i.e., when checking the last mirror, the information obtained in the first mirror might have changed by that time). This temporal blind spot implies that adding more mirrors or cameras would likely not completely eliminate the threat that large blind spots around the truck pose to vulnerable road users (Mole and Wilkie, 2017; Richter and Sachs, 2017) and possibly even result in new types of visual scanning mismatches. Although the extension of the front-end and the lowering of the window line—introduced by the new European regulation (Transport, 2019)—might improve the situation, some blind spots will remain.

In summary, prior research suggests that crashes between trucks and VRUs originate from the combination of visual attention lapses/slips (e.g., distraction, visual scanning mismatches, temporal blind spots), reduced visibility of the VRU (e.g., spatial blind spots), and expectation mismatches (e.g., expectation about the truck driver or VRU behavior). These factors are often interrelated: for example, a visual scanning mismatch (e.g., driver directing the gaze forward, while there is a safety–critical visual information on the right) can be driven by a VRU being in the blind spot, when the driver first scanned the environment for relevant visual inputs.

Currently, the "Informal Working Group on Awareness of Vulnerable Road Users proximity in low speed maneuvers" is preparing regulations for the United Nations (UN) that will require the mandatory installation of a blind spot information system in trucks for the detection of bicycles (Working Party on General Safety, 2019). Despite the high relevance on the international regulatory agenda, there is still a lack of research that provides detailed information about truck drivers' behavior, to support the design of blind spot information systems and other types of systems that warn for the presence of a VRU. Although previous studies have determined the location of visual glances of passenger cars' drivers at intersections (see Li et al., 2019 for a review of these studies and for the authors' analysis of a naturalistic dataset), few of these studies have specifically investigated how the glance locations might affect the potential interactions with VRUs: Wu and Xu (2017) mined the SHRP2 dataset and found that car drivers showed "high acceleration and low observation frequency under Right-Turn-On-Red (RTOR)", results that combined represent a potential threat for pedestrians; Jansen et al. (2017) looked at the UDRIVE dataset and found that drivers checked their blind spots in 4% of the cases, during right turn maneuvers at intersections and roundabouts from four European countries. Overall, these findings are surely interesting, but may not be easily transferrable to drivers of heavy goods vehicles, especially with regards to glance behavior and visual cues which drivers are scanning for (Kircher and Ahlström, 2020). With respect to truck drivers, Kircher and Ahlström (2020) have identified that the glance behavior of truck drivers in interactions with cyclists was related to the infrastructure design (e.g., presence of traffic lights, position of bicycle lane). However, their gaze analysis focused on glances towards the cyclist and a comparison to baseline behavior (i.e., no cyclist present) is missing. Apart from the research from Kircher and Ahlström (2020), there is a lack of published studies investigating the behavior of truck drivers—in particular glance behavior— during the interaction[1] with vulnerable road users in turning maneuvers. This study is a first exploration of the topic and investigates the two most common conflict situations with VRUs during right turn maneuvers of trucks, in a controlled setting on a test-track. The goal of

[1] Within the paper, the terms *interaction* and *encounter* have been used. The term *interaction* is defined as "a situation where the behavior of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future" (Markkula et al., 2020). The term encounter is defined instead as "an elementary event in traffic that may, but not necessarily will, turn into a conflict/accident." (Fyhri et al., 2017). The first term implies an adaptation of behavior of both road users which was not possible in the scenarios tested in our experiment, since the VRU targets were moving on a fixed trajectory. For that reason, the term encounter was preferred in the paper when referring to the scenarios involving the truck drivers and the VRU.

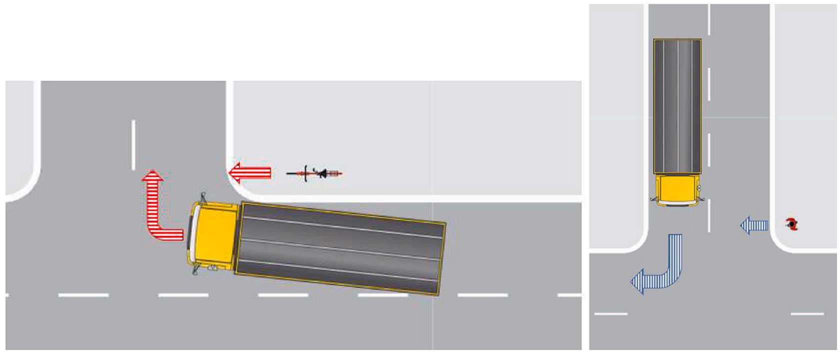


Fig. 1. Cyclist crossing scenario (left) and pedestrian crossing scenario (right).

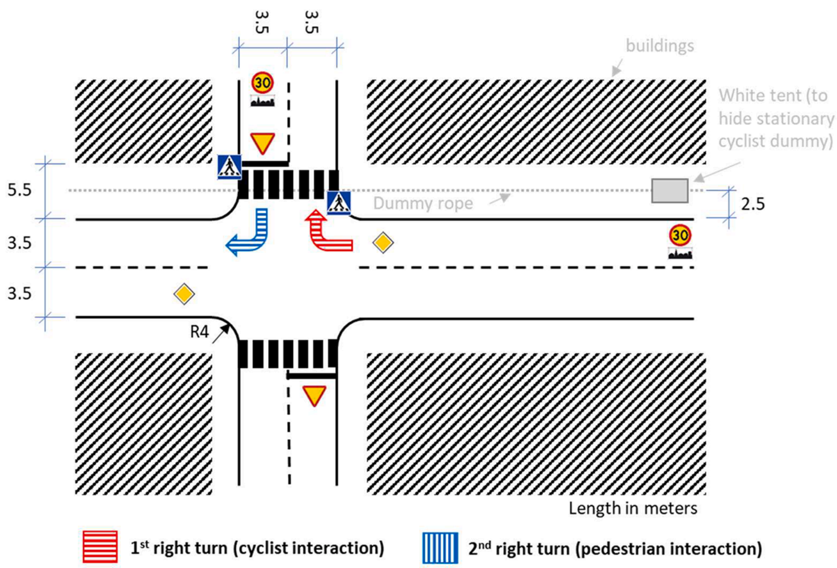


Fig. 2. Intersection design at the City Area of the AstaZero test track.

this study is to evaluate our hypothesis that the kinematic and visual behavior of truck drivers is different when a VRU is present in the two scenarios studied, compared to the situation when the driver can perform the right turn undisturbed (i.e., no VRU is present).

2. Methods

In order to collect information on truck driver behavior, a test-track experiment was set up, focusing on the two most critical interaction scenarios between trucks and VRUs: right turn maneuvers of trucks in right-hand traffic, either with a cyclist going alongside with the intention to cross the intersection (Fig. 1, left), or with a pedestrian crossing in front of the truck before the turning maneuver (Fig. 1, right).

The experimental set-up was submitted for ethical review before the experiment, in accordance with the guidelines provided by the Swedish act concerning the Ethical Review of Research Involving Humans (SFS 2003:460), and it was deemed requiring no ethical review (Etikprövningsmyndigheten Dnr: 2019-02058).

Fig. 3. Volvo FH tractor semi-trailer combination used in the experiment. All pictures and videos (except Fig. 6) have been taken either during the pilot test or after the experiment, and are reported here to support the readability of the paper. To avoid interfering with the experiment, none of these recordings were done during the actual data collection. The setup during the experiment might therefore differ slightly from the one shown in the images/videos. In particular, the white tent used to hide the stationary dummy was not present during the recordings.

Fig. 4. Interior view of Volvo FH tractor used in the experiment.

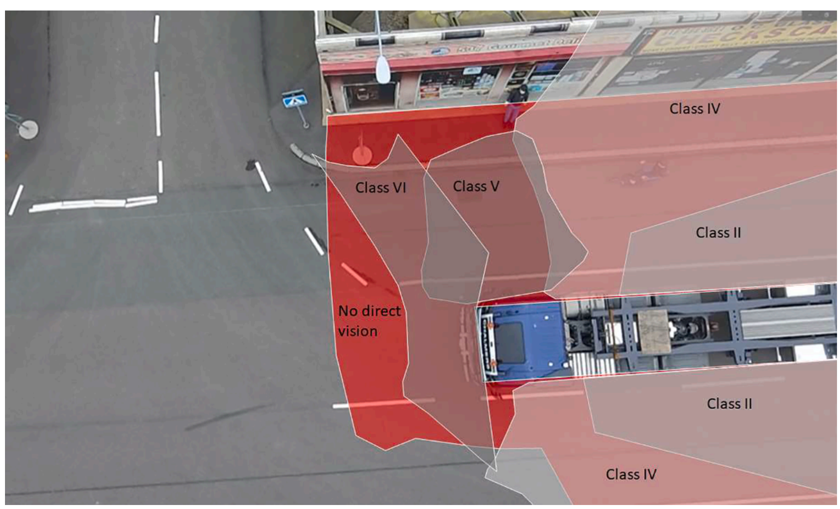


Fig. 5. Areas covered by the different mirrors and direct vision (screenshot taken from Video D.1).

2.1. Participants

Thirteen participants – 11 males and 2 females – aged between 28 and 63 years, with an average of 43.4 ± 12.3 years completed the experiment. The participants had their CE driver's license (tractor and trailer license) for 21.0 ± 11.2 years on average (min 9 years, max 41 years) and were regularly driving a truck (3–7 days per week). The drivers had varying experience with ADAS systems, from having no systems at all in their trucks to fully equipped vehicles (including Advanced Emergency Braking System, Adaptive Cruise Control and Lane Keep Assist).

2.2. Test track

The experiment was conducted at the City Area of the AstaZero test track close to Göteborg, Sweden (for more information, see also AstaZero, 2019). The intersection design used in this experiment was a four-way intersection, with one lane in each direction, meeting orthogonally (see Fig. 2 for more details). The participants were asked to follow a specific, predefined route during the entire experiment (see Appendix A), approaching the intersection from different directions. Signs were placed at the intersection in order to indicate to the drivers where to go and who had the right of way. This was especially relevant as the drivers were alone in the truck cabin during the laps. At the entrance of the city area, the drivers were reminded of the 30 km/h speed limit by corresponding signs.

2.3. Truck

The participants drove a Volvo FH tractor-semitrailer combination (Fig. 3). The truck was equipped with an OpenDLV logger (used to store all data and synchronize the different signals), CAN-logger (providing the CAN signals), GPS as well as 2 cameras (one facing the driver and one facing the road ahead). The data of the driver-facing camera was the basis for the gaze annotations. The truck is equipped with a Class II rear-view mirror and a Class IV blind spot mirror, mounted on both sides of the cab. Besides, it is also provided with a Class VI mirror for the blind spot in front of the truck, mounted in the upper right corner outside of the windscreen, and a Class V blind spot mirror, mounted outside in the upper corner of the right window (see also Fig. 4).

The areas covered by the mirrors and the areas outside of direct vision can be seen in Fig. 5. The direct vision area is defined to guarantee the visibility of markings on the ground, and therefore represents the worst-case scenario. In our experiment, the upper body of the cyclist would be also visible in direct vision when the cyclist is next to the truck or ahead of it, and the cyclist would always be visible in one of the different mirrors before reaching the intersection.

2.4. VRU targets

Two targets were used to replicate the motion of a cyclist (4activeBS bicyclist target) and a pedestrian (4activePS pedestrian target) during the experiment (hereafter referred to as cyclist and pedestrian for brevity), to minimize the risk of personal injuries. For both targets, separate trigger points for the initiation of their movement were defined.

The targets were mounted on a platform that was attached to a rope and moved by two propulsion units placed far outside the intersection (about 100 m in each direction). The propulsion units, rope and platform were in place throughout the whole experiment, parked in the same position. Only in the laps where needed, the targets would be mounted to the platform, out of sight for the participants.

2.5. Test protocol

During the experiment, each participant had to complete 6 laps. In each lap, the participants had to follow the same route (see Appendix A). The participants were told that the purpose of the experiment was to assess a new steering support system, and they were therefore naive to the real purpose of the experiment. Before the first lap, they were asked to set-up everything in the truck to their needs, i.e., to adjust the steering wheel, seat, and mirrors. They were reminded to obey the speed limit of 30 km/h and to drive in the way they typically did in naturalistic conditions. The participants were informed about the placed traffic signs, and that they were not alone on the test track, meaning that other traffic elements would be present.

After the instructions and filling in a demographic questionnaire, the experiment was started with a “Training lap”, in which the participants were driving on the test track and were accompanied by a member of the experiment team, to get acquainted with the truck and the route. During the five laps after the training lap was completed, a car was driven on the test track as well, following a predefined route: the car approached the 4-way intersection on three occasions per lap, approximately at the same time as the truck was coming from the opposite direction. The presence of the car induced additional attentional demand for the participants, by replicating a more realistic driving situation. The interactions with the car were designed to ensure that the truck had the right of way, i.e., the truck did not need to yield for the car, to minimize the risk of potential unintended conflicts.

Laps two and three were “Baseline laps”, in which the participants were alone in the truck and no further interactions apart from the one with the car occurred at the intersection. For these laps, no targets were mounted on the platform, so the drivers could only see the rig and rope in these rounds.

In lap four, at the first right turn on their route (see Appendix A), the participants needed to give the right of way to a cyclist travelling on the adjacent bicycle path in the same direction, at 15 km/h, with the intention to cross the road which the truck wanted to turn into (see Video 1). During this lap, the movement of the cyclist was initiated when the truck passed the trigger point, located 66 m before the intersection. Directly after that, the cyclist left the white tent—that was used to hide the stationary target—and emerged from it shortly before the truck passed the tent. At that moment, the cyclist was ahead of the truck, and was overtaken by the truck about 20 m before the intersection. Due to experimental restrictions, the cyclist stopped sharply, just before entering the intersection.

Video 1. First right turn maneuver (with cyclist target)

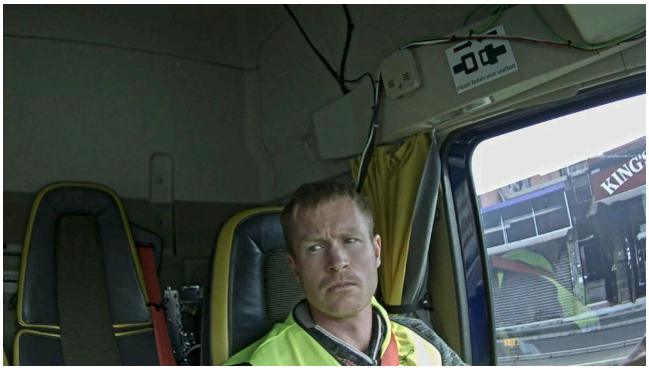


Fig. 6. Example of image file used for the gaze analysis.

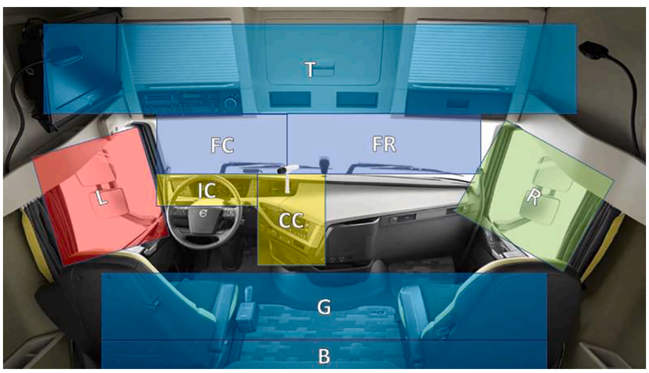


Fig. 7. In-cab gaze categories used for the analysis of gaze behavior and position of the camera. The categories shown are FC – Front Center, FR – Front Right, R – Right, L – Left, IC – Instrument Cluster, CC – Center Console, G – Ground/In-cabin floor, B – Behind seat and T – Top. In addition to the ones shown, EC – Eyes closed, TR – Transition and U – Unknown were used.

In lap five, during the second right turn maneuver on their route, a pedestrian crossed the road in front of the truck. The pedestrian target was mounted on the platform once the truck had cleared the intersection, after the first right turn maneuver: this procedure avoided that the participants could see the mounted target during the first right turn maneuver and that they would expect something to happen during the second right turn maneuver. The pedestrian's movement was initiated when the truck passed the trigger point located 36 m before the intersection and emerged from behind a corner when the truck approached the intersection from the north. The pedestrian crossed the road at the

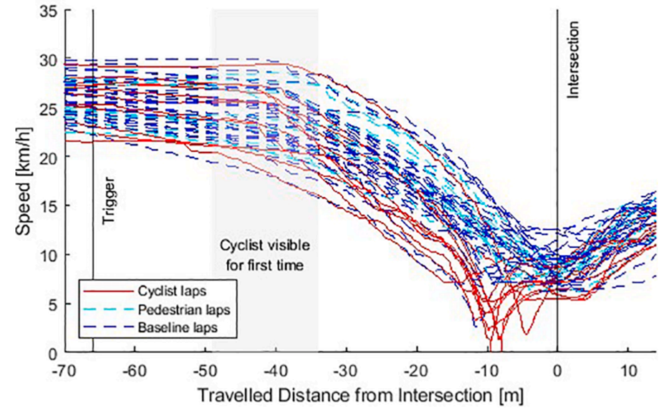


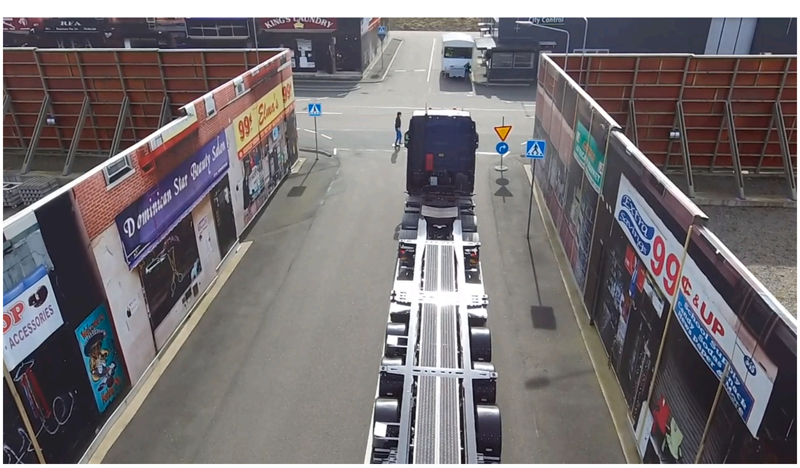
Fig. 8. Plot of speed over travelled distance (for cyclist (red), pedestrian (light blue) and baseline (blue) laps) in the first right-turn maneuver. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intersection, from the left to the right, at 6 km/h in front of the truck approaching the intersection (see Video 2). The order of laps four and five was counter-balanced between participants to allow a check for bias in the dataset, as the first scenario could have affected the driver's behavior in the second scenario.

Finally, the participants drove an additional Baseline lap (Lap 6) that could in the later analysis be compared to the previous Baseline laps, to assess the potential adaptation in behavior after the encounters with the VRUs.

After the participants had completed all laps of the experiment, they were asked to fill two additional questionnaires. The first of these questionnaires was used to obtain general information about driving patterns (e.g., what type of truck they drive, what safety systems the truck is equipped with, where their eyes are focused in certain driving situations). When the participants had completed this questionnaire, the real purpose of the experiment was revealed to them. Afterwards, they were asked to fill in the last questionnaire that contained specific questions about the two encounters with the targets.

Appendix B shows a summary of the set-up previously described for each lap: type of lap, presence of the test-leader in the truck, presence of the cyclist/pedestrian target during the turning maneuver and the presence of the car.



Video 2. Second right turn maneuver (with pedestrian target)

Table 1
Overview of driver behavior performance indicators for the different laps in the first right-turn maneuver.

	Distance at start of braking [m]	Speed at start of braking [km/h]	Distance at end of braking [m]	Speed at end of braking [km/h]
Cyclist-target-present lap	42.3 ± 4.3	23.7 ± 4.3	9.3 ± 3.2	3.3 ± 2.4
All baseline laps (incl. pedestrian-target-present lap)	41.3 ± 8.3	24.7 ± 8.3	1.3 ± 4.6	8.0 ± 1.7
Baseline 1 (lap 2)	42.8 ± 8.2	24.1 ± 2.9	3.1 ± 7.1	7.8 ± 2.5
Baseline 2 (lap 3)	39.2 ± 6.1	24.5 ± 3.0	0.6 ± 3.2	8.6 ± 1.7
Baseline 3 (lap 6)	44.4 ± 9.1	25.3 ± 1.8	0.3 ± 3.3	7.8 ± 1.1

2.6. Analysis

The analyses were performed with Matlab using the CAN and GPS data extracted from the overall dataset. The signals were already synchronized during the data collection within the OpenDLV logger. Additional metrics (e.g., distance travelled) were calculated based on the recorded signals and the identification of the trigger points. The start of the braking maneuver was defined as when the truck decelerated with more than 0.5 m/s^2 whereas the end of the braking maneuver was coded when the truck had reached the lowest speed during the turning maneuver (or stopped completely), both of which were manually checked for all laps.

The gaze analysis and naming conventions follow the recommendations provided by the ISO 15007:2020 standard (International Organization for Standardization, 2020). Before performing the gaze annotation, the original video data recorded from the interior camera was split into individual image files, one per frame (see Fig. 6 for an example of an image resulting from this procedure). The video from the interior camera was recorded with a frequency of 25 Hertz, so the above-described procedure produced 25 images per second, to be used for the gaze analysis.

The individual image files were loaded in Matlab, using the app 'Image Labeler', which was also used for classifying the gazes into the different categories. Building on previous research (Morando et al., 2016; Pipkorn and Bianchi Piccinini, 2020) and on the ISO 15007:2020 standard (International Organization for Standardization, 2020), we identified nine in-cab categories (see Fig. 7 and Appendix C) and three additional categories for other or unknown glances: "eyes closed", "transition" and "unknown". There were no separate categories for the mirrors, because we judged that it was not possible to distinguish glances directed towards the mirrors from glances directed towards other areas of interest in the same direction (e.g., glances directed towards the right mirror versus glances directed towards the right window). The gaze annotations were performed manually by a trained annotator who watched the individual video frames and classified the gaze according to the categories. In line with what was suggested by Jansen et al. (2021), the annotator was initially provided with a reference set of images, to support the appropriate classification of the gaze annotations. In situations where the annotator was unsure about the coding, the annotations were discussed with the two authors.

3. Results

The results presented in this paper are based on the analysis of the recorded data of the 13 participants. Since CAN data is missing for the first two participants, due to an error in the CAN logging system, the analyses that rely on kinematic information are only conducted for the remaining 11 participants. Due to time constraints, participant 10 could not perform the second baseline lap, hence the corresponding lap is empty.

3.1. First right turn maneuver – cyclist encounter

As a first step, the criticality of the scenario was estimated by calculating a surrogate value of the minimum time to collision (TTC). Since no information on the exact position of the cyclist was available from the data, the minimum TTC was calculated for each time point, considering the distance to the location where the trajectories of the truck and cyclist would intersect and current speed at the specific time point. The resulting minimum TTC had the lowest values ranging from 2.7 s to 6.7 s for the different drivers, indicating a low criticality of the scenario in conformity with the purpose of the study.

Fig. 8 shows a plot of the trucks' speed over the distance travelled for all participants before, during and after the first right turn maneuver, i.e., where the cyclist target would be present in lap 4 (or lap 5, depending on the counterbalancing). For this maneuver (named "cyclist encounter"), also the lap where the driver encountered the pedestrian target can be considered as a baseline lap, as the encounter with the pedestrian occurs at the second right turn, after the truck has cleared the first right turn. The pedestrian lap is therefore included in the plot with a

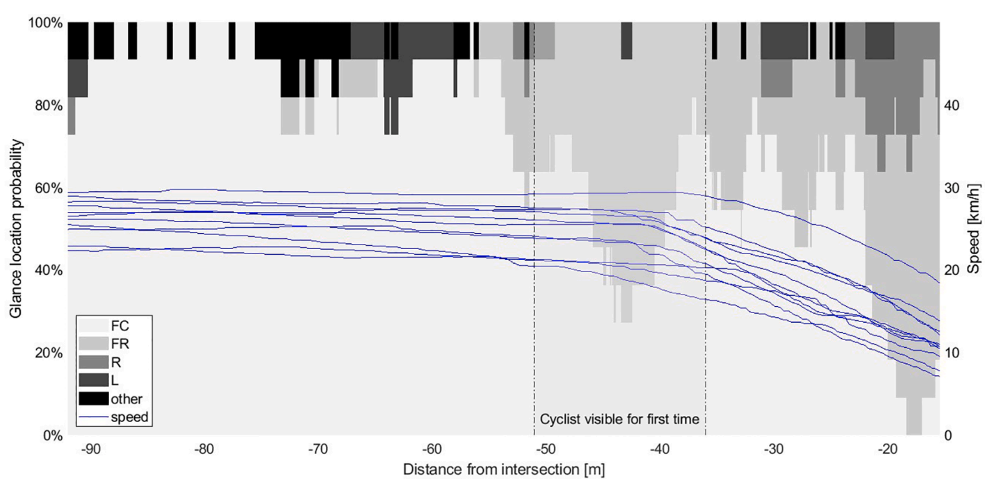


Fig. 9. Glance location probability in 1st right turn maneuver with cyclist target present, based on distance from intersection.

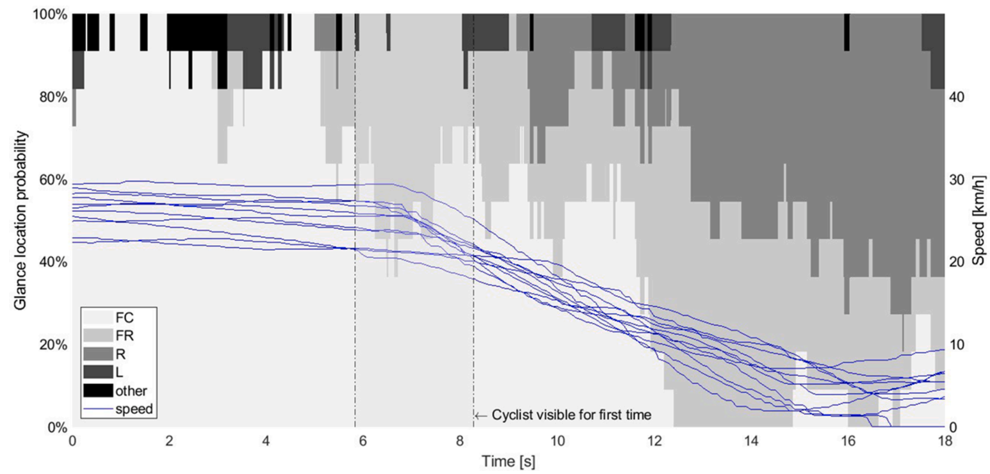


Fig. 10. Glance location probability in 1st right turn maneuver with cyclist target present, based on time from passing the trigger.

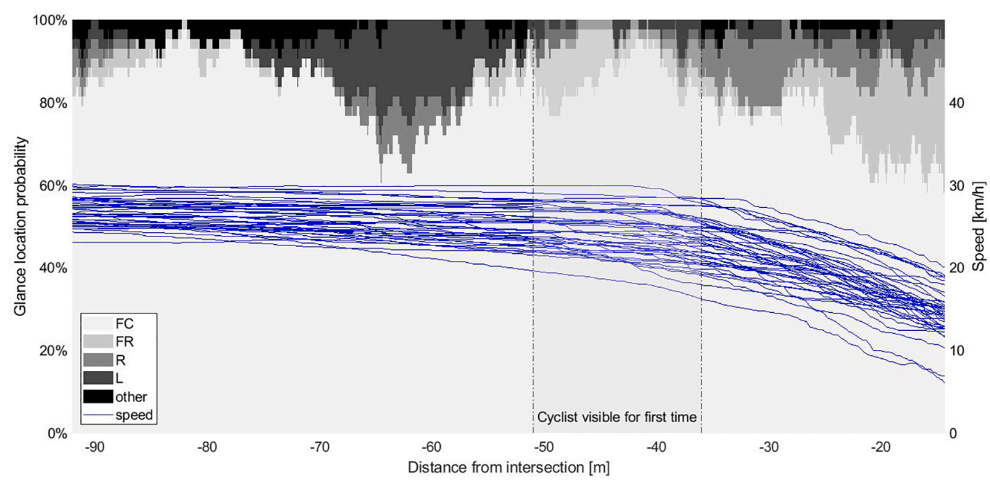


Fig. 11. Glance location probability in 1st right turn maneuver in baseline laps, based on distance from intersection.

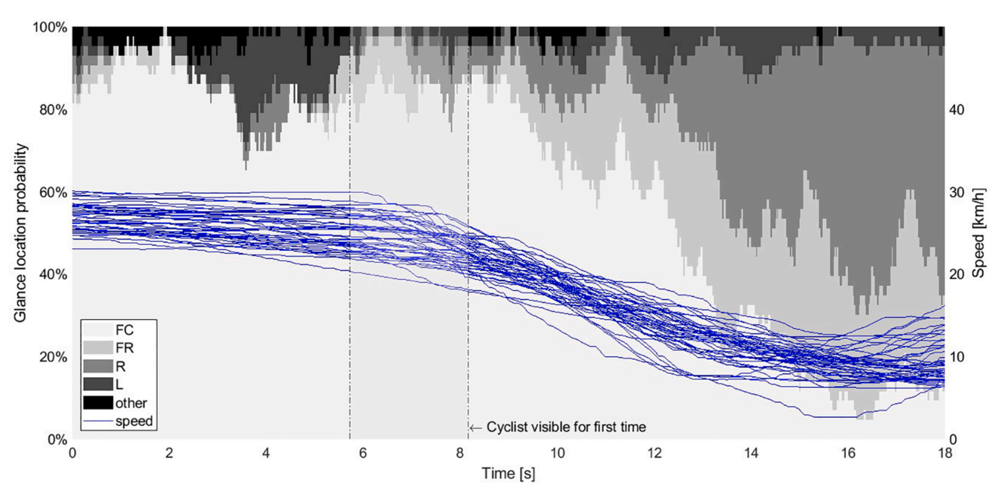


Fig. 12. Glance location probability in 1st right turn maneuver in baseline laps, based on time from passing the trigger.

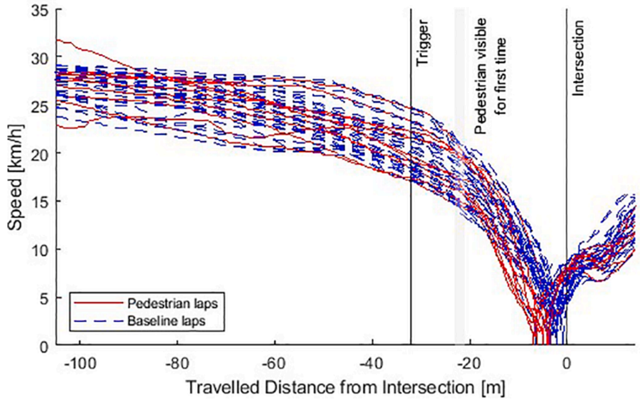


Fig. 13. Plot of speed over travelled distance (for pedestrian (red) and baseline (blue) laps) in the second right-turn maneuver. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Overview of driver behavior performance indicators for the different laps in the second right-turn maneuver.

	Distance at start of braking [m]	Speed at start of braking [km/h]	Distance at end of braking [m]	Speed at end of braking [km/h]
Pedestrian-target-present lap	97.5 ± 37.9	27.5 ± 2.6	5.9 ± 1.5	0.9 ± 1.1
All baseline laps	99.8 ± 34.1	27.3 ± 1.5	3.7 ± 1.6	3.3 ± 2.2
Baseline 1 (lap 2)	94.9 ± 34.3	26.8 ± 1.3	4.5 ± 2.3	1.8 ± 2.3
Baseline 2 (lap 3)	107.3 ± 38.7	27.4 ± 1.4	3.9 ± 2.1	3.7 ± 2.2
Baseline 3 (lap 6)	89.3 ± 22.4	27.1 ± 1.8	3.7 ± 1.2	4.3 ± 1.5

light blue line and in the analysis as well.

In Fig. 8, the vertical line in black at −66 m shows when the truck is passing the trigger point for the movement of the cyclist target. The grey area marks the range in which the drivers are first able to see the cyclist target leaving the tent in their laps: this information is based on the review of the videos collected by the forward camera. The vertical line in black at 0 marks the point where the trajectory of the truck would intersect with the trajectory of the cyclist target at the intersection and where a collision would occur if the driver did not perform any avoidance maneuver (assuming that the cyclist target would continue through the intersection). The graph shows that the initiation of the braking maneuver occurs at similar distances from the intersection (41.3 ± 8.3 m for baseline laps and 42.3 ± 4.3 m for cyclist laps) and similar speeds (24.7 ± 8.3 km/h for baseline laps and 23.7 ± 4.3 km/h for cyclist laps), but that the drivers brake harder when there is a cyclist present. This results in a lower minimum speed (8.0 ± 1.7 km/h for baseline laps and 3.3 ± 2.4 km/h for cyclist laps) that is reached further away from the intersection (1.3 ± 4.6 m for baseline laps and 9.3 ± 3.2 m for cyclist laps), see also Table 1. From about 30 m before the intersection, the red curves start to separate from the blue curves, indicating that the drivers have adapted their behavior to the presence of the cyclist. At this point, the truck is approaching the cyclist, whose back is roughly at the same distance from the intersection as the front of the truck. No remarkable differences in speed profiles could be identified based on the order of the encounters, implying that the speed profiles were similar regardless of which scenario the participants faced first.

A paired-samples *t*-test was performed in Matlab to compare the means of the four dependent variables (‘distance at start’, ‘speed at start’, ‘distance at end’ and ‘speed at end’ of braking), between baseline and cyclist laps. The values for baseline lap 2 were considered the most representative of the baseline laps and were used for this comparison. While the distance and speed at start of braking show no significant difference ($t = 1.899$, $p = 0.087$ and $t = -0.035$, $p = 0.973$ respectively), the distance and speed at the end of braking show a significant difference between baseline lap 2 and cyclist laps ($t = 10.534$, $p < 0.000001$ and $t = 6.339$, $p < 0.0001$ respectively). These results are in line with the speed profiles in Fig. 8, as the cyclist appears for most drivers after they started braking for the intersection.

The results of the gaze analysis show a clear shift of gazes towards the right in the lap where the cyclist was present, compared to the baseline laps. The share of glances to FR increases at the expense of glances towards FC, when the cyclist becomes visible. Some participants could spot the cyclist earlier (due to the wind opening the side of the tent) and some only once it had left the tent, hence the two peaks in Fig. 9: the first peak is located at about 45 m from the intersection and the second peak at about 35 m. In baseline 3 laps, more glances towards FR could be observed compared to baselines 1 and 2, suggesting a learning pattern amongst the drivers (expecting something to happen). Also, when crossing the earlier intersection (located before the intersection where the drivers need to perform the right turn maneuver, see Appendix A), there are glances towards L (see Fig. 11), presumably drivers checking the mirrors and the left leg of the intersection at around 65 m before the intersection. These glances towards L are less dominant in the cyclist lap, hinting towards drivers focusing on the cyclist rather than on other traffic elements. The timewise analysis[2] (Fig. 10 and Fig. 12) shows a similar pattern, although some of the peaks are less prominent.

3.2. Second right turn maneuver – pedestrian encounter

For the pedestrian encounter, the criticality of the scenario was also assessed at first. No information on the exact position of the pedestrian was available from the data, hence the analysis of the criticality is based on the surrogate minimum TTC. This indicator is calculated for each time point, considering the distance to the location where the trajectories of the truck and pedestrian would intersect and current speed at the specific time point. The value of minimum TTC varied between 2.8 s and 4.9 s between the different drivers. These values of TTC show a low criticality of the situation, which is to be expected given the experimental setup.

Similar to Fig. 8 for the first right turn, Fig. 13 shows the plot of speed over the distance travelled for all participants before, during and after the second right turn maneuver, i.e., where the pedestrian target would be present in lap 5 (or lap 4, depending on the counterbalancing). In this specific analysis, the cyclist lap is excluded from the baselines, as the encounter with the cyclist at the first right turn maneuver of this lap might have influenced the truck driver’s behavior when approaching the second right turn. In Fig. 13, the range of distances at which the pedestrian is first visible to the participants (grey area in Fig. 13) has a

[2] *The cut-off points in the distance and time-based graphs are not the same. The gaze coding was performed in the time domain, and remapped to the distance travelled afterwards. The distance-based graph is therefore cut off as soon as the first driver reached the minimum speed (typically within or before the intersection amongst all drivers), as this meant no more recoding of gaze on the travelled distance could be performed. The time-based graphs are cut off at the time corresponding to the first driver clearing the intersection (i.e., no more glance data is available for this driver and the glance location probabilities would no longer sum up to 100%).*

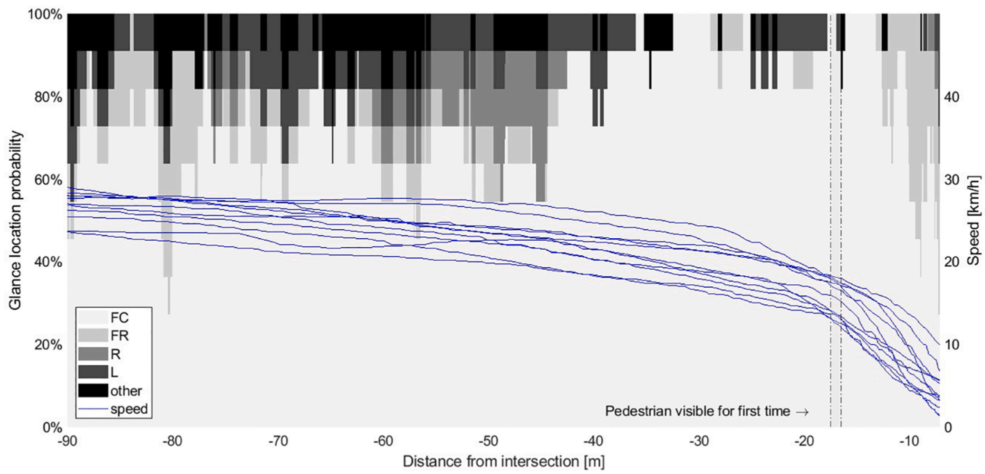


Fig. 14. Glance location probability in 2nd right turn maneuver with pedestrian target present, based on distance from intersection.

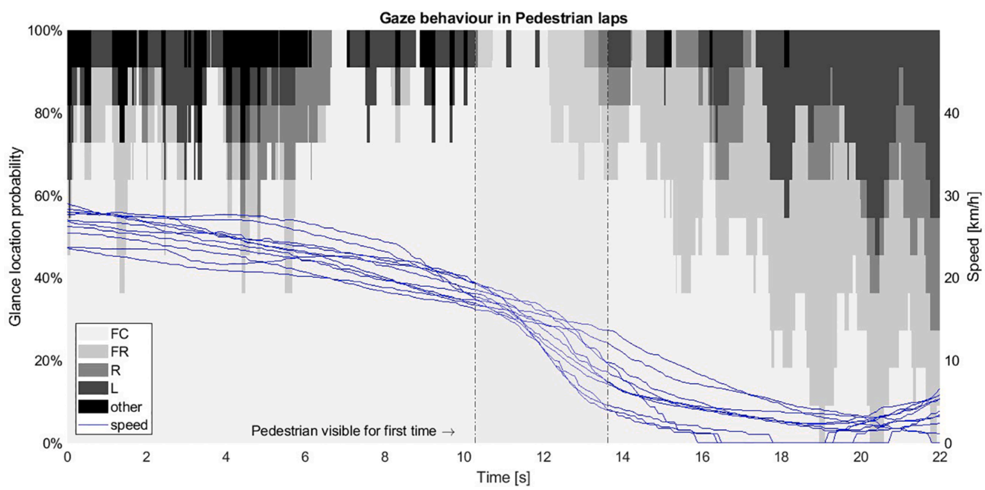


Fig. 15. Glance location probability in 2nd right turn maneuver with pedestrian target present, based on time from passing the trigger.

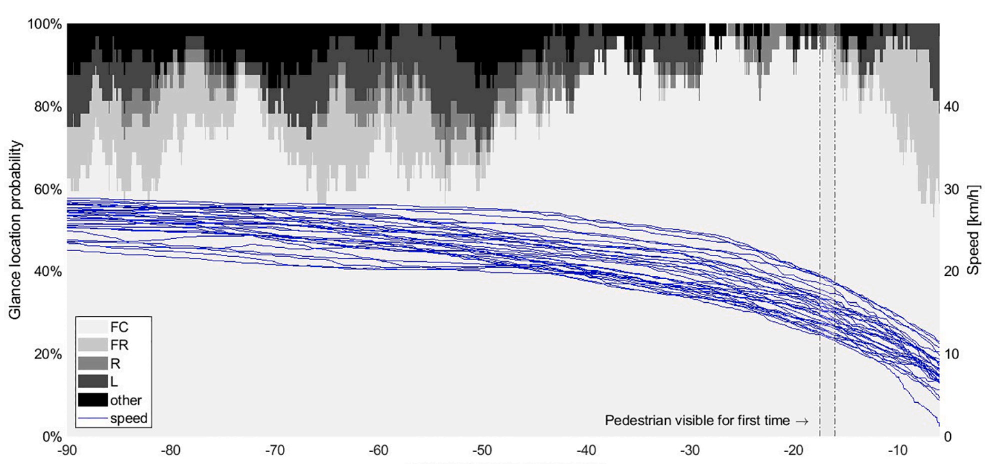


Fig. 16. Glance location probability in 2nd right turn maneuver in baseline laps, based on distance from intersection.

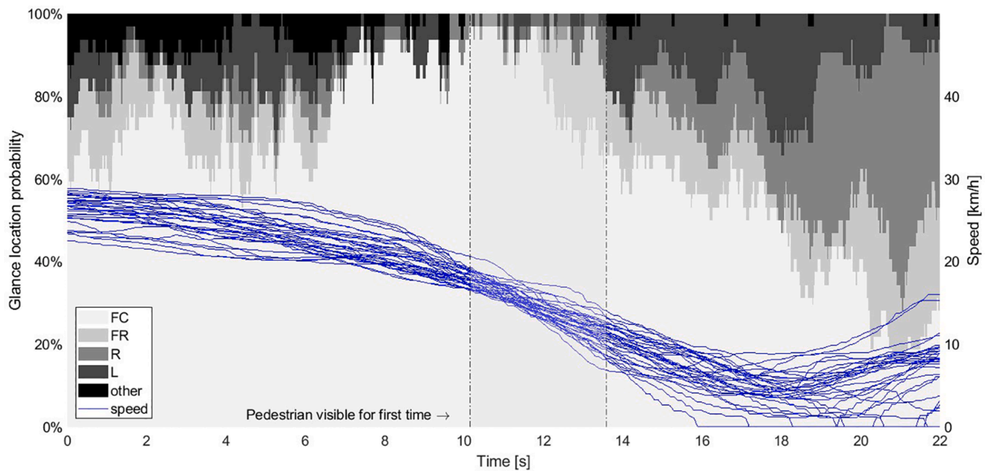


Fig. 17. Glance location probability in 2nd right turn maneuver in baseline laps, based on time from passing the trigger.

smaller variability, compared to the previous encounter with the cyclist. This occurs because the pedestrian appeared from behind the corner and could not be spotted before that.

Table 2 shows that the initiation of the deceleration maneuver occurs at similar distances from the intersection (99.8 ± 34.1 m for baseline laps and 97.5 ± 37.9 m for pedestrian laps) and similar speeds (27.3 ± 1.5 km/h for baseline laps and 27.5 ± 2.6 km/h for pedestrian laps). However, the drivers brake harder when there is a pedestrian present, resulting in a lower minimum speed (3.3 ± 2.2 km/h for baseline laps and 0.9 ± 1.1 km/h for pedestrian laps) that is reached to a small extent further away from the intersection (3.7 ± 1.6 m for baseline laps and 5.9 ± 1.5 m for pedestrian laps). Most drivers come to a full stop before the intersection, even when the pedestrian is not present. However, when the pedestrian is present, they stop even further away from the intersection, i.e., they stop before being able to check around the corner of the buildings for crossing traffic. From about 14 m before the intersection, the red curves in Fig. 13 start to separate from the blue curves, indicating that the drivers have adapted their behavior to the presence of the pedestrian. At this point, the pedestrian is about halfway into the adjacent lane on the left (i.e., cleared one-fourth of the intersection). Overall, compared with the cyclist encounter, the drivers showed a less clear behavioral pattern and a less significant drop in their speed profile, resulting in a larger standard deviation for the distance at the start of the braking maneuver. No remarkable differences in speed profiles could be identified based on the order of the encounters, i.e., regardless of which scenario the participants faced first the speed profiles were similar.

A paired-samples *t*-test was performed in Matlab to compare the means of the four dependent variables ('distance at start', 'speed at start', 'distance at end' and 'speed at end' of braking), between baseline and pedestrian laps. As for the cyclist encounter, the values for baseline lap 2 were considered the most representative of the baseline laps and were used for this comparison. While the distance and speed at the start of braking show no significant difference ($t = -1.032$, $p = 0.326$ and $t = -0.090$, $p = 0.930$ respectively), the distance and speed at end of braking show a significant difference between baseline lap 2 and pedestrian laps ($t = 3.426$, $p = 0.007$ and $t = 3.920$, $p = 0.003$ respectively). Since the pedestrian appears after the drivers started braking for the intersection (Fig. 13), these results are expected.

The results of the gaze analysis show a different approach to the intersection, compared to the cyclist encounter. Overall, drivers are looking more frequently at the instrument cluster (majority of gazes in "Other") compared to the first right turn maneuver (see Fig. 14 and Fig. 16). Around the distance where the pedestrian is spotted for the first time, all drivers look straight ahead. Some drivers clearly track the movement of the pedestrian with a smooth pursuit movement, whereas in the first two baseline laps drivers were looking left and right more frequently. The increased FC glance probability indicates a higher importance of this area of interest when a pedestrian is present, compared to the baseline laps. Baseline lap 3 seems to show some learning effect among the drivers, as it shows a more similar gaze pattern to the pedestrian lap at the intersection rather than the previous two baseline laps. The timewise analysis[3] (Fig. 15 and Fig. 17) shows a similar pattern, with some more dominant peaks when approaching the intersection.

3.3. Questionnaire

When asked after the experiment whether the participants had noticed the targets in the respective laps, all replied with "Yes". Most participants experienced the situations as realistic, with two participants mentioning that in a real-world scenario "the bicycle never stops, in real world it would have moved on". In general, the participants described their own reaction to the situation as "slowing down and checking the mirrors and what the cyclist or pedestrian wants to do"—these statements are supported by the previously shown speed graphs and gaze analysis. No influence of previous experience (both in terms of driving experience and experience with ADAS) on driving or gaze behavior was identified.

4. Discussion

The current study presents the results of an experiment conducted to assess the behavior of truck drivers when approaching intersections, where a cyclist or a pedestrian are crossing the path of the truck in perpendicular direction. The experiment was conducted at the city environment of the AstaZero test track and involved 13 truck drivers. The participants completed six laps on a pre-defined route: one training lap, two baseline laps, one lap where they encountered the cyclist target crossing, one lap where they encountered the pedestrian target crossing, and one final baseline lap.

The results of the experiment show that the truck drivers adapted their driving behavior in the laps where the cyclist or the pedestrian

[3] *The cut-off points in the distance and time-based graphs are not the same. The gaze coding was performed in the time domain, and remapped to the distance travelled afterwards. The distance-based graph is therefore cut off as soon as the first driver reached the minimum speed (typically within or before the intersection amongst all drivers), as this meant no more recoding of gaze on the travelled distance could be performed. The time-based graphs are cut off at the time corresponding to the first driver clearing the intersection (i.e., no more glance data is available for this driver and the glance location probabilities would no longer sum up to 100%).*

were crossing the intersection, compared to the baseline laps. Both the speed and distance from the intersection at the end of the maneuver were significantly different between baseline and VRU laps, indicating that drivers considerably reduced their speed and finally came to a full stop of the vehicle (or attained a lower minimum speed) further away from the intersection in the VRU laps, compared to the baseline laps. However, the adaptation in driving behavior was not remarkable until the participants were approximately 30 and 14 m distant from the intersection, respectively for the scenario with cyclist and pedestrian crossing. Based on the interviews conducted with the participants at the end of the study, these large reductions in speed seem to be driven by the visual glances directed towards the VRUs: for example, the drivers stated that they slowed down and checked the movement of the cyclist and pedestrian targets, to create an expectation of what the VRU was planning to do. This is also supported by the results of the gaze behavior analysis, that showed more glances towards front right and right compared to baseline laps during the cyclist encounter and more glances towards the front center and front right during the pedestrian encounter. Summala et al. (1996) had identified that car drivers checked the left side more frequently with VRUs present, which is a pattern we could not observe for the truck drivers, even though there was an oncoming vehicle. There were some glances towards the left mirror when approaching the intersection, but they were less frequent when VRUs were present compared to the baseline laps. Pokorny and Pitera (2019) had identified that truck drivers would stop further away from the stop line at red lights with VRUs present. Although there were no traffic lights in our experiment, also our results show that the truck drivers reached lower speeds further away from the intersection, which would be in line with the results of Pokorny and Pitera (2019).

The results from these analyses can provide valuable information for the design of ADAS that warn the drivers about the presence of a cyclist travelling in parallel direction (e.g., Blind Sport Information Systems, BLIS) or that intervene to avoid a collision with a cyclist or a pedestrian (Automatic Emergency Braking Systems, AEBS). This information can also be used to inform the upcoming UN regulations on blind spot information systems in trucks (Working Party on General Safety, 2019) about the kinematic adaptation of truck drivers during the interaction with cyclist. For the scenarios considered in this study, the analyses assessed the distances from the intersection at which the truck drivers would start to adapt their behavior to the presence of a cyclist or a pedestrian. This information could be used by BLIS or AEBS to determine if the truck drivers have initiated a speed reduction maneuver, presumably after noticing the VRU. If the appropriate sensor of BLIS or AEBS has detected a cyclist or pedestrian but the driver has not slowed down (i.e., he/she is following their usual "baseline" speed profile), a warning should be triggered to the driver. On the other hand, when the appropriate sensor has detected a cyclist or pedestrian and the truck driver has started the deceleration of the vehicle according to the "VRU" speed profile, the provision of the warning could be suppressed to avoid unnecessary nuisance to the driver and to increase the acceptance of the system.

In addition, these driver models can be used to increase the quality and fidelity of simulations aiming to assess the safety benefits introduced by ADAS (Bärgman et al., 2017; Kovaceva et al., 2020), in conflict situations involving trucks and VRUs. Future work should focus on using the collected data as a basis for estimating the behavior of a larger population of drivers and to include these estimations in counterfactual simulations aiming to assess the safety benefits of AEB. By creating synthetic data with Bayesian methods, it would be possible to overcome the limitation associated to the small sample size of this study.

Nonetheless, the outcomes of the study and the resulting models of driver behavior should be improved by considering a larger population of truck drivers and a larger sample of scenarios. Regarding the latter, combining different intersection configurations (e.g., 3-legs intersection), traffic densities (e.g., vehicles present in all the legs of the intersection) and positions of the VRU relative to the truck driver, would create a wider range of scenarios. These varied scenarios would enable assessing the kinematic and visual behavior of truck drivers also in more complex situations, where spatial and temporal blind spots might easily materialize. Since the purpose of our study was to investigate "normal" driving behavior (i.e., the adaptation of the driver's behavior to the situation), the participants did not encounter critical situations. As a result, the contributing factors (such as presence of spatial or temporal blind spots) that were previously found in the literature could not be observed in our experiment. To achieve this objective, datasets collected during field studies should be coupled with data collected in naturalistic settings, including Naturalistic Driving Studies (NDS), Field Operational Tests (FOTs) and field data collected from infrastructure (such as the one described in Madsen and Lahrmann, 2017). This study should be nevertheless considered as a first exploratory research, that can provide preliminary indications on how drivers behave in these situations.

CRediT authorship contribution statement

Ron Schindler: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing - original draft. **Giulio Bianchi Piccinini:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing - review & editing.

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Appendix A

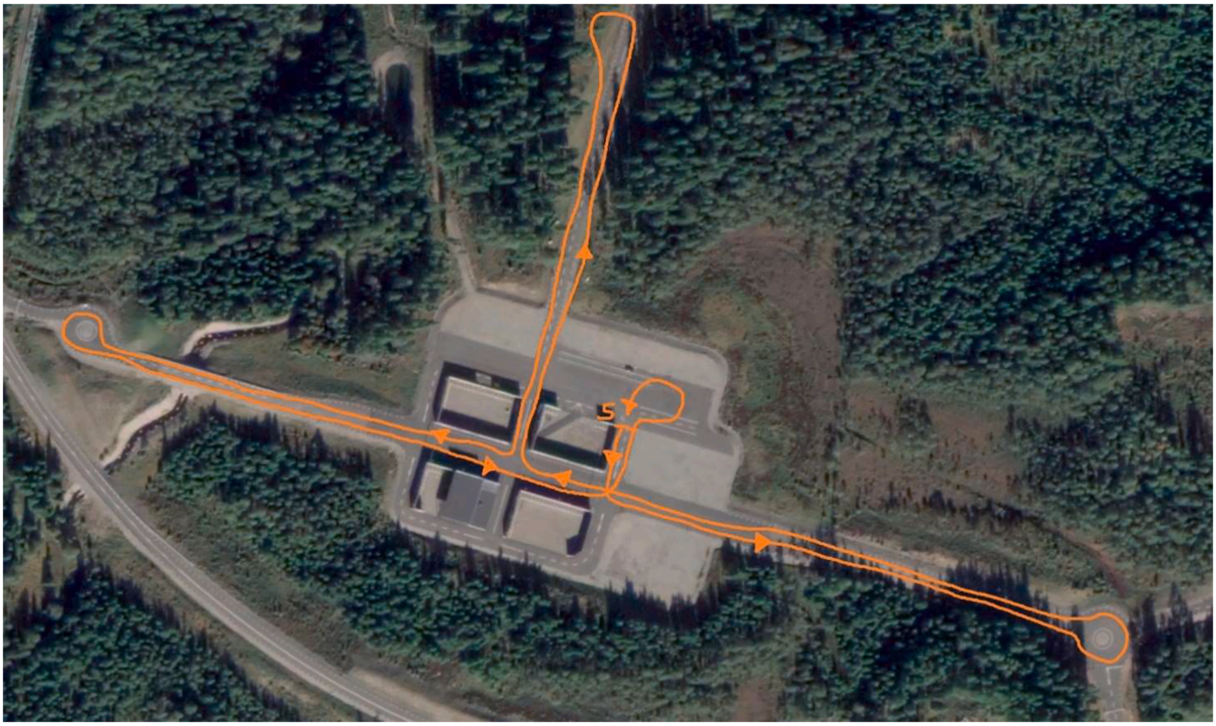


Fig. A1. Design of City Area at AstaZero – the orange line shows the route (start and end marked by S) and the intersection used for the VRU encounters, displayed in Fig. 2.

Appendix B

Table B1
Summary of set-up for each lap.

Lap number	Lap type	 Presence of test leader in the truck	Presence of cyclist or pedestrian target	 Presence of car
1	**Training**	✓	✗	✗
2	**Baseline 1**	✗	✗	✓
3	**Baseline 2**	✗	✗	✓
4	**Cyclist***	✗		✓
5	**Pedestrian***	✗		✓
6	**Baseline 3**	✗	✗	✓

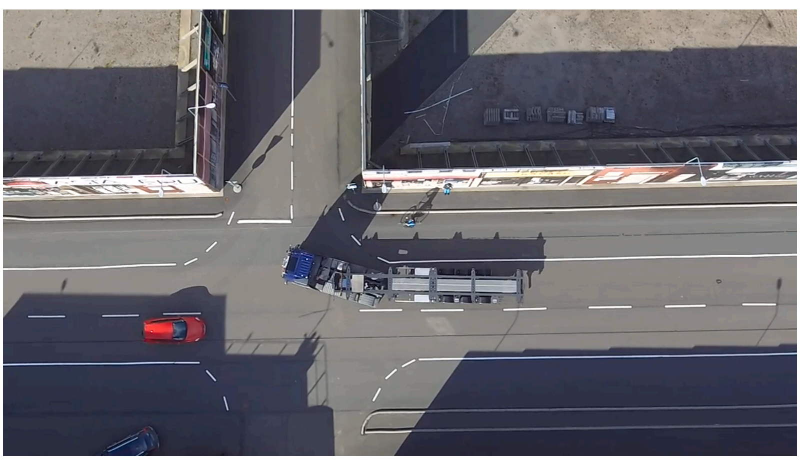
* Order depending on counterbalancing per participant.

Appendix C

Table C1
Overview of gaze location coding.

Type	Explanation
FC	Front center
FR	Front right
R	Right window
L	Left window
IC	Instrument cluster
CC	Center console
G	Ground/Floor
B	Back (behind seat)
T	Top (cabinets above windscreen)
EC	Eyes closed
TR	Transition
U	Unknown

Appendix D



Video D.1. Top view video of cyclist interaction.

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