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Required Field of View of a Sensor for an Advanced Driving Assistance System to Prevent Heavy-Goods-Vehicle to Bicycle Accidents

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Abstract: Accidents involving cyclists and trucks are among the most severe road accidents. In 2021, 199 cyclists were killed in accidents involving a truck in the EU. The main accident situation is a truck turning right and a cyclist going straight ahead. A large proportion of these accidents are caused by the inadequate visibility in an HGV (Heavy Goods Vehicle). The blind spot, in particular, is a significant contributor to these accidents. A BSD (Blind Spot Detection) system is expected to significantly reduce these accidents. There are only a few studies that estimate the potential of assistance systems, and these studies include a combined assessment of cyclists and pedestrians. In the present study, accident simulations are used to assess a warning and an autonomously intervening assistance system that could prevent truck to cyclist accidents. The main challenges are local sight obstructions such as fences, hedges, etc., rule violations by cyclists, and the complexity of correctly predicting the cyclist's intentions, i.e., detecting the trajectory. Taking these accident circumstances into consideration, a BSD system could prevent between 26.3% and 65.8% of accidents involving HGVs and cyclists.

Keywords: Blind Spot Detection; heavy goods vehicle; truck; autonomous brake; right turn accidents

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1. Introduction

Although the number of traffic fatalities in the EU is decreasing, approximately 20,000 people are still killed on the roads in the EU every year [1]. Approximately 1900 cyclists (9% of all road fatalities) die every year, and, compared to other road users, the number of fatally injured cyclists has remained almost constant over the past years. Passenger cars are the most common type of opponent involved in fatal accidents with cyclists in the EU [1]. Accidents involving HGVs, however, are more severe because of the high mass and the likelihood of being run over [2–7]. In total, 199 (11%) of the fatally injured cyclists are victims in accidents with heavy goods vehicles [1]. In some countries, the number of cyclist killed in HGV collisions is up to 30% [8,9]. Wang and Wei [10] reported that in Taiwan, 75% of vulnerable road users were killed in HGV accidents. It has been shown that cyclists are at greater risk of accidents simply because of the presence of HGVs [11] and that HGV-bicycle accidents tend to have more severe consequences for the cyclists involved than any other type of accident [12]; in addition, trucks are more frequent in fatal bicycle accidents [3]. Studies on fatal cycling accidents in London have shown that HGVs were the most common vehicle category in accidents involving cyclist fatalities [13]. Kim et al. [12] associate the involvement of a truck in a crash with a significant increase in the likelihood of fatal injuries to cyclists in the US. Lee and Abdel-Aty [14] found, in an analysis of data from Florida (US), that the larger size of the truck correlated with an increased likelihood of serious injury to pedestrians at intersections. Adminaite et al. [15] describe accidents between trucks and vulnerable road users as particularly problematic and point out that the main reason for these collisions is the limited field of vision of truck drivers, so that vulnerable road users are particularly susceptible to being in the blind spot and being overlooked by truck drivers. Different studies reported the major cause of truck versus bicyclist crashes is the inadequate visibility condition when bicyclists are in the vehicle's blind spot [2,5,16,17]. The most frequent accident scenario is therefore an HGV turning right and the cyclist going straight ahead and getting hit by the front or right side of the vehicle [2]. Pokorny et al. [8] reported that 12% of collisions between trucks and cyclists were a direct result of the blind spot. These accidents were, on average, more severe than other types of accidents between trucks and cyclists. In other studies, almost 20% of accidents between HGVs and cyclists are reported within this scenario [2,18–20]. In the Netherlands, 41% of accidents between HGVs and cyclists are blind spot accidents [21].

Why do truck drivers not see vulnerable road users in their blind spots, even though trucks are equipped with numerous mirrors? Talbot et al. [22] mention three possible causes. First, the drivers are looking in the right direction, but they fail to see the cyclists. As a second cause, they mention the need to pay attention to other road users due to the volume of traffic, which was also identified by Summala et al. [23]. Such an accident situation is highly dynamic and thus, third, the drivers look at the blind spot, but not at the time when the cyclists would be visible in the mirrors. Due to the large number of mirrors, drivers also need considerable time to check all mirrors, which can sometimes take up to four seconds [24]. The correct adjustment of mirrors is defined in Directive 2003/97/EC [25]. The mirrors are adjusted when the truck and the other participant are stationary. In many cases, however, traffic scenarios are dynamic situations, i.e., the participants are moving relative to each other, and therefore do not reflect several situations [22].

There are several ways to reduce the number of cyclists being fatally injured. The risk can be reduced by an increase in the risk awareness of all parties involved, i.e., vehicle drivers as well as cyclists (e.g., the blind spot problem, [5]). Infrastructure measures (e.g., separate signal phases [26,27]) can also be implemented. Advance driver assistance systems (ADAS) can also have a positive impact on the avoidance of accidents with cyclists (e.g., blind spot monitoring [28]). The expectation is that ADAS will be highly effective in terms of accident prevention. That is why the European Commission has decided that, from 2022 onwards, new vehicles will only be registered with systems designed to detect and warn vulnerable road users [29].

There has not yet been sufficient research into the extent to which these systems could influence cycling accidents. The objective of the study is to investigate the minimum longitudinal and lateral view of an ADAS in preventing heavy goods vehicle versus bicycle accidents.

2. Literature on the System Effectiveness

New truck models introduced to the market with a gross vehicle weight of more than 3.5 tonnes must be equipped with a BSD system from 2022, and generally all newly registered trucks (also with a gross weight of more than 3.5 tonnes) from 2024 [30]. Wilmink et al. [31] estimate that a BSD system could prevent approximately 39 fatalities and approximately 1900 injuries to vulnerable road users in Europe every year. A study by the Insurance Institute for Highway Safety (IIHS) quantified the potential of a BSD system at 79 fatalities and 39,000 injuries per year (Insurance Institute for Highway Safety, 2010), cited in [10]. According to Kingsley [32], 5.9% of accidents involving trucks could be avoided with a BSD system. The extent to which vulnerable road users are also affected was not specified in the study. According to Kühn et al. [33], a turning assistant would result in a potential accident avoidance rate of 42.8% between trucks and cyclists or pedestrians. In terms of injury severity, a turning assistant could prevent 31.4% of fatalities, 43.5% of serious injuries, and 42.1% of minor injuries. According to Wang and Wei [10], a BSD system would have a potential of 24% for accidents involving pedestrians, 10% for cyclists, and 11% for accidents involving motorcycles. In the truck-bicycle accidents identified by Hoedemaeker et al. [34], which were associated with the blind spot, approx. 71% could potentially be avoided with a BSD system. Silla et al. [21] estimated the potential at approx. 78%. In a before-and-after study, Tomasch and Smit [35] estimated the potential of an aftermarket BSD system at up to one third, assuming that accidents are reduced to the same extent as the warning messages after activation of an aftermarket assistant. In a prospective simulation study of accident data, an average accident avoidance potential of 15% was identified for such a system [36].

The ADAC (Allgemeiner Deutscher Automobil-Club e.V.) examined nine different aftermarket turning assistants in real-life test conditions [37]. None of the systems were rated "very good" (grade range between 1.0 and 1.5). Two of the systems were rated "good" (grade range 1.6 to 2.5), two systems were in the range between 2.6 and 3.5 (grade "satisfactory"), and one system was rated 4.4 ("sufficient", grade range 3.6 to 4.5). Four of the systems examined failed the tests and were rated "poor" (grade range worse than 4.6). Good systems did not produce any false positives and were able to detect cyclists even at a greater distance from the truck. Furthermore, the communication between the system and the truck drivers was described as "easy". Moreover, such systems are characterized by the fact that vulnerable road users and static objects can be distinguished. Vulnerable road users are detected in advance at different speeds, distances, and in different test scenarios and drivers are warned. Inadequate turning assistants produced a high number of false positives and only had a small field of view, causing drivers to not be warned in time. Some systems only recognize cyclists when they are overtaking the truck, but not when the cyclists are riding next to the truck or the truck is overtaking the cyclists. In one of the systems tested, the warning only worked if the turn signal was also on. The best system is also the most expensive assistant, with the top three systems being the most expensive. For the systems evaluated, a higher price correlates with the overall rating. Cheap systems can therefore only inadequately meet the complex requirements of road traffic.

3. Materials

The accidents used in this study are based on the road accident database CEDATU (Central Database for In-Depth Accident Analysis) [38]. The data collection is entirely retrospective. It is based on court accident data. These data are collected by the police and contain general information about the accident, such as the road users involved, age, vehicle data, etc. The police take pictures of the accident scene and prepare a sketch of the accident scene. They take pictures of the vehicles and interview the road users and witnesses involved in the accident. Injury data are collected by the hospital and are included in the court data.

Unfortunately, access to data is not granted for every court case of interest, which leads to a bias in CEDATU compared to Austrian national statistics. The aim is to have a dataset in CEDATU that is fully equivalent to the national statistics, but this will take time, as only approximately 200 to 300 cases can be investigated per year due to limited human resources.

Out of the approximately 4750 road accidents in CEDATU, 38 accidents of HGVs with cyclists were available for the study. Most of them are accident scenarios in which the HGV was turning right and the cyclist was going straight ahead (accident type number 312, Figure 1). This corresponds very well with the national statistics Austria, in which the right-turning HGV is also the most frequent type of accident involving a cyclist. Furthermore, crossing accidents (accident type number 511), accidents at entrances (accident type number 948), and accidents in which the HGV is turning right or left (accident type number 622 and 611) are of importance. Overtaking accidents (accident type number 112) and lane change accidents (accident type number 121 and 123) are the second most important in the national statistics but are underrepresented in the CEDATU sample. Approximately three quarters of the accidents in the sample took place in an urban area, which corresponds very well with the figures in the national statistics (Table 1). The sample of CEDATU accidents covers approximately 60% of the accidents in the national statistics.

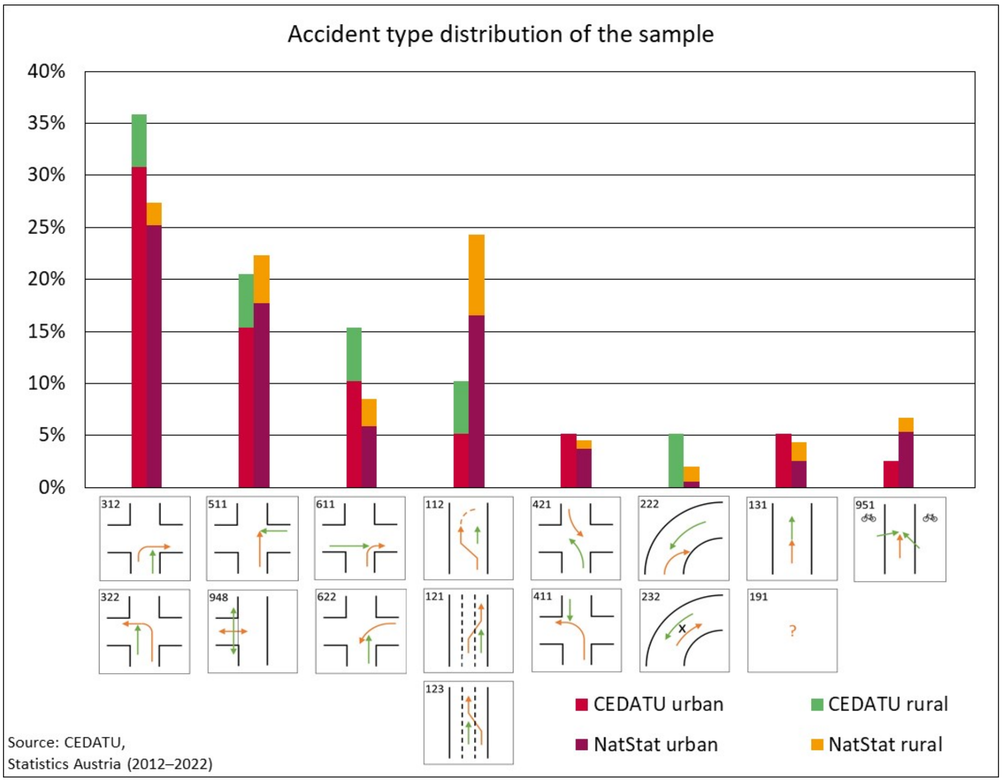


Figure 1. Accident type distribution of the HGV vs. cycle collisions analyzed. A description of the accident types is given in Appendix A.

Table 1. Accident type distribution of HGV vs. cycle collisions in the sample analyzed and the national statistics between 2012 and 2022.

Accident Type	CEDATU			National Statistics			CEDATU			National Statistics		
	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total
312, 322	12	2	14	128	11	139	30.8%	5.1%	35.9%	25.2%	2.2%	27.4%
511, 948	5	2	8	90	23	113	12.8%	5.1%	20.5%	17.8%	4.5%	22.3%
611, 622	4	2	6	30	13	43	10.3%	5.1%	15.4%	5.9%	2.6%	8.5%
112, 121, 123	2	2	4	84	39	123	5.1%	5.1%	10.3%	16.6%	7.7%	24.3%
411, 421	2	0	2	19	4	23	5.1%	0.0%	5.1%	3.7%	0.8%	4.5%
222, 232	0	2	2	3	7	10	0.0%	5.1%	5.1%	0.6%	1.4%	2.0%
131, 191	2	0	2	13	9	22	5.1%	0.0%	5.1%	2.6%	1.8%	4.3%
951	1	0	1	27	7	34	2.6%	0.0%	2.6%	5.3%	1.4%	6.7%
Total	28	10	38	394	113	507	71.8%	25.6%	100.0%	77.7%	22.3%	100.0%

4. Method

The methodology used is referred to as a counterfactual simulation [39–41]. Corresponding driving situations are evaluated by means of a before-and-after analysis using a "what-if simulation" approach [41]. Another expression for this method is prospective safety performance assessment of pre-crash technology by virtual simulation [42,43] and is currently being developed as an ISO standard [44]. The methodology has already been applied in several studies e.g., [28,42,45,46]. In this method, an accident scenario is simulated twice. The present study investigates real accidents. In the first simulation run, these real accidents are reconstructed and referred to as the baseline. In the second step, these reconstructed accidents are simulated again but the vehicles are virtually equipped with an ADAS (the "what-if simulation"). This simulation is referred to as the treatment. Within the treatment simulation, the minimum longitudinal and lateral view of an ADAS that is able to completely avoid a collision is evaluated.

4.1. Accident Reconstruction (Baseline)

Accident reconstruction is used to analyze traffic accidents in detail. Accidents are divided into a pre-collision, collision, and post-collision phases and certain parameters, such as initial speed, reaction time, braking deceleration, collision speed, collision angle, etc., are calculated. All factors that have a significant influence on the accident are taken into consideration (e.g., road conditions, weather conditions, speed limit on the road or speed limit, road width, etc.). The purpose is to calculate all phases of the accident sequence in terms of space and time [47–49]. Accident reconstruction is carried out with the simulation software PC-Crash [50], which is used by accident experts and in accident research. PC-Crash has been validated in various studies [51–53].

The reconstruction methods used are described in Burg and Moser [49] and Hugemann [54]. A key parameter is the collision speed of the truck and bicycle. This is a function of the final positions of the parties involved the position of the collision. A multi-body simulation in PC-Crash is used to calculate the collision speed [53]. As the mass ratio between the pedestrian and the truck is so high, the change in collision speed during the impact of the truck can be neglected. The initial speed of the vehicle is calculated from the course of the road, road conditions, the skid marks on the road (if any), the tachograph or EDR data, and witness reports. On the basis of these data, a time-speed-acceleration history and the trajectory followed in the pre-crash phase are calculated. The pre-crash phase is reconstructed for up to five seconds, as proposed in Schubert et al. [55]. The time-speed-acceleration history and the trajectory followed are used as the baseline for the treatment simulations.

A symptomatic accident is given in Figure 2. The HGV intends to turn right at the intersection and the cyclist is going straight ahead. The pictures below reflect the situation from the truck driver's perspective at different times. Seven seconds before the collision, the truck is approaching the junction. The cyclist is approaching the junction on the right-hand side on a cycle path. At this point, the cyclist is not visible on the right-hand side, nor is he visible in the right-hand side mirrors. Six seconds before the collision, the light turns green. At the same time, the cyclist becomes visible to the driver. Now it can become very complex for the truck driver. As soon as the traffic light turns green, the vehicles start to accelerate. The truck driver must now pay attention to the vehicles in front. At the time when he wants to turn right, he must also keep an eye on the oncoming traffic, as turning right sometimes requires steering slightly to the left. This is about two seconds before the collision. The cyclist is now invisible again, obstructed by the right-hand parts of the truck cab. He is also not visible in the side mirrors. The truck driver has two options as to how the cyclist could proceed. Either the cyclist turns right and follows the cycle lane, or he goes straight ahead and crosses the junction. Obviously, the truck driver should have been more cautious and stopped when in doubt.

The accident is now reconstructed to such an extent that a sufficiently long time history of the speed and acceleration before the collision is available. Figure 3 shows the relative trajectory of a cyclist in relation to the HGV as an example of an accident with a truck turning right and a cyclist going straight ahead. The collision position was on the right side of the truck. The relative movement looks quite strange. This is because the truck first has to steer slightly to left in order to be able to turn right at the junction. Due to the different relative speeds at certain points in time, the cyclist is in front of the truck and then falls behind when the truck is traveling faster than the cyclist.

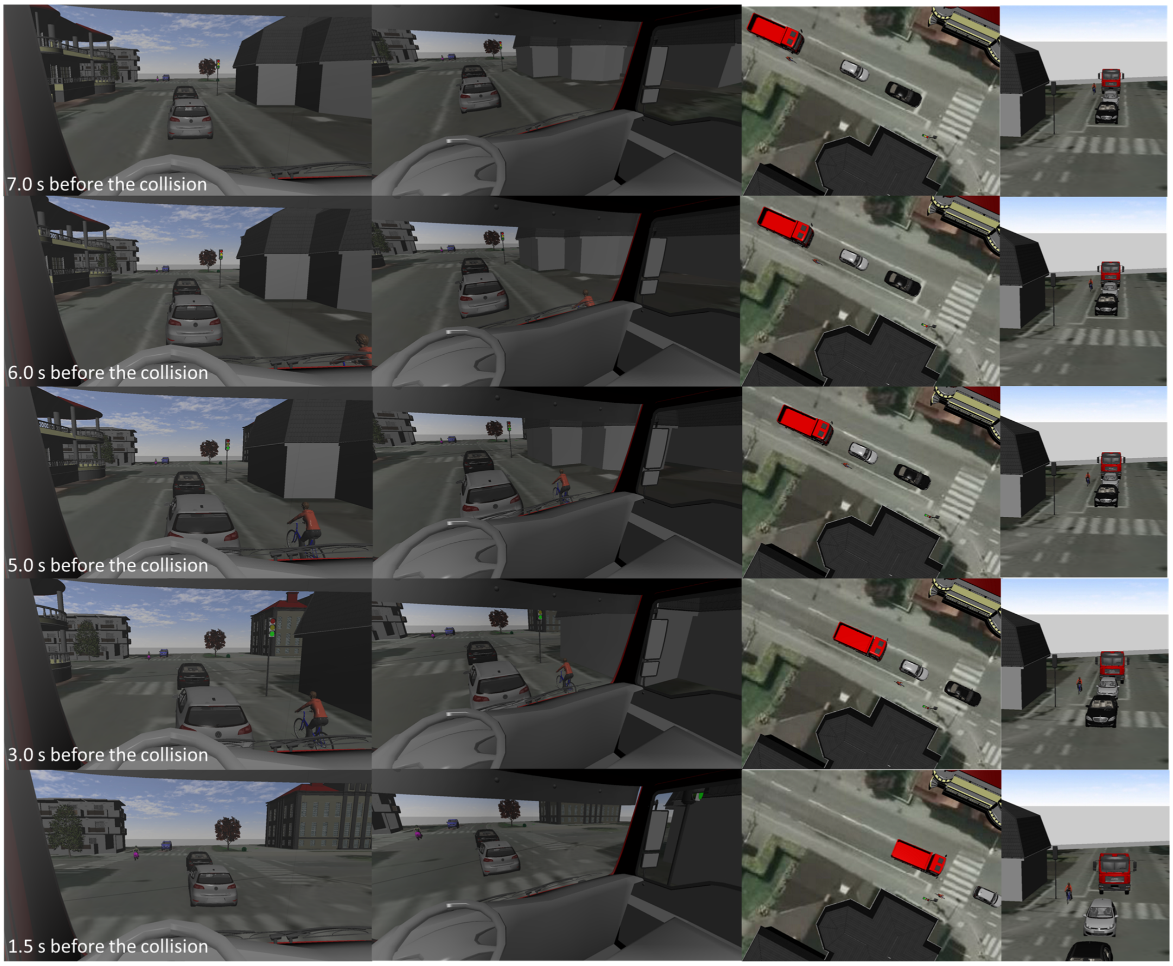


Figure 2. Junction accident with right-turning HGV crossing the bicycle's path and at different time steps (far left: driver's view; left mid: driver's view when paying attention to the right side; right mid: top view; far right: scenario view from opposite direction).

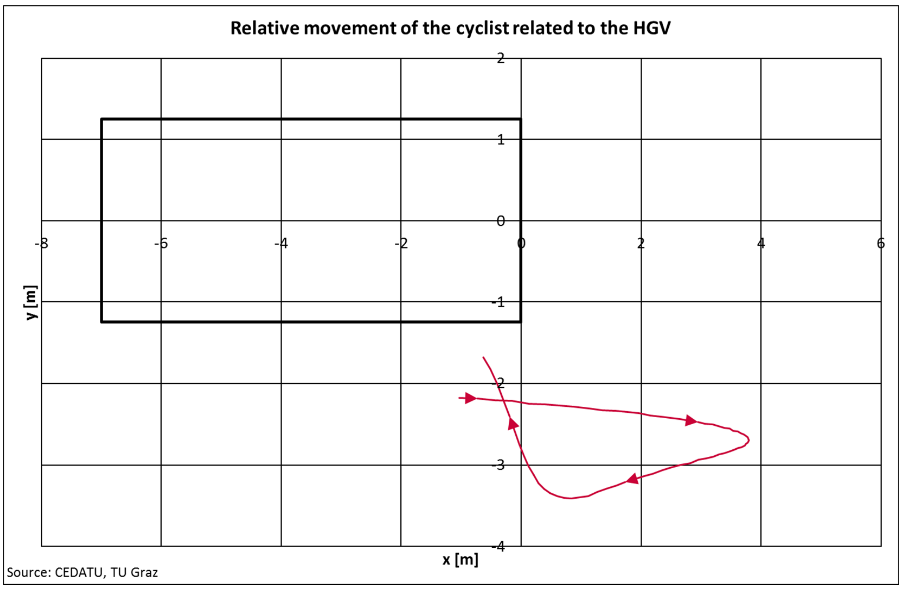
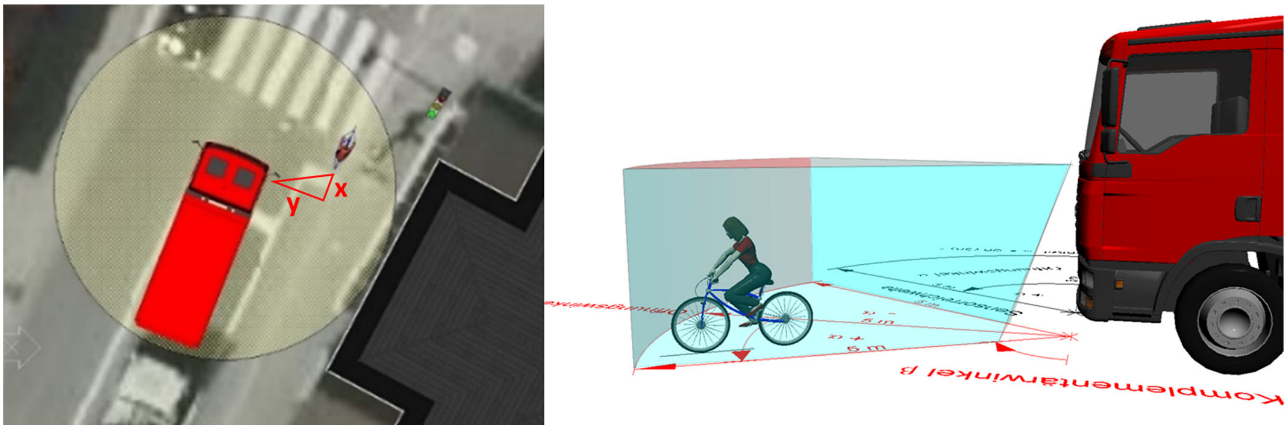


Figure 3. Relative trajectory of the cyclist in relation to the HGV. The rectangle represents a generic shape of the HGV. The red line with directional markings represents the cyclist's movement relative to the truck.

4.2. Treatment Simulation ("What-If Simulation")

After the accident had been fully reconstructed, the simulations were used to calculate at what point the truck still had the possibility to stop in time and avoid a collision. The treatment simulations have now been used to determine the necessary x and y distances required by an assistance system to detect cyclists. Figure 4 shows the required longitudinal and lateral distances of a generic assistance system that is able to detect a cyclist. At the time of the system response, the cyclist must be fully within the sensor's field of view for at least 150 ms [56,57]. The system response is either a warning to the driver or autonomous braking. After triggering the warning, a driver reaction time of 0.8 s [58–61] was taken into consideration. A comprehensive summary of driver reaction times can be found in Green [62]. A reaction time of 0.8 s should be considered sufficient for a driver who is not under the influence of substances (alcohol, medication, drugs) or is fatigued or distracted. An actuator time of 0.2 s was assumed for the reaction time of the autonomous system [56,57]. After the reaction time, the braking phase started. The build-up time to maximum deceleration was set at 0.5 s [49]. The maximum deceleration depends on road conditions [49], but all the accidents investigated were on dry roads. New trucks reliably achieve braking acceleration in a range between 7 and 8 m/s^2 [63]. Since most of the accidents in the accident data involved old and new vehicles and the condition of the tires is not known, the deceleration was limited to 5 m/s^2.



(**a**) (**b**)

Figure 4. (**a**) Longitudinal and lateral distances for detection of cyclists and (**b**) vertical view of an assistance system that fully detects the cyclist.

Based on the assumptions made, a warning system would require a visibility range of approximately one meter in the longitudinal direction and 3.5 m in the lateral direction (Figure 5). An autonomously intervening system would require approximately 0.3 m in the longitudinal direction and a lateral view of 3.3 m to avoid this collision. The collision takes place at the end of the bicycle's trajectory, which is in the front lateral area of the truck. The field of view of an assistance system is based on complete avoidance of a collision independent of visual obstructions caused by any objects (e.g., hedges, fences, etc.). The field of view therefore refers to an ideal system, and thus the ranges refer to theoretical configurations.

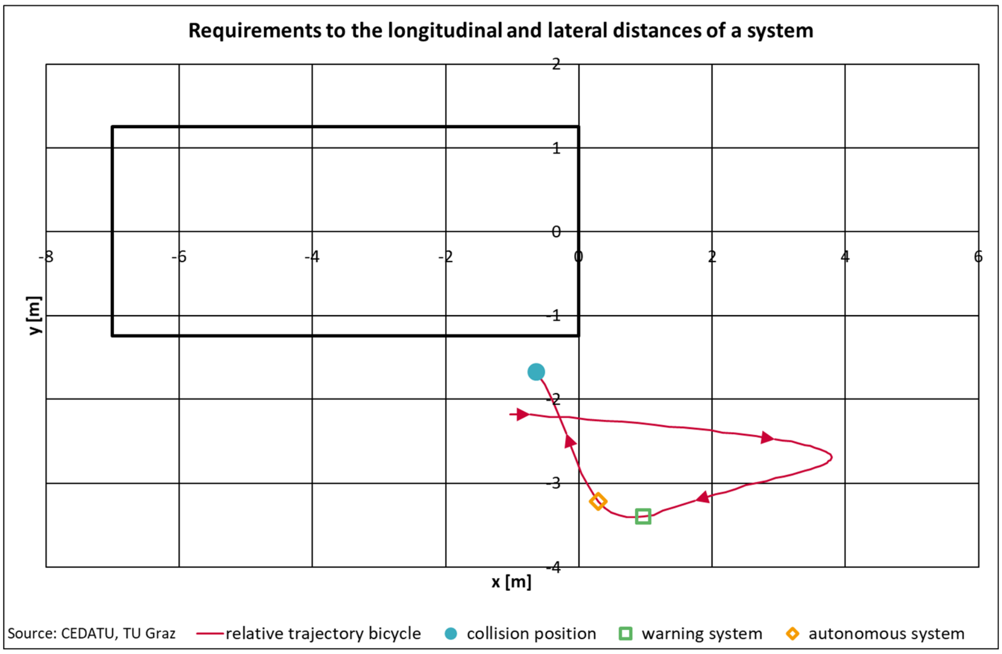


Figure 5. Theoretical required longitudinal and lateral distances for proper detection of a cyclist to avoid a collision. The rectangle represents a generic shape of the HGV. The red line with directional markings represents the cyclist's movement relative to the truck. The rectangle markers indicate the positions where a particular system needs to take action.

5. Results

All road accidents in the sample were reconstructed and the effectiveness of an assistance system evaluated. Different accident types require different sensor configurations. For accidents involving trucks turning to the right, lateral view is of particular importance. However, rearward-facing observation is also required for trucks. For an ideal warning system, a lateral view of approximately 10 m is required for this type of accident (Figure 6). A forward-facing view of approximately 2.5 m and a rearward-facing view of approximately 17.5 m is required. Somewhat different ranges are required for an ideal autonomous system (Table 2). For left-turning and crossing accidents, the requirements differ significantly from those for right-turning accidents. If the truck is on the priority road, a much longer view in the longitudinal and lateral direction is necessary. For these accidents, a longitudinal view of approximately 58 m and lateral view of approximately 21 m are required. When the truck is on the non-priority road, significantly closer ranges are required and the system will need to monitor the area directly surrounding the truck. Approximately 8 m would be necessary to the front and to the side. The longest ranges in the longitudinal direction are for accidents with oncoming traffic. This category also includes turning off accidents as these are also accidents with oncoming traffic. However, the relative speeds are considerably lower in this case. Only a few traffic accidents in the sample were available for an in-depth analysis of accidents when overtaking or changing lanes. The problem here is rather a falling cyclist due to the suction effect of the truck or the cyclist's instability during the overtaking maneuver. In another type of accident, some cyclists are very careless and cross the road without paying sufficient attention to traffic. For this type of accident, a system would require a huge longitudinal view and also have a sufficient range to the side in order to stop in time.

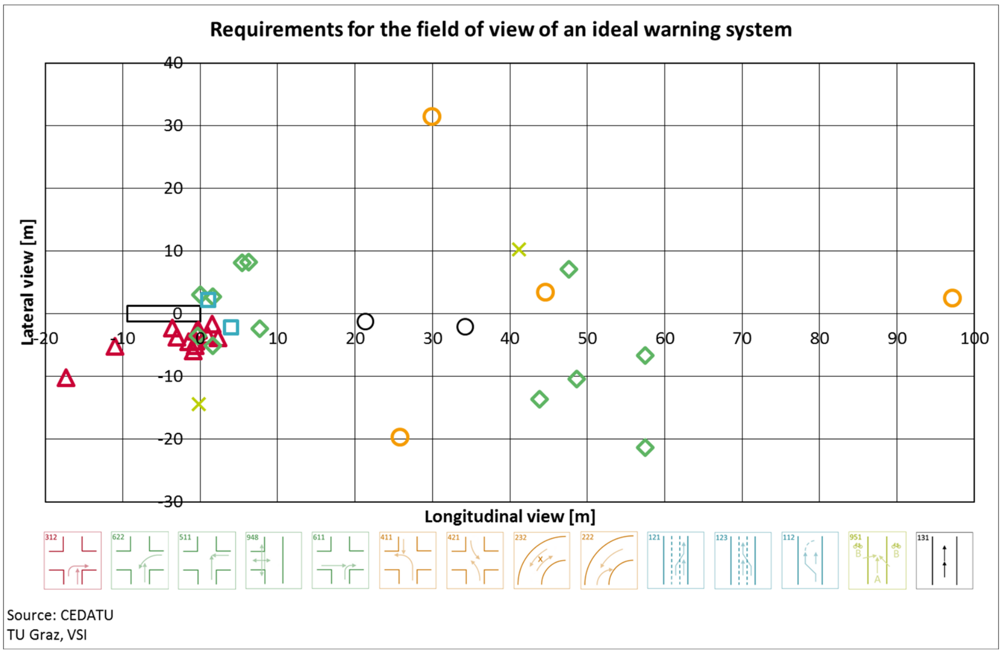


Figure 6. Theoretical requirements for the longitudinal and lateral field of view of an ideal warning system for the different accident types. A description of the accident types is given in Appendix A.

The requirements for a sensor vary depending on the location of the accident (Table 2). In urban areas, a warning system would need to have a forward-facing view of up to 97 m and a lateral view of up to 14 m. In rural areas, this would be a forward-facing view of up to 58 m and a lateral view of up to 31 m. With an autonomous system, the forward-facing view would be up to 76 m and the lateral view up to 13 m in urban areas. In rural areas, the forward-facing view should be up to 47 m and the lateral view up to 23 m. For both systems, the rearward-facing view would be up to 11 m in urban areas and up to 17 m in rural areas.

Table 2 summarises the requirements for a warning or ideal autonomous intervention system in terms of longitudinal and lateral field of view. The "Avoidance" column indicates whether the accident can be avoided or not, or whether further requirements are necessary, with information on the circumstances identified in the "Circumstances" column.

Without taking into consideration specific accident circumstances and further requirements to the system, 10 (26.3%) road accidents are potentially avoidable. Three cases could not be avoided due to sight obstructions, and in three cases the cyclist had violated the rules, i.e., ignored the priority of the truck. In eight accidents, a collision might be prevented if the cyclist's driving path was known in advance, i.e., it would have to be determined in advance that the cyclist would cross the truck's driving path.

In UN R 151 [64], test scenarios are defined for the assessment of blind spot assistance systems to avoid collisions with cyclists. In the test, a constant speed is defined for both the truck and the bicycle. Tests in which the truck is stationary and is moving-off and the bicycle is in the blind spot are described in UN R 159 [65]. In the UN R 159 test, the truck accelerates in a straight line and the cyclist moves parallel in the same direction. However, the two regulations do not take into consideration the starting to move and turning scenarios. For this reason, the two factors, speed and starting to move, were taken into account when assessing the effectiveness of the system. In six and three accidents, respectively, the speed was below 10 km/h or the truck was starting to move. These accidents can only be avoided if the system also works under these conditions. Finally, ten accidents cannot be prevented at all.

Table 2. Theoretical requirements for the longitudinal and lateral field of view of a warning system and an ideal autonomous intervening system for the different accident types and circumstances that influence avoidability. Specific accident types are aggregated (Gx). U (urban) and R (rural) indicate the accident location.

Case	Type	Accident Group	Site	Warning System x [m]	Warning System y [m]	Autonomous System x [m]	Autonomous System y [m]	Avoidance	Circumstances
#01	312	G1	U	−11.0	−5.2	−9.2	−5.4	yes	-
#02	312	G1	R	−17.3	−10.2	−16.7	−10.6	further requirements	1
#03	312	G1	U	1.5	−1.7	1.5	−1.6	further requirements	5
#04	312	G1	U	−0.7	−5.1	−0.2	−4.0	further requirements	5
#05	312	G1	R	−3.6	−2.3	−2.4	−2.1	further requirements	5
#06	312	G1	U	−0.6	−4.3	−0.7	−3.5	yes	-
#07	312	G1	U	−0.9	−5.9	−0.2	−5.4	yes	-
#08	312	G1	U	−1.5	−4.5	−1.6	−4.5	yes	-
#09	312	G1	U	1.0	−3.4	0.3	−3.2	yes	-
#10	312	G1	U	2.3	−3.9	0.8	−3.6	further requirements	2
#11	312	G1	U	−3.0	−3.8	−3.4	−3.8	yes	-
#12	312	G1	U	−0.2	−2.5	−0.5	−2.6	further requirements	6
#13	312	G1	U	−0.5	−2.8	−0.7	−2.9	yes	-
#14	322	G1	U	34.3	−2.1	25.7	−1.9	further requirements	2
#15	511	G2	R	57.5	−21.3	46.0	−15.8	no	2
#16	511	G2	U	1.6	2.7	1.8	1.9	further requirements	6
#17	511	G2	U	−0.3	−3.5	−0.1	−2.8	further requirements	5
#18	622	G2	U	0.0	3.0	0.0	3.0	further requirements	5
#19	948	G2	R	47.6	7.1	36.9	5.4	no	4
#20	948	G2	U	1.6	−5.1	1.4	−3.4	further requirements	6
#21	611	G2	R	7.7	−2.4	5.0	−2.0	yes	-
#22	622	G2	U	6.3	8.2	4.2	5.7	further requirements	5
#23	622	G2	U	43.8	−13.6	35.1	−9.6	no	1, 3
#24	622	G2	R	57.5	−6.7	46.8	−4.8	no	3
#25	622	G2	U	5.5	8.1	3.6	5.5	yes	-
#26	622	G2	U	48.6	−10.4	38.6	−8.6	further requirements	2
#27	222	G3	R	30.0	31.4	23.7	23.0	no	8
#28	232	G3	R	25.9	−19.8	20.5	−12.1	further requirements	1
#29	411	G3	U	44.7	3.4	33.5	2.9	no	3
#30	421	G3	U	97.3	2.4	75.7	1.8	further requirements	2
#31	112	G4	R	32.7	2.2	22.9	0.6	no	7
#32	121	G4	R	0.0	0.0	0.0	0.0	no	4
#33	121	G4	U	0.0	0.0	0.0	0.0	no	4
#34	123	G4	U	2.5	−2.2	1.7	−2.2	further requirements	2
#35	951	G5	U	41.1	10.3	31.1	8.1	further requirements	2
#36	951	G5	U	−0.2	−14.4	1.4	−13.3	further requirements	2
#37	131	G6	U	21.4	−1.4	15.4	−1.2	yes	-
#38	191	G6	U	0.0	0.0	0.0	0.0	no	4

[1] Sight obstructions. [2] Driving path of cyclist. [3] Rule violation of the cyclist. [4] No collision in real accident. [5] Speed below 10 km/h. [6] HGV starting to move. [7] Other circumstances.

6. Discussion

6.1. Accident Location

Accidents in urban areas differ from those on rural roads due to a variety of conditions. Although speed limits are much lower in urban areas, obstructions such as parked vehicles or objects on the roadside can make it much more difficult to see and detect the cyclist. The mean forward field of view in the urban area is 23.6 m (standard deviation: 3.3 m), which is significantly lower than in the rural area at 37 m (standard deviation: 9.7 m). This is related to the lower driving speed in urban areas and situations at junctions where the truck starts to move. However, a significantly longer forward-facing field of view was required in the urban area than in the rural area. This relatively long field of view was determined for accident type 421, where the road users are moving towards each other. In order to avoid this accident, it would be necessary to react at a point where it is not yet foreseeable that a road user will turn at the junction. At the moment when the intention of the road user becomes apparent, the collision cannot be avoided. It is therefore necessary to know the intention and the trajectory in advance. Obviously, it is very difficult to judge the driven trajectory in situations where road users are travelling in opposite directions and one road user is turning into the driven lane of the other road user. In these accident situations, the trajectory must be known and the intention to cross one's own lane must be known in advance. Otherwise, a collision cannot be avoided.

The necessary requirements for a sensor do not only depend on the location of the accident, but also on the type of accident. Accident analysis has clearly shown that in many cases of truck accidents, there is insufficient visibility of the close surroundings, so a sensor system that monitors the close proximity of the truck would make a significant contribution to accident prevention. This is particularly true of turning accidents involving cyclists travelling straight ahead and accidents at junctions where cyclists cross the road directly in front of the truck, usually when the truck is starting to move.

6.2. Effectiveness with an Infinite Sensor Range

With regard to all accidents investigated, an assistance system with an infinite sensor range would be able to prevent 26.3% of accidents involving trucks and cyclists. If all accidents classified as possibly avoidable on the basis of the existing test conditions of UN R 151 [64] and UN R 159 [65] were also covered by the assistance system, effectiveness would increase to 50.0%. If local visual obstructions could also be removed, effectiveness could be increased to 57.9%. Effectiveness could be increased to 65.8% as long as the cyclist complies with the traffic rules, e.g., does not violate the right of way.

Only a few studies in the literature refer to the avoidance potential of BSD systems in truck and bicycle accidents. Hoedemaeker et al. [34] estimate the potential of a BSD system at approximately 71%. Silla et al. [21] estimates the potential of a BSD system at approximately 78%. According to Wang and Wei [10], a BSD system would have a potential of 10%. Other studies includes pedestrians, too. Based on a natural driving study, Tomasch and Smit [35] estimate the potential of a blind spot assistant at up to a third. Kühn et al. [33] estimates the potential for accident avoidance between trucks and cyclists or pedestrians at 42.8%.

The evaluation of the above studies is based on a purely descriptive analysis of defined pre-crash scenarios, without considering accident reconstruction with relative movement of the road users and without distinguishing between different intervention strategies. It is only an assessment of how many accidents could potentially be avoided.

6.3. Effectiveness with Different Sensor Ranges

6.3.1. Ideal Conditions

The required field of view in the longitudinal and lateral directions for an ideal warning or ideal autonomously intervening system is based on full avoidance of a collision regardless of local sight obstructions, rule violations by cyclists, etc. An ideal warning system would therefore require a forward-facing view of approximately 98 m and rearward-facing view of approximately 18 m. Laterally, a system would need to be able to detect a cyclist within approximately 31 m to the left and 21 m to the right. These requirements take into consideration all bicycle accidents and not just accidents when turning right. An ideally autonomous system requires a forward-facing field of view of approximately 76 m and a rearward-facing view of approximately 17 m. To the side, the system would have to be able to detect a cyclist within a range of approximately 23 m to the left and approximately 16 m to the right. At the specified distances, the driver or the system would have to intervene in order to prevent a collision. However, this also indicates that the cyclist would have to be fully detected even before that point. Table 3 indicates different ranges of a sensor and the number of accidents that are potentially covered by this range. Without consideration of any specific accident circumstances a sensor range of 10 m would cover 50% of the accidents. Up to approximately 50 to 60 m, the proportion of accidents increases. With a range of more than 60 m, only a few more accidents will be covered by a warning system, and 50 m by an autonomous system. The accident analysis revealed that in some accidents, the cyclist fell and either had no contact with the truck or skidded against the truck. It is therefore not possible to maximize the potential to one hundred percent.

Table 3. Maximum (theoretical) effectiveness of an assistance system with different sensor ranges and proportion of accidents that could be potentially covered by the sensor without consideration of specific accident circumstances in relation to all 38 accidents investigated.

System		**Sensor Range**									
		10 m	**20 m**	**30 m**	**40 m**	**50 m**	**60 m**	**70 m**	**80 m**	**90 m**	**100 m**
Warning system	effectiveness	50.0%	57.9%	63.2%	71.1%	84.2%	89.5%	89.5%	89.5%	89.5%	92.1%
	number of accidents	19	22	24	27	32	34	34	34	34	35
Autonomous system	effectiveness	52.6%	60.5%	71.1%	84.2%	89.5%	89.5%	89.5%	92.1%	92.1%	92.1%
	number of accidents	20	23	27	32	34	34	34	35	35	35

6.3.2. Real Conditions

In addition to the accidents in which the cyclist fell without physical contact with the truck, there are other factors that influence whether an accident is completely avoidable, e.g., sight obstructions, rule violation cyclist (not yielding at red lights), cyclist's trajectory, etc.

Table 4 contains a summary of the accident circumstances with the required sensor ranges. If all the circumstances are taken into consideration, for instance, 21.1% (8 out of 38) of collisions can be avoided if the sensor range is 10 m. However, without the circumstances of the accident, the potential to avoid the accident would increase. The number of avoidable accidents in the "avoidance" category is taken as the reference. Any elimination of an accident circumstance would increase the potential of an assistance system. At a range of 10 m, however, there were obviously no sight obstructions, rule violations by the cyclist, or other circumstances that would have had an impact on the effectiveness. Nevertheless, if the cyclist's driving trajectory were known, the effectiveness of the assistance system could be increased from 8 potentially avoidable accidents to 10, i.e., 26.3%. For the circumstances speed or starting to move, the effectiveness could be increased to 36.8% (from 8 to 14) and 28.9% (from 8 to 11), respectively. If there are infrastructural obstructions to visibility such as bushes, hedges, fences, etc., even an assistance system cannot detect the cyclist. Other significant circumstances are rule violations by the cyclist. Taking all accident circumstances into consideration, a total of 19 accidents could be covered with a range of 10 m (Table 3). If the system only has to warn or intervene when there is no possibility of the cyclist stopping in time before crossing, it is simply not possible to avoid an accident. Otherwise, false positives would increase and reduce the acceptance of such systems.

Table 4. Number of accidents that could be potentially covered by a warning assistance system with different sensor ranges with consideration of specific accident circumstances in relation to all 38 accidents investigated.

Circumstances	**Sensor Range**									
	10 m	**20 m**	**30 m**	**40 m**	**50 m**	**60 m**	**70 m**	**80 m**	**90 m**	**100 m**
Avoidance	8	9	10	10	10	10	10	10	10	10
Sight obstructions	0	1	2	2	3	3	3	3	3	3
Cyclist's trajectory	2	3	3	4	6	7	7	7	7	8
Rule violation cyclist	0	0	0	0	2	3	3	3	3	3
Speed	6	6	6	6	6	6	6	6	6	6
Starting to move	3	3	3	3	3	3	3	3	3	3
Other	0	0	0	2	2	2	2	2	2	2
Total	19	22	24	27	32	34	34	34	34	35

However, with a greater range of the system and taking the mentioned circumstances into consideration, the effectiveness of the system could be significantly increased.

6.3.3. Accident Type Groups Under Real Conditions

A warning assistance system with a field of view of 360° and a range of 10 m would be able to cover 19 accidents; 11 of these accidents apply to trucks turning right and cyclists going straight ahead. Only six of these could be avoided without further limitations such as sight obstructions, information about the cyclist's driving trajectory, speed, etc. (Table 5). Group G2 refers to the left-turning and crossing accidents and is the second largest group of accidents that can be prevented by an assistance system with a range of 10 m. The two main circumstances of the accident are speed and moving-off, so that a total of seven accidents could be prevented if these two circumstances were taken into consideration.

Table 5. Number of accidents that could be potentially covered by a warning assistance system with a field of view of 360° and a range of 10 m and specific accident circumstances separated into different accident groups.

Circumstances	Accident Type Group						
	G1	**G2**	**G3**	**G4**	**G5**	**G6**	**Total**
Avoidance	6	2	0	0	0	0	8
Sight obstructions	0	0	0	0	0	0	0
Cyclist's trajectory	1	0	0	1	0	0	2
Rule violation cyclist	0	0	0	0	0	0	0
Speed	3	3	0	0	0	0	6
Starting to move	1	2	0	0	0	0	3
Other	0	0	0	0	0	0	0
Total	11	7	0	1	0	0	

The technologies currently available (camera, RADAR (Radio Detection And Ranging), LIDAR (Light Detection And Ranging), etc.) make it possible to monitor the vehicle's surroundings. These technologies are combined (=sensor fusion) to optimise detection and provide an accurate understanding of the environment. Most technologies have ranges that extend well beyond the immediate area around the vehicle [66]. However, the lateral visibility range of the systems tested by ADAC [37] was less than 6 m. One system was unable to detect cyclists at a distance of more than 2.5 m.

Meanwhile, the unit cost of sensors is decreasing and is now quite low, depending on the technology [67]. Although there are relatively cheap aftermarket systems available, they performed less well in the tests [37]. The best performing aftermarket turning safety assistance systems were associated with the highest costs.

The requirements for a turning assistant differ quite significantly with regard to the field of view for avoiding all the cyclist accidents investigated. To avoid these accidents, an ideal warning or an ideal autonomous system would have to be able to monitor at least approximately 6 m to the right, but also approximately 18 m to the rear. With these specifications, 13 accidents could be fully avoided, as long as the circumstances of the accident are taken into consideration. In three accidents, the collision speed would be less than the UN R 151 [64] test speed, and they are labeled as not explicitly avoidable or only avoidable if an assistance system also fulfilled this criterion. Another accident could only be prevented if the assistance system were able to detect the cyclist when starting to move and turning at the same time. In one accident, sight obstructions were present and in another accident, the trajectory of the cyclist would have to be known in order to avoid the accident.

6.3.4. Cyclist Behavior

In many cases, the behavior of the cyclist, i.e., prediction of the trajectory, is an essential factor to prevent accidents. Studies show that cyclist behaviour is very difficult to predict in advance [34,68,69] so that a collision can still be prevented, especially if the cyclist is travelling parallel to the vehicle and turns into the vehicle's path just before the collision. Predicting what a cyclist will do often depends on strong indicators, such as head movement [70], hand gesture to indicate change of direction [69], etc.

If the cyclist is coming from a clearly visible cycle path and is crossing the road, the cyclist could often stop in time before the collision, but the HGV would have to react much earlier to avoid a collision in case the cyclist does not stop. However, if the cyclist stops as required, unnecessary error warnings ("false-positives") are issued and the system is deemed unreliable with a poor acceptance [71], meaning that drivers ignore warnings [72] and stop using it [73]. False-positives are therefore a major challenge. Furthermore, rule violations, e.g., ignoring the priority of the HGV, running red lights, are a very common contributing factor in accidents [74–76] and are a considerable burden on the assistance system. If the driver of the HGV reacts when the cyclist starts crossing the road, the accident cannot be avoided. If the system reacts earlier, this can lead to many false positives and would have a huge impact on the acceptance of an assistance system. In real-world tests, a high number of false positives have already been identified, particularly when the system was unable to distinguish between stationary objects and vulnerable road users [37].

Cyclists sometimes fall only because the HGV has overtaken them. This can only be prevented if there is sufficient distance between the cyclist and the truck. The Austrian Road Traffic Regulations [77] specifies a minimum distance of 1.5 m in urban areas and 2 m on rural roads. However, this can sometimes be very difficult to monitor. An assistance system that continuously monitors the minimum distance could help.

7. Limitations

Only 38 road accidents were available for analysis in this study. Although a similar number of accidents were available for analysis in other studies [34], the number of cases analysed is not sufficient to draw general conclusions. Nevertheless, these different situations can contribute to an insight and to the definition of requirements for systems that may be able to prevent such accidents. However, the cases showed that the accident situations can be very complex and the requirements vary from accident to accident.

Overtaking accidents or lane change accidents are very biased in the sample, i.e., there are many more accidents in the national statistics than in the CEDATU sample.

In the overtaking accidents, the lateral distance between the truck and the cyclist was not examined. Accidents where there was no contact between the truck and the cyclist were therefore classified as unavoidable.

In the treatment simulation, an attentive driver was assumed for the warning system. This driver responded with a reaction time of 0.8 s. It was assumed that the drivers were not under the influence of substances, nor were they fatigued, distracted, psychologically stressed, or aggressive.

The market penetration rate has been assumed to be 100%.

8. Conclusions

Although there are a large number of mirrors on trucks, sight conditions while driving are no longer optimal. The reason for this is that, in accordance with European regulations, the mirrors are evaluated in a stationary condition [22]. In addition, drivers also need a certain amount of time to properly check the mirrors, which can take up to four seconds [24]. An assistance system is able to monitor the surrounding of the truck continuously. The most significant benefit would be the prevention of accidents in blind spots, i.e., HGV turning right and cyclist going straight ahead.

Nevertheless, it is not possible to prevent all accidents involving cyclists. The main problems are sight obstructions due to fences, bushes, hedges, etc., rule violations by the cyclists, and missing information on the cyclist's trajectory. For specific types of accident, in particular with oncoming traffic, the cyclist's intention to cross the truck's driving trajectory must be known in advance in order to prevent a collision. Otherwise, it is not possible to avoid a collision due to physical limits, e.g., road friction and maximum possible deceleration.

It is estimated that an assistance system could potentially prevent between 26.3% and 57.9% of accidents involving HGVs and cyclists, depending on whether the identified accident circumstances are taken into consideration.

The maximum theoretical effectiveness of a driver warning system with an infinite sensor range is 26.3% without further consideration of circumstances. If the system successfully meets the existing UN R 151 [64] and UN R 159 [65] test conditions, the effectiveness increases to 50%. If local sight obstructions are also removed, the effectiveness increases to 57.9%. One of the most difficult challenges is predicting the cyclist's riding behaviour, i.e., the trajectory. If the cyclist's trajectory can be very accurately predicted in advance, the effectiveness increases to 78.9%. This is rather unlikely, as the intention of the cyclist can only be recognised at a very late stage, which makes it extremely difficult to avoid a collision. At the least, the collision speed could be reduced.

It has been shown that several accidents occur in the immediate vicinity of the truck. A system with a range of 10 m could potentially prevent 50% of the accidents studied.

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Conflicts of Interest: Author Karin Ausserer is employed by Faclum-Applec Ventures GmbH. Author Jannik Rieß was employed by the Faclum-applec ventures GmbH and now is employed by Austria Tech. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Accident type classification in Austria.

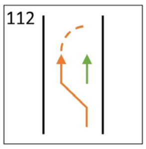
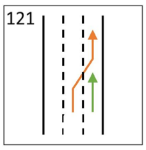
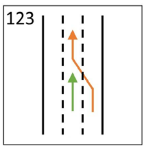
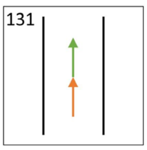
Accident Type	Pictogram	Description
112		collision between two vehicles driving in the same direction after overtaking on the left side and returning to the original lane
121		collision between two vehicles driving in the same direction due to changing into the right lane
123		collision between two vehicles driving in the same direction due to changing into the left lane
131		rear-end collision into moving vehicle on a straight section

Table A1. *Cont.*

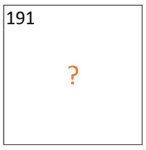
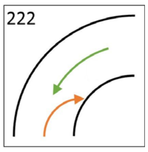
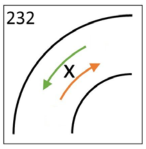
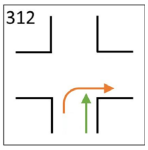
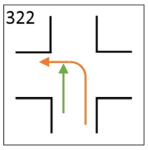
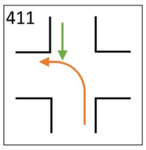
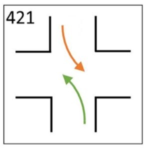
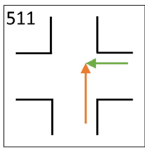
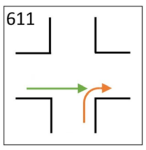
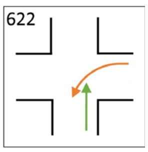
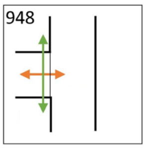
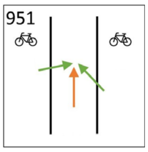
Accident Type	Pictogram	Description
191		
222		leaving the road to the right due to a vehicle proceeding in the opposite direction in a right-hand curve, without a collision
232		Lateral (sliding) collision between two vehicles proceeding in opposite direction in a curve
312		collision of a vehicle which is turning right at a junction with another vehicle which is passing by and moving straight
322		collision of a vehicle which is turning left at a junction with another vehicle which is overtaking or passing by and moving straight
411		collision of a vehicle which is turning left with another vehicle which is proceeding from the opposite direction and moving straight
421		lateral (sliding) collision between two vehicles turning left in opposite direction
511		collision at a junction of two vehicles proceeding at right angles to each other
611		collision at a junction of a vehicle which is turning right and a vehicle from left which is crossing straight
622		collision at a junction of a vehicle which is turning left with a vehicle from left which is moving straight

Table A1. *Cont.*

Accident Type	Pictogram	Description
948		collision by the entrance of a building or plot
951		Collision with a cyclist entering the lane

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