# Pre-Crash Analysis of accidents Involving Turning Trucks and Bicyclists

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***Abstract*** Although not happening very often, accidents between turning trucks and bicycles are an important contributor to injuries of high severity levels (i.e. MAIS4+ and including fatalities) of cyclists. In order to analyse the pre-crash situation of real-world accidents and changed boundary conditions (e.g. introduction of certain active safety systems), the so-called Pre Crash Matrix (PCM) was developed by the Dresden Accident Research Team (Verkehrsunfallforschung an der TU Dresden GmbH / VUFO) back in 2008. By including 5 seconds before the accident in the crash analysis, it is possible to check, for example, whether or not a sensor system would have been able to recognise the dangerous situation in time to avoid or mitigate the accident.

In the current PCM version it is impossible to analyse turning trucks in order to evaluate possibilities to avoid this dangerous situation. The objective of this paper is to develop a methodology to include these accidents in the PCM and to evaluate the methodology using individual accidents. In order to analyse the pre-crash phase of turning trucks in the context of the PCM, a tool was developed to extract the vehicle dynamics from the reconstruction tool PC-Crash. This tool describes the infrastructure and the pre-crash dynamics of the involved accident partners and allows simulation of the pre-crash phase, with modified boundary conditions.

The selected individual turning truck accidents demonstrate the potential of blind-spot assistance systems for trucks.

***Keywords*** accident avoidance, pre-crash matrix (PCM), bicycles, turning trucks.

## I. INTRODUCTION

Increasing the share of bicycles in the choice of transport means is a common objective of many German regions in order to reduce pollution, congestion and other negative effects of motorised individual transport. However, the accident share increases for cyclists when this mode of transport is chosen more frequently. This is a significant issue because the injury risk of cyclists when involved in accidents is quite high.

In bicycle accidents with trucks, lorries and vans (hereafter HGV, for heavy goods vehicles) the injury risk appears worse than for bicycle accidents with passenger cars. In particular, conflicts between right-turning HGV and cyclists using the bicycle path appear to be critical.

In order to evaluate the benefit of specific active safety systems in accident conditions, VUFO, as one of the two German In-depth Accident Study (GIDAS) accident investigation teams, developed the so called Pre-Crash Matrix (PCM). Unfortunately, the system for creating the matrix does not yet allow for simulation of turning truck movements and truck-trailer combinations; the simulation of pure truck accidents has just started for cases without important pre-crash manoeuvres.

This paper describes the PCM system in general and a new approach to obtaining the vehicle dynamics from PC-Crash, including truck-trailer combinations, in particular. This approach will then be demonstrated using 5 HGV-to-bicycle accidents. Finally, the pre-crash data of these accidents will be used to evaluate active safety systems.

In order to select relevant example cases, regional police accident data of Lower Saxony are analysed. This analysis is completed by GIDAS data analysis.

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## II. METHODS

### *Pre-Crash Matrix*

The GIDAS collects a representative (regarding accidents with personal injury) accident sample for Germany using an on-the-spot approach. In principle, this data sample allows an evaluation of the effectiveness of passive and active safety systems. However, in terms of using the data for estimating the influence of future active safety systems on particular accident scenarios, the available information in the GIDAS data sample is not sufficient (e.g. the time history does not last long enough in the pre-crash phase and the reliability of the pre-crash data is limited – see Fig. 1).

In order to address these shortcomings, VUFO (the Dresden GIDAS data collector) developed the so-called Pre-Crash Matrix (PCM) [1-3]. Here, the vehicle dynamics of the collision partners is simulated for a period of 5 seconds before the crash.

The PCM ingredients are a digital sketch of the accident, including the road layout, the driving courses of the opponents, amongst others (Fig. 2), the vehicle dynamics of the opponents (i.e. velocity in longitudinal and lateral direction, acceleration in longitudinal and lateral direction, global yaw angle, steering angles of both front wheels, etc.) and static information of the vehicles, such as dimensions, wheel base, track width, etc. The vehicle dynamics information is currently captured by simulating the pre-crash phase using a highly sophisticated vehicle dynamics simulation programme.

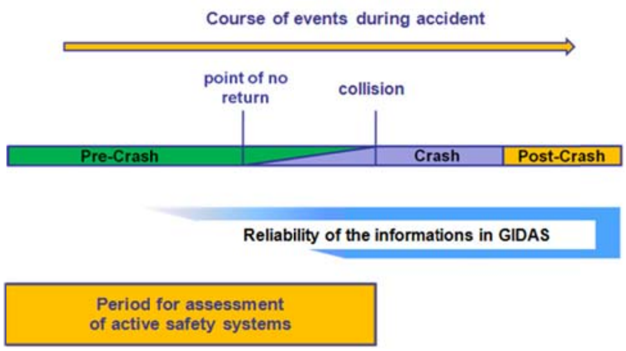



Fig. 1. Phases of accident events [2].

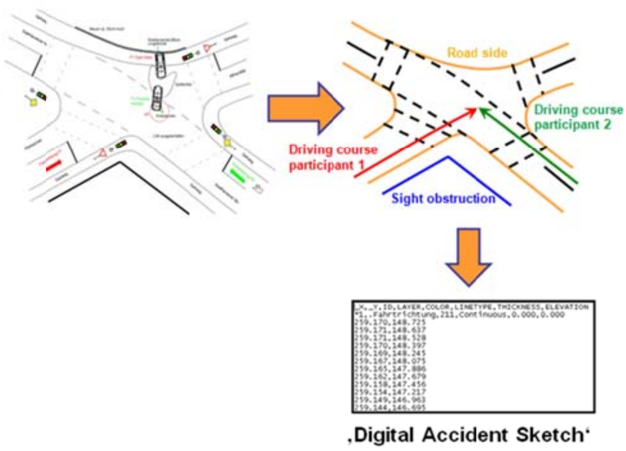



Fig. 2. Creation of the digital sketch [2].

The 2014 version of the PCM data set was limited to two participants only, excluding trucks and swerving accidents, amongst others. A number of restrictions resulted from the chosen vehicle dynamics simulation program. For 2015 it was decided for the standard PCM to include trucks, so long as special truck vehicle dynamics were not relevant in the accident (i.e. truck driving straight ahead) as a first step. By this decision it is possible to expand the PCM scope significantly – however, inclusion of truck manoeuvres and truck-trailer combinations is still missing.

A new approach for the creation of the PCM data set uses the OLE connection of PC-Crash version 10.1 (Fig. 3). In principle, this approach allows the inclusion of trucks and truck-trailer combinations in other driving manoeuvres than simply running straight ahead, such as, for example, turning trucks. Although PC-Crash is not considered as a fully-fledged replacement of the currently used vehicle dynamics simulation programme it appears that the simplifications in the PC-Crash vehicle dynamics model are acceptable when taking into account the uncertainties resulting from accident reconstruction.

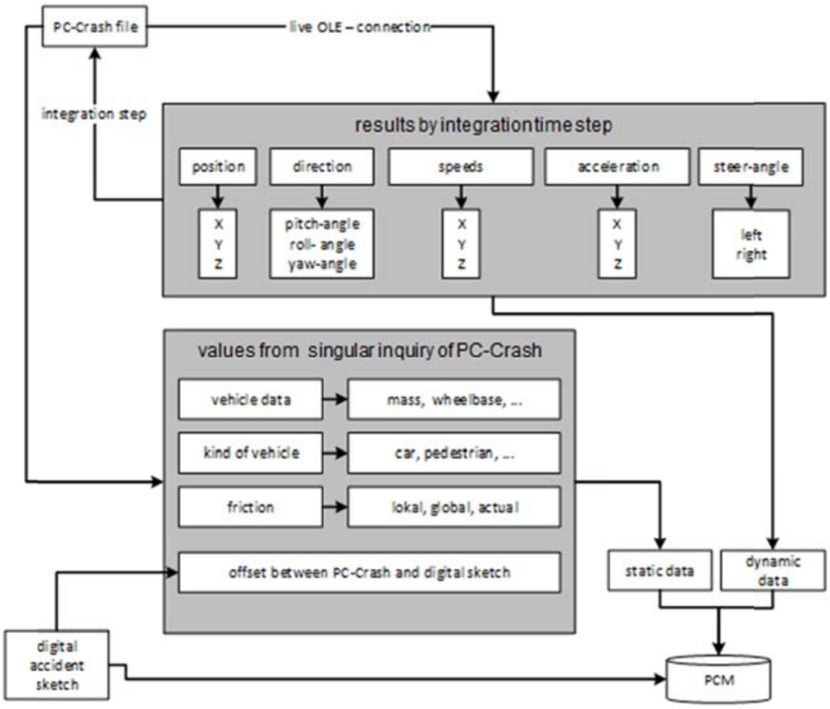



Fig. 3. Approach for PCM creation using PC-Crash for the vehicle pre-crash movement simulation.

The PCM file architecture according to Fig. 2 and Fig. 3 already allows the inclusion of turning HGV without trailer. The main issue for including truck-trailer combinations for the PCM is the missing definition of the additional vehicle part - (Fig. 4) shows a proposal how to integrate the trailer into the PCM structure by adding new values into the participant record (additional vehicle part including dimensions, number of axels and position of axels) and dynamics record (linking position between the truck and the trailer).

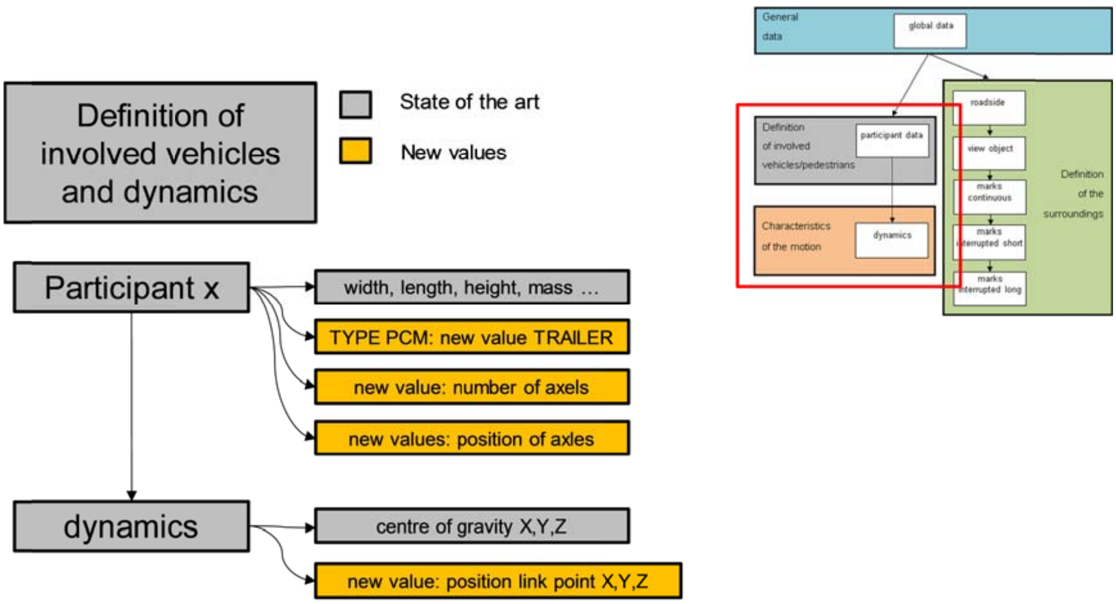


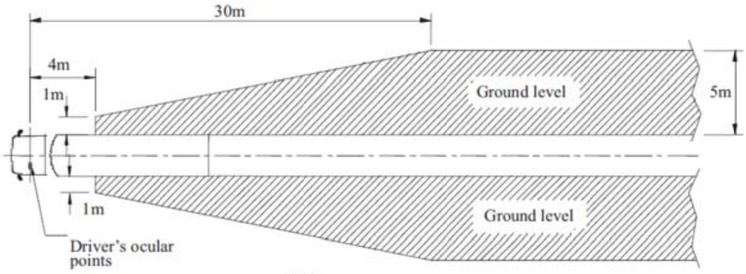
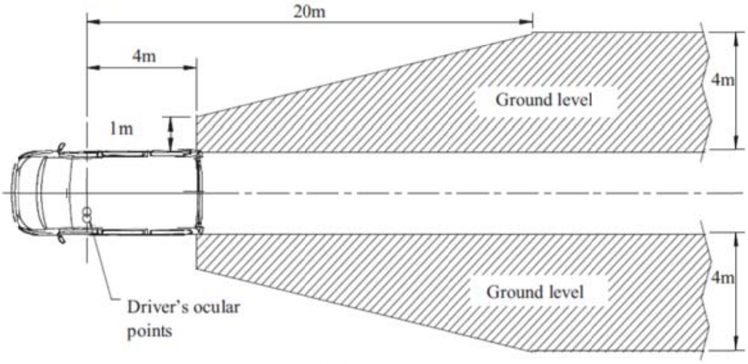
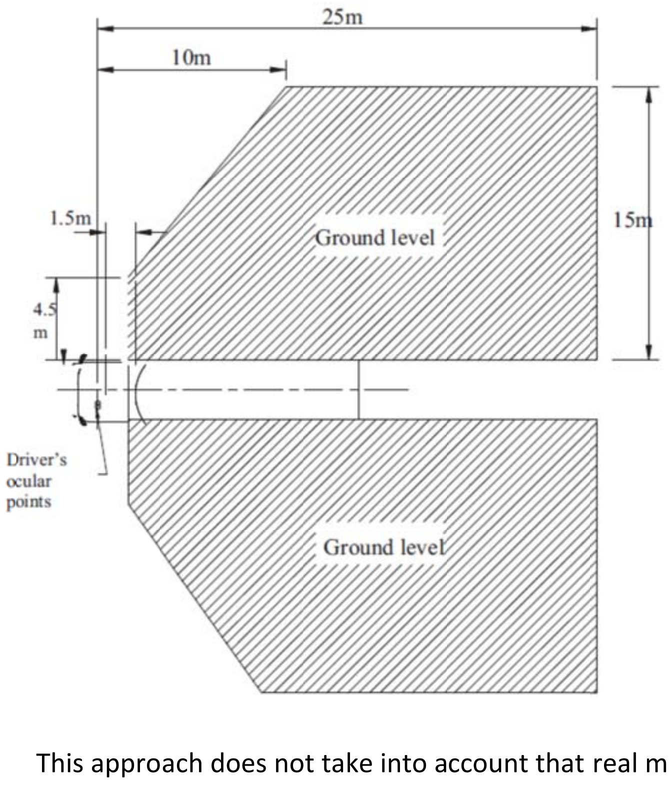

Fig. 4. Proposal how to integrate truck-trailer combinations in PCM, right part [1].

For this study, the analysed accidents were originally reconstructed using PC-Crash, with a focus on the crash and post-crash phases. In order to be able to include the accidents into the PCM, the existing reconstruction files were expanded with information from the interviews with the participants that is regularly conducted during the case acquiring process and the results from the reconstruction to simulate the movements in the period of up to 5 seconds before the accident. Accuracy for the period before the impact and possible pre collision marks compared to the post-crash phase is less due to missing physical evidence. However, this is generally true for the PCM approach and the limitations are accepted by the current PCM users (mainly Automotive Industry including OEM and Safety System developers).

For the analysis in this study the PC-Crash results are used directly without using the PCM format. Regarding validation of the models the authors rely on the validation of PC-Crash including the vehicle geometry.

The indirect fields of vision were validated using the specific requirements according to UNECE R46 (Uniform Provisions Concerning the Approval of Devices for Indirect Vision and of Motor Vehicles with Regard to the Installation of these Devices). According to this regulation the N1 vehicles need to be equipped with Class III devices and N2 and N3 vehicles need to be equipped with class II and class IV devices (Table I). If an N1 or N2 vehicle was equipped with a wide angle mirror during the accident it was anticipated that this device would be compliant with class IV requirements.

TABLE I
UNECE R46 REQUIREMENTS FOR HGV INDIRECT FIELD OF VISION

| | |
|---|---|
|   | Class II devices (mandatory for N2 and N3 vehicles) |
|   | Class III devices (mandatory for N1 vehicles) |
|   | Class IV devices (mandatory for N2 and N3 vehicles) |

This approach does not take into account that real mirrors will likely have a larger field of vision than actually required and that drivers not always adjust the mirrors to the optimum. It is expected that these two effects will compensate each other.

Regarding the direct field of visions cameras are placed at the approximate head position in combination with the PC-Crash vehicle geometries.

### *Accident Data*

Several accident data sources were used for this study. To analyse the relevance of truck-to-bicycle accidents, the German national accident statistics of the year 2013 were used. As the regional statistics of the state of Lower Saxony allow further analysis in addition to the published one and include the three-digit accident type, which is not the case for all German states, the data sets of Lower Saxony for the years 2008–2013 were used. Finally, GIDAS, as the most detailed data set, was also used. On the one hand, all recorded bicycle-to-HGV accidents were used for descriptive accident analysis and, on the other hand, individual cases from Hannover for the year 2013 were used for detailed analysis. The 2013 cases were selected because the reconstructions for that year are already completed and the accident descriptions almost comply with the PCM requirements.

## III. RESULTS

### *Accident Analysis*

*Descriptive Accident Analysis*

The German national statistics show a slightly increasing trend for slightly injured bicyclists for all accident configurations, i.e. this analysis is not limited for bicycle-to-HGV accidents (Fig. 5). It is expected that this trend follows an increased share of bicycle trips.

For seriously injured bicyclists there is a slightly decreasing trend, and for fatally injured cyclists there is a strongly decreasing trend.

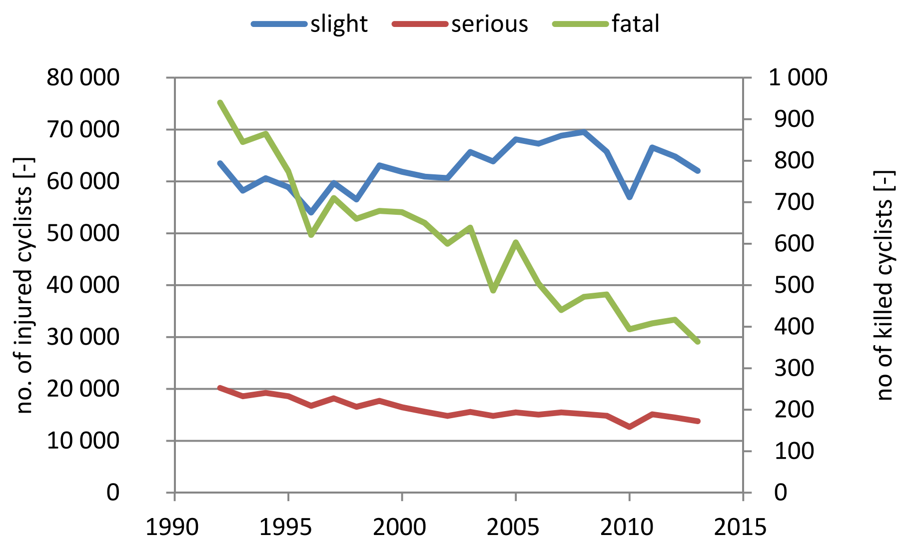



Fig. 5. Development of cyclist accidents and injury severity in Germany.

Most bicycle accidents happen in collision with passenger cars. However, the risk for fatal injuries compared to the accident risk is especially high for single bicycle accidents and for bicycle-to-HGV accidents (Fig. 6).

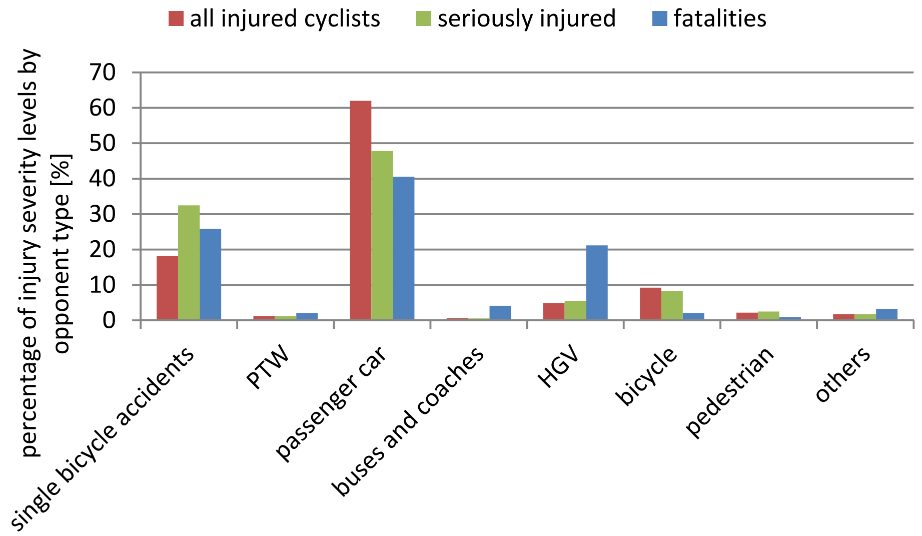



Fig. 6. Injury severity levels depending on accident opponent.

The national statistics counts police reported accidents. In the literature the issue of underreporting of accidents in the national statistics is often discussed (e.g., [4]). When analysing hospital data there are injured people from road accidents included that are unknown in the police reports because the accident itself was not reported to the police. This issue was recognised more often for cyclists than for any other road user. While for the first accident configuration (single bicycle accidents) an important under-reporting for slightly injured bicyclists is expected [4], and therefore the data is expected to be biased towards too low numbers of slightly injured bicycles, the bicycle-to-HGV accidents account for approx. 20% of the fatal accidents, but for only approx. 5% of the slightly and severely injured cyclists. This means that this configuration happens seldom, but is connected with a high risk of fatal injury.

In the German accident data the type of accident describes the conflict situation which resulted in the accident, i.e. a phase in the traffic situation where the further course of events could no longer be controlled because of improper action or some other cause. Unlike the kind of accident, the type of accident does not describe the actual collision but indicates how the conflict was touched off before this possible collision. The determination of the type of accident also plays an important role for local accident analysis since the type of accident is marked by coloured pins on the maps of the local police authorities. The following seven types of accidents are distinguished [5]:

1) Driving accident: The accident was caused by the driver's losing control of his vehicle (due to not adapted speed or misjudgement of the course or condition of the road, etc.), without other road users having contributed to this. As a result of uncontrolled vehicle movements, however, a collision with other road users may have happened. A driving accident however does not include accidents in which the driver lost control of his vehicle due to a conflict with another road user, an animal or an obstacle on the carriageway, or because of a sudden physical incapacity or a sudden defect of the vehicle. In the course of the driving accident, this vehicle may collide with other road users, so that this is not necessarily a single vehicle accident. For this study the loss of control could be caused by either of the two opponents (bicycle or truck).

2) Accident caused by turning off the road: The accident was caused by a conflict between a vehicle turning off and another road user approaching from the same or opposite direction (incl. pedestrians) at crossings, junctions and entries to premises or car parks. Whoever follows the priority turn of a main road is not considered as turning off.

3) Accident caused by turning into a road or by crossing it: The accident was caused by a conflict between a road user turning into a road or crossing it and having to give way and a vehicle having the right of way at crossings, junctions, or exits from premises and car parks.

4) Accident caused by crossing the road: The accident was caused by a conflict between a vehicle and a pedestrian on the carriageway, unless the pedestrian walked along the carriage-way and unless the vehicle turned off the road. This applies also where the pedestrian was not hit by the vehicle. Even if the pedestrian who caused the accident was not hit, the accident is classified as caused by crossing the road. A collision with a pedestrian walking along the carriageway is recorded as a no. 6 type of accident.

5) Accident involving stationary vehicles: The accident was caused by a conflict between a moving vehicle and a parked/stopping vehicle or a vehicle manoeuvred in connection with parking/ stopping. Accidents with vehicles waiting just because of the traffic situation are not included. For this study this applies most often for stationary trucks and cyclists for example an accident with an opening door.

6) Accident between vehicles moving along in carriageway: The accident was caused by a conflict between road users moving in the same or opposite direction, unless this conflict belongs to a different type of accident.

7) Other accident: This includes all accidents that cannot be allocated to any other type of accident. Examples: U-turning, reversing, accidents between parked vehicles, obstacle or animal on the carriageway, sudden failure of the vehicle (brake failure, defective tyre, etc.).

The bicycle-to-truck accident data of Lower Saxony shows a high number of accidents caused by vehicles that are turning off the road and vehicles that are turning into a road or crossing it, as shown in Table II. For those accidents the fatality rate (no. of fatalities divided by the no. all injured multiplied by 100) of 3 and 2.3 is considerably high. In addition, accidents occurring between vehicles that are moving along the carriageway are also high (2.35).

TABLE II
BICYCLE-TO-TRUCK ACCIDENTS IN LOWER SAXONY BETWEEN 2008 AND 2013

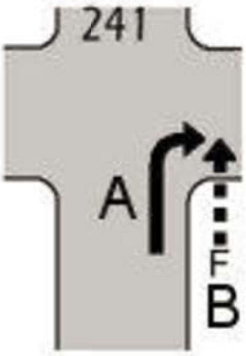
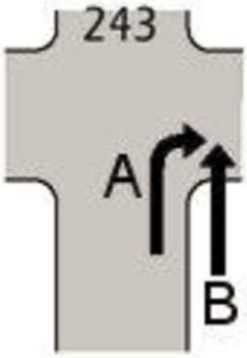
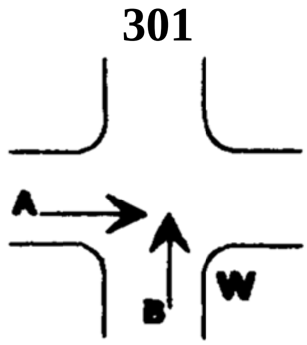
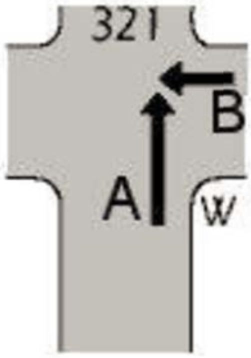
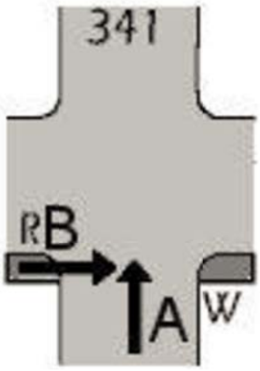
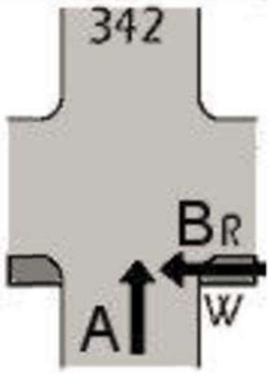
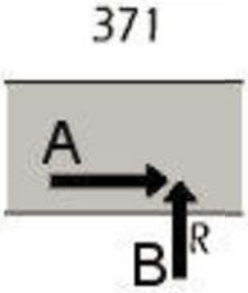
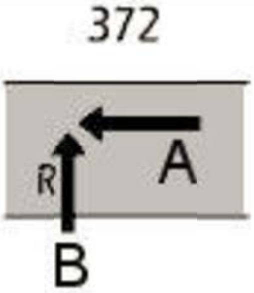
| accident type | all injured | fatalities | severely injured | slightly injured | fatality rate (no. of fatalities / no. of all injured * 100) |
|---|---|---|---|---|---|
| driving accident | 67 | 1 | 11 | 54 | 1.49 |
| accident caused by turning off the road | 725 | 22 | 120 | 583 | 3.03 |
| accident caused by turning into a road or crossing it | 1292 | 30 | 234 | 1027 | 2.32 |
| accident caused by crossing pedestrian | 1 | 0 | 0 | 1 | 0.00 |
| accident involving stationary vehicle | 168 | 0 | 36 | 128 | 0.00 |
| accident between vehicles moving along in the carriageway | 298 | 7 | 67 | 218 | 2.35 |
| other accidents | 246 | 4 | 39 | 195 | 1.63 |

In addition to the official definition of types of accidents the German Insurers (GDV) developed the expanded 3 digit type of accident. This three-digit accident type coding allows further insight into the traffic situation of the accidents (i.e. the direction of turning, the location of the opponents on the road, etc.). Accident types (amongst the bicycle-to-HGV accidents) that were recorded more than 100 times in the six-year period in Lower Saxony, or where more than four fatalities were counted, are displayed in Table III. In particular, cases with the HGV turning right and the bicycle using the cycle path or pavement while cycling in the same direction as the HGV (accident types 241, 243) account for 306 accidents (11%) and 14 fatalities (22%). This is the largest group with respect to fatalities and the second largest group with respect to accidents with injuries.

The GIDAS data confirms that accident type 243 is the most common one with respect to the number of accidents with injuries and the number of accidents with MAIS3+ injuries (20% and 19%, respectively). Furthermore, this accident type accounts for 12 of 19 cases in which the cyclist was overran.

TABLE III

ACCIDENT TYPES WITH HIGH NUMBER OF ACCIDENTS OR HIGH NUMBER OF FATALITIES IN LOWER SAXONY BETWEEN 2008 AND 2013

| accident type 241 | accident type 243 | accident type 301 |
|---|---|---|
|  A: truck; B: bicycle |  A: truck; B: bicycle |  both could be either A or B |
| 67 cases with 4 fatalities | 239 cases with 10 fatalities | 109 cases with 5 fatalities |
| | | |
| accident type 321 | accident type 341 | accident type 342 |
|  both could be either A or B |  A: truck; B: bicycle |  A: truck; B: bicycle |
| 143 cases with 4 fatalities | 189 cases without fatalities | 370 cases with 1 fatality |
| | | |
| accident type 371 | accident type 372 | accident type 399 |
|  A: truck; B: bicycle |  A: truck; B: bicycle | other turning into or crossing accidents |
| 128 cases with 9 fatalities | 51 cases with 4 fatalities | 76 cases with 4 fatalities |
| | | |
| accident type 652 | accident type 799 | |
|  both could be either A or B | other accidents | |
| 30 cases with 4 fatalities | 114 cases with 2 fatalities | |

***Single Case Analysis***

In order to check the new PCM approach, 5 bicycle-to-HGV accidents of accident type 243 were selected for further analysis. The selection tried to strike a balance between different HGV types (e.g. with and without trailer, van vs. truck, etc.) Unfortunately, only one truck-trailer combination was available in the data set with sufficient information to conduct the PCM preparation.

**CASE 1**: a garbage truck without trailer turned right at a crossing with cycle path at the pavement with a distance of approx. 1 m to the road. The driver of the garbage truck did not notice the cyclist using the cycle path. At the crossing the bicycle ran into the right side of the truck, close to the driver cabin. The female adult cyclist sustained MAIS1 injuries.

**CASE 2**: a transporter without trailer turned right at a crossing with cycle path at the pavement with a distance of approx. 2 m to the road. The driver of the transporter did not notice the cyclist using the cycle path. At the crossing the bicycle ran into the right side of the transporter, at the right front edge. The male child (between 6 YO and 12 YO) cyclist sustained MAIS1 injuries.

**CASE 3**: a truck with semi-trailer turned right at a crossing with cycle path at the pavement directly beside the road after waiting for pedestrians to cross the road. The driver of the truck did not notice the cyclist using the cycle path when restarting after waiting. The truck had already started the turning manoeuvre before stopping to wait for the pedestrians. At the crossing the bicycle ran into the right side of the truck, at the position of the cabin. Following the impact the cyclist was overran by the rear wheels of the truck. The female senior cyclist died at the scene due to AIS6 head injuries.

**CASE 4**: a small truck without trailer turned right at a crossing with cycle path at the pavement with a distance of approx. 2 m to the road. The driver of the truck did not notice the cyclist using the cycle path. At the crossing the bicycle ran into the right side of the truck, behind the cabin. The male adult cyclist sustained MAIS1 injuries.

**CASE 5**: a truck without trailer turned right at a crossing with cycle path at the pavement with a distance of approx. 2 m to the road. The driver of the truck did not notice the cyclist using the cycle path. At the crossing the bicycle ran into the right front edge of the truck. The male adolescent (13 YO to 17 YO) cyclist sustained MAIS1 injuries.

The single case analysis includes an assessment, on the one hand, of the accident situation, e.g. whether or not it was possible for the HGV driver to detect the bicycle, and, on the other hand, of what measures could have helped to mitigate the situation.

*Vision Conditions for the HGV Driver*

With knowledge of the trajectories of both opponents in the pre-crash phase, it is possible to check whether or not the bicycle was visible for the HGV driver using the side window or the right rear mirror. In order to analyse the possibilities to notice the bicycle, the standard field of vision and the position of the cyclist with respect to the field of vision during the accident approach phase were evaluated.

In case 1, the bicycle was not visible in the class II mirror but should have been visible in the class IV mirror for the complete 4 s displayed in Annex 1.

In case 2, the reconstruction suggests that the bicycle was visible through the side window and the front window during the whole 5-second period before the accident, see Annex 2.

In case 3, during its approach to the crossing, the bicycle was visible to the truck driver. However, while waiting for the pedestrians to cross the road, the bicycle reached the blind-spot of the truck first for the class II and later also for the class IV mirror and stayed there up to the moment of impact (Annex 3).

In case 4, the bicycle was not visible in the class III mirror but visible in outer edge of the class IV mirror (Annex 4). As this vehicle is not obliged to be equipped with a class IV mirror it remains unclear whether or not the actual mirror captured the cyclist. This is especially true because the wide angle mirror cannot be adjusted independently from the standard mirror in this vehicle.

In case 5, the bicycle was visible in class IV mirror all the time (Annex 5).

*Analysis of Countermeasures*

The review of the single cases suggests that in most of the cases the bicycle was not visible by direct vision or in the standard mirror (cases 1, 3, 4, 5). However, the wide angle mirror should have been a reliable source for detecting of the cyclist in these cases if the mirror was adjusted to the driver and ECE R46 compliant. In case 3 there was a possibility to not detect the cyclists with a poor adjustment of the wide angle mirror. For case 4 the cyclist was also in the exterior corner of the mirror. Taking into account that the vehicle does not need to be equipped with a wide angle mirror and therefore it is unclear whether or not the mirror complies with the Class IV requirements and that the mirror cannot be individually adjusted in this vehicle it is likely that the actual mirror showed less information than it is presented here. In total of the five cases in one case the direct vision was sufficient, in 2 cases the class IV wide angle was sufficient to see the cyclist and for 2 cases a well adjusted ECE R46 class IV compliant wide angle mirror would have been sufficient to detect the cyclist and a warning to remind the HGV driver to watch out for cyclists would have been sufficient. In addition it might be sensible to better train HGV drivers with respect to appropriate mirror adjustment.

Visibility of the cyclist could also be improved by moving the cycle path as close as possible towards the lane of the right turning vehicles, as shown for case 5 as an example in Annex 6.

## IV. DISCUSSION

The analysed accident data shows that conflicts between HGV and bicycles are connected with high injury risks for the cyclists. Those situations where a right-turning HGV crosses a cycle path appear to be particularly dangerous. The detailed reconstruction of 5 accidents with a time period starting 5 seconds before the accident suggests that, without additional measures, the bicycle is often not visible for the HGV driver.

The main limitations of the study are that the actual field of vision remained unclear and that a number of assumptions were used to assess the trajectories of the accident opponents. Starting with the impact speed of both opponents, which can be reconstructed only with relatively large allowance for deviations, the exact braking level and the start of braking is difficult to judge as well. The speed is very important, however, for the analysis of the field of vision.

In principle, it would be necessary to include different scenarios for each accident in order to assess and compare these different scenarios. This approach is not currently included in the PCM studies and was therefore not considered here. With a larger number of accidents, the limitations from the assumptions leading to the trajectories are expected to have a smaller influence on the conclusions.

Furthermore, only two possible solutions for avoiding accidents between right-turning trucks and bicycles were analysed. Other solutions, such as stationary mirrors at the crossings, were not considered. It is therefore not possible to judge which solution is the most effective one. As only 5 individual cases are included in this study, it is difficult to give final recommendations.

## V. CONCLUSIONS

The Pre-Crash Matrix was developed to be a reliable tool for the assessment of safety systems for passenger cars. One of the main objectives of this paper was to check the possibilities of expanding the PCM to include accidents with turning trucks.

Accidents with turning trucks are a particular problem for cyclists using the bicycle path. It was in this scenario that the majority of accidents with fatalities and a large portion of the accidents with injuries amongst the bicycle-to-HGV accidents were observed. The assessment of 5 accidents suggests that right-turning trucks can, in principle, be addressed by the PCM. Some additional definitions are needed to officially include these accidents into the matrix (such as the definition of the trailer, including the link point between truck and trailer).

Furthermore, the analysis of the 5 cases shows the benefit of blind-spot warnings and modifications of the infrastructure (i.e. positioning the cycle path directly beside the road in the crossing area).

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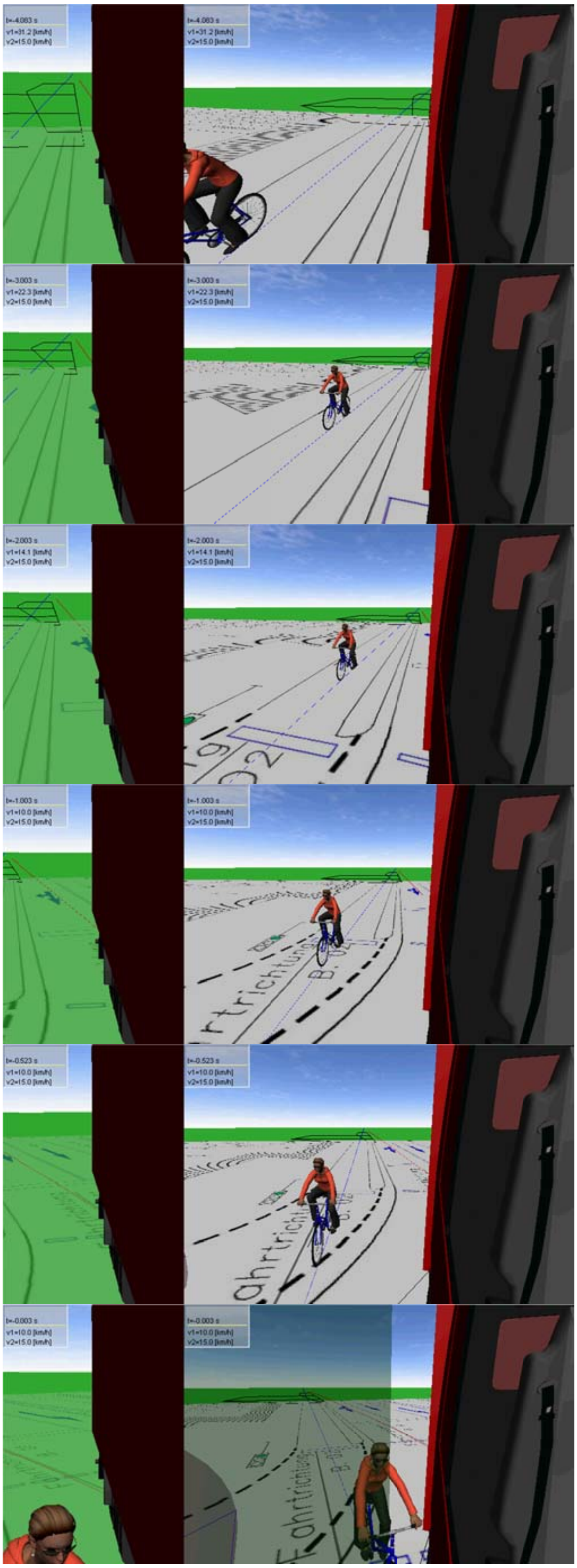
# VII. APPENDIX

***Annex 1: Field of vision case 1***



TTC = 4 s

TTC = 3 s

TTC = 2 s

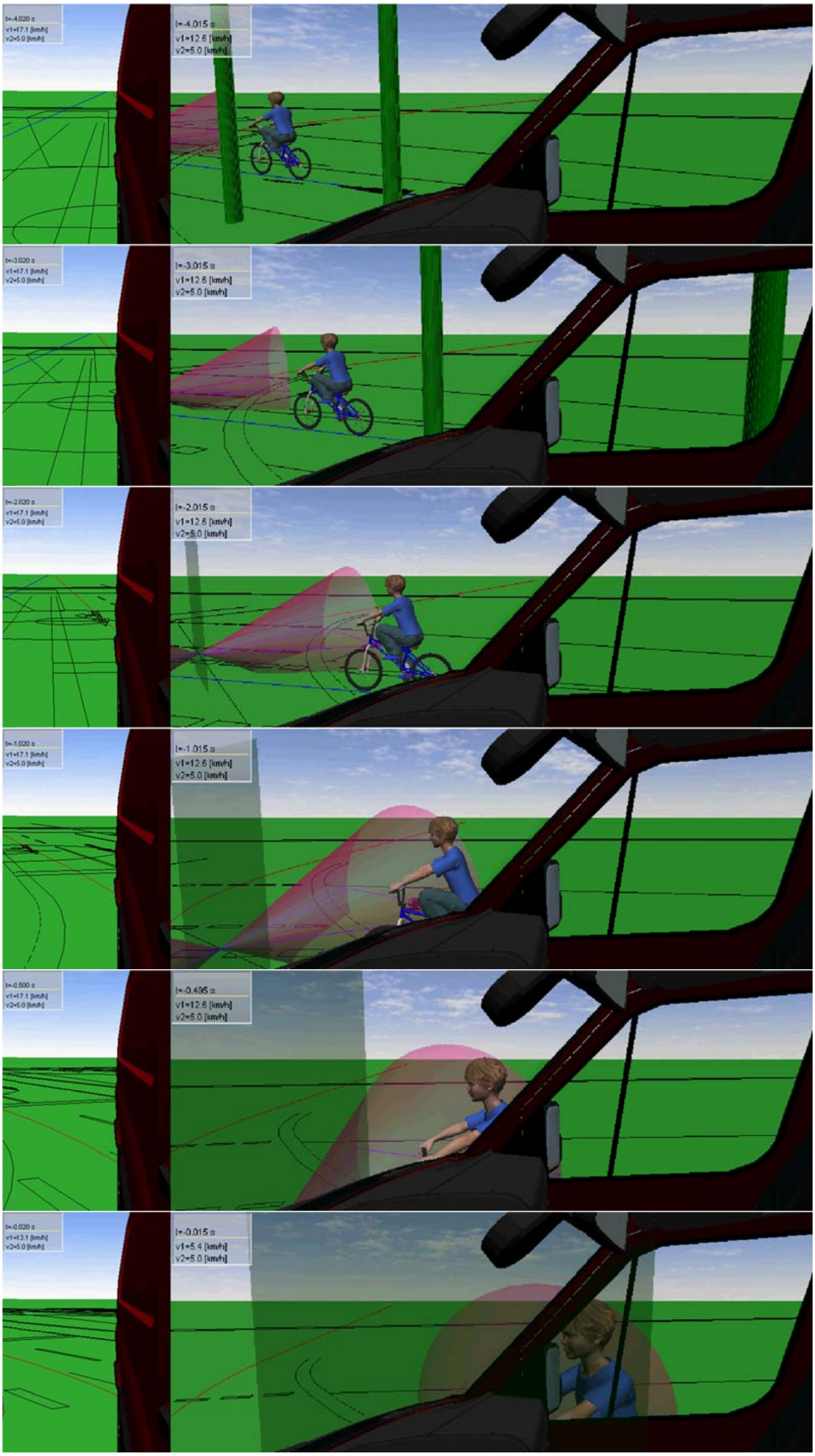
TTC = 1 s

TTC = 0.5 s

TTC = 0 s

class II mirror class IV mirror

### *Annex 2: Field of vision case 2*



TTC = 4 s

TTC = 3 s

TTC = 2 s

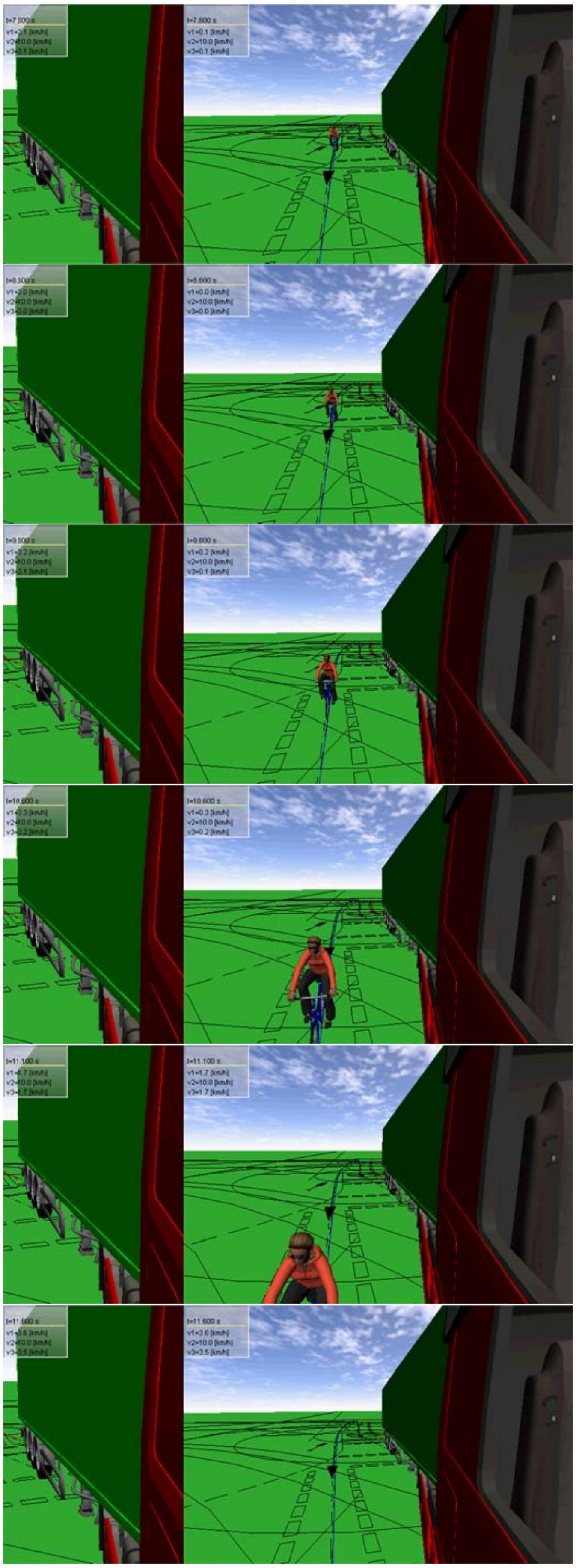
TTC = 1 s

TTC = 0.5 s

TTC = 0 s

class III mirror direct view

***Annex 3: Field of vision case 3***



TTC = 4 s

TTC = 3 s

TTC = 2 s

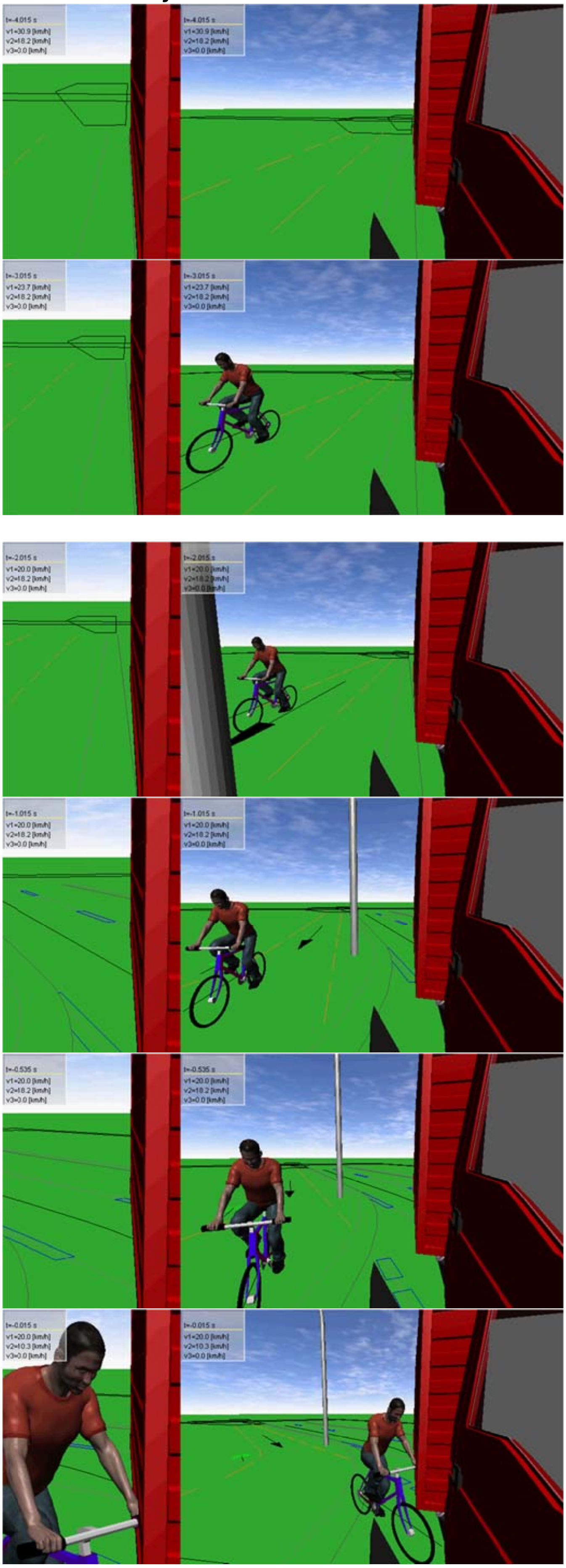
TTC = 1 s

TTC = 0.5 s

TTC = 0 s

class II mirror class IV mirror

***Annex 4: Field of vision case 4***



TTC = 4 s

TTC = 3 s

TTC = 2 s

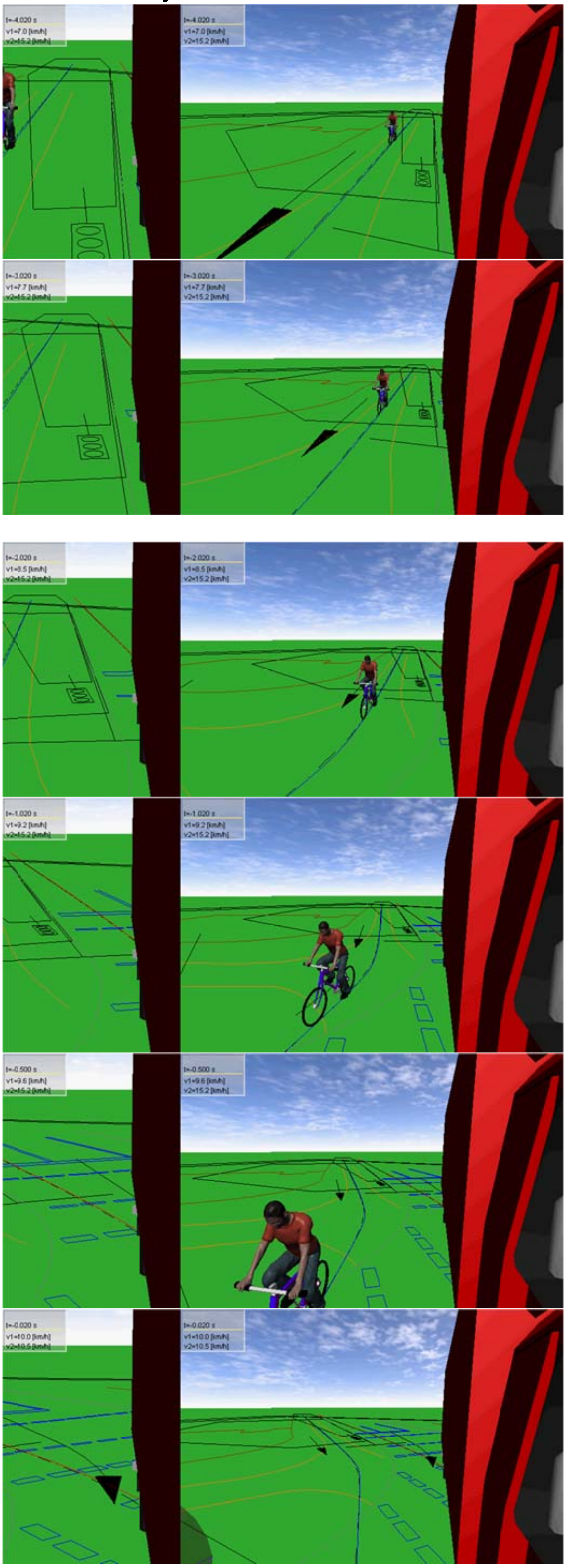
TTC = 1 s

TTC = 0.5 s

TTC = 0 s

class III mirror class IV mirror

***Annex 5: Field of vision case 5***



TTC = 4 s

TTC = 3 s

TTC = 2 s

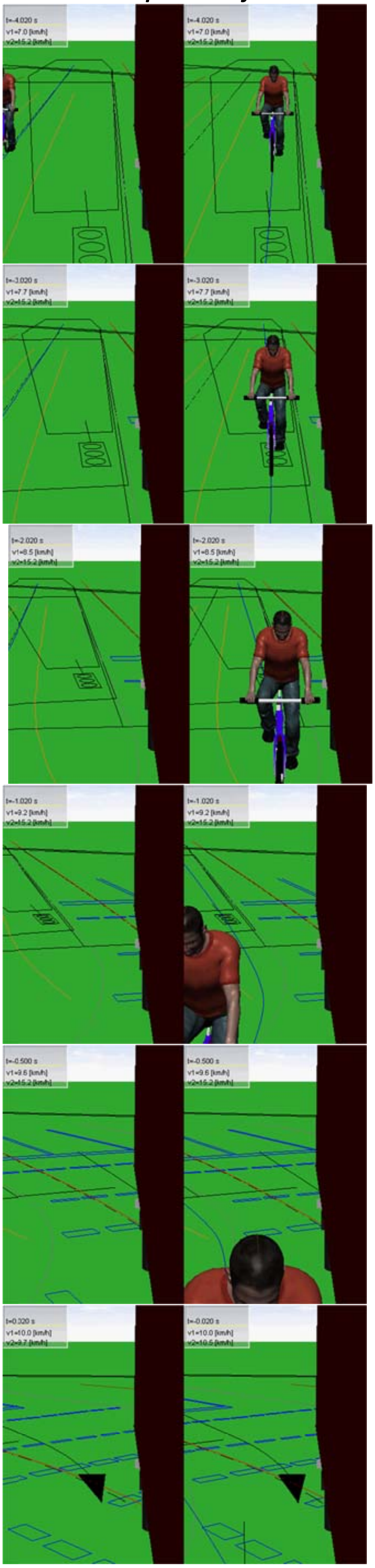
TTC = 1 s

TTC = 0.5 s

TTC = 0 s

class II mirror class IV mirror

### *Annex 6: Comparison of actual and modified cycle path position for case 5*



TTC = 4 s

TTC = 3 s

TTC = 2 s

TTC = 1 s

TTC = 0.5 s

TTC = 0 s

actual cycle path position | improved cycle path position