Method to Evaluate the Effectiveness of an Active Safety System for Cyclist Protection

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ABSTRACT

This paper presents a method for evaluating the effectiveness of a forward-looking bicyclist safety system for passenger cars. The method starts with a detailed analysis of 4286 bicycle-to-car accidents recorded between 2000 and 2013 in the German in-depth accident database GIDAS. The results of the analysis identify relevant parameters influencing bicycle-to-car-accidents which include surrounding conditions (time and location of the accident, obstruction), vehicle parameters (collision speed) and cyclist parameters (helmet use, cyclist age). An aggregation of the accidents to reference scenarios is subsequently presented. With more than 60 % of all bicycle-to-car accidents a crossing cyclist is the major scenario followed by accidents between cyclists and turning vehicles and accidents in longitudinal traffic. A further investigation of these scenarios is conducted by generating plots for the trajectories of the cyclists relative to the vehicle. Results so far for the overall method are presented. Further steps to be taken are described. This includes deriving test scenarios of the reference scenarios, set up a risk-based assessment of the safety system, carry out a benefit assessment with simulations and the evaluation of the risk-based assessment with the simulative benefit assessment. The complete study contributes to a deeper understanding of cyclist accidents and it delivers a method for the assessment of active safety systems preventing bicycle-to-car accidents.

Keywords: Cyclist accidents, Bicycle accident analysis, Bicycle-to-car accidents, Benefit Assessment.

1 INTRODUCTION

According to the German Federal Statistical Office 71,548 cyclist accidents with at least one injured person happened in Germany in 2013 accounting for a total of more than 13,000 severely injured cyclists. More than 350 cyclist fatalities occurred which account for 10.6 % of the total fatalities number in traffic accidents. In 59.1 % of the 71,548 cyclist accidents the cyclist collided with a passenger car [1], [2].

This number highlights the necessity of measures preventing bicycle-to-car accidents. A solution focusing on the vehicle's perspective of those accidents are vehicle safety systems for cyclist protection. Passive and active measures are possible and developed by automotive manufacturers and suppliers. This paper focuses on an active safety system for bicycle protection which includes a forward-looking sensor, a control unit and actuators. The function of the system is an autonomous emergency brake which is triggered by an impending collision with a cyclist.

At an early stage of the development of such systems an effectiveness assessment of the safety system is necessary for further system specifications. Therefore, this paper provides a method for the evaluation the effectiveness of a forward-looking bicyclist safety system.

The remaining content is divided into two parts. The first part describes the general approach for the evaluation of active safety systems. The method is applied to a safety system for the protection of cyclists in bicycle-to-car accidents. The second part presents detailed results which have been derived so far. An outlook for further investigations to be taken is finally given.

2 METHOD TO EVALUATE THE EFFECTIVENESS OF AN ACTIVE SAFETY SYSTEM

The investigation of the general accident situation with respect to bicycle-to-car accidents is the basis for the further assessment of technology preventing these accidents. Parameters influencing the accident are derived within this step. In-depth databases enable a more detailed analysis of accident causation, environmental conditions, vehicular parameters and injury patterns in comparison to national statistical databases and are therefore preferred for further investigation.

Based on the accident analysis the accidents are aggregated into representative sensor-equivalent scenarios referring to the course of events. Sensor-equivalent means that scenarios are aggregated which are similar regarding the detection by the sensors. E.g. focusing on the scenario crossing cyclist, it means, that it does not matter whether the cyclist is crossing the road coming from a cycle path or driving directly on the road. These sensor-equivalent scenarios are further analysed with regard to trajectories of the cyclists relative to the subject vehicle. Vehicle and cyclist collision speed patterns are identified in each scenario.

Test scenarios are consecutively set up with this information. The test scenarios are weighted proportionately according to their share in total accident numbers and are additionally specified in terms of speed ranges of the collision partners and their absolute as well as relative direction of movement. With joining the frequency of a specific speed range and an injury risk for that speed to a risk distribution a risk-based assessment is developed.

For the benefit assessment of the examined safety system real accidents from the in-depth database are simulated twice, once without the safety system corresponding to the accident as it happened in real and once with the safety system installed in the car. Basis of the benefit assessment is the reduction in seriously injured cyclists due to the implementation of the system. Cumulative injury risk is calculated for both simulations. The benefit is subsequently determined.

The final step comprises the quality evaluation of the assessment with the test scenarios compared to the benefit evaluation with simulations. This procedure ensures that the assessment for each system on the basis of test scenarios corresponds to the real situation which is shown by the assessment with simulations on the basis of real accidents. This last step is not a straight-forward process but corresponds to a closed-loop system for adjustment of the test scenarios. This implies that inadequate results in this quality evaluation step leads to a redefinition of the test scenarios and their parameters. The new design is reassessed and the process is iterated until the test design and its risk-based assessment fit to the benefit assessment with simulations.

The complete method described above is shown in **Figure 1**. The remaining part of this paper describes the steps taken so far which cover the detailed accident analysis of bicycle-to-car accidents, derivation of reference scenarios and parts of the further investigation of the reference scenarios. The last section includes the remaining steps of the method in detail.

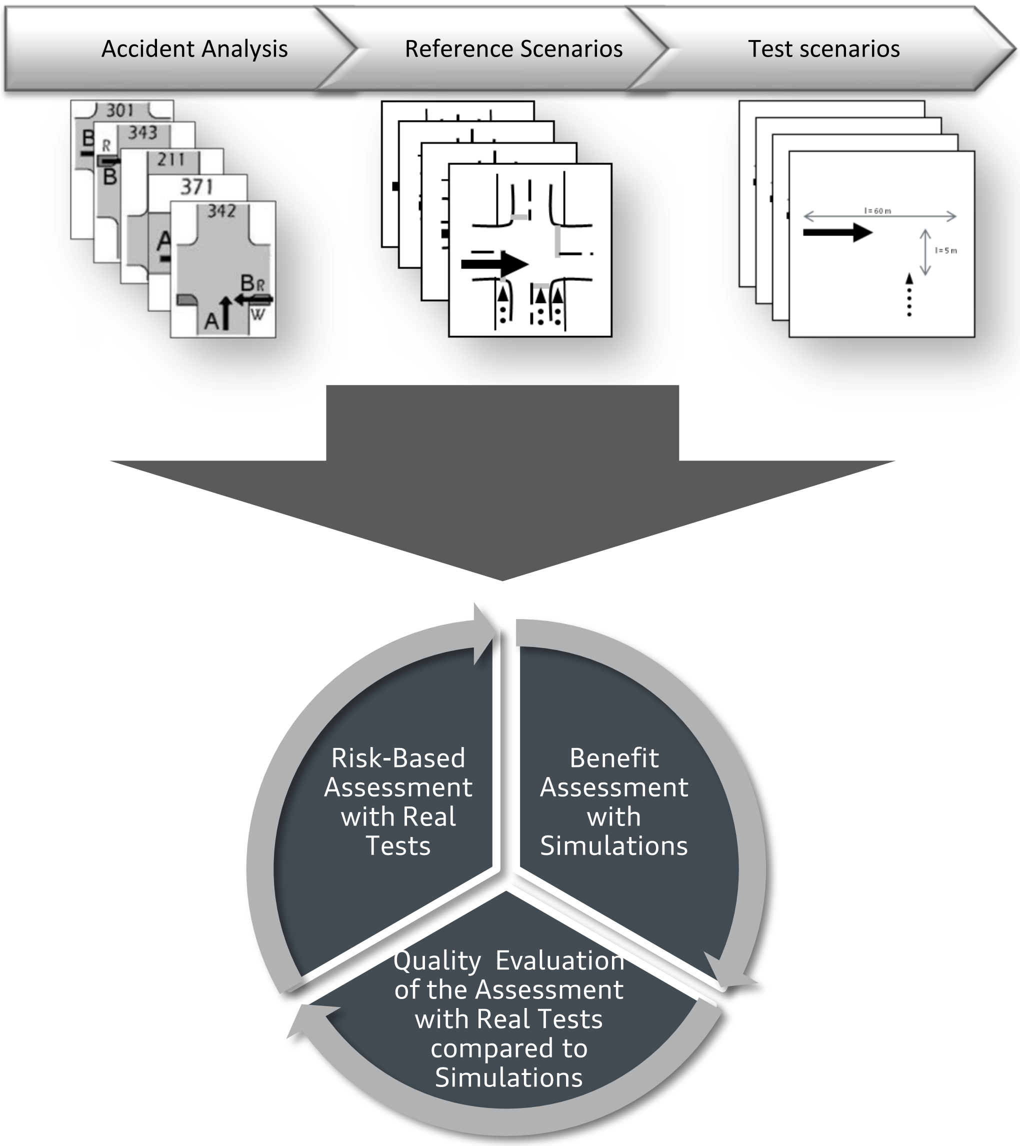

Figure 1. Method to evaluate the benefit of an active safety system for cyclist protection.

3 IN-DEPTH ACCIDENT ANALYSIS

Accidents within the German In-Depth Accident Study (GIDAS) are considered for the following analysis. GIDAS is the largest investigation project in Germany. Accidents including at least one injured person are collected according to a statistical sampling plan summing up to a total of 2000 accidents gathered each year. Recording has been carried out in the greater areas of Hanover and Dresden since 1999 [4]. The database provides detailed information about each accident allowing to examine relevant parameters influencing car-to-bicycle accidents in Germany.

The analysis comprises car-to-bicycle accidents between 2000 and 2013. Only such accidents are included in the analysis in which both passenger car and cyclist had their first collision with each other. This constraint particularly excludes consecutive collisions between the examined cyclist and other passenger cars or the examined car and other cyclists. Additionally accidents are excluded with a cyclist initially hitting the ground and then colliding with a passenger car and with two cyclists having each their first collision followed by a car-to bicycle collision. In addition to these constraints only the bicycle rider is examined. This means that other persons on the bicycle e.g. children in a bicycle-mounted child seat, are excluded from the analysis. Accounting for these limitations the number of examined car-to-bicycle accidents adds up to 4286.

Accidents are investigated with regard to parameters describing the surrounding conditions and parameters describing both accident partners. The analysis focuses on the possible influence of each parameter relating to the cyclist's injury severity. The injury severity of the cyclist is determined with the Maximum Abbreviated Injury Scale (MAIS). The injury scale ranges from 0 (no injury) to 6 (fatal injury) with a value of 1 meaning minor injuries, 2 moderate, 3 serious, 4 severe and 5 critical injuries [5].

The environmental conditions encompass the site and time of the accident as well as possible influences of visual obstructions. 97 % of the accidents happen within urban areas whereas just 3% of car-to-bicycle accidents happen in rural areas. The percentage of at least moderately injured cyclists for accidents in rural areas is twice as high as for accidents happening in urban areas. The share of at least seriously injured cyclists is four times higher for rural than for urban accidents. The reason for this difference in injury severity due to the location of the accident is based on a higher percentage of accidents happening at high speed for rural accidents. Whereas 97 % of urban accidents happen with vehicle collision speeds under 50 kph this only accounts for 70 % of the rural accidents. A similar finding relating accidents in rural areas with higher injury severity is presented by [6], [7].

83 % of the accidents happen at daytime and about 9% at night time, the rest during sunset and sunrise. Accident injury severity for night time accidents is slightly higher than for accidents happening at daytime. Data also shows that vehicle collision speeds at night time are slightly higher than at daytime which accounts for higher injury severities. Visibility of the cyclist is lower at night and therefore the vehicle driver's time to react on the cyclist is shorter for night time accidents than daytime accidents. This finding is supported by previous publications. [8] finds a higher risk for fatal injuries in the evening period and [9]–[11] for accidents happening in darkness and unlit conditions.

Obstructions are relevant for 23 % of all cyclist accidents and with 29 % of cases it is especially relevant for cyclist accidents in which cars and cyclists cross intersections or cyclists cross the road. Obstructions are parking vehicles, driving vehicles, the subject vehicle itself, walls, fences or hedges. The existence of an obstruction does not lead to higher cyclists' injury severities which is unexpected as an obstruction might lead to shorter times to react on the cyclist for the vehicle driver. Therefore, further analysis of obstruction is needed. In particular it is important to analyze the precise time of the cyclist entering driver's the field of vision.

Accident in longitudinal traffic correlates with higher injury risk than for accidents at intersections. The reason for this is that accidents in longitudinal traffic occur at higher speeds than accidents at intersections. 12 % of longitudinal traffic accidents occur at speeds above 50 kph whereas this accounts just for 3 % of intersection accidents. The reason is that 15 % of all accidents happening in longitudinal traffic take place in rural areas while this accounts for less than 3 % for accidents happening at crossings. The correlation between longitudinal traffic and injury severity is supported by results of [12] which shows that speeding at straight sections raises injury severity of cyclists. [8] respectively finds that accidents at intersections lead to lower injury severity than accidents which happen elsewhere.

High vehicle speed, as indicated before, is strongly related to increased injury severity. Whereas 3 % of accidents with a slightly injured cyclist happen at vehicle collision speeds over 50 kph, this share increases to 20 % of accidents with at least seriously injured cyclists. For accidents with at least severely injured cyclists, 30 % happen at vehicle collision speeds above 50 kph. This finding is supported by [6]–[10], all stating that higher speed limits raise cyclist injury severities. In contrast to that, the GIDAS data shows that cyclist collision speed only seems to have an impact on the cyclist injury risk when the cyclist is not hit by the front of the car but crashes into the side of the vehicle.

Only 10 % of the cyclists in the database wear helmets. Those wearing helmets have lower head injury severity scores than cyclists with helmets. Whereas the head AIS score for cyclists without helmets reach up to fatal injuries the head AIS scores for helmet wearing cyclists are at maximum serious injuries. The following publications which state an injury reducing effect as well support the finding presented in this paper [9], [13], [14].

Cyclists above the age of 65 are more likely to have a higher injury severity than middle aged cyclists or children. This is likely to be the effect of a slower reaction and frailty. The finding is supported by results of [6]–[9], [12] which also find a relation between age and higher injury severity.

Summed up, the analysis shows that cyclist accidents and the level of injury severities of the involved cyclists correlates with higher speed due to higher speed limits (urban vs. rural and longitudinal traffic), with darkness (unlit roads) which leads to higher speeds itself as well as with the use of a helmet. This not only gives insight in general parameters influencing bicycle accidents but also shows that not only safety systems in cars are needed to avoid those accidents but in addition further measures have to be established like a safer infrastructure for cyclists and a greater acceptance of cyclists for wearing helmets.

4 REFERENCE SCENARIOS

The accidents are aggregated into representative sensor-equivalent scenarios referring to the course of events. That means that according to the position of the cyclist to the passenger car during the conflict situation preliminary to the collision all accidents are grouped into reference scenario classes with further specified reference scenarios. These reference scenario classes and detailed scenarios are depicted in **Figure 2**.

With more than 60 % the major scenario class with regard to bicycle-to-car accidents is the crossing cyclist. A right turning or left turning vehicle colliding with a cyclist account each for around 11 % of the accidents. Around 8 % of the accidents occur in longitudinal traffic and the rest of the accidents are other scenarios which cannot be merged to the other scenarios.

A cyclist crossing from the right is the most common accident causation with a share of over 40 % of all bicycle accidents. Over half of those accidents happen at crossings with the cyclist coming from a bicycle path from the right. Due to the direction of travelling which is in most cases analogue to that of the road drivers expect the cyclist coming from the left instead of the right side.

Turning vehicles colliding with cyclists come up for 22 % of the accidents. The accidents are further divided in accidents with cyclists coming from the same direction and cyclist from the opposite directions. Opposite direction 1 refers to oncoming cyclists before the turning action and opposite direction 2 refers to the direction where the subject vehicle intends to go after the turning action. While left turning vehicles mainly collide with oncoming cyclists (opposite 1), right turning vehicles usually collide with cyclists coming from the same direction. This is likely due to the usual direction of travel for cyclists.

For accidents in longitudinal traffic oncoming cyclists and lane changes of cyclists (e.g. because of the cyclist's intention to turn left or a change from the bicycle lane on the road) mostly lead to these kind of accidents. Minor situations are cars which rear-end cyclists (same direction of travel), cars and cyclists which drive side by side colliding due to insufficient distance (e.g. collision with the vehicles' exterior rear view mirror) and collisions caused by lane changes of the vehicle (e.g. filtering into traffic).

Other accidents frequently are collisions between cyclists and drivers (or passengers) opening the door of their vehicles and drivers backing out of a driveway or garage. There is no chance to address these accidents with a forward-looking safety system. Other solutions than the safety system investigated have to be found for those accidents.

5 FURTHER INVESTIGATION OF REFERENCE SCENARIOS

The reference scenarios are further investigated. Trajectories and positions of the cyclists relative to the vehicle are further examined. Collision speed patterns are identified for the scenarios. This investigation gives insights to the cyclists' visibility for possible sensor settings of the safety system.

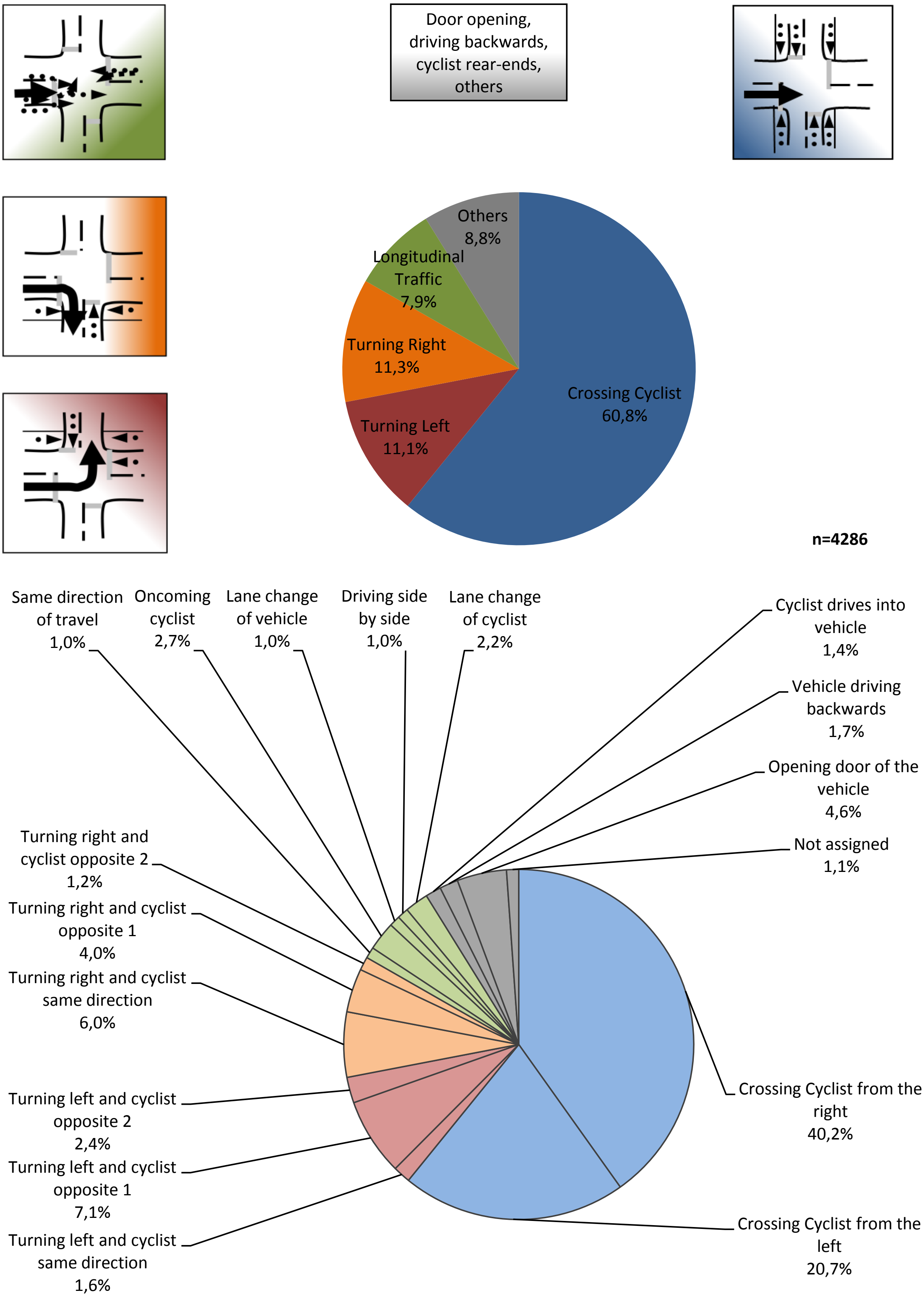

Figure 2. Distribution of reference scenario classes (upper diagram) and reference scenarios (lower diagram).

The analysis includes the simulation of 697 accidents in PC-Crash. Data of the trajectories and positions of each accident are extracted from PC-Crash and plotted for each reference scenario. Starting point of cyclists and vehicles in the simulations is around 5 seconds before the actual collision takes place.

As an example scenario crossing cyclists from the left are investigated. The trajectories of these cyclists are depicted in **Figure 3**. The figure shows that the higher collision speeds of the car lead to steeper trajectories of the cyclists relative to the subject vehicle. These accidents have higher injury severities due to higher collision speeds, nevertheless cyclists are detected by a forward-looking sensor as trajectories have smaller angles relative to the direction of the car.

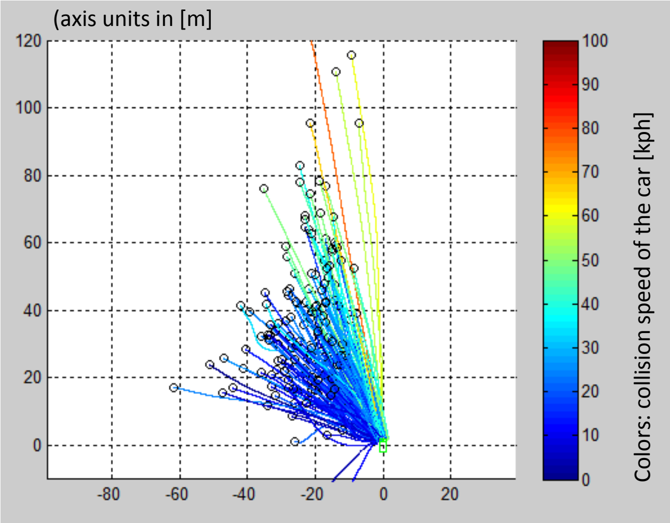

Figure 3 Trajectories of **c**rossing cyclists from the left side (151 cyclists).

Accidents between left turning vehicles and oncoming cyclists show different course of events contrary to the crossing accidents. This is depicted in **Figure 4**. Vehicle collision speeds, with a maximum speed of around 40 kph for this scenario, are lower than for crossing accidents due to the turning maneuver of the vehicles in such scenarios. These turning maneuvers are also the reason for the bending of the trajectories towards the vehicle. Runs of the trajectories indicate that cyclists involved in these accidents are well seen by a forward-looking sensor set. This aspect is to be tested in further simulations for different scenarios.

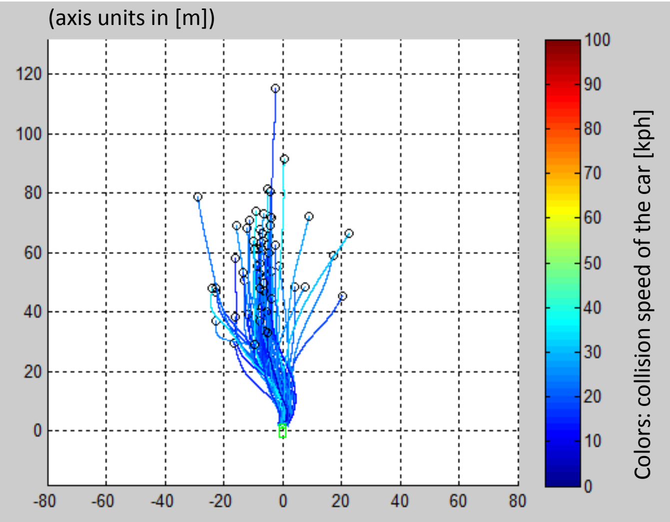

Figure 4 Left turning vehicle and the cyclists' trajectories relative to the vehicle (61 cyclists).

6 FURTHER STEPS

Having the analysis of the reference scenarios completed test scenarios are consecutively defined. These test scenarios are specified in terms of starting points of cyclist and vehicle. Speed ranges of both vehicle and cyclist are determined with the findings of the accident analysis. In addition to that the necessity for scenarios with obstructions or with infant cyclist dummies is to be proven.

With parameters derived from the GIDAS data an injury risk function is set up using a logistic regression model. The injury risk function links the independent variable of the vehicle collision speed to the probability of obtaining a certain injury severity level for the cyclists. The injury risk function serves two purposes in the presented method.

The first one is setting up the risk-based assessment of the test scenarios. The risk is defined as the probability of obtaining a certain injury, displayed by the injury risk function, multiplied with the probability of the incidence of that event, given by the relative frequency of accidents within a speed range in that scenario. So this means the speed distribution of each scenario is converted into a specific risk with the injury risk function. The risk obtained in that step is scaled to a specific number of points given for each scenario. So these steps lead to the risk-based assessment which is shown in **Figure 5.**

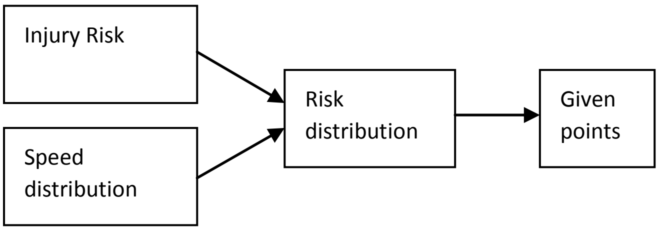

Figure 5 Risk-Based Assessment with Tests.

The second purpose of the injury risk function is to determine the benefit of a specified safety system. Simulations are run without the system, simulating the accidents course of events like it was in real. In addition simulations are run a second time with a vehicle equipped with a parameterized active safety system. Accident parameters might be changed to lower collision speeds with the system and consequently the injury risk changes as well. The collision speed for each accident with and without the safety system is transferred into an injury risk for each cyclist on the basis of the injury risk function. The reduction of seriously injured cyclist, which represents the benefit of the system, is defined as the difference between the cumulative injury risks for the accidents without the system and the accidents with the safety system. The process of Benefit Assessment is shown in **Figure 6**.

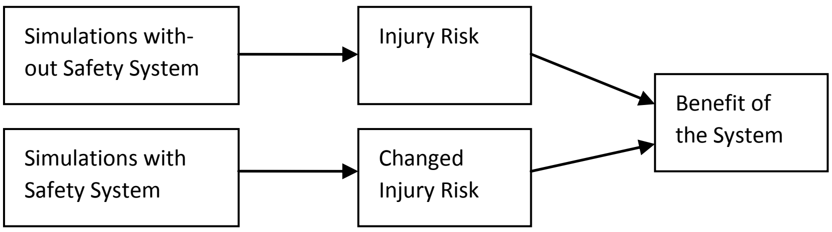

Figure 6 Benefit Assessment with Simulations.

The last step comprises the evaluation of the risk-based assessment of the test scenarios with the simulative benefit assessment. Simulations as well as tests scenarios are conducted with differently parameterized safety systems and points achieved in the risk-based assessment are compared to the benefit assessment with simulations. Sensitivity tests are further conducted. As shown at the beginning in **Figure 1** the last step of the method is an iterative process with probable changes in the test scenario design until the final result is a validated test setup which can be used for the real assessment of a forward-looking safety system for cyclist protection.

7 OUTLOOK

It is apparent that protection of vulnerable road users, particularly cyclists, is a topic of high importance not only due to the quantity of injured cyclists in Germany but due to worldwide cyclists' injury rates. Especially in emerging markets cycling is still one of the most favored means of transport. A continuously rising number of accidents involving cyclists show an increasing need for action. Protection of these road users has to be improved especially in accidents between cyclists and vehicles. Active Safety Systems for cyclist safety present one possible solution for such accidents. This paper provides a method for the assessment of such technologies and show results that are obtained so far. Further investigations are conducted in the future.

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