Car-to-cyclist forward collision warning effectiveness evaluation: a parametric analysis on reconstructed real accident cases

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Abstract
The objective of the study is to quantify the benefits of an earlier brake activation by the drivers potentially achieved by a Forward Collision Warning (FCW) system in simulated car-to-cyclist accident scenarios. A parametric analysis is performed by varying the detection sensor Field Of View (FOV), the FCW trigger time and the driver's reaction lag time to the FCW. Almost two thousand and three hundred car-to-cyclist accidents are clustered in the following five main scenarios: crossing nearside (33%), crossing farside (22%), longitudinal (5%), turning left (12%) and turning right (22%). The remaining is clustered in Others group (6%). For all accident cases, original accident kinematics are processed through Matlab® scripts from which FCW FOV, FCW trigger time and driver's reaction can be modified. The Matlab scripts return the new accident kinematics which can result in the accident being avoided or mitigated. This study shows that a 70° FOV, a FCW trigger time of 2.6s before the impact and a 0.6s driver's reaction to the FCW has a positive result in 82% of the accident cases with 78% being avoided and 4% mitigated. Concerning the parameters, the FOV has a greater influence on the avoidance rates compared to FCW trigger time and driver's reaction. Our study also reveals that FCW system has a higher benefit in the crossing farside scenario and a lower benefit in the turning right scenario. This paper highlights generic characteristics of FCW systems to optimize safety benefit for the different accident scenarios.

Keywords: Forward Collision Warning, Car-to-Cyclist accidents, Accident simulation, Effectiveness

1. Introduction

Advance Driver Assistance System (ADAS) development started more than a decade ago (Mosquet et al. 2016) with the introduction of Electronic Stability Control. ADAS technologies nowadays rated by consumer organizations such as European New Car Assessment Program (Euro NCAP) have taken an increasingly importance due to their safety benefit. Autonomous Emergency Braking (AEB) and Forward Collision Warning (FCW) were first designed to tackle car-to-car crashes and they had entered Euro NCAP assessment for the first time in 2016 for pedestrians and in 2018 for cyclists (Euro NCAP 2019a, Euro NCAP 2019b).

The FCW triggers an alarm to the driver in order to alert him/her of an imminent collision, prompt him/her to brake and support the braking force if required. In the case the driver does not react to the alarm, the brakes are automatically applied to avoid or mitigate the collision. FCW can affect more or less effectively the detection, the identification and the decision making of the driver depending on the warning type, the trigger time, the awareness of the driver of the FCW or the driver distraction. Lylykangas et al. (2016) found faster driver reaction time in emergency scenarios with tactile and visual-tactile signals compared to an only visual one. Regarding trigger time, driver's trust and acceptance can be affected if an alarm is triggered too early as it might appear as a false warning and on contrary, if an alarm is too late as it may decrease the trust in the system by the driver (Zador et al. 2000). Abe and Richardson (2006) studied the effect on driver trust in FCW system and driver expectation from FCW system. They found that faster reactions could be obtained after a critical situation was detected if the alarm was triggered earlier. Bueno et al. (2014) showed the positive effect FCW could have in the case of low distracted drivers. On contrary, on highly distracted drivers, the effects disappear underlying the necessity of attentional resources to process the warning signal.

FCW effect was also studied with a repeatedly exposure to emergency braking (Aust et al. 2013). It appeared that the more exposed were drivers to FCW, the faster they reacted to the signal. Koustanaï et al. (2012) determined FCW effects on drivers. They showed that drivers' interaction with FCW system were more effective when drivers were familiarised with the system compared to unfamiliarised drivers. In terms of reaction towards FCW, different avoidance strategy may emerge. Wu et al. (2017) found that strategies may differ in function of age and geographical criteria. This way, the design of human machine interface appears to be very important. Campbell et al. (2007) made a review of human factor knowledge to consider in the conception of audio, visual or haptics warnings. They gave guidance and recommendations for the design of ADAS in general and FCW in particular. Thus one of requirements in FCW design might be the Human Machine Interface (HMI) to ensure a detected VRU by the car sensors is also detected by the driver. Previous papers mostly focused on driver reaction in rear-end car crashes for the conception of FCW. Findings would need to be checked in car-to-VRU scenarios where VRU detection is more challenging compared to detection of a car which path is easier to predict and visibility generally higher. Accident reconstructions were used by Lenard et al. (2018) to determine the

requirement of ADAS sensors. From the analysis of pedestrian and cyclist accidents they found that the range needed to detect most of the pedestrians and cyclists is similar and in between 42 to 50m whereas the Field of View (FOV) varied significantly between cyclists and pedestrians: of ±80° for cyclists (total 160°) and only ±20° (total 40°) for pedestrians.
Many researches have focused on car-to-car accidents in the evaluation of FCW safety benefit. More evidences are needed to quantify the FCW effect in the case of car-to-cyclist accidents. The purpose of this paper is to quantify the benefit range of FCW systems. Using pre-crash simulations of real-world crashes, the effect of a FCW is checked considering different FCW characteristics (variation of FOV, trigger time) and different driver reactions for various accidents clustered into different scenarios. Safety benefits are quantified in terms of number of accidents that could be avoided or mitigated thanks to the FCW.

2. Materials and methods

2.1 Database description

Car-to-cyclist accident cases used in this paper come from the in-depth accident database of IFSTTAR/LMA and from the GIDAS Pre-Crash-Matrix database.
The EDA crash database of IFSTTAR/LMA gathers accidents in the surrounding of Salon de Provence since 1985 (Ferrandez et al. 1995). Each accident is investigated in real time by a multidisciplinary team composed of a technician and of a psychologist going directly on the accident scene at the same time than the rescue team. Evidences about the involved vehicles, the collision (vehicle final positions, vehicle deformations and impact location), and the environment (infrastructure, road marks, weather and visibility conditions) are gathered among many others. Drivers statements, witnesses and injury records based on medical reports are also recorded. With the merging of all those data, hypothesis of the accident mechanisms are made in order to reconstruct the car and cyclist trajectories, travelling speeds and evasive manoeuvers.

The GIDAS Pre-Crash-Matrix (version PCM 160818_GIDAS_PCM_4.0_2016_1) includes information on pre-crash sequence in a standardized format (GIDAS 2016). The pre-crash kinematics are obtained by simulation until 5 seconds before the crash. Additional information on environment and accident participants are also available. The PCM database can be linked with the GIDAS in-depth accident database which gathers up to 3000 variables on the accident and participant characteristics and on its consequences (vehicle damages, accident severity and road user detailed injury) (VUFO GmbH 2016).

2.2 Accident selection and clustering

In this study, only accidents involving two participants, one car and one cyclist, were considered. Among the 2261 accident cases from our sample, 30 cyclist accident cases come from EDA and 2231 from GIDAS-PCM.
Accidents are clustered into different scenarios based on the trajectories of the car and the cyclist. From literature many ways to cluster accidents are reported depending on the research focus. Accidents can be clustered with respect to cyclists' provenance like in Kuehn et al. (2015) or car trajectory as in CATS (Uittenbogaard et al. 2016) and AsPeCSS project (Rodarius et al. 2014). The latter was chosen in this study and 5 scenarios were defined. These scenarios are commonly referred to in the literature:
- Crossing Nearside scenario (CN): the vehicle drives straight and a cyclist crosses from the closest side of the road (On a 1 way road, a cyclist crossing from the left or the right is also considered as a CN).
- Crossing Farside scenario (CF): the vehicle drives straight and a cyclist crosses at least one lane of road before being hit by the vehicle.
- Longitudinal scenario (L): the vehicle and the cyclist both travel in the same direction on the road, and the car hits the cyclist in the rear during the travel or laterally during an overtaking manoeuver.
- Turning Left (TL) or Turning Right scenario (TR): the vehicle is turning left or right respectively at an intersection and hits a cyclist whatever the trajectory of the cyclist. Situations where the vehicle is outside of an intersection are excluded from this cluster.

Cases where a vehicle follows a curve to the right (or to the left) and a cyclist crosses the road are clustered either in CN or CF scenario. Cases where a vehicle is in a curve and encounters a cyclist travelling in the same direction are clustered in the L scenario.
- Other scenarios: all accidents that cannot be clustered in any of above scenarios.

2.3 Accident reconstruction

From the French accident cases, a kinematic reconstruction is performed based on Lechner and Ferrandez (1990) methodology in order to obtain the accident pre-crash phase. Car and cyclist trajectories are extracted and drawn on a reduced scale map using their initial and final positions. Objects in the surrounding environment that can interfere in the detection process are also added to the scene when the information were available. With those data, a temporal reconstruction is performed based on information such as participants' displacement speed and manoeuvers before the crash. Some assumptions are made during the temporal reconstruction:

- Car and cyclist speeds are constant if brakes are not activated. If brakes are triggered, a constant deceleration speed is considered until the impact point,
- A constant deceleration is considered from initial brake trigger,
- The deceleration value is adapted to accident particular conditions (road and weather conditions, brake conditions) defined by the accident investigation team,
- The cyclist displacement is estimated from its path towards the impact location with the car. Car deformation zones and participants' speed declaration can help quantifying more precisely cyclist's speed.

GIDAS accident pre-crash phase kinematics are readily available in GIDAS-PCM database. PCM description is explained by Schubert et al. (2012).

2.4 Simulation tool

This section presents the algorithm which simulates the accident kinematics including the effect of the FCW. The developed simulation tool is based on Hamdane et al. (2016) simulation tool which was adjusted to account for cyclist detection and introduction of driver's reaction to simulate the possible effect of a FCW. The software is developed in Matlab2012b (Matlab 2012) and requires Matlab Database toolbox. First, data from the original accident reconstructions are extracted such as the kinematic of the car and the cyclist as well as the objects of the accident surroundings. Cyclist's relative positions to car sensors and relative speed are computed backwards from the reported impact location with a time step of 0.01s between each position. Range and FOV of the FCW are overlaid on the car trajectory to determine whether the cyclist is inside the FCW detection cone. A 50m detection range is considered in all simulations as a range that can be easily reached with current sensor technology (Mukhtar et al. 2015).

Additionally, occlusion of the cyclist along the time by objects in the scene is considered. FCW is triggered at a chosen theoretical time under the conditions that the cyclist is in the FCW field of detection and not obstructed by objects in the scene. In the event that the cyclist is hidden, the FCW will be delayed to the time when the cyclist becomes visible again (see Figure 1). This way, the algorithm determines the moment when FCW message is delivered to the driver. From there, it is possible to determine brake activation considering some delay depending on the driver's reaction to the FCW. Driver's reaction is defined as the lag time after the FCW is triggered to activate the brakes. From the brake activation, a brake deceleration profile with a constant deceleration value of 0.8G is applied (see Figure 1). It corresponds to an ideal braking model without transient state and ideal road surface conditions (Brach and Brach 2005, Byatt and Watts 1981 and Lechner and Ferrandez 1990). As an example, a FCW sets at 2.6s before the time to collision and a driver's reaction of 1.2 second will lead to a brake application at 2.6s-1.2s=1.4s Time To Collision (TTC). If the cyclist is occluded until 1.9s before the impact, then the FCW will trigger when the cyclist becomes visible at 1.9s and the brake will be applied at 1.9s-1.2s=0.7s TTC.

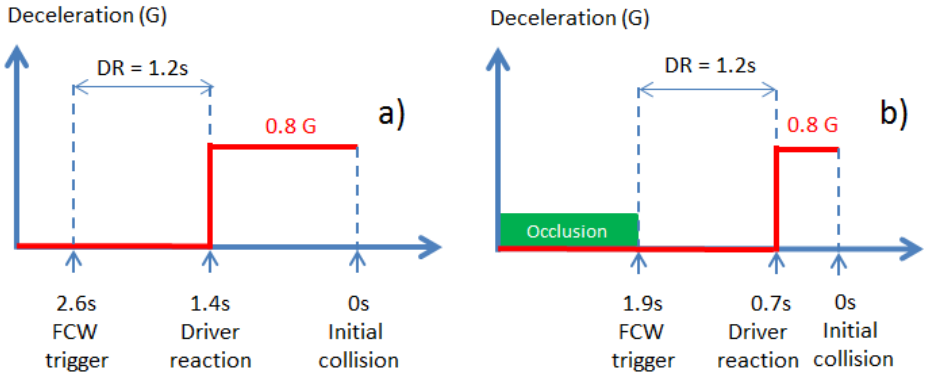


Figure 1: FCW trigger model in the simulation. In this example the FCW theoretical trigger is 2.6s. In case a) the FCW triggers at its theoretical time of 2.6s with brake activation 1.2s later. In the case of occlusion b), the FCW triggers when the cyclist is visible for the first time after the theoretical trigger time which is 1.9s and then, brakes are activated 1.2s later.

A comparison is then made in order to determine if the brake activation in the new simulation is earlier than in the original accident. If brake activation happens later compared to the original accident, then it is considered that there is no effect and the original accident kinematic is kept. Otherwise, the original accident kinematic is replaced by the newly computed kinematics from the brake application time:

- Car new instantaneous speeds are computed from the brake activation,
- Car new positions are computed following the original trajectory but with consideration of the new instantaneous speeds,
- Car and cyclist trajectories are extended linearly after having reached the original impact location based on the last known segment before the impact until the car stops. The time step of the last segment is 0.01s. Finally, from the new kinematics and the participants geometrical dimensions, it is determined if the collision is avoided, mitigated or if there is no effect (depends if the bounding boxes of the car and the cyclist intersect or not). The car dimensions are those of the car involved in the real accident and recorded in the accident databases. The cyclist dimensions are the ones of a rectangular box of 1900mm length, 500mm width. The values are standardized according to Euro NCAP test protocol (Euro NCAP 2019a),
- In the case of a collision mitigation, the speed reduction is computed.

The Figure 2 summarizes the simulation algorithm.

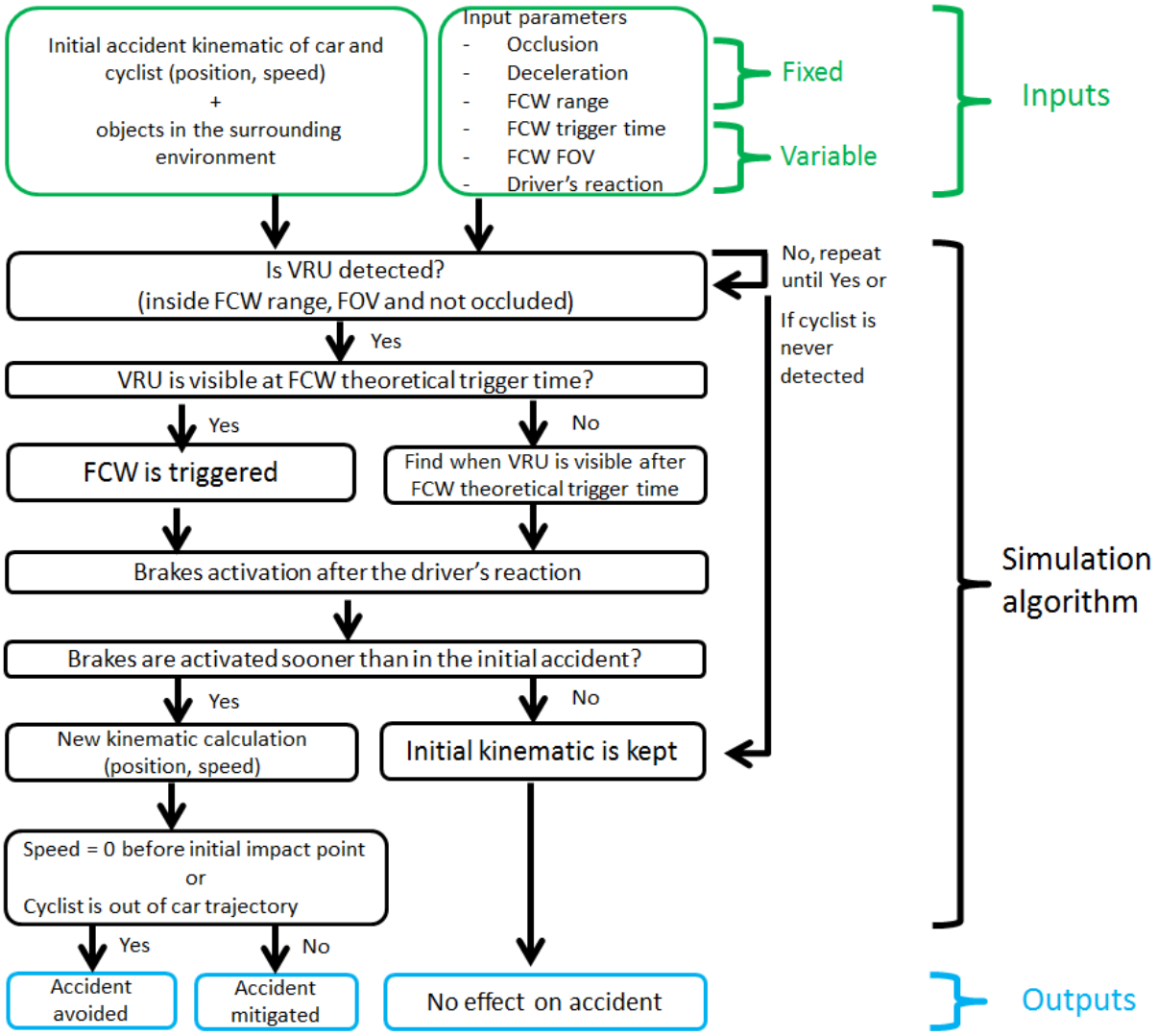


Figure 2: Accident simulation algorithm with FCW effect.

Figure 3 illustrates an accident reconstruction from the EDA database with the described algorithm (images a and a') considering for the same accident a FCW with two different FOVs (images b, c and d) for a FOV=30° and images (b', c' and d') for a FOV=50°. The considered accident case is categorised into the turning left scenario. In this accident, the driver did not brake prior the collision. The original accident kinematics and bounding boxes are in black and red for the car and the cyclist respectively (Fig. 3-a and Fig. 3-a'). The red circles highlight the different cyclist's position.

For the first simulation with a FOV 30° (total detection cone of 60°), image b represents the car with the detection at TTC 2s. It can be seen that the cyclist is outside the detection cone and thus FCW is not triggered. The kinematic of the accident continues (image c and d) and the cyclist remains outside car's detection cone which leads to the impact as in the original accident with no trigger of the FCW. This simulation shows as a result that the FCW has no effect with a FCW FOV of 30°.

Image b' represents the car's detection cone at TTC 2s. It can be seen that the cyclist is inside the 50° FOV (total detection cone of 100°). Thus FCW warning message is given to the driver at TTC 2s. As in the simulation, driver needs 0.6s to start braking, the braking is triggered at TTC 1.4s prior the impact (image c'). In image d' which is TTC 0s, it can be seen that the vehicle has stopped earlier. Here the bounding boxes of the car and the cyclist do not intersect. Thus this simulation leads to an accident avoidance.

Original accident kinematics	New accident kinematics with FCW (FOV 30°, FCW Trigger 2s, driver's reaction 0.6s)		
TTC 0s	TTC 2s	TTC 1.4s	TTC 0s

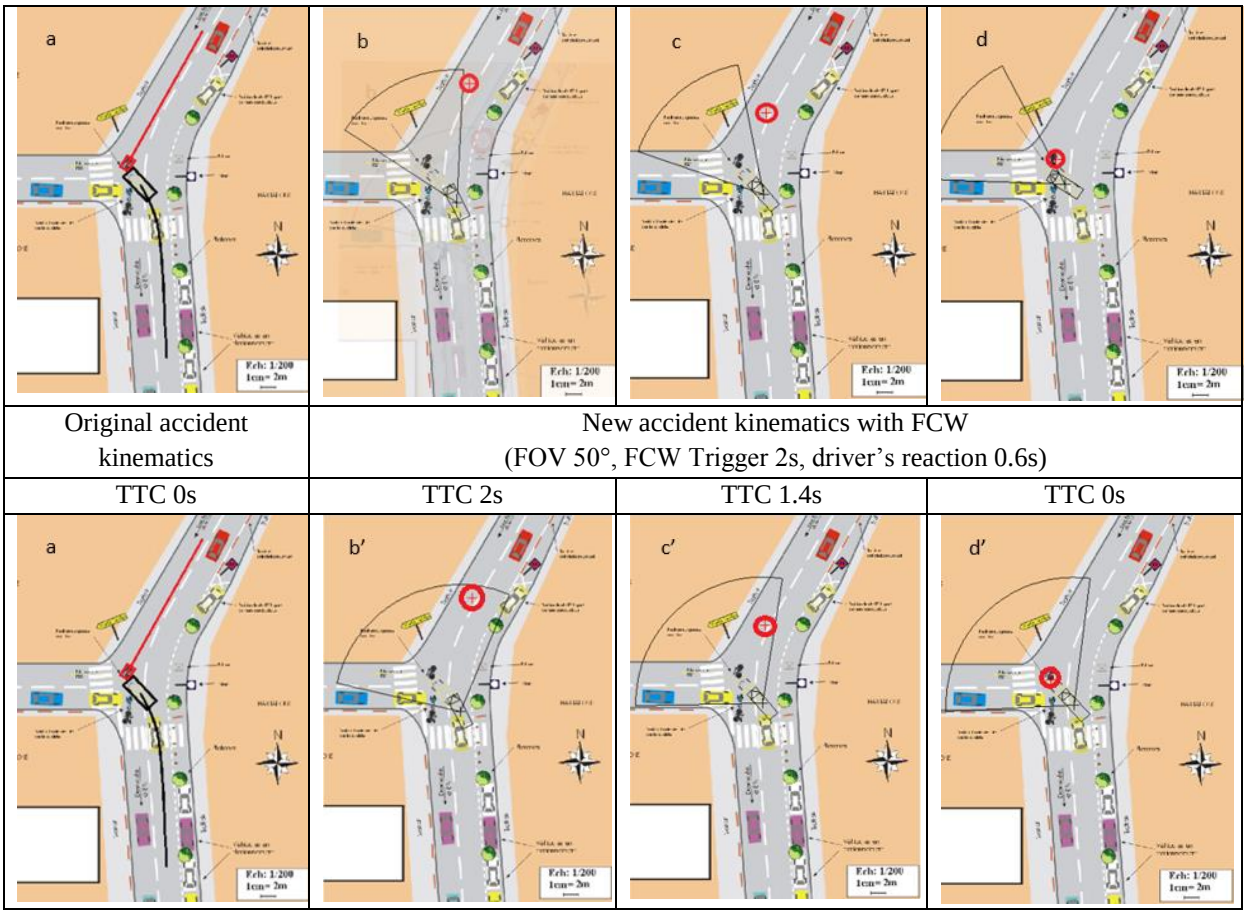


Figure 3: Reconstruction simulation example integrating the effect of FCW. Images a and a' represent the original accident kinematic. Images b, c and d represent a simulation where the FCW has no effect as it is not triggered due to a little FOV (30°). Images b', c' and d' illustrate collision avoidance with a FCW 50° triggered at TTC 2s resulting in a braking activation at TTC 1.4s.

2.5 Parametric analysis description

As presented before, FCW performances can vary depending on detection sensor FOV, FCW trigger time and driver's reaction to the warning. FCW performances can additionally be affected by obstacles obstructing the FOV. In this study, obstruction is kept as in the real accident and no variation is performed on the obstruction and timing. Therefore the parametric analysis varies only on sensor FOV, FCW trigger time and driver's reaction to the FCW:

- The FOV value corresponds to half of the detection cone, i.e. a FOV of 50° corresponds to a detection cone of 100°. The parametric analysis considers three FOV values (30°, 50° and 70°) which correspond to 60°, 100° and 140° detection cone respectively. The choice of these values is motivated by the fact that for an optimistic pedestrian detection, Hamdane et al. (2015) found that a 35° FOV appears to be optimum. As cyclist speed is higher than pedestrian's one, the maximum FOV has been doubled compared to the optimal value found by Hamdane et al. (2015) study and an intermediate value (50°) is chosen in addition.
- FCW trigger time represents the time-to-collision (TTC) when the warning is emitted if a cyclist is detected in the FOV and range of the sensor. FCW trigger times considered in this study are 1.7s, 2s, 2.3s and 2.6s TTC according to the Euro NCAP protocol (Euro NCAP 2019a). FCW trigger time can be later than these theoretical values if the cyclist is obstructed by an object in the accident scene at the time of the theoretical trigger. In this case, the FCW is triggered later when the cyclist becomes visible.
- Driver's reaction time corresponds to the latency between the FCW trigger and the brake application. It corresponds to the time necessary to a driver receiving a FCW to process the information and activate the brakes. Bucsuházy et al. (2016) analysed driver reaction time under expected, unexpected stimulus and under critical braking situation. They found that decision time combined to muscle response time median value was lower than

0.5 second when participants were instructed how to react to a visual stimulus. Johansson and Rumar (1971) analysed drivers' reaction time in unexpected traffic situation and found that the median braking response time was 0.9 second. Abe and Richardson (2005) found that the mean braking reaction time was between 0.88 to 1.11s in a car-following situation depending on the trigger time of an alarm and the lead vehicle deceleration (the more critical the situation was, the smaller the reaction time was). Work load effect when phoning while driving was studied by Haque and Washington (2013) who showed that detecting an event in peripheral vision when engaged in a hand free or a handheld phone conversation was longer compared to no phone conversation condition. Calvi et al. 2015 showed that due to phone conversation, driving performance were reduced in car-following conditions with car speed reduction as compensation. Makishita and Matsunaga (2008) also studied the influence of mental workload for different age groups on driver reaction. They showed that mental calculations which can be represented as a mental distraction close to an intense phone discussion, increased reaction time for all age groups and particularly for elderly drivers. Reaction time could be increased up to 0.5s for elderly drivers whereas for middle and young drivers, the value went up to 0.2s. Considering these studies, latencies of 0.6, 0.9 and 1.2s for driver's reaction are considered.

3. Results

3.1 Accident classification

Accident distribution within the five main scenarios is shown in Figure 4. Crossing scenario accounts for 55% of our sample. Among the crossing scenario, 33% cases are CN and 22% are CF. Turning scenario represents 34% of the overall sample, 12% of turning cases are TL and 22% are TR. L scenario represents only 5% of our accident sample. Other scenario cases account for 6% of the overall sample.

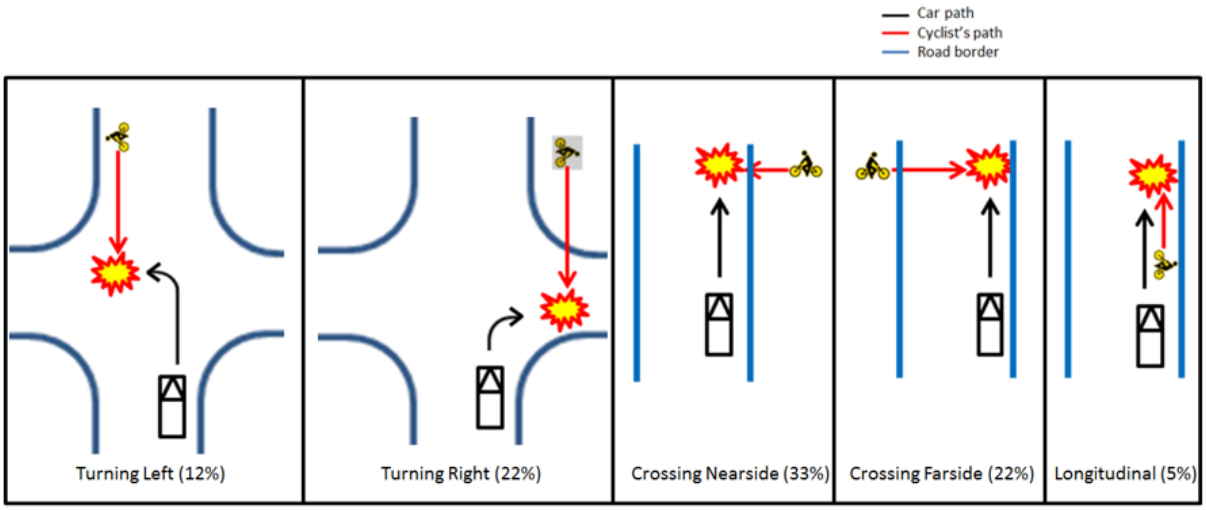


Figure 4 : Case distribution over the 5 main scenarios

3.2 Simulation results

Effect on kinematics of the 2261 car-to-cyclist accidents included in EDA and PCM databases was calculated using the simulation tool and considering parameter variations as described previously (3 FOV values, 4 FCW trigger time and 3 driver reaction values). In total, 81396 simulations were performed. Figure 5 shows the overall results as the proportion of mitigated cases versus the proportion of avoided cases. The proportion of cases where there is no effect can be obtained by subtracting the sum of the avoided and mitigated cases to 100%.

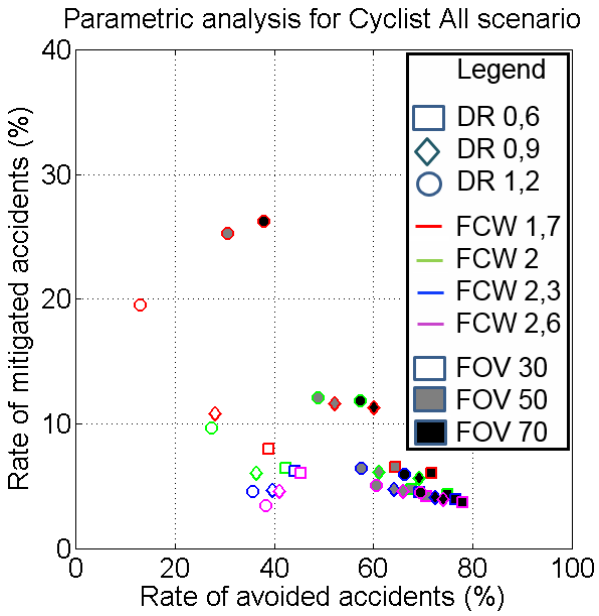


Figure 5: Results of the parametric analysis for all cyclist accidents (N = 2261)

As expected, earlier reaction (i.e. earlier FCW and quicker driver reaction) and high FOV maximize avoidance. Later reaction (i.e. later FCW and slower driver reaction) and high FOV maximize mitigation. A 70° FOV combined with a FCW 2.6s TTC and driver's reaction of 0.6s can affect positively 82% of our sample by avoiding 78% of the cases and mitigating 4% of them. Still a longer reaction time of 1.2s for a 70° FOV with a 2.6s FCW trigger allows avoiding about 69% of cases and mitigating 5% of them. To reach at least 50% avoidance, it appears that a FOV 50° is required if drivers react in 0.9s whatever the alarm timing.

It can be noticed that a non-neglected accident proportion are not affected by FCW (about 20%). It can be caused by the cyclist being still outside of the sensors maximum FOV (70°) or sensor range (value fixed at 50m) in the case of high driving speed by the car. FCW has also no effect in our simulations if the brake timing as recorded in the pre-crash databases happened earlier than the one computed by the simulation algorithm.

Figure 6 shows the results of the same parametric analysis split by accident scenario.

For CN scenario, avoidance rate goes from 11 to 81% while mitigation rate goes from 5 to 25%. With the best parameter set considered in this paper, at least 88% accidents could be positively affected by the FCW system with 81% avoidance and 7% mitigation. With regard to driver's reaction, more than 50% avoidance rate could be achieved if this parameter is considered to be 0.9s, whatever the trigger time of the FCW if the FOV is at least 50°.

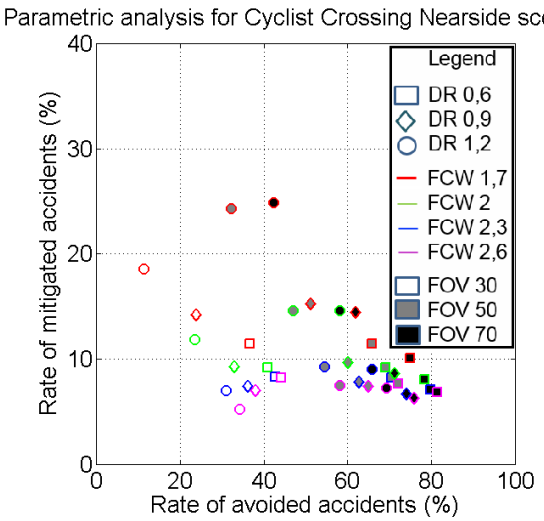
For CF scenario, avoidance rate goes from 10 to 93% while mitigation rate goes from 1 to 34%. With the best parameter set considered here, 94% accidents can be avoided or mitigated. 50% avoidance rates could be reached with a FOV of 50° and if the driver reacts in 0.9s whatever the trigger timing of the device.

For L scenario, avoidance rate goes from 12 to 81% while mitigation goes from 2 to 53%. With the best parameter set considered here, at least 84% cases can be avoided or mitigated. In this scenario, the FOV influence is not as critical as it can be in other scenarios. As the cyclist may already be in front of the car, then the needed FOV to detect the cyclist can strongly be reduced. A focus on the trigger time and on the driver's reaction is more needed on this particular scenario. It can be highlight that if a driver reacts in 1.2s, the avoidance rate drops drastically between FCW 2.3s and FCW 2s even if the avoidance rate remains close to 50%.

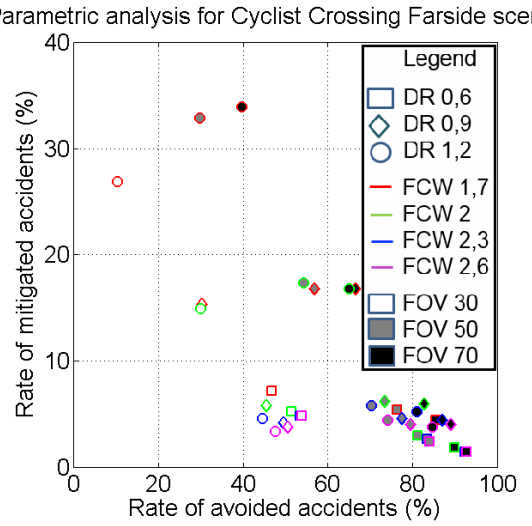
For TL scenario, avoidance rate goes from 28 to 87% while mitigation goes from 2 to 30%. With the best parameter set considered here, a positive effect can be estimated for 90% of the cases. It can be noticed that a 50% avoidance rate is reached for the values studied in this paper except if drivers react in 1.2s.

For TR scenario, avoidance rate goes from 14 to 76% while mitigation goes from 2 to 21%. With the best parameter set, positive effect could be observed for 79% cases. A gap can be observed in figure 5e between 30° FOV detection and 50 and 70°. To affect at least 50% of cases, a FOV of 50° is required with a FCW trigger at 2s.

In summary, the best parameter set in this study and identified for each scenario can affect about 88% of CN cases (81% avoided and 7% mitigated), 94% of CF cases (93% avoided and 1% mitigated), 84% of L cases (81% avoided and 3% mitigated), 90% of TL cases (87% avoided and 3% mitigated) and 79% of TR cases (76% avoided and 3% mitigated). These results show that FCW would have the highest benefit in the CF scenario whereas TR scenario would be the most challenging to optimise FCW parameters. It can be noticed that with a FOV of 50° and with a driver's reaction of 0.9s, avoidance rates reach more than 50% whatever the scenario with a mitigation rate up to 21% depending the scenario. Table 1 sums up the parameter values that allow reaching the maximum sum of the mitigation and avoidance rates in all scenarios and at least 50% for the sum of the mitigation and avoidance rates in all scenarios.



a)



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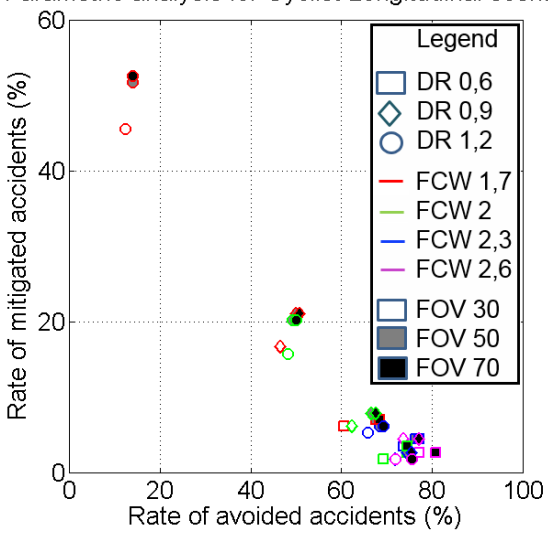

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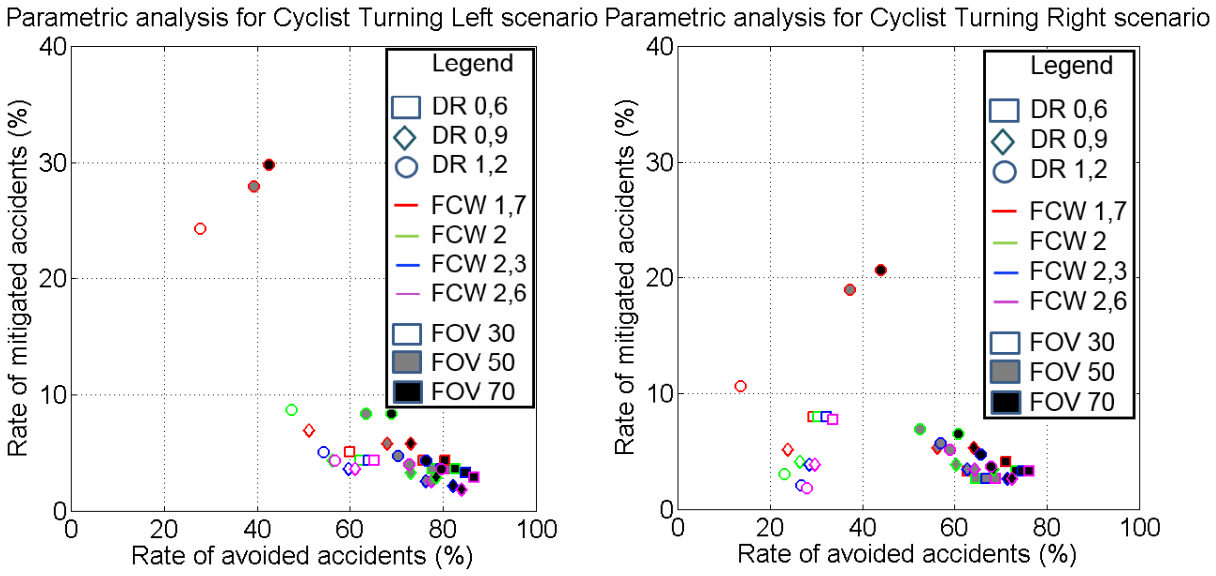

d) e)

Figure 6: Results of the parametric analysis per scenario (a. Crossing Nearside, b. Crossing Farside, c. Longitudinal, d. Turning Left, e. Turning Right).

		CN	CF	L	TL	TR
FOV 70°, FCW 2.6s, DR 0.6s	Avoidance rate	81%	93%	81%	87%	76%
	Mitigated rate	7%	1%	3%	3%	3%
FOV 50°, all FCW, DR 0.9s	Avoidance rate	51%	57%	50%	68%	56%
	Mitigated rate	15%	17%	21%	6%	5%

Table 1: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance and mitigation rate in all scenarios.

4. Discussion

This research estimates the potential safety benefit of a FCW system based on the simulation of 2261 real-world car-to-cyclist accident cases. The accuracy of the estimated benefit is of course influenced by the FCW model but also is highly dependent on the accident reconstruction quality. In-depth accident investigations allow reconstructing the accident pre-crash phase kinematic, however it is difficult to gather data on the dynamic surroundings, such as moving vehicles that may have occluded the cyclist prior to impact.

Regarding the addition of the FCW, several assumptions are made through the algorithm:

- The driver is assumed to brake along the reconstructed car trajectory and does not attempt evasive manoeuver. Consequently, when applying the brake in the simulation, the car original trajectory is kept and extrapolated in time after the time zero is reached in the real accident. This assumption seems acceptable considering current knowledge on driver reaction in evasive manoeuvres and due to the lack of data about the dynamic environment (Hayashi et al. 2012).
- The brake activation depends on the FCW trigger time and also on the original accident. If brake activation in the original accident is earlier than the FCW trigger time, then no effect is considered in simulation and the original kinematic is kept. It could be argued that a FCW could help to increase the force applied by the driver on the brake from the beginning of the braking. Further research could analyse if the FCW could improve driver's initial braking especially for late triggering. In the case where the driver brakes moderately before the impact, the FCW benefits is unknown.
- The brake model is simplified as an ideal braking model has been considered. A more realistic model will reduce the safety benefit observed in this study.
- The detection sensors triggering the FCW are considered as ideal as they can detect the cyclist whatever the conditions (e.g. weather like rain, fog or by sudden illumination changes).

- The detection sensor is assumed to be located in car geometrical centre whereas cameras are generally placed on the windshield at the central mirror. This should be acknowledged as increasing slightly the detection cone.
- The system algorithm is also assumed being able to predict accurately the path of the cyclist to trigger appropriately the FCW.

Despite all these assumptions and limitations, the analysis gives some general trends for each accident scenario. The FOV has a higher effect than brake application timing resulting from the combination of the FCW trigger time and driver reaction latency. This effect can be explained by the fact that if the cyclist is not detected (not inside the FOV or not inside detection range due to car and/or cyclist speed), then the FCW does not trigger and then there is also no driver's reaction. This way, cyclist detection is important in order to be able to trigger an alarm. This trend can be found in CN, CF, TL and TR scenarios. For L scenario, FOV parameter has less influence due to the scenario configuration. Due to the trajectories of both the cyclist and the car, the cyclist is already inside the detection field of view and thus detected.

It seems that the highest benefit of the FCW is obtained for Crossing Farside and Turning Left scenarios while the least benefit is obtained for the Turning Right scenarios.

To authors' knowledge, this is the first study in which the potential effect of FCW is examined per scenario. However, some recent studies have analysed AEB benefit. The main difference between current paper and others is on the introduction of variations for the driver reaction. Lenard et al. (2018) analysed the characteristics for an AEB and found that 90% cyclists were within a ±80° FOV (e.g. a total 160° angle) and within 50m far from the car. Thus, collisions with cyclist can be highly reduced with wider FOV. Even if our FOV parameter does not reach the 80° value, it can be noticed that a 70° FOV (e.g. total FOV of 140°) and a 50m range FCW also greatly affect positively the avoidance and the mitigation rates. Zhao et al. (2019) analysed the AEB effectiveness based on accident reconstructions from video recorder mounted on taxi vehicles. They showed that FOV parameter has a significant influence on collision avoidance. The higher is the FOV, the more accident can be avoided. They also found that with an ideal AEB system, i.e. no system braking delay and 360° detection cone, some collisions were unavoidable due to cyclists' sudden appearance in front of the car. This result is similar to the results found in this study. Collisions can be avoided at best but in some cases, the visibility criterion is so important that even mitigation is not possible when the cyclist becomes only visible when very close to the car. Ohlin et al. (2017) analysed the effect of combined measures in reducing real life bicycle injuries on Swedish accidents. They found that AEB effectiveness can reach 70% for pedestrians and cyclists. Rosén (2013) also worked on cyclist AEB on 607 GIDAS-PCM cyclist cases. He also found positive effect for 55% of fatal cases and 33% of severe cases. Yue et al. (2018) also assessed the benefits of ADAS. The conclusion of their review study estimated that collision avoidance systems are limited to 70% effectiveness rate. Even if our results for FCW are optimistic, Ohlin et al. (2017), Rosén (2013) and Yue et al. (2018) results illustrate the high potential ADAS can have on road safety for bicycle.

Wu et al. (2017) examined avoidance strategies for drivers equipped with a FCW for rear-end collision. They found difference depending on the driving experience. Older drivers with more experience tend to steer if there are no car in the others lane contrary to younger drivers who are more likely to brake to reduce accident severity. Also according to Bueno et al. (2014), FCW device is effective on low distracted drivers. However, depending on the distraction level, it can affect the visual behaviour and then braking performance (Harbluk et al. 2007). It may also play a role in the case of an unexpected event that is not perceived by the driver. One of the challenge for the FCW design might be the Human Machine Interface (HMI) to ensure a detected VRU by the car sensors is also detected by the driver. This way, FCW can help drivers to manage faster a hazardous situation if he did not anticipate the risk. However, one critical challenge for FCW design is highlighted by Dozza et al. (2017). Driver response depends on factors like visibility or time-to-arrival which is the time to arrive to a pedestrian or cyclist. Thus determining the most appropriate warning time to get the most appropriate reaction to a hazard is an important point. This is why, during the design of such system, the choice of the driver model has to be considered carefully. As shown by Bärgman et al. (2017), the choice of the driver models is of importance when considering the evaluation of a non-automatic ADAS like FCW. The driver reaction depends also on the FCW. Indeed, it appears that the type of signal (audio, video, haptic) can play an important role to reach an optimal reaction of the driver. Lylykangas et al. (2016) analyzed drivers' reaction time in emergency scenarios with FCW. They found that tactile and visual-tactile signals help drivers react faster compared to an only visual signal. Aust et al. (2013) also analyzed a combination of audio and visual signal in order to study FCW effect for

repeatedly exposure on emergency braking. They found that the more drivers were exposed to FCW, the faster they can react to the signal. This is also confirmed by Koustanaï et al. (2012) where the FCW was more effective with familiarized drivers compared to unfamiliarized. Variations of driver reaction considering above parameters are considered in this paper by including a large range of driver reaction time (from 0.6 to 1.2s) but are not varied depending on driver's characteristics in our samples. Additionally, acceptance of the FCW by the driver and quicker reaction to it may depend on the balance between the number of true positive and false negative FCW trigger.
Predicting driver's intention might be of interest in order to maximise true positive system activation, thus reduce driver's annoyance (Diederichs et al. 2015) and alarm the driver earlier if it is identified that the driver has no awareness of the risk.

5. Conclusion

The theoretical benefits of a cyclist FCW is evaluated based on 2261 car-to-cyclist accidents. Using accident pre-crash phase reconstructions, the effect of the FCW is modelled in order to determine if the accident can be avoided or mitigated. Results show that an earlier reaction (i.e. earlier FCW and quicker driver reaction) and high FOV maximize avoidance. Later reaction (i.e. later FCW and slower driver reaction) and high FOV maximize mitigation. Except for L scenario, FOV has the largest effect on avoidance rate.
Results in this study are optimistic and show the benefit margin considering various combinations of FOV, FCW trigger times and driver reaction to the warning. Our paper also highlights the most important parameter among FOV, FCW trigger time and driver reaction for each of the five main car-to-cyclist accident scenarios. It also reveals that CF and TL are the scenarios in which FCW can have the highest benefit whereas the CN and TR are the most challenging scenarios.
The simulation tool was applied previously to car-to-pedestrian accidents and in the current paper to car-to-cyclist accidents. It could be extended to car-to-powered two-wheelers accidents in future.

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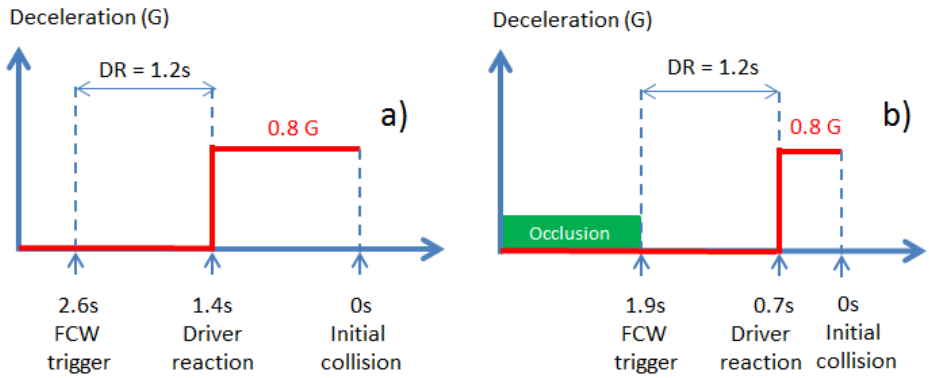
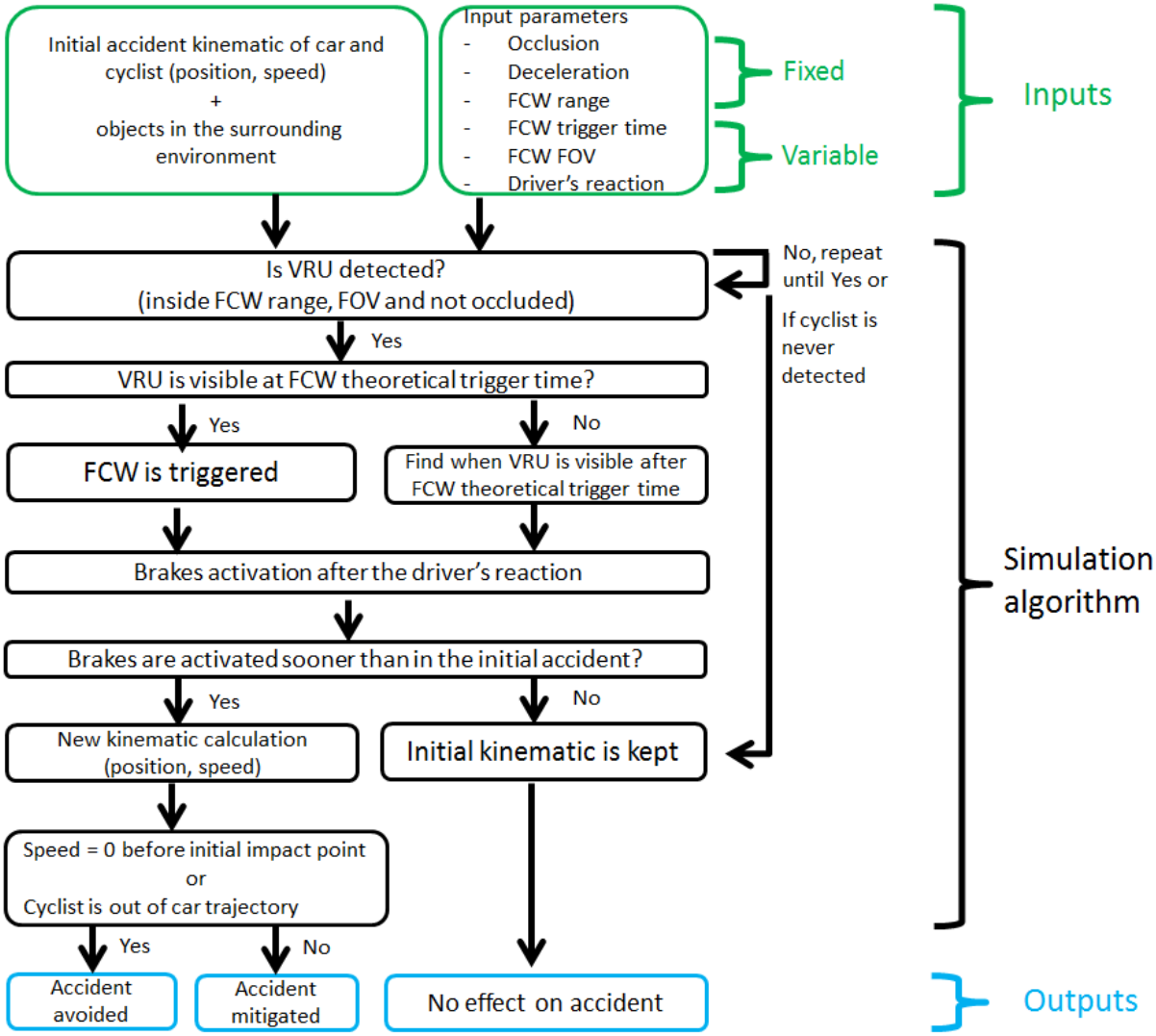
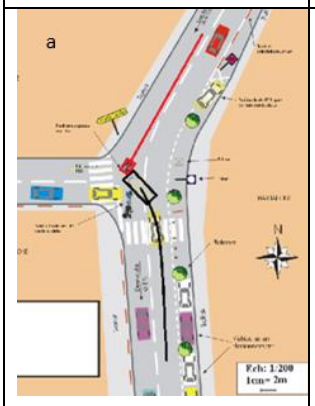
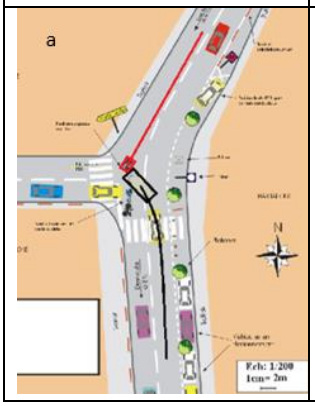
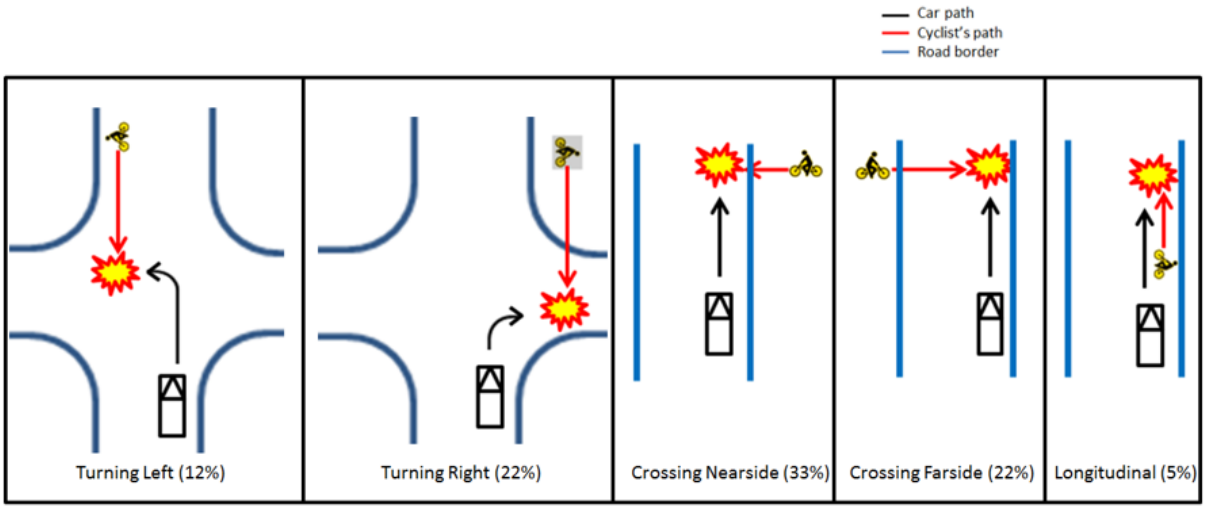
		CN	CF	L	TL	TR
FOV 70°, FCW 2.6s, DR 0.6s	Avoidance rate	81%	93%	81%	87%	76%
	Mitigated rate	7%	1%	3%	3%	3%
FOV 50°, all FCW, DR 0.9s	Avoidance rate	51%	57%	50%	68%	56%
	Mitigated rate	15%	17%	21%	6%	5%

Table 1: Parameter combinations that allow reaching a maximum avoidance and mitigation rate and at least 50% avoidance and mitigation rate in all scenarios.

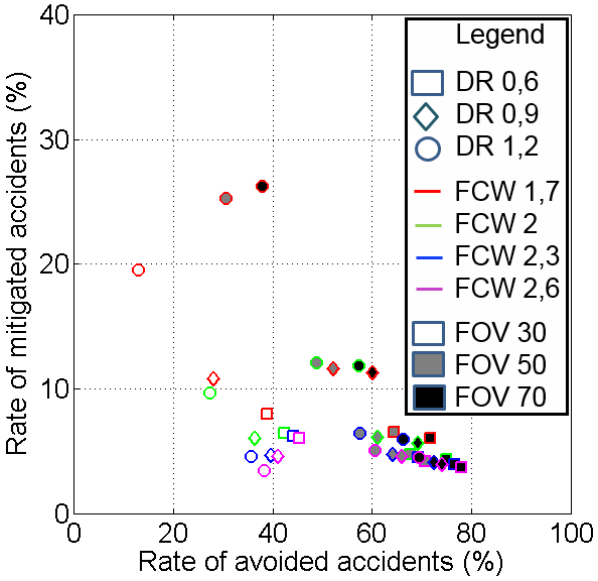

Deceleration (G)
DR = 1.2s
0.8 G
a)
2.6s
FCW
trigger
1.4s
Driver
reaction
0s
Initial
collision
Deceleration (G)
DR = 1.2s
0.8 G
b)
Occlusion
1.9s
FCW
trigger
0.7s
Driver
reaction
0s
Initial
collision


Initial accident kinematic of car and cyclist (position, speed)
+
objects in the surrounding environment
Input parameters
- Occlusion
- Deceleration
- FCW range
- FCW trigger time
- FCW FOV
- Driver's reaction
Fixed
Variable
Inputs
Is VRU detected?
(inside FCW range, FOV and not occluded)
No, repeat until Yes or
If cyclist is never detected
Yes
VRU is visible at FCW theoretical trigger time?
Yes
No
FCW is triggered
Find when VRU is visible after FCW theoretical trigger time
Brakes activation after the driver's reaction
Brakes are activated sooner than in the initial accident?
Yes
No
New kinematic calculation (position, speed)
Initial kinematic is kept
Speed = 0 before initial impact point
or
Cyclist is out of car trajectory
Yes
No
Accident avoided
Accident mitigated
No effect on accident
Simulation algorithm
Outputs

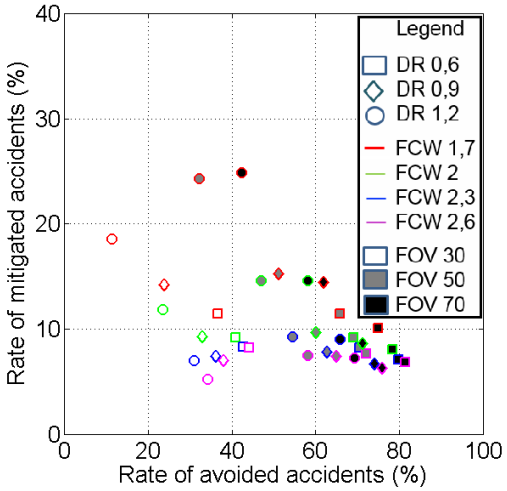
Original accident kinematics	New accident kinematics with FCW (FOV 30°, FCW Trigger 2s, driver's reaction 0.6s)		
TTC 0s	TTC 2s	TTC 1.4s	TTC 0s
			
Original accident kinematics	New accident kinematics with FCW (FOV 50°, FCW Trigger 2s, driver's reaction 0.6s)		
TTC 0s	TTC 2s	TTC 1.4s	TTC 0s
			



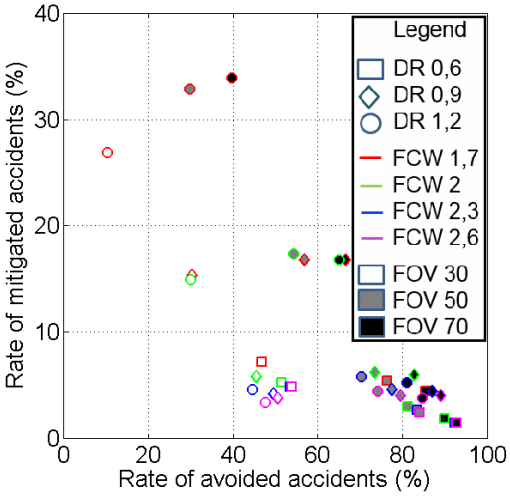
Parametric analysis for Cyclist All scenario



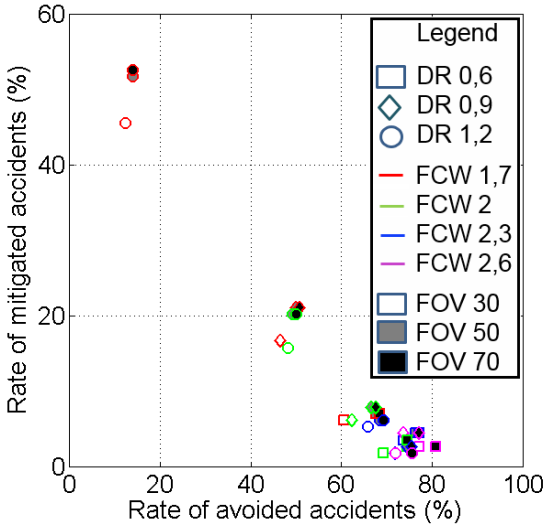
Parametric analysis for Cyclist Crossing Nearside scenario



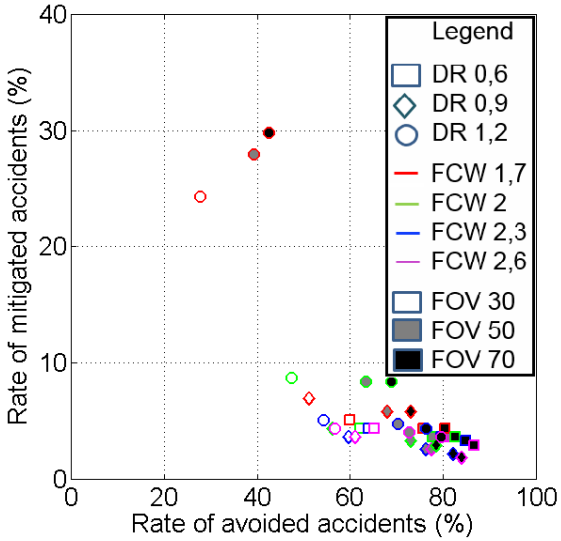
Parametric analysis for Cyclist Crossing Farside scenario



Parametric analysis for Cyclist Longitudinal scenario



Parametric analysis for Cyclist Turning Left scenario



Parametric analysis for Cyclist Turning Right scenario

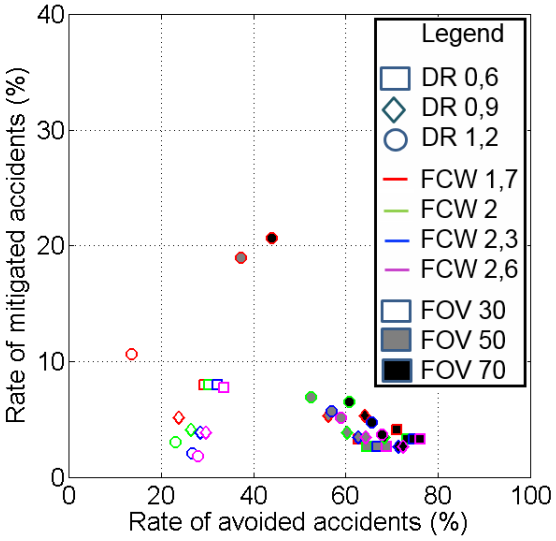


Figure 1: FCW trigger model in the simulation. In this example the FCW theoretical trigger is 2.6s. In case a) the FCW triggers at its theoretical time of 2.6s with brake activation 1.2s later. In the case of occlusion b), the FCW triggers when the cyclist is visible for the first time after the theoretical trigger time which is 1.9s and then, brakes are activated 1.2s later.

Figure 2: Accident simulation algorithm with FCW effect

Figure 3: Reconstruction simulation example integrating the effect of FCW. The first line represents a simulation where the FCW has no effect as it is not triggered (image a, b, c and d). The second line illustrates collision avoidance with a FCW triggered at TTC 2s resulting in a braking activation at TTC 1.4s (image a', b', c', d').

Figure 4 : Case distribution over the 5 main scenarios

Figure 5: Results of the parametric analysis for all cyclist accidents (N = 2261)

Figure 6: Results of the parametric analysis per scenario (a. Crossing Nearside, b. Crossing Farside, c. Longitudinal, d. Turning Left, e. Turning Right).