# Elastic Band Based Pedestrian Collision Avoidance using V2X Communication

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*Abstract*— **This paper is on a pedestrian collision warning and avoidance system for road vehicles based on V2X communication. In cases where the presence and location of a pedestrian or group of pedestrians cannot be determined using line-of-sight sensors like camera, radar and lidar, signals from pedestrians' smartphone apps are used to detect and localize them relative to the road vehicle through the DSRC radio used for V2X communication. A hardware-in-the-loop setup using a validated automated driving vehicle model in the high fidelity vehicle dynamics simulation program Carsim Real Time with Sensors and Traffic is used along with two DSRC modems emulating the vehicle and pedestrian communications in the development and initial experimental testing of this method. The vehicle either stops or, if possible, goes around the pedestrians in a socially acceptable manner. The elastic band method is used to locally modify the vehicle trajectory in real time when pedestrians are detected on the nearby path of the vehicle. The effectiveness of the proposed method is demonstrated using hardware-in-the-loop simulations.**

***Keywords—pedestrian collision avoidance, V2X communication, elastic band method***

## I. Introduction

Connected and autonomous vehicles are expected to be available in series production in the near the mid-term future [1]. Collision avoidance is an active and important field of current research in autonomous driving and has, thus, been treated extensively in the literature. [2] proposes an active collision avoidance system which integrates estimation of conflict probability, model predictive control and dedicated short-range communications (DSRC) techniques to allow safe lane-changing maneuvers by self-steering vehicles in the presence of the uncertainties associated with nearby vehicles and the surrounding environment. Another collision avoidance system is presented in [3] based on the information provided by a laser scanner sensor, in which the system first tries to stop the vehicle and then controls vehicle steering to change the vehicle trajectory in order to avoid the accident if reduction in speed is not sufficiently effective.

A collision avoidance algorithm based on state estimation was proposed in [4] by introducing the concept of force fields and warning function in a roundabout, ensuring safety when vehicles are close to the conflict area by selecting the safety operation mode. [5] presents the implementation of an obstacle avoidance method on an automated guided vehicle using stereoscopic vision by creating a disparity map and measuring the relative distances of the objects in the scene. The method in [5] not only avoids collision but it also classifies the detected object into one of the specified categories using a supervised learning algorithm.

Cooperative Collision Avoidance (CCA) is a relatively new research topic. There are no many studies in the literature about CCA by means of V2X (Vehicle-to-Everything) communication technologies. According to CCA research studies, CCA systems rely on V2V (Vehicle-to-Vehicle) communications [6-8] or Vehicle-to-Infrastructure (V2I) communications [6] to detect the possibility of an accident and also to achieve cooperative collision avoidance [7]. The major reason for using CCA systems in VANETs (Vehicular ad hoc networks) is the noticeably long response time of any human driver to apply the brake following an emergency scenario [8].

In advanced cooperative collision avoidance systems the position of vulnerable road users (VRU) is provided by vehicle-to-vehicle, vehicle-to-infrastructure [9] or vehicle-to-pedestrian (V2P) communication (collectively referred to as V2X). In many situations, pedestrians cannot be detected by vehicle sensors because of a limited field of view, extreme weather conditions or obstructions. Cooperative methods based on V2X communication have the potential to provide an alternative solution in those cases [9].

DSRC is a short- to medium-range wireless communication channel, operating in the 5.8 or 5.9 GHz wireless spectrum, specifically designed for automotive use. Time critical safety related systems in the connected vehicle environment are based on DSRC [10]. DSRC technology provides many advantages like interoperability, high reliability, fast network acquisition, low latency, privacy and security [6, 7]. The U.S. Department of Transportation (DOT) has estimated that Vehicle-to-Vehicle (V2V) communication based on DSRC can address up to 82% of all crashes in the United States involving unimpaired drivers, potentially saving thousands of lives and billions of dollars [11].

DSRC technologies were developed specifically for vehicular communications. The most important motivation for using DSRC is to enable collision prevention applications.

The most attractive features of DSRC technology are low latency and high speed data exchanges, which are important for the V2X latency-critical safety applications [6, 7]. These applications can also provide safety benefits to vulnerable road users such as pedestrians and cyclists.

Autonomous and conventional vehicles can use advanced sensors to detect obstacles and avoid V2P collisions [12]. However, they still have a problem in detecting a person blocked by vehicles, trees or building corners (Non-Line-of-Sight, abbreviated NLoS)). They also have difficulty in seeing or sensing the other side of a hilly/curved road [13]. In these conditions, it is also more difficult for drivers to notice the pedestrian in time and avoid the accident. Although sensor fusion can tackle this to some extent, the NLoS scenarios will not be fully resolved [14-16]. Recently, the city of New York has been using V2X and smartphone based technologies for improving pedestrian safety [14].

Under blocked visibility and extreme weather conditions, we can use vehicle-to-pedestrian wireless communication to swap messages between road users, sending their location, speed, and direction retrieved from sensors [13]. Experiments and evaluations [18, 19] show that using WiFi is not practical in all collision avoidance scenarios. Unlike IEEE 802.11p, WiFi suffers from limited communication range [15, 20] and weak mobility support [13]. Moreover, DSRC is the only short-range wireless technology that provides performance that is immune to bad weather conditions (e.g., fog, heavy rain, snow) [15]. The mobile-accessible pedestrian signal system would use DSRC to communicate information. On the other hand, DSRC hardware is not available on current smartphones yet and the effort to adapt it for smartphones has started only recently [15, 21].

In August 2013, Honda announced its development of a V2P communications technology based on DSRC on 5.9 GHz for pedestrian Safety [16]. Authors of [17] integrate DSRC into conventional smartphones without doing any hardware or chip upgrade. The smartphone is used only on the pedestrian side while vehicles use dedicated hardware [13]. They implemented firmware and software of the DSRC stack within the Wi-Fi chipset on the smartphone, utilizing the smartphone GPS capability for positioning. They performed real-world use field tests with vehicles and developed DSRC smartphones [17]. In this paper, we assume that all pedestrian smartphones are equipped with this capability.

The future V2X network will be heterogeneous to support communications between devices with different moving patterns via several communication interfaces such as DSRC, LTE, and WiFi [20, 23, 24]. Development of future V2X solutions are expected to balance various issues such as the implementation cost, performance in real environments, and compatibility with the current vehicular network system solutions.

This paper is on collision avoidance of a road vehicle equipped with a DSRC V2X modem with pedestrians equipped with modified smartphones that can communicate with these modems. The organization of the rest of the paper is as follows. Section II introduces the elastic band based method for locally deforming the autonomous vehicle path for avoiding collision while maintaining the desired social distance with the pedestrians, if necessary. Section III is on the hardware-in-the-loop simulator used in the development and HiL simulation evaluation of the collision avoidance method introduced in this paper. HiL simulation results are presented in Section IV and the paper ends with conclusions in Section V.

## II. COLLISION AVOIDANCE ALGORITHM AND COOPERATIVENESS

Our autonomous vehicle uses coordinated longitudinal cruise and lateral steering controllers designed using parameter space methods [25, 26]. Our collision avoidance algorithm is based on the use of the elastic band theory [27, 28] for collision free path planning and collision avoidance. In the elastic band method, the initial trajectory of the vehicle is deformed by internal and external forces acting on the band if an obstacle with collision risk is determined. In [18], a socially acceptable distance was added to the deformed trajectory in order to respect the social distance of pedestrians.

In Figure 1, the internal forces act like spring forces which hold the elastic band together while external forces keep the band away from obstacles like artificial potential field generated forces. The initial vehicle path in Figure 1 is treated as an elastic band in the vicinity of an obstacle with collision risk and is deformed by both internal and external forces to maneuver the vehicle around the obstacle if possible. If this is not possible, the vehicle stops and waits for the obstacle to move away.

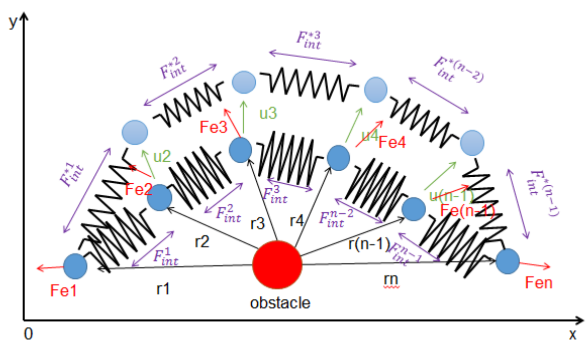


Figure 1: An initial path deformed by internal and external forces with the presence of an obstacle.

Ignoring the system dynamics, we can define the variation of internal forces as follows:

$$F_{int}^{*i} - F_{int}^{i} = k_s(u_{i+1} - u_i) \quad (1)$$

Where $F_{int}^{*i}$ and $F_{int}^{i}$ are final and initial forces in the ith elastic band part. $k_s$ is the spring constant and $u_i$ is the displacement of the ith knot. On the other hand, the external force $F_{ei}$ acting on i^th knot can be modeled as follows:

$$F_{ei} = -[k_s(u_{i+1} - u_i) + k_s(u_{i-1} - u_i)] \quad (2)$$

For simplicity, external force $F_{ei}$ can be written with their $x$ and $y$ components in matrix form as:

$$F_{ex,ey} = \mathrm{k_s} K u_{x,y} \quad (3)$$

where

$$F_{ex,ey} = \begin{bmatrix} F_{ex1} & F_{ey1} \\ F_{ex2} & F_{ey2} \\ \vdots & \vdots \\ F_{exn} & F_{eyn} \end{bmatrix} \; u = \begin{bmatrix} u_{x1} & u_{y1} \\ u_{x2} & u_{y2} \\ \vdots & \vdots \\ u_{xn} & u_{yn} \end{bmatrix} \quad (4)$$

and

$$K = \begin{bmatrix} -1 & 2 & -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 2 & -1 & 0 & \dots & 0 \\ \dots & \ddots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \dots & -1 & 2 & -1 \end{bmatrix} (5)$$

External force $F_{ex,ey}$ acting on each knot is obtained by

$$F_{ex,ey} = \begin{cases} -ke\left(\|r_{x,y}\| - r_0\right)\frac{r_{x,y}}{\|r_{x,y}\|}, \|r_{x,y}\| \le r_0 \\ 0, \; \|r_{x,y}\| > r_0 \end{cases} \quad (6)$$

where $r_{x,y}$ is the position vector between each knot and the obstacle. $ke$ is the stiffness value for the external force constant, and $r_0$ is the threshold distance.

Combining equations (3) and (6), we can determine the displacement of the knot as

$$u_{x,y} = (\frac{1}{\mathrm{k_s}})K^{-1}F_{ex,ey} \quad (7)$$

Since the elastic band has to be held on the initial path, the first and the last knot should be fixed. So, we have $u_{x1,y1} = [0,0]$ and $u_{xn,yn} = [0,0]$. Therefore, the final position of the knot $P_{x,y}^{def}$ on the deformed path can be calculated as

$$P_{x,y}^{def} = P_{x,y} + u_{x,y} \quad (8)$$

where $P_{x,y}$ is the initial position of the knot and $\mathrm{u_{x,y}}$ is the displacement of the knot.

In order to consider the personal space of pedestrians and ensure human safety, $d$ is compared with socially acceptable distance $d_{safety}$ and is extended when $d < d_{safety}$. Here, $d$ denotes the distance between the final position of the knot $P_{x,y}^{def}$ and the pedestrian(s). The safety regions around pedestrian(s) are shown in Fig. 2. The total socially acceptable distance from the pedestrians to the center of gravity of the vehicle is given as

$$d_{safety} = d_{ped} + d_{social} + d_{vehicle} \quad (9)$$

where $\mathrm{d_{ped}}$ stands for the distance that the pedestrian(s) may advance by during the collision avoidance maneuver, $d_{social}$ represents the personal space of the pedestrian(s) that has to be respected by the automated vehicle and $\mathrm{d_{vehicle}}$ is the distance compensating for vehicle dimension. The $d_{vehicle}$ value set for our experimental vehicle is 0.5 m and $d_{social}$ is defined as 1.5 m in this paper. $d_{ped}$ is given in equation (10) as

$$d_{ped} = \frac{V_{ped}}{V_{veh}} s \quad (10)$$

where $V_{veh}$ is the vehicle speed, $s$ is defined as the distance between the vehicle and the pedestrian(s) in the beginning of the collision avoidance maneuver. So, $\frac{s}{V_{veh}}$ can be seen as "time-to-collision". $V_{ped}$ is the velocity of pedestrian(s)' possible motion in any direction.

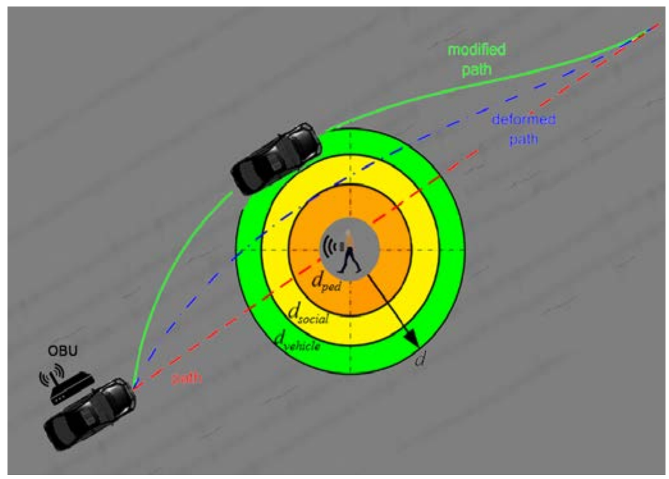


Figure 2: Illustration of Cooperative Collision Avoidance.

As a result, if the final position of the knot $P_{x,y}^{def}$ calculated from the elastic band theory is within the safety distance $d_{safety}$, the position of the knot will be adjusted to create a safety region around the pedestrian(s). The algorithm for the autonomous drive with elastic band collision avoidance is presented in the flowchart of Fig. 3.

In our V2P communication concept, we assume that pedestrians have DSRC communication capable smartphones. So, the V2P communication scenario is similar to V2V considering the low speed of pedestrians who have DSRC units. Personal Safety Message (PSM) which is defined in the SAE J2735 DSRC Message Set is used to broadcast safety data according to standards regarding the kinematic state of the pedestrian.

The pedestrian's smartphone generates and transmits the PSM (position, heading, speed, etc.) to a vehicle based OBU (On-Board Unit) over a DSRC wireless communication link. The OBU receives and interprets the PSM for the autonomous vehicle as a pedestrian warning message, which can be used to estimate the oncoming collision. If there is a collision risk, the autonomous vehicle takes necessary action immediately to avoid the collision. Figure 2 illustrates the vehicle DSRC communicating with the pedestrian smartphone, calculating the path according to the algorithm discussed above and maneuvering around the pedestrian.

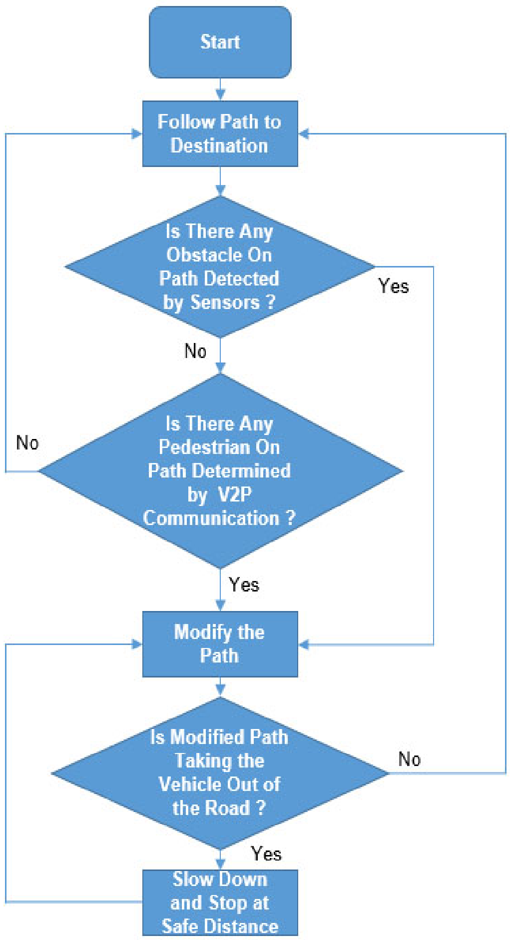


Figure 3: Flow chart of elastic band collision avoidance system.

## III. HARDWARE-IN-THE-LOOP SIMULATOR

The cooperative collision avoidance between an autonomous vehicle and pedestrian(s) is developed and tested using a hardware-in-the-loop (HiL) simulator. The HiL simulator illustrated schematically in Fig. 4 consists of three main elements. The first one is a dSpace SCALEXIO computer which runs a Simulink autonomous driving model along with a CarSim vehicle dynamics model in real-time. The second element is the dSpace Microautobox (MABX) electronic control unit which runs a Simulink model to control vehicle steering, throttle and braking in real-time. The MABX has numerous types of I/O ports that can be used for communication with other devices. It is compact and robust, thus, widely used also in the other autonomous vehicle studies. MABX and SCALEXIO communicate with each other via the Controller Area Network (CAN) bus.

The vehicle dynamics parameters in CarSim are validated using data from vehicle dynamics testing of our real autonomous vehicle. Thus, we can make sure simulation results are very close to results in the real world. This feature provides a significant advantage such as being able to transfer and implement algorithms and controllers which we simulate and develop on the HiL system into the real vehicle directly, without any significant modification.

In real-world application of CCA, the pedestrian's smartphone communicates with the DSRC modem on the vehicle, as explained in the previous section. This communication was simulated by two DSRC modems communicating with each other as shown in Fig. 4. These modems are the third main element of the simulator. The one representing the pedestrian smartphone, sends Pedestrian Safety Messages to the other modem representing the vehicle. The one representing the OBU of the vehicle, receives these messages and sends necessary information such as position and speed, to MABX via CAN.

## IV. HARDWARE-IN-THE-LOOP SIMULATIONS

In this study, two scenarios are tested with CCA where two important problems are considered. These problems are NLoS and reduced visibility due to bad weather conditions. In these conditions, it is difficult for the driver and line-of-sight sensors to detect the pedestrian in time and avoid the pedestrian without V2X technology. The vehicle has an OBU and the pedestrian has a smartphone with DSRC capability, so that they can communicate with each other.

Since the HiL simulator's two main elements run Simulink models, several models were created for these elements, representing two scenarios. The two models created for MABX include necessary controllers, ones created for SCALEXIO include CarSim vehicle dynamics. Additionally, each of them have CAN communication blocks which allows them to transfer data between each other.

### *A. First Scenario*

In the first scenario, a setting with a two-way narrow road was considered. Several vehicles are approaching from the opposite side. Suddenly, a pedestrian is running into the road and the sensors of the ego vehicle cannot detect the pedestrian because of NLoS as shown in Fig. 5. Moreover, because of the narrow road, the vehicle cannot maneuver to the left or the right to avoid the pedestrian without going out of the road.

A two-way road was modeled in CarSim, where there is currently traffic flow on the opposite lane. There is a line-of-sight sensor mounted on the front bumper of the vehicle, which can detect both vehicles and pedestrians. Two vehicles approach our vehicle in the opposite lane near a pedestrian crosswalk. These two vehicles are very close to each other such that neither the line-of-sight sensor on our vehicle nor the driver can see past these vehicles. A pedestrian tries to cross the road behind these vehicles. Using this setting, two cases are simulated, with CCA and without CCA.

When there is no DSRC signal coming from the pedestrian, the autonomous vehicle cannot predict that there is a pedestrian about to step on the crosswalk, because of NLoS. When the pedestrian enters the scan field of the radar sensor in subplot 3 of Fig. 5, the vehicle receives a full brake command from the controller. Screenshots from the simulation are shown in Fig. 5. It can be seen that even if the vehicle travels at relatively low speed (25 kph / 15 mph), fully

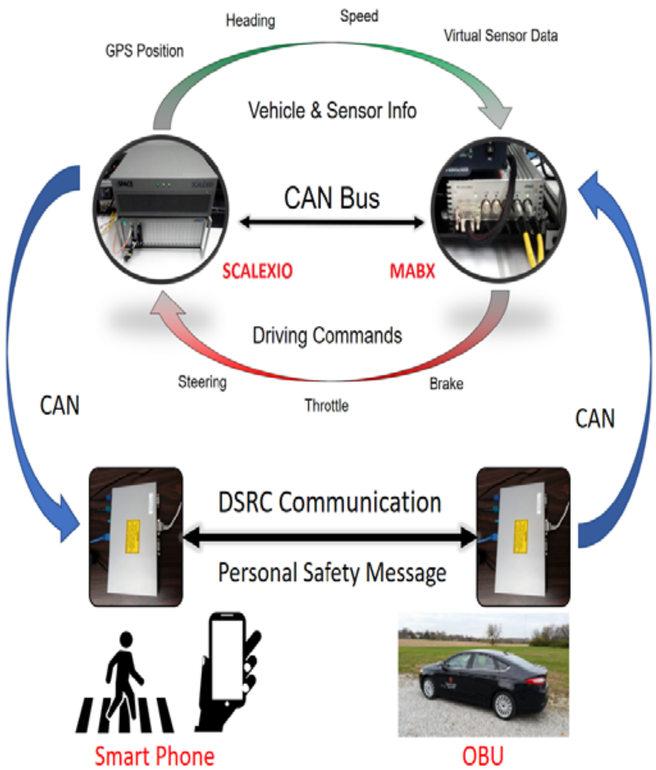


Figure 4: Communication between HIL elements.

braking when it detects the pedestrian visually, is not enough to avoid the accident.

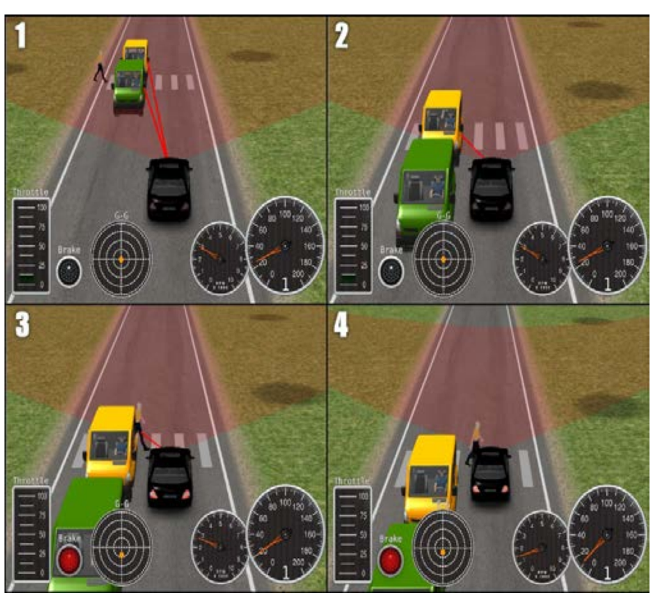


Figure 5: First scenario without CCA.

However, in the second case with the smartphone of the pedestrian communicating to the OBU of vehicle, the vehicle is able to understand that there is a pedestrian on the crosswalk. Since it cannot avoid the collision by maneuvering left or right, the vehicle collision avoidance algorithm chooses to brake. It stops at the safe distance according to pedestrian position, allowing the pedestrian to cross the road at a socially safe distance. After the pedestrian crosses and the distance between the vehicle and pedestrian is not within the socially acceptable collision avoidance distance, the autonomous vehicle issues the throttle command and accelerates. Screenshots from the simulation are shown in Figure 6.

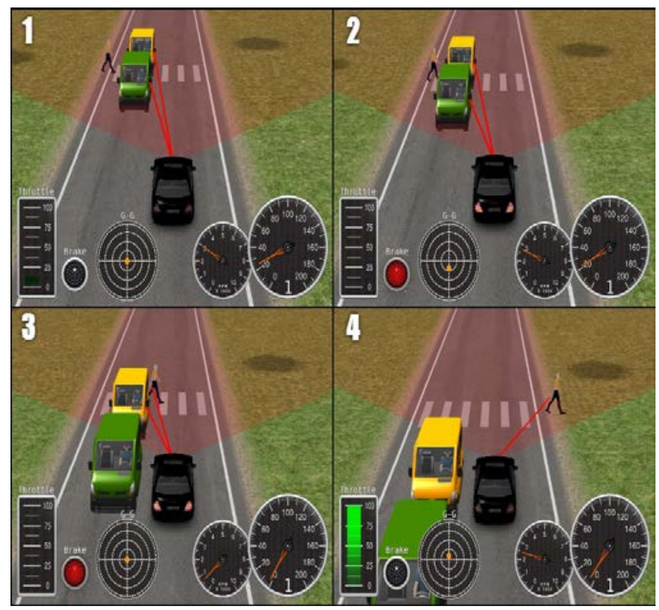


Figure 6: First scenario with CCA.

## *B. Second Scenario*

In the second scenario, a vehicle is driven on a parking lot, while a group of pedestrians are walking across the road talking to each other, without noticing that there is a vehicle approaching. Also, because of the bad weather conditions, neither driver nor sensors on the vehicle can detect these pedestrians. Considering this setting, it is obvious that avoiding the collision is very difficult without CCA.

With CCA, the smartphones of the pedestrians communicate with the OBU and the vehicle receives the position and speed of the pedestrian(s). After deciding that it is about to drive into the socially acceptable collision avoidance distance of the pedestrians, the vehicle decides to avoid the pedestrians. The original vehicle path is modified locally using the elastic band approach discussed in Section II. The autonomous vehicle uses the path following algorithm to follow the modified path, instead of the original path and maneuvers to the left and drives behind the pedestrians, avoiding them safely. Screenshots from this simulation are shown in Fig. 7.

## V. CONCLUSION

Pedestrians are among the most exposed road users in possibly lethal collisions. Advanced sensors on the vehicle can be used to detect pedestrians and avoid collisions in many situations. However, these line-of-sight sensors cannot detect pedestrians in blocked visibility (NLoS scenario), limited field of view and bad weather conditions. V2X communication can provide safety even under these harsh circumstances by transmitting and receiving safety messages with DSRC technology.

Within this study, a collision avoidance method which possesses the power of cooperativeness is presented. This CCA method was constructed using DSRC technology to achieve V2X communication and also avoidance with elastic band theory. HiL simulations were carried out to determine the reliability of the algorithm, providing results very close to real life due to the real-time processing and usage of real hardware for communication and usage of high fidelity validated vehicle dynamics models. It was seen that the HiL simulator introduced in this paper is a useful tool for developing and evaluating cooperative collision avoidance algorithms for autonomous vehicles. Our future work will include further development of the collision avoidance algorithm and experimentation with real autonomous vehicles and smart phones.

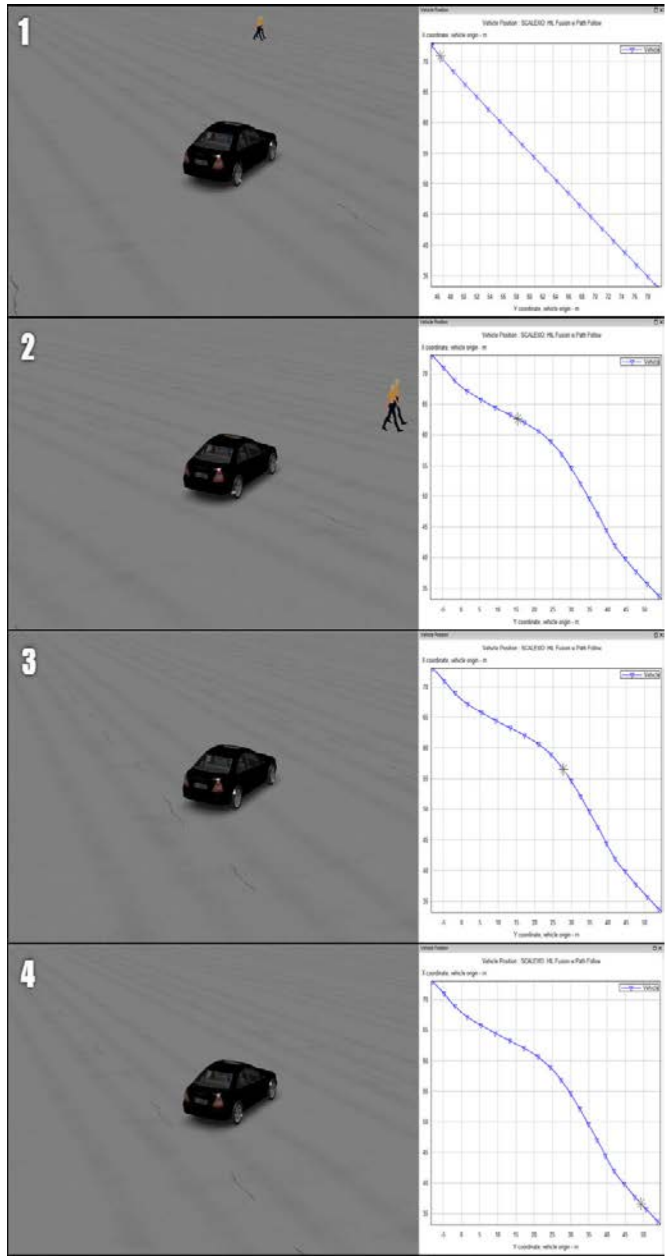


Figure 7: Second scenario.

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