

# Improve Road Safety Using Combined V2V and Pre-Collision Systems

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## ABSTRACT

In current vehicle to vehicle (V2V) communication systems, each vehicle broadcasts its motion status and receives information from other vehicles in order to make safety decisions and actions. State-of-the-art pre-collision systems (PCS) utilize onboard sensors to collect potential crash object information for making safety action decisions. This V2V-PCS combination enables a vehicle to not only send its own motion information, but also its PCS detected information to other vehicles. Conceptually, the additional information should help a V2V enabled vehicle make its safety related decisions more accurately and efficiently. The objective of this study is to find if a combined V2V and PCS system (V2V-PCS) can further improve the safety of not only V2V-PCS enabled vehicles but also other non V2V-PCS enabled vehicles on the road. This paper describes a process that can be used to analyze pedestrian and vehicle scenarios, and determine whether or not the safety of pedestrians could be improved by a V2V-PCS system. It also gives an analytical method for determining the benefit of using V2V-PCS. The environments set up for V2V-PCS simulation and real vehicle testing are also described.

**Keyword:** Pre-collision systems, V2V

## 1. Introduction

Based on statistics from the 2005-2008 National Automotive Sampling System (NASS) General Estimates System (GES) crash databases, V2V-based safety applications would potentially address about 4,336,000 police-reported light-vehicle crashes annually, with the 95 percent confidence interval between 3,691,000 and 4,981,000 [1]. The advancement in computation power and communication capability enables the practical implementation of vehicle to vehicle communication (V2V) systems. The advantage of V2V systems has been well discussed in many literatures. Pilot V2V implementation programs are conducted in several countries [2, 3]. The fundamental advantage of V2V is its capability of exchanging vehicle information that enables the intelligent decisions regarding road safety and efficiency. V2V-based safety applications predominantly apply to crashes that involve multi-vehicle pre-crash scenarios. This analysis is conducted with support from the Intelligent Transportation System's program for safety and mobility applications based on V2V and vehicle-to-infrastructure (V2I) communications [4]. To improve the intelligence of V2V systems, there are studies for incorporating information from traffic lights and road sensors through vehicle to infrastructure (V2I) systems, vehicle to pedestrian (V2P) systems into V2X systems. However, the current development of V2X systems is based on the concept that each participant provides its own operating information to the V2X system. There will be a long time period that V2V capable and non-V2V vehicles coexist on roads. The current design of the V2X systems does not benefit non-V2X equipped objects (vehicle and pedestrians) since the information of these objects cannot be entered into the V2X systems. To solve this problem, there should be a way to gather the information of non-V2V enabled objects on the road, transmit this information the V2X system, and use the information to improve the safety of all objects on the road.

PCS system is an active safety component in many commercially available vehicles. A PCS has sensors (video camera, radar, lidar, etc.) to detect vehicles, pedestrians and bicyclist. The sensor information is presently used for collision imminent warning, automatic braking and maneuvering. If the PCS sensor information of a vehicle can be broadcast to a V2V network, other V2V enabled vehicles may use the information to improve the safety of the sensed objects. This paper discusses the future technology development in combining V2V and PCS together to enable a V2V vehicle to broadcast its PCS detected information and use received information to make better crash avoidance decisions. The combined V2V-PCS can effectively extend the information gathering range of V2V vehicles and enables all V2V vehicles to get information of non-V2V enabled objects.

This paper describes a systematic process to investigate all V2V-PCS scenarios that potentially benefit the pedestrians with the adoption of the combined V2V-PCS systems. First the variables and their values relevant to V2V-PCS scenarios are identified. Then all scenarios generated from the combination of the variable values are examined to determine if they can improve pedestrian safety. The computation method for determining if the V2V-PCS improves the pedestrian safety for each scenario is described. The calculation of the first appearance location of the pedestrian to the vehicle and time to collision due to the location of the obscure object is described. The result of this study serves three purposes, (1) it provides a baseline to describe the usefulness of a V2V-PCS system, (2) it provides all pedestrian V2V-PCS simulation scenarios and crash calculation for future study and demonstration, and (3) it supports the establishment of testing scenarios for the performance evaluation of the V2V-PCS enabled vehicles.

## 2. Environment description and scenario categorization

It is assumed that there are three types of vehicles on the road: vehicles without V2V capability, vehicles with V2V capability but no PCS capability, vehicles with both and V2V and PCS capabilities. Each vehicle can be either moving or stationary. It is also assumed that pedestrians and stationary objects on the road do not have V2V capability. To describe V2V-PCS scenarios for pedestrian safety, the objects in the scenarios include pedestrians, vehicle potentially crashes the pedestrians (crashing vehicle), and V2V-PCS enabled vehicle that broadcast the pedestrian information and objects that obscure the view of the crashing vehicle. To describe the scenarios that a V2V-PCS system could show pedestrian safety advantage, following variables are identified:

1. *Crash Location* – The crash location variable has four relevant values: not-at-intersection, before-intersection in-intersection, after intersection.
2. *Crashing Vehicle Motion Direction*: possible values are *straight forward, turn left, turn right, merge left, and merge right*. In not-at-intersection scenarios, crashing vehicles cannot turn left or right so there are only three possible values: *straight forward, merge left, and merge right*; in intersection related scenarios, merging while turning is equivalent to turning with a different radius, so there are only three possible values: *straight forward, turn left, and turn right*.
3. *Pedestrian motion direction relative to the crashing vehicle*: Four possible values are *Left to Right, Right to Left, Along Traffic, and Against Traffic*.
4. *Obscure object*: There are seven interested values for this variable: no obscure object, stationary/moving obscure objects on left/front/right. The presence of obscure objects blocks the view of the crashing vehicle and shortens the reaction time to a potential collision.

For the convenience of describing the V2V-PCS scenarios, the notations for these variables and their values are defined in Table 1.

Table 1. Variables and values relevant for describing V2V-PCS scenarios

Crash location	Crashing vehicle direction	Pedestrian direction respect to crashing vehicle	Obscure object- location with respect to crashing vehicle (M=motion, S=Stationary)
IB – before intersection	VLT – left tern	PLR – left to right	OS/M – obscure obj.
IA - after intersection	VRT – right turn	PRL – right to left	OS/M – obscure obj.
II – in intersection	VST - straight	PAL – along traffic	OS/M – obscure obj.
IN – not in intersection	VLM – left merge	PAG –against traffic	ON – no object
	VRM –right merge		
	VLC – left curve		
	VRC –right curve		

168 different scenarios can be identified based on the combination of all possible values of environment variables as described in Table 1. In which 108 are intersection related and 60 are non-intersection related. 108 intersection related cases are calculated as  $1(\text{intersection}) \times 3(\text{Before, In, or After intersection}) \times 3(\text{Turn left, Turn right, Straight Forward}) \times 4(\text{Left to Right, Right to Left, Along Traffic, Against Traffic}) \times 3(\text{moving obscure objects, stationary obscure objects, no obscure object})$ . 60 non-intersection scenarios are calculated as  $1(\text{non-intersection}) \times 5(\text{Curve$

left, Curve right, Straight Forward, Merge left, Merge right) \*4(Left to Right, Right to Left, Along Traffic, Against Traffic)\*3(moving obscure objects, stationary obscure objects, no obscure object).

Each of these 168 scenarios was studied to determine if it could benefit from the use of V2V-PCS systems. The basic idea is to check if the crashing vehicle can get potential crash information earlier when a V2V-PCS system is adopted. The crashing vehicle may not be able to see the pedestrian for various reasons. If there is another vehicle (the informing vehicle) that has the PCS capability to detect the pedestrian and send the information to the crashing vehicle, the crashing vehicle may be able to take measures in advance to avoid the collision. Here it is assumed that pedestrians do not detect the potential danger and cannot send their location information to vehicles. According to the selection criteria described above, 96 scenarios (listed in Table 2) are able to benefit from V2V-PCS systems and 72 Scenarios will not benefit from V2V-PCS systems.

Table 2. 96 scenarios that the V2V-PCS system can improve the pedestrian safety

Location	Vehicle	Pedestrian and the Obscure object
IB	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
IA	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
II		None
IN	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VLC	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VRC	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_ON; PAG_ON
	VLM	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VRM	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON

Table 3. 72 Scenarios that the V2V-PCS cannot improve the pedestrian safety

Location	Vehicle	Pedestrian and the Obscure object
IB	VLT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VRT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VST	PAL_OS; PAL_OM; PAG_OS; PAG_OM
IA	VLT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VRT	PAL_OS; PAL_OM; PAG_OS; PAG_OM
	VST	PAL_OS; PAL_OM; PAG_OS; PAG_OM
II	VLT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VRT	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
	VST	PLR_OS; PLR_OM; PLR_ON; PRL_OS; PRL_OM; PRL_ON; PAL_OS; PAL_OM; PAL_ON; PAG_OS; PAG_OM; PAG_ON
IN	VST	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VLC	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VRC	PAL_OS; PAG_OS; PAL_OM; PAG_OM
	VLM	None
	VRM	None

To make the graphical description easier, following icons are used in figures:

-  The pedestrian sign represents the pedestrian without the capability to communicate with vehicles.
-  The red vehicle represents the crashing vehicle equipped with V2V (may have PCS capability).
-  The yellow vehicle represents the informing vehicle equipped with both PCS and V2V.
-  The blue vehicle represents the stationary vehicle equipped with both PCS and V2V
-  The hexagon represents the obscure object.

Figure 1A demonstrates a situation that the use of a V2V-PCS system could improve the safety of a pedestrian. The red car (crashing vehicle) is going straight forward. The stationary blue car is waiting for a left turn signal and obscures the view of the red car. The pedestrian is walking across the road from left to right. The red car may not be able to stop due to the short reaction time. If the yellow car (the informing vehicle) coming from the other side or the blue car has pedestrian PCS and V2V capability, they can detect the pedestrian and send the pedestrian motion information to the red car so that the red car can take measures in advance to avoid potential crash to the pedestrian. If the red car is equipped with V2V but no PCS, it can generate warning to the driver, and or generate pre-braking command to the brake system to be ready for real brake. If the red car has both PCS and V2V capabilities, it can pay special attention to the location where the pedestrian is expected to appear and make quicker and better decisions. The V2V-PCS is useful even if the obscure blue car is not present (Figure 1B). If the pedestrian is far from the fast moving red car, the sensors in the red car may not be able to detect the pedestrian so the PCS on the red car may not be able to make effective braking decision. Since the pedestrian is much closer to yellow car, the V2V-PCS of the yellow car can provide pedestrian information before the red car can recognize the pedestrian.

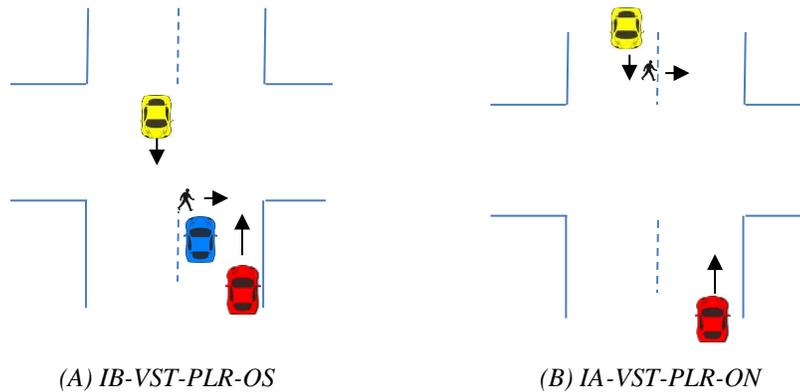


Figure 1. Example scenarios showing that the V2V-PCS system may prevent a crash to the pedestrian.

Figure 2 demonstrates a scenario that the V2V-PCS system cannot improve the safety of a pedestrian. The red car (crashing vehicle) is going straight forward. The obscure blue car is in front of the red car. The pedestrian is walking along the road. Even the pedestrian information sent by the blue car and received by the red car, there is not a situation that the red car can crash to the pedestrian.

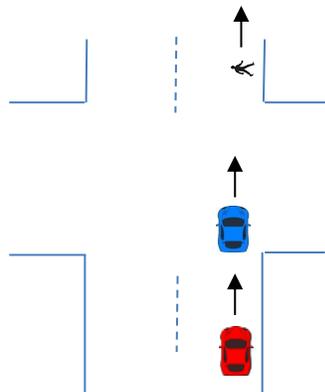


Figure 2. A scenario IA-VST-PAL-OM showing the scenarios at the V2V-PCS system does not help pedestrian safety.

### 3. Analysis of scenarios

All scenarios that V2V-PCS systems improve the safety of the pedestrians are identified in last section. The next step is to answer two practical questions quantitatively,

- A. Given any scenario as described in Table 2 with detailed motion information of all objects, how do we know if there is a crash or not? The answer to this question is useful for developing a V2V-PCS warning/braking strategy.
- B. Given any scenario as described in Table 2 with the positions and speeds of all objects except the initial position of the crashing vehicle, what is the initial position of the crashing vehicle so that there is a crash to the pedestrian at a specific location of the vehicle? The answer to this question is useful for setting up the test scenario for evaluating the effectiveness of the V2V-PCS systems.

To answer these questions, scenarios in Table 2 are reorganized into three categories based on the vehicle motion direction: vehicle move straight, vehicle change/merge lanes, and vehicle move in a curved lane.

### 3.1. The straight moving vehicle crashes a pedestrian crossing a street

This subsection provides a method to check if there will be a crash when a pedestrian is crossing the road and vehicle is moving straight. This method is essential for evaluating whether or not a V2V-PCS system is capable of improving a pedestrian's safety. Figure 3 depicts a situation where a straight moving vehicle crashes into a pedestrian crossing the street. The red car is moving straight forward with center at the y-axis, while a pedestrian crosses the road from left to right with an angle of  $\Theta$  to x-axis. Assuming the crash location is at the origin of the coordinate system, the following equations can answer the aforementioned two questions.

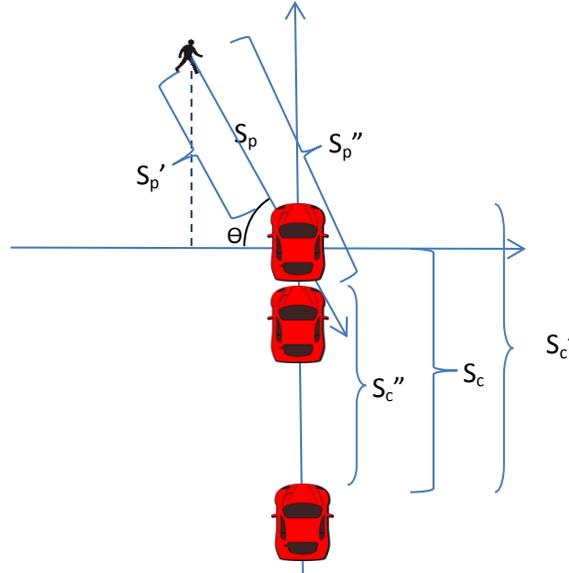


Figure 3. The straight moving vehicle crashes a pedestrian crossing a street.

Definition of notations in Figure 3:

- $\Theta$ : The angle of the pedestrian's motion with respect to x axis
- $L_c$ : The length of the vehicle
- $W_c$ : The width of the vehicle
- $S_c$ : The distance between the vehicle's initial position (front center) and the potential collision point
- $S_c'$ : The distance between vehicle's initial position (front left corner) and the potential collision point
 
$$S_c' = S_c + 0.5W_c \tan \Theta$$
- $S_c''$ : The distance between vehicle's initial position (front right corner) and the potential collision
 
$$S_c'' = S_c - 0.5W_c \tan \Theta$$
- $S_p$ : The distance between pedestrian's initial position (front center) and the collision point
- $S_p'$ : The distance between the pedestrian's initial position and the collision point with vehicle's front left corner
 
$$S_p' = S_p - 0.5W_c / \cos \Theta$$
- $S_p''$ : The distance between pedestrian's initial position and the collision point with vehicle's front right corner
 
$$S_p'' = S_p + 0.5W_c / \cos \Theta$$

- $v_p$ : The velocity of the pedestrian (Assume the pedestrian is moving at a constant speed)
- $v_c$ : The initial velocity of the vehicle
- $a_c$ : The acceleration of the vehicle

**A. Determine if there is a collision between the vehicle and the pedestrian**

According to Figure 3, potential crash time  $t_c$  is bounded by two conditions, one where the pedestrian is struck at the left front corner of the vehicle and one where the pedestrian is struck at the right front corner of the vehicle. The time interval for the pedestrian to move between these two points can be expressed as  $[t_p', t_p'']$ , and the time interval for the vehicle to move between these two points can be shown as  $[t_c', t_c'']$ . Vc crashes to the pedestrian when  $[t_c', t_c'']$  overlaps  $[t_p', t_p'']$ .

$t_p'$  and  $t_p''$  can be calculated as  $S_p'/v_p$  and  $S_p''/v_p$ , respectively.  
 $t_c'$  and  $t_c''$  can be calculated using Newton's laws of motion:  $t = (-v_c \pm \sqrt{v_c^2 + 2a_c S_c}) / a_c$ ,  
 If  $a_c > 0$ , If  $\sqrt{v_c^2 + 2a_c S_c} \geq v_c > 0$ , Then  $t = (-v_c + \sqrt{v_c^2 + 2a_c S_c}) / a_c$   
 If  $v_c > \sqrt{v_c^2 + 2a_c S_c'} > 0$ , Then no positive t, invalid for this application.  
 If  $a_c < 0$ , If  $v_c \geq \sqrt{v_c^2 + 2a_c S_c'} > 0$ , Then  $t = (-v_c + \sqrt{v_c^2 + 2a_c S_c'}) / a_c$   
 If  $0 < v_c < \sqrt{v_c^2 + 2a_c S_c'}$ , Then  $t = (-v_c + \sqrt{v_c^2 + 2a_c S_c'}) / a_c$   
 If  $a_c = 0$ ,  $t = S_c/v_c$

**Example 3.1.A:**

Given the situation in Figure 2 and the variable values in the following table

$a_c$	$v_c$	$v_p$	$\Theta$	$L_c$	$W_c$	$S_p$	$S_p'$	$S_p''$	$S_c$	$S_c'$	$S_c''$
5m/s <sup>2</sup>	13.5m/s	1.5 m/s	60°	4.8m	1.8m	7.5m	5.7m	9.3m	55m	56.56m	53.44m

The calculation of  $(t_p', t_p'')$  is (3.8 sec, 6.2sec), and  $(t_c', t_c'')$  is (3.96 sec, 4.18 sec). Since there is an overlap time range which is [3.96 sec, 4.18 sec], it there is collision between the pedestrian and the crashing vehicle during this time interval.

**B. Determine the initial positions of Vc and the pedestrian that guarantee a crash**

According to Figure 3, the crashing vehicle is on y-axis and the crash point is at the origin, so the initial position of the vehicle is (0, - $S_c$ ) and the initial position of pedestrian is ( $-S_p \cos \Theta$ ,  $S_p \sin \Theta$ ). To guarantee a crash for vehicle testing, the initial position of the vehicle can be decided according to the initial position of the pedestrian and vice versa. In other word, the travel time for the pedestrian to reach origin should be the same as that for the vehicle. If the desired crash point is not at the middle front of the vehicle, the path of vehicle in the y-direction can be shifted along the-x axis accordingly.

**3.2 The vehicle crashes a pedestrian crossing a street while change lanes**

This section provides the method to check if there is a crash when a pedestrian is crossing the road and vehicle is changing lanes. Figure 4 depicts the situation that a vehicle crashes into a pedestrian crossing the street while changing lanes. The red car Vc is changing to the left lane centered at y-axis while a pedestrian crosses the road from left to right with an angle of  $\Theta$  to x-axis. The definitions of the notations in Figure 4 are the same as that in Section 3.1. The additional notation  $\alpha$  is the angle between y-axis and the line from the vehicles initial position to origin.

**A. Determine if there is a crash between Vc and the pedestrian**

Practically, in the vehicle changing lanes cases, the distance that the vehicle moves forward is much longer than the distance that the vehicle moves laterally (equals the width of a lane). Thus the width of the lane that the vehicle merges can be ignored so that these cases can be regarded as the vehicle moving straight forward as described in Section 3.1. So the method described in Section 3.1 can be used for these change lanes cases.

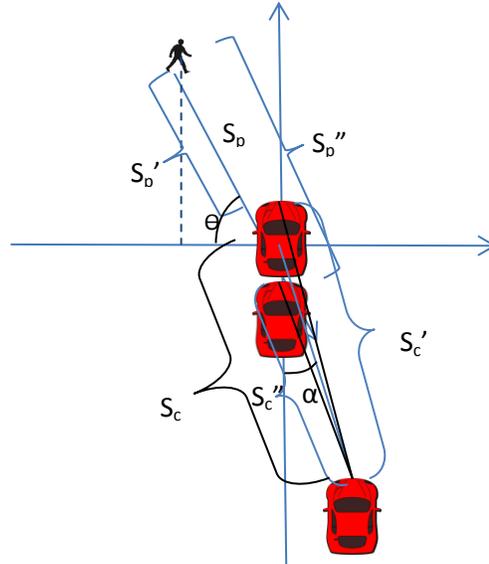


Figure 4. The vehicle changes lanes and crashes a pedestrian crossing a street.

### B. Determine the initial positions of Vc and the pedestrian for vehicle V2V-PCS performance evaluation

According to Figure 3, the initial position of Vc is  $(S_c \sin \alpha, -S_c \cos \alpha)$  and the initial position of the pedestrian is  $(-S_p \cos \theta, S_p \sin \theta)$ . To guarantee a crash in V2V-PCS evaluation, the initial position of the vehicle needs to be decided according to the initial position of the pedestrian and vice versa. In other words, the travel time for the pedestrian to reach origin should be the same as that for the vehicle. If the desired crash point is not at the middle front of the vehicle, the path of vehicle in the y-direction can be shifted along the-x axis accordingly.

### 3.3 The vehicle crashes the pedestrian while following a curved road

This subsection provides the method to check if there will be a crash when a pedestrian is crossing the road and vehicle is moving along a curved road (depicted in Figure 5). The red car is curving with center at y-axis while a pedestrian crosses the road from left to right with an angle of  $\theta$  to x-axis. It is assumed that the crash location will be at the origin of the coordinate. The curved lane in a non-intersection location can be considered as a straight lane in terms of traveling distance and time. Therefore, the method described in section 3.1 for determining if there is a collision between the vehicle and the pedestrian can be directly applied is this case. The method described in Section 3.2 for determining the initial positions of Vc and the pedestrian that guarantee a crash also can be directly applied is this case.

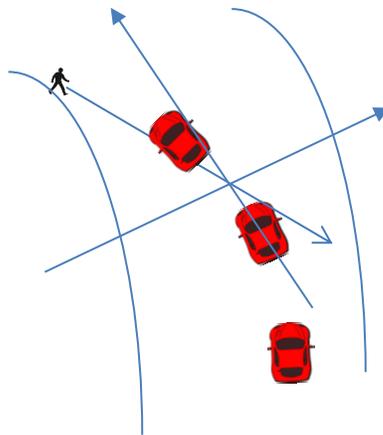


Figure 5. The vehicle crashes a pedestrian crossing a street while curving.

#### 4 Add obscuring objects to the scenarios

The presence of obscuring objects does not change the collision time. However, they would delay a vehicles ability to recognize the pedestrian, which leads to less time for the vehicle to react to imminent crash to the pedestrian. To analyze the effect of the obscuring objects, the following question needs to be answered:

*Given the path of the pedestrian and the location of the obscuring objects, how could the locations of the obscuring objects be determined so that the object obscures the vehicles view of the pedestrian?*

By answering this question, the time between the first appearance point of the pedestrian and a collision, or time to collision (TTC), can be calculated. If PCS systems are obscured then vehicles must rely more on V2V systems. Figure 6 will be used to describe the effect of the location of obscuring objects on potential crashes. For the simplicity of explanation, it is assumed that the camera is located at the front center of each vehicle. Notations in Figure 6 are defined as follows

- Lvs & Wvs: The length and width of the blocking vehicle Vs.
- Pp: The coordinates of the pedestrian.
- Pvc: The front center position of Vc.
- Pvc' & Pvc'': The initial position and the final position that Vc is blocked by Vs.
- Pvs-fr: The coordinates of the front right corner of Vs
- Pvs-rl: The coordinates of the rear left corner of Vs

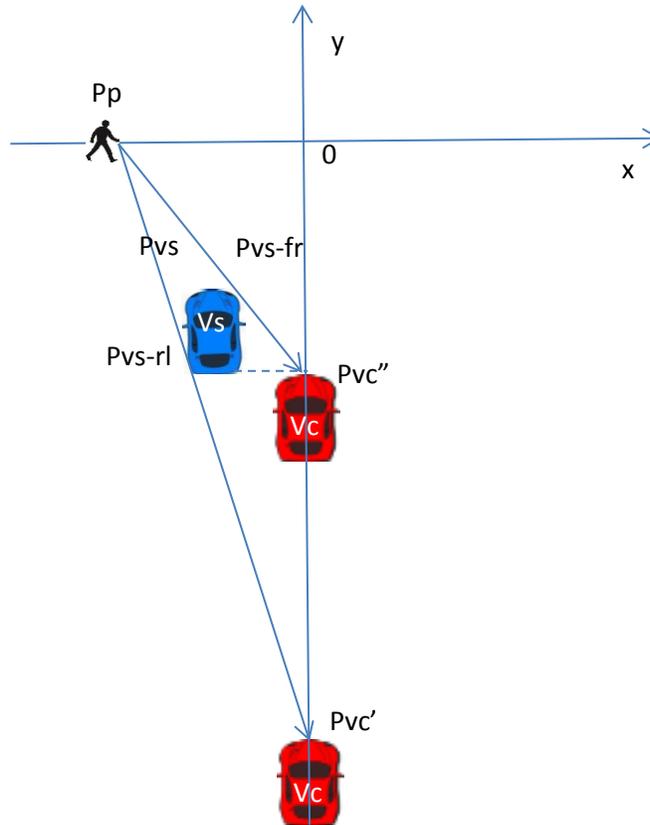


Figure 6. Add obscure vehicle Vs to scenarios

According to Figure 6, the range of positions that the blocking vehicle Vs blocks the crashing vehicle Vc's view of the pedestrian is from Pvc' to Pvc''. For a given Pvs, Lvs and Wvs, Pvs-fr and vs-rl can be calculated. If Pp is given, Pvc' can be calculated as the point on y-axis and on the line of PpPvs-rl, and Pvc'' can be calculated as the point on y-axis and on the line of PpPvs-fr. If Pvc is between Pvc' and Pvc'', Vc cannot see the pedestrian.

## 5 Conclusion

This paper used an exhaustive analysis method to identify the scenarios that a combined PCS and V2V system can improve the pedestrian safety theoretically. 96 out of 168 pedestrian related scenarios can benefit from V2V-PCS system. The method for determining if there is a potential crash for all 96 cases for given vehicle and pedestrian motion parameters is described. The method for creating a crash condition for V2V-PCS system evaluation is also described. The calculation of the first appearance location of the pedestrian to the vehicle and time to collision due to the location of the obscure object is described. These results lay a good foundation for further V2V-PCS system studies.

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