

Perceived Safety: A New Metric for Evaluating Safety Benefits of Collective Perception for Connected Road Users

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Abstract—This paper proposes the concept of perceived safety to quantitatively evaluate the safety benefits of collective perception to connected road users in safety critical scenarios. It is assumed that connected vehicles and infrastructure network transmit collective perception messages (CPMs) that contain not only basic information about the transmitter, but also key information about other objects detected via its on-board sensors. The detected objects may include non-connected road users that could be either occluded or out of the sensor range of the other connected road users. Our perceived safety framework provides a systematic way to determine when information perceived by a vehicle is sufficient to safely perform a given maneuver based on the sensory set, wireless connectivity, and dynamics of the ego vehicle. We illustrate the perceived safety framework by considering a lane change scenario, and show by simulations that CPMs enhance the ability of connected automated vehicles to perform safe lane changes.

I. INTRODUCTION

The benefits of wireless communication in transportation have been recognized in the past decades, leading to extensive research, standardization, and implementation of vehicle-to-everything (V2X) communication messages. For instance, communication between connected road users is done by the standardized basic safety messages (BSMs) or by collective awareness messages [1], [2] which feature the current state of transmitting vehicle (e.g., position, velocity, heading, etc.). Communication between road users and infrastructure can be accomplished by standardized signal, phase and timing (SPaT) messages [1] that include traffic signal phase and time to phase change. While benefits of V2X communication using the above message sets are evident for high penetration rates of connected vehicles, justifying benefits at low penetrations of connected vehicles presents a challenge to mass deployment.

Benefits of V2X communication at low penetrations can be realized via more complex messages, which not only contain information about the transmitter, but also information captured by its on-board sensors [3]. These so-called collective perception messages (sometimes called environmental perception messages) [2], [4], [5] may provide information about unconnected road users thereby increase the *effective penetration* of connected vehicles in the environment [6]. Collective perception messages (CPMs) have been extensively studied from the communications perspective. For example, effects of market penetration rate on the percentage of perceived vehicles in the network and the channel load have been studied in [7]. In [4], the communication performance and efficiency of

CPMs are evaluated using different generation rules. In [8], an urban scenario was considered to obtain the performance of CPM communication including channel busy ratio (CBR) and number of detected objects per CPM at different market penetrations.

In this paper, we develop the perceived safety analysis which we use to assess the safety benefits that CPMs bring to connected vehicles in a dynamical setting. We demonstrate the concept through a lane change scenario, however, our framework can be extended to other dynamical settings such as intersections and pedestrian crossings. Perceived safety analysis first determines if a specific action taken by an ego vehicle violates safety conditions (called the ground truth safety). Then, it is determined if the sensor set of the ego vehicle is able to perceive the safety condition (called perceived safety). The false negative scenarios when the sensor set is not able to capture that the safety condition is not met are then evaluated by a metric called perceived safety error. This metric is simple and effective to quantify the benefits of collective perception.

The paper is organized as follows. In Section II, we introduce the lane change on a two-lane highway where connected vehicles may use CPMs to improve safety. We define the general notions of ground truth safety and perceived safety in Section III. In Section IV, we quantify the safety benefits of CPMs. Finally, the paper is concluded in Section V.

II. LANE CHANGE: SENSOR LIMITATIONS AND COLLECTIVE PERCEPTION

Consider a two-lane highway as shown in Fig. 1 containing the ego vehicle labelled “E”, and remote vehicles identified by the lane (left “L” and right “R”) and index (1, 2, 3, ...). We consider that the ego vehicle is an automated vehicle that intends to change lanes. The ego vehicle is equipped with a set of sensors including a front camera for monitoring traffic ahead as well as blind spot detectors to monitor traffic approaching from behind. The ego vehicle’s dynamics are given by

$$\dot{s}_E = v_E, \quad \dot{v}_E = \text{sat}(u_E), \quad (1)$$

where s_E is the position of the front bumper along the road, v_E is the velocity, and u_E is the commanded acceleration of the ego vehicle. The saturation function $\text{sat}(\cdot)$ incorporates the physical limitations of the vehicle’s acceleration and braking capabilities [9]. In this paper, we consider that the acceleration

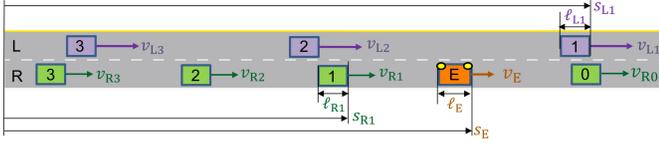


Fig. 1. Two-lane highway with ego vehicle “E” and remote vehicles. The ego vehicle intends to change lanes as seen by yellow turn indicators. The corresponding lane indices and vehicle indices are provided.

limitation is $4 \text{ [m/s}^2\text{]}$ and the braking limitation is $-8 \text{ [m/s}^2\text{]}$, which are typical for a standard passenger vehicle. The highway also features remote vehicles, for which the subscript indicates the lane and the vehicle number in that lane. That is, for remote vehicle j in the left lane we have

$$\dot{s}_{Lj} = v_{Lj}, \quad \dot{v}_{Lj} = \text{sat}(u_{Lj}). \quad (2)$$

Similarly, the dynamics of vehicle j in the right lane corresponds to subscript $R.j$. As the ego vehicle makes a lane change, its sensor set plays a critical role in detecting remote vehicles whose safety might be compromised by the decision of the ego vehicle to make a lane change.

The left column of Fig. 2 shows three different scenarios where the sensor set of the ego vehicle may not be adequate to provide enough information to make a safe lane change. In Fig. 2A the ego vehicle is in the right lane with dense slow traffic, and intends to make a left lane change. The left lane contains vehicles moving close to free flow speed at relatively low density. The limited range of the ego vehicle’s blind spot sensors does not allow the ego vehicle to change lanes without the risk of forcing the remote vehicle approaching in left lane to brake harshly to avoid collision.

In addition to being limited in range the ego vehicle’s sensors may be blocked by obstacles and, as a result, the ego vehicle may not be aware of remote vehicles that present safety hazards. For instance, in Fig. 2B the ego vehicle is in the left lane traveling behind a remote vehicle and attempting a lane change to the right. The remote vehicle is blocking the ego vehicle’s front range sensor and occluding a stationary vehicle in the right lane. This may lead to the ego vehicle performing heavy braking or crashing into the stationary vehicle in the

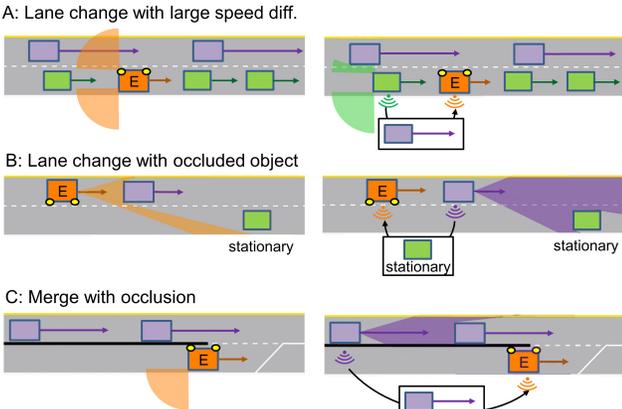


Fig. 2. Left column: Three scenarios in which the ego vehicle’s sensor limitations may compromise safety. Right column: How collective perception messages may improve the safety of the ego vehicle for each scenario.

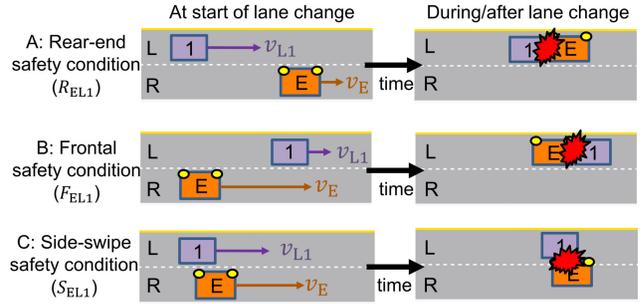


Fig. 3. Breakdown of the lane change scenario with two vehicles (ego vehicle E and remote vehicle L1) into three different ways the ego vehicle may compromise safety during the lane change.

right lane after the lane change. Another example of a sensor occlusion compromising a safe lane change is shown in Fig. 2C, where the ego vehicle is about to merge into the left lane. Here a barrier is preventing the ego vehicle from sensing the remote vehicles in the left lane, thus creating a situation where the ego vehicle may need to make a harsh maneuver in order to avoid collision.

The right column of Fig. 2 shows how the shortcomings of sensors in each scenario can be overcome by collective perception messages (CPMs) transmitted from remote vehicles to the ego vehicle. These CPMs contain information not only about the state of the transmitting remote vehicle, but also information about other vehicles detected by the transmitting vehicle’s sensors [8], [10]. Thus, the ego vehicle may be aware of vehicles that are out of its sensor range as in Fig. 2A, or occluded by obstacles as in Figs. 2B-C. This additional awareness may improve the safety of the ego vehicle’s lane change.

III. PERCEIVED SAFETY ANALYSIS

In the previous section, we demonstrated that CPMs may enhance the safety of the ego vehicle when performing a lane change. This motivates us to develop the *perceived safety framework* to quantify the benefits that CPMs can bring to a general class of safety critical scenarios. To illustrate this framework, we focus on the lane change scenario on a two-lane highway, however, the framework can be generalized beyond lane changes and for multiple vehicles.

Without loss of generality, we consider a scenario where the ego vehicle wants to move to the left lane where a remote vehicle is traveling, see Fig. 3. In this case, the ego vehicle may compromise safety in three different ways during the lane change. First, in Fig. 3A we show a scenario where the ego vehicle is traveling with a slower speed than the remote vehicle, and the ego vehicle intends to change lanes to the left. As demonstrated on the right, if the ego vehicle is to change lanes under certain initial conditions, the remote vehicle might either have a rear-end collision with the ego vehicle or have to brake harshly to avoid doing so. Thus, the rear-end safety condition can be formulated as

$$R_{EL1} := \{s_E - s_{L1} - \ell_E > 0 \rightarrow u_{L1}(s_E, s_{L1}, v_{L1}, v_E) > a_{L1\min}\}, \quad (3)$$

indicating that the ego vehicle's lane change should not force the remote vehicle to brake with a deceleration less than $a_{L1\min}$.

Second, the front-end safety condition, e.g., in Fig. 3B, considers scenarios where the ego vehicle would need to brake harshly to avoid hitting the remote vehicle in the left lane when merging behind it. This can be formulated as

$$F_{EL1} := \{s_{L1} - s_E - \ell_{L1} > 0 \rightarrow u_{E1}(s_E, s_{L1}, v_{L1}, v_E) > a_{E1\min}\}. \quad (4)$$

Third, the sideswipe safety condition is ensured if the ego vehicle does not merge to the left lane when the vehicles are side-by-side as in in Fig. 3B. That is,

$$S_{EL1} := \{s_{L1} - s_E - \ell_{L1} > 0 \vee s_E - s_{L1} - \ell_E > 0\}, \quad (5)$$

where \vee is the logical disjunction indicating "or". Thus, a safe lane change is ensured when all of the above conditions are met which we refer to as the *ground truth safety*, i.e.,

$$T := R_{EL1} \wedge F_{EL1} \wedge S_{EL1}, \quad (6)$$

where \wedge is the logical conjunction indicating "and".

When the ego vehicle is equipped with sensors or receives information via wireless links (including CPMs), we can define the *perceived safety conditions* as follows. These conditions characterize whether the vehicle perceives that performing a lane change is safe. The perceived rear-end safety condition is

$$\tilde{R}_{EL1} := R_{EL1} \vee \{E \text{ does not perceive } s_{L1}, v_{L1}\}. \quad (7)$$

In other words, the ego vehicle perceives that it is safe from a rear-end collision when it either does not sense the remote vehicle, or when it senses that the remote vehicle satisfies R_{EL1} . Similarly, the perceived front-end and the sideswipe conditions can be defined as

$$\tilde{F}_{EL1} := F_{EL1} \vee \{E \text{ does not perceive } s_{L1}, v_{L1}\}, \quad (8)$$

and

$$\tilde{S}_{EL1} := S_{EL1} \vee \{E \text{ does not perceive } s_{L1}, v_{L1}\}, \quad (9)$$

and the condition for perceived safety is

$$\tilde{T} := \tilde{R}_{EL1} \wedge \tilde{F}_{EL1} \wedge \tilde{S}_{EL1}. \quad (10)$$

For simplicity, we assume that the ego vehicle can always detect if a remote vehicle is side-by-side with it in an adjacent lane, i.e., $\tilde{S}_{EL1} := S_{EL1}$.

Fig. 4 illustrates the difference between the ground truth safety and the perceived safety for the ego vehicle E executing a left lane change from the right lane where traffic moves at a homogeneous flow speed of $v_E^* = 20$ [m/s]. The left lane contains vehicle L1 moving at $v_L^* = 30$ [m/s] which starts 200 [m] behind the ego vehicle, as seen in Fig. 4A. Here, we use the car-following models detailed in the next section and the safety bounds on acceleration to be $a_{E\min} = a_{L1\min} = -3$ [m/s²]. For the ground truth timeline in Fig. 4B, we see that a lane change is not considered safe for 10.8 – 19.4 [s]

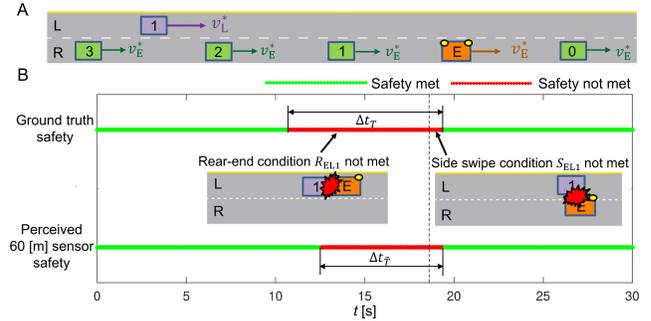


Fig. 4. (A): Left lane change scenario initialized with constant speeds v_L^* and v_E^* for left and right lanes, respectively. (B) Safety timeline with ground truth safety and perceived safety versus time of initiating the lane change. The dashed black line separates the cases where the rear-end safety and sideswipe safety conditions are not fulfilled.

as the rear-end safety criterion is not being met first, and then the sideswipe criterion is not met. We also see that if the ego vehicle is equipped with blind spot sensors of 60 [m] range, these sensors would not capture the entire time interval where the ground truth safety condition is not met.

We evaluate the performance of sensors and wireless communication by their ability to correctly capture the scenarios where the ground truth safety conditions are not fulfilled. To do this, we introduce the notion of perceived safety error, which is defined as the fraction of the time when T does not hold but \tilde{T} does, in other words, a false negative safety detection. For our lane change example, the perceived safety error is

$$P_E = 1 - \frac{\Delta t_{\tilde{T}}}{\Delta t_T}, \quad (11)$$

where $\Delta t_{\tilde{T}}$ and Δt_T are indicated in Fig. 4 B. For a given set of sensors and communication, P_E can vary between 0 and 1. Ideally, we desire $P_E = 0$. For the example in Fig. 4, $P_E = 0.21$. In the next section, we use the perceived safety error to compare the performance of an ego vehicle during a lane change for a sensor-only scenario and a sensor-plus-connectivity scenario.

IV. CASE STUDY: LEFT LANE CHANGE

In this section, we demonstrate the safety benefits of CPMs to connected vehicle performing a lane change maneuver. We consider the scenario in Fig. 5A, where an automated ego vehicle merges to the left lane. To model the longitudinal motion of the human-driven remote vehicles, we use the optimal velocity model with reaction time delay from [9] which were matched to the car-following behavior of real human drivers. For the ego vehicle, we use the automated vehicle car-following law with delay from [9] which was implemented on a prototype connected automated vehicle to perform car following [11]. We assume that the right lane is moving at homogeneous flow, i.e., vehicles are traveling at a constant speed v_E^* with constant inter-vehicle spacing given by the car-following models, while the vehicle on the left is initialized to travel with a constant speed v_L^* .

Blind spot sensors on the ego and human-driven vehicles are assumed to have 60 [m] range. We assume that human-driven vehicles can react to vehicles up to 100 [m] ahead.

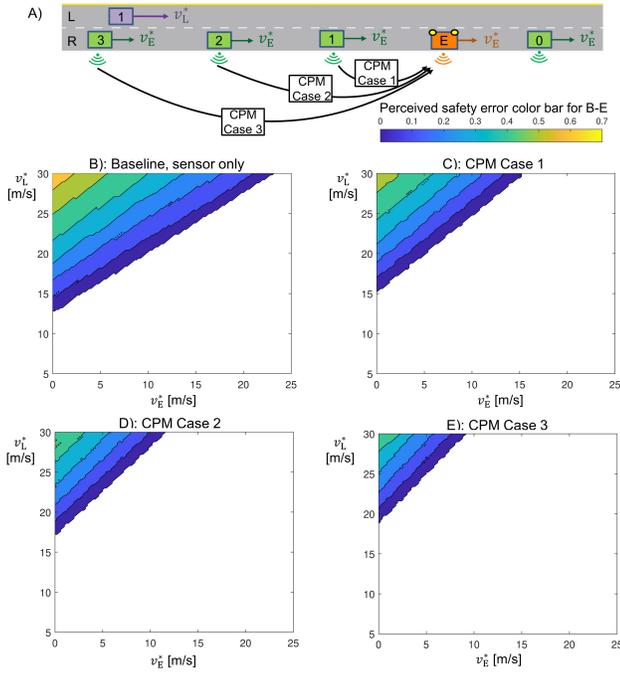


Fig. 5. (A): Left lane change with connected ego vehicle. (B)-(D): Perceived safety error P_E contours for different speeds of ego vehicle E and left lane remote vehicle L1. $P_E = 0$ in the white region.

CPMs are sent from remote connected vehicles in the right lane with a rate of 10 [Hz] as long as they can detect vehicle L1 approaching in the left lane. The ego vehicle uses received CPMs to track and predict the position and speed of vehicle(s) included in these CPMs assuming a constant-speed model.

We show the perceived safety error P_E as a function of v_E^* and v_L^* for the baseline scenario in Fig. 5B, where the ego vehicle is relying solely on its sensors. In this baseline scenario, for a large enough speed difference between the left and right lanes, P_E increases from 0 to over 0.6. For example, if the right lane is in standstill, and the vehicle in the left lane is traveling over 13 [m/s], the sensors will not be able to completely capture when the lane change is not safe. Furthermore, when vehicles in the right lane are close to standstill traffic and the vehicle in the left lane is moving close to the free flow speed of 30 [m/s], the ego vehicle is not aware that a lane change is dangerous over 60% of the time.

For the cases shown in Fig. 5 C-E where the ego vehicle relies on CPMs received from vehicle R1, R2, and R3, respectively. For example, having the remote vehicle R1 immediately behind ego vehicle E and sending CPMs yields an improvement over the baseline scenario. In this case, the perceived safety error decreases for all velocity combinations and the velocity ranges with $P_E = 0$ increases. Also, receiving messages from a connected vehicle located further upstream (e.g., from R2 or R3 rather than from R1) further reduces the perceived safety error. For example, Fig. 5 E demonstrates that if the right lane is in close to standstill, CPMs capture when the lane change is not safe even when the left lane traffic is moving faster than 17 [m/s]. Note that, although the results are obtained for the car-following models in [9], similar trends can

be obtained for other car-following models.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced the perceived safety analysis framework to evaluate the awareness of connected vehicles in a dynamic environment. We demonstrated this concept by examining a lane change scenario and showed how V2V communication using collective perception messages can enhance the awareness of the lane-changing vehicle compared to using on-board sensors only. We plan to use this framework to characterize the awareness of connected vehicles in more general and realistic traffic scenarios like highway driving and urban intersections. Our ultimate goal with the framework is not only to demonstrate the benefits of augmenting sensory information with V2X communication, but also to investigate the impact of different classes of messages [12], [13] that a connected vehicle can use to improve its awareness of surrounding vehicles. We also plan to use the perceived safety analysis framework to assess the impact of key communication factors such as market penetration rate, message frequency, and latency requirements on the safety and awareness of connected vehicles.

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