Evaluating Intent Sharing Communication using Real Connected Vehicles

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***Abstract*— In this paper we experimentally evaluate intent sharing, an emerging vehicle-to-everything (V2X) communication class that allows vehicles to share their intended future motion. Using commercially available radios, we implement intent sharing messages according to two different realizations of vehicle intent: (i) bounds of kinematic variables over a time horizon; (ii) expected trajectory specified as target road segments. We test intent messages using real vehicles on highways both in rural and urban environments. The collected data is used to evaluate the performance in terms of packet delivery ratio. Furthermore, using numerical simulations, we reveal the benefits of intent sharing in resolving conflicts during cooperative maneuvers and investigate the effects of packet delivery ratio on the gained benefits.**

I. Introduction

Vehicle-to-everything (V2X) communication can provide powerful means to enhance traffic safety and efficiency by enabling cooperation between vehicles [1]. Prior results show that in a fully automated environment, vehicles may negotiate about their future trajectories via maneuver coordination messages [2]. However, in the next few decades, mixed-autonomy, where vehicles of different levels of automation share the roads [3], is widely expected to be the dominant traffic environment. In such an environment, negotiating may not always be feasible, but vehicles may cooperate by sharing their status and intent. In status sharing, connected vehicles exchange status information such as position and velocity, where basic safety messages (BSMs) [4] and cooperative awareness messages (CAMs) [5] are standardized examples. On the other hand, in intent sharing, the information regarding a vehicle's future motion is shared [6], [7]. A specific example of ongoing standardization of intent sharing is the Maneuver Coordination Message [8], [9], which contains vehicle's planned and desired future trajectories.

Compared to sharing instantaneous status information, intent sharing enables a vehicle to achieve a more accurate prediction of its future surroundings, and thus, benefit its decision and control. Our previous works [10]–[12] developed a tool called conflict analysis to interpret status and intent information. This allows for efficient decision making and controller design for conflict-free maneuvers in mixed traffic. However, so far the existing studies on intent sharing, including the ongoing standardization, are restricted to theory, and the benefits of sharing intent have never been experimentally evaluated using real vehicles. This paper fills this gap between theory and practice.

In this study we use commercially available V2X communication devices to create intent messages according to two different definitions of vehicle motion intent: (i) bounds of kinematic variables (e.g., speed and acceleration) over a time horizon; (ii) expected trajectory specified as target road segments. Here, the intent of type (i) is based on our prior work [10], while the intent of type (ii) is based on ongoing standardization. We test intent messages using real connected vehicles on public highways. We quantify intent packet delivery ratio (PDR), i.e., the percentage of transmitted intent packets that are received by the receiving vehicle, and evaluate the effects of packet size. Furthermore, using numerical simulations, we demonstrate the benefits of intent messages in resolving conflicts during cooperative maneuvers. We show that receiving intent messages can reduce a vehicle's decision conservatism and improve its time efficiency. Finally we assess how the benefits of intent depend on the PDR.

II. Implementing Intent Sharing Communication

In this section, we define the aforementioned two types of vehicle motion intent, and show how such intent messages are created using V2X devices.

A. Kinematic Bounds Intent

This subsection focuses on the first type of vehicle intent, which uses the bounds of model-based kinematic variables (e.g., velocity and acceleration). Such bounds shall be more restricted than a vehicle's physical motion limits. We refer to this as *kinematic bounds intent*; see Fig. 1(a) for a conceptual example of such bounds. Focusing on a vehicle's longitudinal motion, we formally provide such definition below.

Definition 1: (Kinematic bounds intent) The intent of a vehicle's longitudinal motion is represented by a lane number n, a restricted velocity domain $v(t) \in [\underline{v}, \overline{v}]$ and acceleration (input) domain $a(t) \in [\underline{a}, \overline{a}]$ over a future time period $t \in [t_0, t_0 + \Delta t]$, where t_0 is the current time, Δt is the intent horizon, $v_{\min} \leq \underline{v} \leq \overline{v} \leq v_{\max}$, $a_{\min} \leq \underline{a} \leq \overline{a} \leq a_{\max}$, and $v_{\min}$, $v_{\max}$, $a_{\min}$, and $a_{\max}$ are the vehicle's physical velocity and acceleration limits. ■

For a highway driving example, an intent message may contain the information that for the next $\Delta t = 5$ [s], the vehicle will be traveling on its current lane (lane number

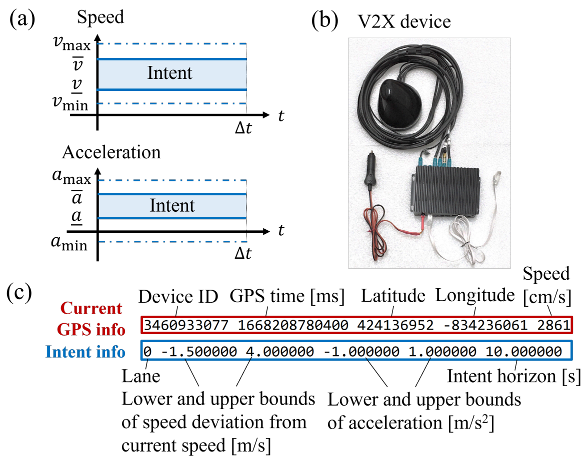

Fig. 1. Intent information defined using a vehicle's kinematic variable bounds. (a) A schematic plot where a vehicle's intent is represented by restricted domains of speed and acceleration (specified by their lower and upper bounds) over a time horizon. (b) V2X communication device used to implement intent messages. (c) An example of kinematic bounds intent message transmitted in our experiment.

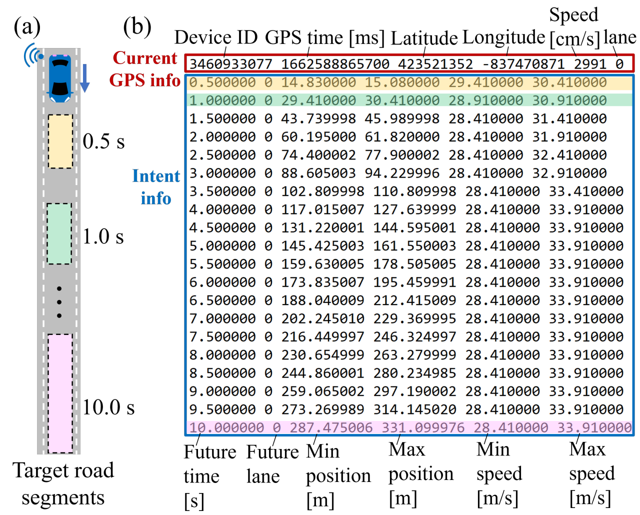

Fig. 2. Intent information defined using target road segments. (a) A schematic plot where a vehicle's intent is shared as road segments that will be occupied in discrete future time moments. (b) An example of such intent message transmitted in our experiment.

$n = 0$) with velocity between $\underline{v} = 22$ and $\overline{v} = 25$ $[\mathrm{m/s}]$, and acceleration between $\underline{a}_1 = -1$ and $\overline{a}_1 = 1$ $[\mathrm{m/s^2}]$.

Based on Definition 1, a vehicle's intent can be efficiently encoded into a set of parameters indicating the intended bounds of velocity and acceleration. This allows for data-compact implementation when creating intent messages. Note that compared to receiving only vehicle status, the information of restricted bounds on kinematic variables allows the intent receiver to achieve a more accurate prediction on the intent sender's possible future trajectories by using a longitudinal dynamics model. Although Definition 1 uses constant intent bounds, it can be adapted to cases where these bounds become time-varying. Moreover, Definition 1 can be extended to describe a vehicle's lateral motion intent using a lateral dynamics model and the bounds on the corresponding states and inputs. This is left for future work.

We remark that such definition of intent is implementable on vehicles of different automation levels. For a connected automated vehicle, the intended velocity and acceleration bounds may be extracted from its motion planner, which prescribes general future behaviors for the vehicle. For a connected human-driven vehicle such intent bounds may be extracted from the human driver's historical behavior data when involved in similar scenarios.

To create such intent messages, we utilize the WAVE Short Message Protocol (WSMP) [13] via commercially available V2X Onboard Units (OBUs) shown in Fig. 1(b). WSMP is a network layer messaging protocol allowing the transmission of messages with customized payload and packet sending rate. We implement intent messages in C language using the application programming interface (API) provided by the OBU manufacturer, where appropriate data structures are used to store and transmit the parameters of the intent.

Fig. 1(c) shows an example of such intent packet transmitted in our experiment, which consists of the vehicle's current GPS and intent information. Note that the vehicle's intended speed bounds are constructed by adding the speed deviation bounds to its current speed. These bounds' values were extracted from a human-driven vehicle's highway driving data. Due to the data-compact representation of vehicle intent in Definition 1, our intent packet has a small payload size of 51 bytes, which can be reduced using less digits for the parameters. Note that the overall packet size may become slightly larger after being cryptographically signed. As will be shown later via experiments and simulations, having smaller packet size contributes to less intent packet drops and better secured benefits.

B. Road Segment Intent

Now we describe the second type of intent, which is defined as an expected future trajectory represented by a series of road segments (i.e., geographical positions) that will be occupied for a set of discrete future time moments; see Fig. 2(a) for a conceptual illustration. Note again that this realization is based on ongoing standardization. We refer to this type of intent as *road segment intent*. For longitudinal motion, we provide the formal definition below.

Definition 2: (Road segment intent) The intent of a vehicle's longitudinal motion is represented by a lane number n and a series of position domains $r(t_k) \in [\underline{r}(t_k), \overline{r}(t_k)]$ at discrete future time moments t_k, $k = 1, 2, \ldots, N$, where t_N denotes the end of the intent horizon. ■

The road segment intent message can also be implemented using WSMP as described in the previous subsection. Fig. 2(b) shows an example of such intent packet transmitted in our experiment, where each row in the intent section corresponds to a road segment to be occupied at the indicated future time; see also the rectangles with corresponding colors in Fig. 2(a). In addition to road segment information (min/max positions), this intent packet also contains information of the vehicle's speed range when occupying each road segment. Note that the values of these parameters can be obtained using the kinematic bounds intent in Fig. 1(c). That is, the same intent information was encoded in two different ways

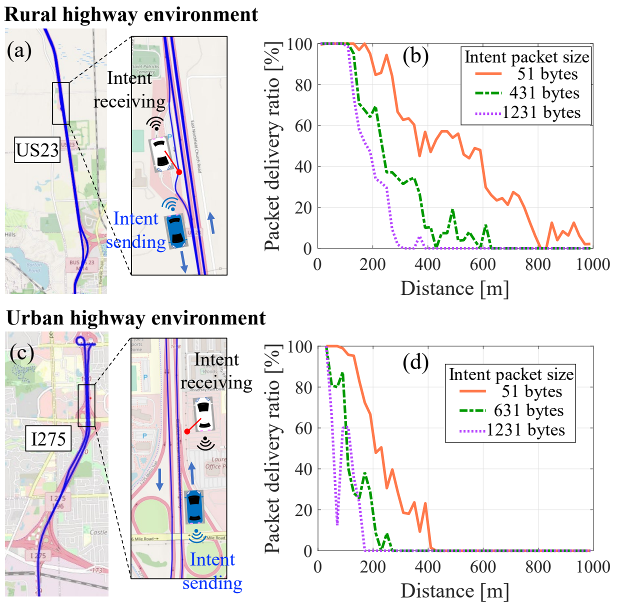

Fig. 3. Experiments of intent sharing communication on highways and the corresponding PDR results. Here, the packet size of 51 bytes is associated with kinematic bounds intent, while other packet sizes are of road segment intent. (a)-(b) On rural highway US-23; (c)-(d) On urban highway I-275; both in the state of Michigan.

based on Definitions 1 and 2.

Compared to the kinematic bounds intent, the road segment intent is model-free and more straightforward for the intent receiver to interpret, leading to less computational load in predicting the sender's future trajectories. However, due to the discrete time nature in describing target road segments, large data space is usually required. That is, to specify a fine enough future trajectory, detailed time discretization is needed. This can lead to large packet size, e.g., 431 bytes for the intent packet shown in Fig. 2(b). As demonstrated experimentally below, larger packet size can significantly compromise the packet delivery ratio (PDR). On the contrary, the kinematic bounds intent packet enables continuous time prediction on the intent sender's future state while maintaining a compact size.

In summary, so far, we have implemented intent messages according to two definitions. The next section presents experimental results where the intent messages were tested on public roads with real vehicles.

III. Testing Intent Messages on Highways

We tested the transmission of intent messages using real human-driven vehicles equipped with commercially available V2X devices in two different environments: one on a rural segment of the highway US-23 and the other on an urban segment of the highway I-275, both in southeast Michigan.

Fig. 3(a) depicts the experimental setup on highway US-23, where the intent receiving vehicle (white) stayed at a rest area near the highway, while the intent sending vehicle (blue) traveled along the highway transmitting the default BSMs and the designed intent packets both at a rate of 10 Hz. The blue trajectory illustrates the intent sender's route. Note that the position of the standstill intent receiving vehicle was selected considering potential application of intent sharing in highway merge, while our analysis is still applicable to a larger variety of scenarios. We tested both types of intent messages. For road segment intent, while maintaining a 10 [s] intent horizon, different time discretizations were used to create intent messages with different numbers of target road segments, and thus different packet sizes (up to 1231 bytes).

The reception of intent packets indeed depends on the distances and the objects between the vehicles. When communication interruption happened, intent packet drops occurred. Based on the recorded numbers of intent packets sent and those actually received, we calculated PDR as a function of the distance between the intent sender and receiver. Fig. 3(b) shows the results corresponding to three different packet sizes. The most lightweight one, i.e., kinematic bounds intent (51 bytes), had the best PDR among the three, while sharper drops were observed with the increasing distance for larger packet sizes (431 and 1231 bytes) associated with road segment intent. This shows a clear trend that larger intent packet size can cause greater degradation of packet delivery.

Similar experiments were performed on the urban highway I-275, as depicted by Fig. 3(c), where the white vehicle parked at the roadside received intent messages from the blue vehicle traveling on the highway. Fig. 3(d) plots the PDR calculated corresponding to the indicated packet sizes. Again, a qualitatively similar trend is observed, i.e., intent packets suffer significantly more drops as the packet size increases. Due to more obstacles (e.g., traffic, buildings) in the urban environment, smaller PDRs are observed for all three sizes of intent packet compared to the rural environment.

Having tested and evaluated the transmission of intent messages on public roads, we evaluate the benefits of intent messages in resolving conflicts during cooperative maneuvers in the next section, and investigate the effects of PDR on such benefits using the experimental results.

IV. Evaluating Benefits of Intent Messages

We perform simulations for a merge scenario illustrated in Fig. 4(a), where an on-ramp vehicle (white) stays in front of a merge zone (yellow rectangle with length 50 [m]), attempting to merge onto a main road from standstill. A main road vehicle (blue) is approaching using cruise control with its speed set to 30 [mi/hr] (≈ 13.4 [m/s]). We feed real data of a human-driven vehicle with such cruise control speed into the simulation. The main road vehicle shares its status via BSMs and its cruise control intent via intent messages, both at a rate of 10 Hz. Using kinematic bounds intent as an example, the cruise control intent shall contain the information that for the next 10 [s], the main road vehicle will be traveling on the rightmost lane with a speed deviation range of $[-0.55, 0.437]$ [m/s] from its current speed, and an acceleration range of $[-0.3, 0.3]$ [m/s^2]. Note that these parameters are determined from real data. Again, the same information can be encoded in a discrete time manner via road segment intent but with a larger packet size. We define a conflict zone (red rectangle) near the end of the merge zone with a length of 20 [m], and consider the initial position of the main road vehicle to be 120 [m] away from the merge

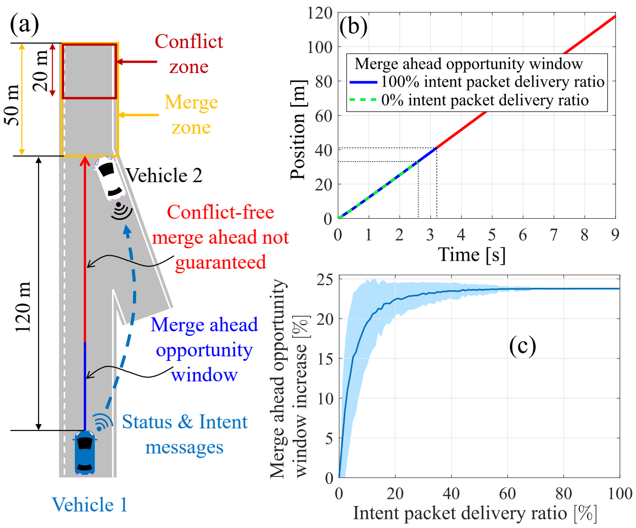

Fig. 4. Evaluating benefits of intent messages under different PDRs. (a) Simulation setup of a merge scenario where the main road vehicle sends status and intent information to the merging vehicle. (b) Position profile of the main road vehicle, with the merge ahead opportunity window highlighted under 100% and 0% intent PDRs. (c) Improvement of merge ahead opportunity window as a function of intent PDR, where the solid line is the mean value and the shaded area illustrates the standard deviation.

zone. Assuming the lengths of both vehicles are 5 [m], we say that a conflict happens if both vehicles appear (even partially) inside the conflict zone in the same time instance.

Using received V2X messages, the on-ramp vehicle needs to determine whether it can merge ahead of the main road vehicle without a conflict. As conceptually depicted in Fig. 4(a), there exists a merge ahead opportunity window when the main road vehicle is far away (blue segment). As the main road vehicle approaches, such opportunity disappears and a conflict-free merge ahead is no longer guaranteed; (red segment). The on-ramp vehicle checks if a merge ahead opportunity exists at each BSM receiving time under the available intent information. To do so, we utilize an extended version of the tool called conflict analysis. While the details of conflict analysis are omitted here, we refer the interested readers to our previous work [10], [12].

Fig. 4(b) shows the position profile of the main road vehicle, while highlighting the merge ahead opportunity windows under perfect intent sharing (100% intent PDR) and under status sharing only (0% intent PDR). Under intent information, a significant increase in merge ahead opportunity window (in terms of time and distance) is observed, implying better chance for the on-ramp vehicle to merge ahead without conflict. This leads to better time efficiency of merging and improved throughput of the on-ramp.

Considering status sharing as a baseline, we quantify the increase of merge ahead opportunity window under intent sharing for different PDRs. In the simulations, we assume that the transmission of each intent packet follows a Bernoulli distribution with the PDR being the probability of receiving it. Fig. 4(c) shows the results, where simulations were repeated 500 times for each different PDR. The solid line is the mean value while the shaded area represents the standard deviation. It is observed that the benefits of intent sharing are maintained even for relatively low PDR; see the almost flat segment of $40\% - 100\%$ PDR. This tolerance comes from the fact that an intent packet, once received, can provide a long horizon of anticipation towards the future. However, sharp degradation of the benefits appears for lower PDR. This suggests the importance of data-efficient design of intent packets.

V. Conclusion

This paper evaluated intent-sharing communication using real connected vehicles. We created intent messages, which encode a vehicle's future motion information, using the V2X protocol WSMP on commercially available V2X radios. We tested intent messages on public roads to evaluate the transmission performance of intent packets under two different designs. Experimental data showed that large packet size can lead to degraded packet delivery ratio (PDR). Numerical simulations further revealed that intent sharing benefits a vehicle's safety and time efficiency, and demonstrated that low PDR can compromise such benefits. Our future directions include implementing more sophisticated intent information and extending the experimental work to higher level of cooperation, e.g., negotiation.

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