Augmenting Autonomous Vehicle Technology with I2V Information


Mengqiao Yu, Aditya Medury, Offer Grembek, Alex Kurzhanskiy, Pravin Varaiya (PI)

Background
Worldwide R&D activity in highly autonomous vehicles (HAV) is accelerating. In his introduction to the just-released NHTSA report, “Federal Automated Vehicle Policy”, Secretary Anthony R. Foxx predicts that automated vehicles may “uproot personal mobility as we know it”. The excitement around HAVs starts with safety, and the report outlines a Vehicle Performance Guidance that manufacturers and regulators must follow to ensure that HAV performance meets the safety implicit in the SAE definitions of automation Levels 3-5. An HAV is supposed to have an automatic control system for each Operational Design Domain (ODD) (e.g. freeway driving, city-street driving, parking, etc.), together with the ODD’s Object and Event Detection and Response (OEDR) capabilities. The HAV is responsible for performing the OEDR while in its ODD and automation is engaged.

The ODD we investigated in our project was a signalized intersection used by vehicles, bicycles and pedestrians. Intersections present a very demanding environment for an HAV. Challenges arise from more complex vehicle trajectories; absence of lane markings to guide vehicles; split phases that prevent determining who has the right of way; invisible vehicle approaches; illegal movements; simultaneous interactions among pedestrians, bicycles and vehicles. Unsurprisingly, most demonstrations of automated vehicles are on freeways; but the full potential of automated vehicles – personalized transit, driverless taxis, delivery vehicles – can only be realized when HAVs can sense the intersection environment to safely maneuver through intersections.

HAVs are equipped with an array of sensors (e.g., video cameras, LiDARs, GPS) to interpret and suitably engage with their surroundings. Advanced algorithms utilize data streams from such sensors to support the movement of autonomous vehicles through a wide range of traffic and climatic conditions. However, there might be situations, in which additional information about the upcoming traffic environment would be beneficial to better inform the vehicles’ in-built tracking and navigation algorithms. A potential source for such information is from in-pavement sensors at an intersection that can be used to differentiate between motorized and non-motorized modes and track road user movements and interactions. This type of information can be provided to the HAV as it approaches an intersection.

1 At SAE Level 3, an automated system can both actually conduct some parts of the driving task and monitor the driving environment in some instances, but the human driver must be ready to take back control when the automated system requests;
At SAE Level 4, an automated system can conduct the driving task and monitor the driving environment, and the human need not take back control, but the automated system can operate only in certain environments and under certain conditions; and
At SAE Level 5, the automated system can perform all driving tasks, under all conditions that a human driver could perform them.
Source: https://www.transportation.gov/sites/dot.gov/files/docs/AV%20policy%20guidance%20PDF.pdf
intersection, and incorporated into an improved prior for the probabilistic algorithms used to classify and track movement in the HAV’s field of vision. In addition, the in-pavement sensors can also provide HAVs greater context about the approaching intersection, such as its typical traffic mix, the yielding rates of drivers to pedestrians, red-light-running rates, etc. Such insights can augment the streams of data already available to the native vision-based algorithms.

We believe that an autonomous vehicle can form a real-time “map” of an intersection, provided that its on-board sensing capability is augmented by infrastructure sensors that (1) capture all vehicle movements in the intersection; (2) provide full signal phase information; (3) indicate vehicle encroachment on bicycle and pedestrian movements; and (4) detect hazardous illegal movements.

**Project Results**

To demonstrate the proposed concept, we used an intersection in Danville, CA, which is equipped with micro-radar wireless sensors detecting pedestrians and bicycles, magnetic wireless sensors detecting vehicles, and the conflict monitoring card identifying signal phases, depicted in Figure 1.

![Figure 1 Danville intersection – picture, layout and infrastructure schematics.](image)

There are 29 magnetic sensors denoted by rectangles. These detect passage of vehicles. Each sensor outputs an ‘on’ when a vehicle enters its detection zone (about 1’ diameter) and an ‘off’ when the vehicle leaves. The cross walk on the approach from the West contains 12 micro-radar sensors denoted by triangles. These report an ‘on’ when an object enters its field of view together with a ‘bulk’ value.
that is proportional to the area of the object that reflects the microwave. In addition, the traffic controller provides the current phase of the signal. All sensor measurements and the signal phase are time-stamped by the same UTC clock with an accuracy of 10ms. The synchronous measurements are used to reconstruct vehicle and pedestrian trajectories.

To analyze and fuse measurement data coming from multiple detection sources, we used the MATLAB application developed for processing and visualization of information coming from micro-radar, magnetic sensors, signal phase system and video, shown in Figure 2. This tool enables:

- Taking advantage of the time synchronization of the various data streams to depict a visual representation of the various activations/de-activations in a manner that could mimic modes moving from one part of the intersection to another;
- Integration of videos with the sensor data;
- Accessing and visualizing data from different dates and times with the help of interactive user interface;
- Labeling micro-radar events to be later used for construction of pedestrian trajectories.

Figure 2 Screenshot of the MATLAB application for analysis of vehicle and pedestrian trajectories based on detector data.

The UI components displayed in Figure 2 are:

A. This module allows for different dates and times to be selected for viewing, either as a movie, or by manually moving the frames backwards or forwards. The frames per second are selected as a function of the frequency of the micro-radar, 8 Hz – either 1, 2, 4, or 8 frames per second.
B. This module provides a time-space diagram of the micro-radar activation/deactivations. The y-axis represents the location of the sensors along the crosswalk. The x-axis represents time, with 0
corresponding to the current time, while positive and negative values corresponding to future and past time respectively. The blue bars represent the duration of a sensor event. The thickness of the bars is proportional to the average bulk value (an option that is available in module A). The green bars on top show the durations of different phases. When the play option is selected, the time-space diagram moves from right to left, and sensor states of the future get initiated over time.

C. This module provides a visual representation of which sensors are currently active (shown in red). The lighting up of sensors matches the bars in module B, which overlap with time 0.

D. This module includes time-space diagrams of the different magnetic sensors that are located closest to the intersection. The orientation of these time-space diagrams is chosen so that past-to-future event transitions are aligned with the movements of the vehicles.

E. This module displays the video frames associated with the current timestamp, if available.

In the particular instant that is being captured by Figure 2, the video frame shows a combination of pedestrians and cyclists riding/walking their cycle at different parts of the crosswalk. A closer view of the time-space diagram can visually reveal the presence of four trajectories separating out over time, as indicated by the arrows in Figure 3. Phase 14 corresponds to the lead pedestrian phase for this crosswalk, while phase 4 corresponds to the vehicular phase for north-to-south-and-west movements. The presence of a vehicle stopping in front of the stop bar location is getting captured by a long micro-radar event in the time-space diagram as displayed around y=30.

Figure 3 Separation of pedestrian trajectories using the time-space diagram.
To demonstrate how sensor measurement fusion and infrastructure-to-vehicle (I2V) technology could improve HAV’s safety and efficiency at the intersection, we designed six scenarios and implemented them in the field.

**Scenario 1: Signal Confusion and Limited Line of Sight**

Figure 4 depicts Scenario 1. HAV (A) does not know, which movement, B or C, has the right of way. Restricted to its camera’s line of sight, HAV may be unaware of the upcoming traffic (C) from the east. Through I2V, the HAV can get information about the approaching vehicle and its right of way.

Approaching the intersection, the HAV should make a decision about the right turn on red light. Its onboard camera does not provide enough data to make this decision. The bottom part of Figure 4 indicates the additional information the HAV will receive about the state of the intersection:

- remaining red time;
- one of two conflicting movements, B and C, has the right of way – it is C; and
• there is an approaching vehicle from direction C – information from magnetic sensors indicates the presence of the vehicle coming from that direction.

Based on its on-board camera vision and this additional information, the HAV can make a decision to stop.

**Scenario 2: Yellow Interval Dilemma**

Figure 5 depicts Scenario 2. HAV (A) approaches the intersection following another vehicle. This approach happens in high speed, because the signal shows green. Suddenly, green switches to yellow, and the leading car brakes abruptly. This may cause the rear-end collision.

I2V can provide the information about the remaining green time to the HAV. The signal phase indicator in the bottom right of Figure 5 shows that although currently the HAV’s movement has green light, in 2 seconds it will be yellow, placing the vehicle in front into the dilemma zone – to cross or to stop. Seeing
that the light is about to change, HAV should slow down preparing to stop, independently of what the vehicle in front decides to do.

**Scenario 3: Collision with Red Light Runner**

Figure 6 depicts Scenario 3. The HAV, shown in green, has the right of way and starts crossing the intersection following the rules, when it gets hit by the red-light runner (shown in red) moving in perpendicular direction. Google HAV found itself in this kind of crash in September 2016. We did not stage the actual accident in Danville. However, studying the historical video footage from the intersection camera, we found the situation resembling Scenario 3, where the accident was barely avoided, shown in the bottom part of Figure 6. There, a vehicle with the right of way (circled in green) crossing the intersection was almost hit by the red light violator (circled in red) speeding in perpendicular direction. The crash was avoided thanks to fast reaction of the driver in the first vehicle, who applied brakes in time.

I2V can provide an advance warning to the intersection-crossing HAV about the speeding violator. This information can be obtained from the combination of signal phase data and the speed of the violator inferred from the firing sequence of magnetic sensors at the intersection approach. Depending on the relative position of the HAV and the violator, the HAV must then make a decision to brake, to swerve, or to speed up to avoid the crash.

---

2 Google car was operating in its autonomous mode at the time of the crash. The human driver slammed on the brakes when he spotted the oncoming van, but it was too late.  
Scenario 4: Delayed Reaction to Pedestrian Crossing

Figure 7 depicts Scenario 4. The right-turning HAV approaches the intersection during the green phase. There are no conflicts with other cars, but there is a pedestrian crossing the street. The HAV must recognize the direction of the pedestrian’s movement: if the pedestrian moves toward the HAV, the HAV has to yield; otherwise, the HAV can turn. There are two challenges: first, the pedestrian must be detected by the HAV; and second, the direction of pedestrian’s movement must be identified.

I2V can help detecting pedestrians and identifying their walking direction in a timely manner. This is achieved using micro-radar at the crosswalk and observing its firing sequence, shown in the right bottom of Figure 7.
Scenario 5: Alert for Left Turning Vehicle

Figure 8 depicts Scenario 5. HAV turning left on green (A) shares the exit lane with a car coming from the opposite direction and turning right (B). By the rule, HAV has the right of way, but it must be aware of the potential conflict. In our scenario, the HAV’s on-board camera does not see the vehicle in the right lane, rapidly approaching from the opposite direction, because cars, stopped at the red light, block its view.

I2V, based on the measurements from magnetic sensors, can provide a warning of a potential conflict to the HAV. The warning will be issued only if the combination of the position and speed of the approaching right-turning (or red light running) vehicle admits the collision.
Scenario 6: Limited Line of Sight of Pedestrians and Bicyclists
Figure 9 depicts Scenario 6. The vehicle waiting to turn left (B) is blocking the view of the HAV (A) deciding, whether to turn right on red. In this case, the HAV cannot identify the presence of pedestrians or bicycles on the crosswalk.

I2V using micro-radar readings can rectify this situation.

Next Steps
In the next phase of our research, we will propose developing the prototype I2V system that fuses the data from sensor measurements and sends this combined additional information to the HAV via DSRC, enriching HAV’s perception of the intersection and providing decision support. For this next research phase, we need to:

- classify intersections by complexity of design, operations and traffic;
- specify hazardous conditions that can be rectified by I2V for each intersection class;
- develop algorithms that identify hazardous conditions from the sensor measurements and signal phasing; and
- construct information messages that infrastructure will broadcast to vehicles.