Introducing an Intelligent Intersection

A Research Report from the University of California Institute of Transportation Studies

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August 2018

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. UC-ITS-2018-13	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Introducing an Intelligent Intersection		5. Report Date August 2018
		6. Performing Organization Code ITS-Berkeley
7. Author(s) Offer Germbek Ph.D., Alex A. Kurzhanskiy Ph.D., Aditya Medury Ph.D., Pravin Varaiya Ph.D., Mengqiao Yu		8. Performing Organization Report No.
9. Performing Organization Name and Address Institute of Transportation Studies, UC Berkeley 109 McLaughlin Hall Berkeley, CA 94720		10. Work Unit No.
		11. Contract or Grant No. UC-ITS-2018-13
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org		13. Type of Report and Period Covered Final Report (June 2017 – June 2018)
		14. Sponsoring Agency Code UC ITS

15. Supplementary Notes
DOI:10.7922/G22N50F6

16. Abstract
This project seeks to remove one important cause of intersection accidents: drivers, pedestrians and cyclists make mistakes because they lack sufficient information about the movement of others as they proceed through an intersection. There is spatial and temporal uncertainty. This missing information can be supplied by an 'intelligent intersection'. It describes the signal from all approaches; predicts when the signal phase will change; uses sensor data to determine which blind spots are occupied; and predicts red light violations before they occur. The intelligent intersection broadcasts this information via radio and can be received by a connected vehicle or indeed anyone in the intersection with a smartphone or bluetooth device, so most intersection users will get this information. The objective of this research is to design intelligent intersection infrastructure and evaluate its performance in terms of safety and mobility benefits.

17. Key Words Intersections, traffic safety, detection and identification systems, intelligent transportation systems, smartphones, pedestrians, cyclists, drivers		18. Distribution Statement No restrictions.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified	21. No. of Pages 64	22. Price

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

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ACKNOWLEDGMENTS

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Introducing an Intelligent Intersection

UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

August 2018

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Executive Summary

Intersections are dangerous: 40% of all crashes, 50% of serious collisions, and 20% of fatalities occur in intersections. Bay Area fatalities increased 43% between 2010 and 2016 to reach 455 killed, of which, in San Francisco, 62% were cyclists or pedestrians. Intersections are challenging because of complex interactions among pedestrians, bicycles and vehicles; absence of lane markings to guide vehicles; split phases that prevent determining who has the right of way; obstructions from stopped vehicles; and illegal movements. Improving intersection safety is urgent. There have been two policy responses: Vision Zero and Automated Vehicles.

At least 9 cities in California, including San Diego, Los Angeles, San Francisco and Sacramento, have adopted Vision Zero (VZ) Action Plans to eliminate serious accidents and deaths by restricting vehicle movement while facilitating walking and biking. VZ investments focus on physical modification of the road infrastructure to favor walking and biking. But the safety record of these modifications is mixed, and some changes are expensive, e.g. the 13 'protected intersections' built in 2015-16 each cost between $250K and more than $1M.

Automated vehicle (AV) manufacturers offer a dramatic path to safety, claiming that with their 3D maps, many sensors and tireless robotic driving, AVs will prevent 94% of all crashes involving human error. In fact, AV safety performance (accidents and disengagements per automated vehicle miles traveled) today is 13 to 100 times worse than that of human drivers; AV fatality rate is equally bad. AVs also find intersections challenging: 58 of 66 (88%) AV crashes reported to the DMV occurred in intersections. Even if AVs eventually become safe, it will be 15 years before they are widely deployed. Meanwhile pedestrians and cyclists face high risk of injury and death.

This project seeks to remove one important cause of intersection accidents: drivers, pedestrians and cyclists make mistakes because they lack sufficient information about the movement of others as they proceed through an intersection. There is spatial and temporal uncertainty. Spatial uncertainty arises from the fact that the traffic signal we see as we approach the intersection does not tell us who else entering from the other approaches has the right of way. For example, if we are making a right turn, we do not know which other driver, pedestrian or cyclist also has the right of way conflicting with our own right turn. Second, if we are approaching the intersection during green or yellow we don't know if there is enough time for us to drive through before the light changes to red. Third, we may not see conflicting movements due to blind spots created by vehicles stopped in adjacent lanes. Fourth, we may not see red light violators.

This missing information can be supplied by an 'intelligent intersection'. It describes the signal from all approaches; predicts when the signal phase will change; uses sensor data to determine which blind spots are occupied; and predicts red light violations before they occur. The intelligent intersection broadcasts this information via radio and can be received by a connected vehicle or indeed anyone in the intersection with a smartphone or bluetooth device, so most intersection users will get this information.

Vision Zero investments may improve safety, but they can be expensive and reduce mobility. Automated vehicles may in 15 years yield safety benefits. The intelligent intersection complements both approaches because neither approach provides the information which serves as an additional safety buffer for pedestrians, cyclists and drivers.

Our objective is to design this intelligent intersection infrastructure and evaluate its performance in terms of safety and mobility benefits. Upgrading to an intelligent intersection costs between $25K and $100K, depending on what sensors are already in place. Traffic data collected at an intersection can be analyzed to estimate how many crashes can occur. Intersections can be ranked accordingly and limited funds can be directed at the most unsafe intersections.

Chapter 1

Introduction

Intersections are very dangerous. 40% of crashes, 50% of serious collisions, 20% of fatalities occur in intersections. Bay Area fatalities increased 43% between 2010 and 2016 to reach 455 killed, of which, in San Francisco, 62% were cyclists or pedestrians. It is claimed that AVs will prevent 94% of all crashes involving human error with no sacrifice of mobility. However, the safety performance of AVs today is far below that of human-driven cars. Responding to the road safety crisis, cities have launched Vision Zero (VZ) plans, seeking to eliminate traffic injuries and deaths, through physical modification of the road infrastructure to reduce vehicle mobility and create a safe passage for cyclists.

However, crashes happen because drivers, cyclists and pedestrians face uncertainties that lead to wrong decisions and end in crashes. Spatial uncertainty occurs when an agent at an intersection is unable to detect other agents; temporal uncertainty occurs when the agent is unable to accurately predict its own and others' right of way. These challenges are not fully addressed by the 'road diet' and road redesign prescribed in VZ plans. Nor are they handled by AVs that only rely on on-board sensors.

These uncertainties can be addressed by an *Intelligent Intersection*. The intelligent intersection does not require costly physical modification of road infrastructure, but provides the following functionality:

1. Communicate not just with connected vehicles (CVs), but with all connected agents crossing the intersection, including vehicles, bicyclists and pedestrians.
2. Inform agents approaching the intersection about current signal phase and its estimated remaining duration. Phases in actuated signals vary depending on presence and volume of vehicular and pedestrian traffic.
3. Inform agents crossing the intersection about their potential blind zones.
4. Inform agents about the detected activity in their blind zones e.g., a bicyclist can be notified about a pedestrian that [s]he cannot see, but who may be crossing her/his path.
5. Accept 'give-me-green' requests from the approaching agents and prioritize signal phasing appropriately.
6. Warn agents crossing the intersection about detected red light violations. To ensure safety, violators must have the right of way.

The intersection intelligence has three components: sensing, interpretation of sensor measurements and connectedness. With the advent of new technologies, urban intersections are being increasingly equipped with various types of video and in-pavement sensor architectures to facilitate round-the-clock monitoring and optimization of multimodal flows. Unlike the moving frame of reference of the AV, the sensors associated with the intersection are fixed and embedded within the infrastructure, such as in-pavement sensors in the

vehicular lanes and crosswalks, signal controller status, overhead cameras, etc. This difference in perspective can be exploited to alert agents traveling in the intersection about the presence of others in advance of their arrival into their detection zones, thus potentially gaining critical time (fractions of a second) in taking better decisions.

In addition to the potential of infrastructure to vehicle (I2V) information, infrastructure sensors themselves can also be used to routinely monitor safety-critical dynamics of modes, such as drivers yielding to pedestrians, pedestrians crossing on red, red-light running, etc., over long periods of time. Thus, using advanced sensing platforms to proactively monitor safety-critical events of multi-modal road users provides an opportunity to supplement the traditional assessment of the safety performance of these facilities, which is largely based on either crash history or citizens' grievances. These come at a cost of between $25K and $100K per intersection depending on its size and sensor configuration. With over 300,000 signalized intersections in the U.S., methodologies described in this report will help identify intersections whose instrumentation is critical or, at least, is desired to ensure safe and efficient AV operation.

The rest of this report is organized as follows:

- Chapter 2 provides the background for the presented research.
  - Section 2.1 explains the challenges of AV operation at urban intersection.
  - Section 2.2 analyzes the accident of an Uber AV in Tempe, AZ, in March 2017, and its causes.
- Chapter 3 addresses intersection analysis.
  - Section 3.1 discusses intersection operational design domain.
  - Section 3.2 presents methodology for identification of potential blind zones.
  - Section 3.3 introduces methodology for assessing intersection's safety.
  - Section 3.4 talks about detection of objects in blind zones.
- Chapter 4 describes the concept of an *intelligent* intersection.
- Chapter 5 presents the Intelligent Intersection Toolbox (IIT), a software library of algorithms needed for the implementation of intersection intelligence.
- Chapter 6 shows how to classify of intersections by their complexity, using city of Berkeley as a case study.
- Chapter 7 concludes the report.

Chapter 2

Background

2.1   Why Intersections are Unsafe

Unlike streets with well-defined lane dividers, intersections do not have markers in the pavement that separate users and movements. The paths of vehicles, bicyclists and pedestrians cross each other within intersections, creating 'conflict zones' and the potential for crashes. So avoidance of crashes requires the movements of different agents to be separated in time or space. It is impossible to fully achieve this separation and so the risk of intersection crashes remains.

Traffic signal control provides limited separation because it does not simultaneously give the right-of-way (green light) to two conflicting movements. Although critical to safety, its effectiveness is often compromised. A driver (or autonomous vehicle) planning a certain movement (say a left turn) can see from the signal light whether her own planned left turn is permitted, but she may be unable to figure out whether another conflicting movement (say a through movement or a right turn by another vehicle or bicycle, or a pedestrian crossing) is also permitted. That is, the signal light visible to the driver does not provide the complete phase information. Similarly, a pedestrian or bicyclist undertaking a movement may be unaware of a permitted conflicting vehicle movement. This *spatial uncertainty* about rights-of-way is eliminated by an intelligent intersection that provides the complete phase information.

Furthermore, road users do not rely solely on their current view of the traffic signal. They also (implicitly) predict how the signal will change in the next few seconds. An accurate prediction of the duration of the current phase and the upcoming phase can be supplied by the intersection, thus reducing *temporal uncertainty* about rights-of-way. This information can be provided by processing signal phase data accumulated at the intersection. The information is part of the signal phase and timing (SPaT) I2V message that the SAE has standardized [20]. Intelligent intersections would broadcast SPaT messages [9].

Even when the driver (bicyclist or pedestrian or AV) knows the complete phase, her knowledge of the intersection state will be limited by the extent to which her view of the intersection is obscured by other users. If the driver cannot fully see a conflict zone, she must guess whether there is a hidden user undertaking a movement in the conflict zone. This dilemma can lead either to slow driving that is overly cautious (when there is no hidden user), or to driving optimistically at a normal speed with greater risk of a crash (because there is a hidden user). The intelligent intersection can process sensor measurements to determine the

presence or absence of a hidden user and communicate that to the driver, thereby eliminating the risk of an overly pessimistic or optimistic assessment [11].

Lastly, even when no conflicting movement is present, a crash may occur from the illegal movement of another car, bicycle or pedestrian. A common example is a car or bicycle running a red light or a pedestrian crossing against a 'dont walk' signal. If appropriate sensor measurements (similar to that collected by a red-light camera system) can be acquired and processed rapidly, the driver at risk could be warned to take evasive action [1].

In summary, by acquiring and processing appropriate sensor data the intelligent intersection can broadcast messages that give complete phase information, predict the signal phase and timing in the next cycle, accurately assess the occupancy of blind zones, and warn of the danger from traffic signal violators. All agents in the intersection can receive these messages via their cellphone or bluetooth device. Upgrading to an intelligent intersection costs between $25K and $100K, depending on what sensors are already in place. Traffic data collected at an intersection can be analyzed to estimate how many crashes can occur. Intersections can be ranked accordingly and limited funds can be directed at the most unsafe intersections.

2.2   Case Study: Uber Accident in Tempe, AZ, in March 2017

The accident illustrated in Figure 2.1 occurred on March 24, 2017. Vehicle V_1 (Honda CRV) northbound in the left turn lane of S. McClintock Dr entered the intersection during green with 5s left in the crosswalk timer, stopped, made a slow left turn onto E. Don Carlos Ave, and collided with vehicle V_2 (Uber automated Volvo), southbound in lane 3 of S. McClintock Dr, which had entered the intersection on yellow at 38 mph (56 fps). After being hit, the Volvo continued across the intersection, struck a traffic signal pole, flipped on its side and collided with Vehicles V3 (Hyundai EST) and V4 (Ford Edge), which were stopped in traffic southbound in lane 2 of S. McClintock Dr. The self-driving Uber had the right of way and was programmed to enter the busy intersection at the speed limit while the light was yellow, but a human driver likely would have slowed down [15].

Four possible errors contributed to the accident. The Uber automated Volvo (V_2)

1. may not have known that traffic in the opposing direction was permitted to turn left;
2. did not predict that the light would turn yellow before it entered the intersection;
3. did not consider that the vehicles stopped in the adjacent lanes 1 and 2 prevented it from seeing a left-turning vehicle until the Uber was within 10 feet of the stop bar and at a speed of 56 fps it could not come to a stop within 10 feet. (At a deceleration of 32 f/s^2, the Uber would stop in 49 ft.)

The Honda (V_1) driver's view

4. was obstructed by vehicles stopped in lanes 1 and 2 and she could only see 10 feet into lane 3, and seeing no vehicle there, concluded that none was going to cross the intersection; she did not realize that the obstruction by stopped vehicles was hiding a vehicle more than 50 feet away approaching at 40 mph.

Figure 2.2 shows a snapshot of a PreScan [10] simulation of the described collision: 2 seconds before the impact V_1 and V_2 do not see each other.
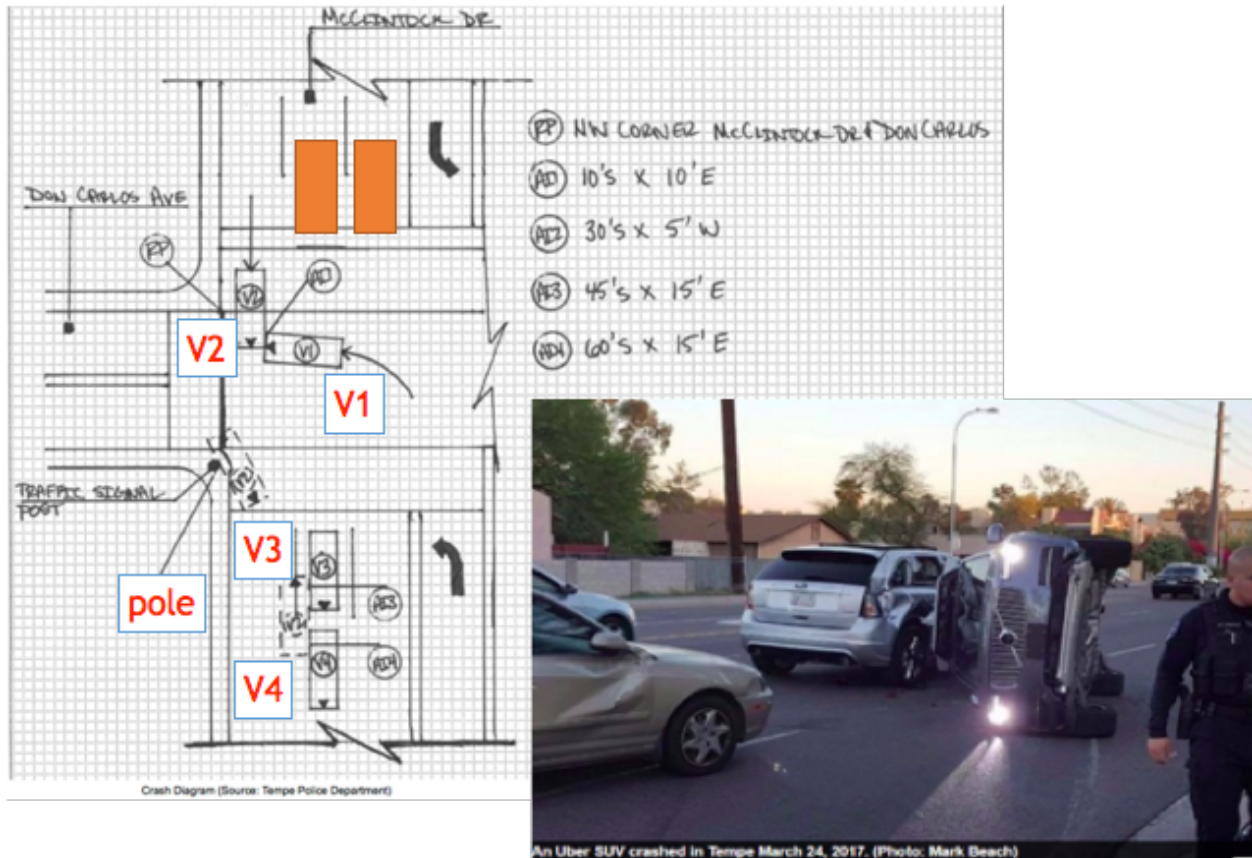
Figure 2.1: Left: diagram from the police report of an intersection where a Honda CRV (V_1) traveling north made a left turn and collided with an Uber automated Volvo (V_2) traveling south at 38 mph in a 40 mph zone. After the collision, the Uber Volvo hit a signal pole, and two other vehicles (V3, V4), shown in the inset. Right: the accident caused heavy damage but no one was seriously injured. Source: [24].

Errors 1 and 2 could easily be prevented by a SPaT message that gives the current phase and predicts when it will end [9]. Error 3 could be prevented by a calculation of the 'blind spot' due to the occlusion from the vehicles stopped in the adjacent lane, together with an intersection blind zone occupied message. Error 4 is difficult to avoid but it could be prevented by a warning sign (Signalized Left Turn Assist System) proposed in the CICAS program [23, 13] or by another blind zone occupied message. The blind zone messages could be triggered by strategically placed sensors within the intersection as described in Section 3.4.

Notice that all errors 1-4 above are due to insufficient information that placed the drivers in a dilemma: should they be optimistic and proceed at a normal speed and risk an accident, or should they be pessimistic and slow down or stop.

The accident described above is one of several scenarios that pose dilemmas and induce errors of judgment on the part of intersection drivers [11]. Six other common scenarios are described below and illustrated in Figure 2.3.

1. right-turn-on-red (RTOR) signal phase confusion and limited line of sight (LOS): RTOR vehicle can not determine if opposing traffic has the right of way;
2. delayed reaction to pedestrian crossing: right turn on green (RTOG) vehicle needs a couple of seconds to detect pedestrian walking direction;

a) Left-turning Honda and Uber's AV Volvo are on the collision course

b) Left-turning Honda does not see Uber's AV Volvo

c) Uber's AV Volvo does not see left-turning Honda

Figure 2.2: PreScan simulation of V_1 and V_2 collision—snapshot of the scenario 2 seconds before the accident.

3. yellow interval dilemma: the following through vehicle does not know when the traffic signal will turn yellow, which might trigger a rapid response from the lead vehicle;
4. left-turn alert: left-turn-on-green (LTOG) vehicle cannot detect the right turn vehicle; both share the same lane, creating conflict;
5. limited LOS for pedestrians/bicyclists: vehicle waiting to turn left blocks the LOS of RTOR vehicle, so it cannot see the pedestrian on the crosswalk;
6. collision with red light violator.

1: Signal confusion and limited line of sight
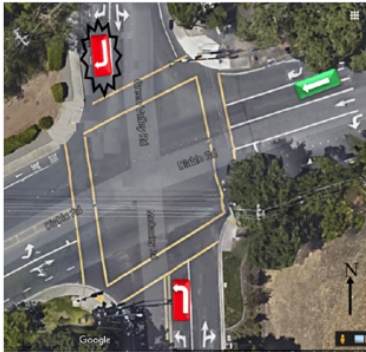
2: Delayed reaction to pedestrian crossing
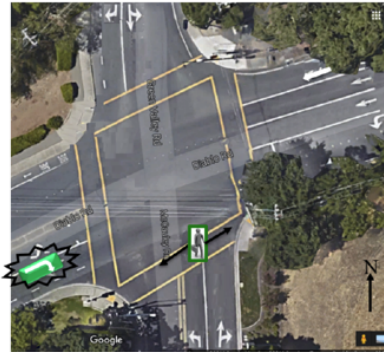
3: Yellow interval dilemma

4: Alert for left turning vehicle

5: Limited line of sight of peds and bicyclists
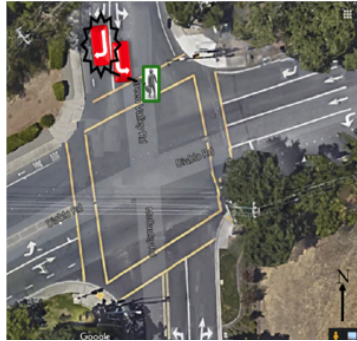
6: Red light violation

Figure 2.3: Common intersection conflict scenarios.

Chapter 3

Intersection Analysis

3.1   Intersection Operational Design Domain

We analyze the intersection ODD in four steps. In step 1, trajectories of users (vehicles, bicycles, pedestrians) are grouped into 'guideways' corresponding to their movements within an intersection. In step 2, 'conflict zones' are identified as regions where two guideways intersect, creating the potential for an accident. In step 3, a procedure is used to determine if a planned movement can be safely executed with the information made available to the user. This information consists in what users themselves can see or sense of the other users in the intersection, together with the SPaT message from the intersection. The message gives the full current phase and an estimate of the time when the phase will change. Most conflicts are resolved by step 3. The conflicts that remain are due to blind zones. Step 4 computes potential blind zones and is discussed in Section 3.2.

The approach is described for a standard four-leg intersection. Upon entering any leg, a vehicle may turn left, turn right, or go straight, giving in all 12 vehicle movements or phases. The eight non-right turn vehicle movements are numbered 1 through 8 and denoted $\phi1, \cdots, \phi8$, as in the inset diagram of Figure 3.1 [8]. Signal lights control which phases are active or actuated, i.e. which movements have the green light. Right turn phases are not numbered, because it is assumed they are always permitted. Pedestrians can only use crosswalks, so they have four movements, phases P2, P4, P6, P8, parallel to $\phi2, \phi4, \phi6, \phi8$. Pedestrian movements are regulated by the 'walk/dont walk' signal, simultaneously with the corresponding phases, so P2 gets 'walk' or 'dont walk' at the same time that $\phi2$ gets 'green' or 'red', etc. Bicycles move alongside vehicles, so they have 12 movements as well, permitted concurrently with the corresponding vehicle movements. (This is a simplification for ease of exposition: pedestrian, bicycle and vehicle movements need not be concurrent.)

Figure 3.1 is used to describe the approach.

Step 1. Construct guideways. A trajectory is a path traced out by a vehicle as it moves through the intersection. (Only permissible trajectories are considered.) A *guideway* is the bundle of vehicle trajectories that make the same movement. A guideway starts from a single lane entering the intersection and ends in a single outgoing lane. There are 12 vehicle guideways corresponding to the 12 phases. (There are more than 12 guideways if there are more than three lanes in one leg.) For the remainder of this section we focus
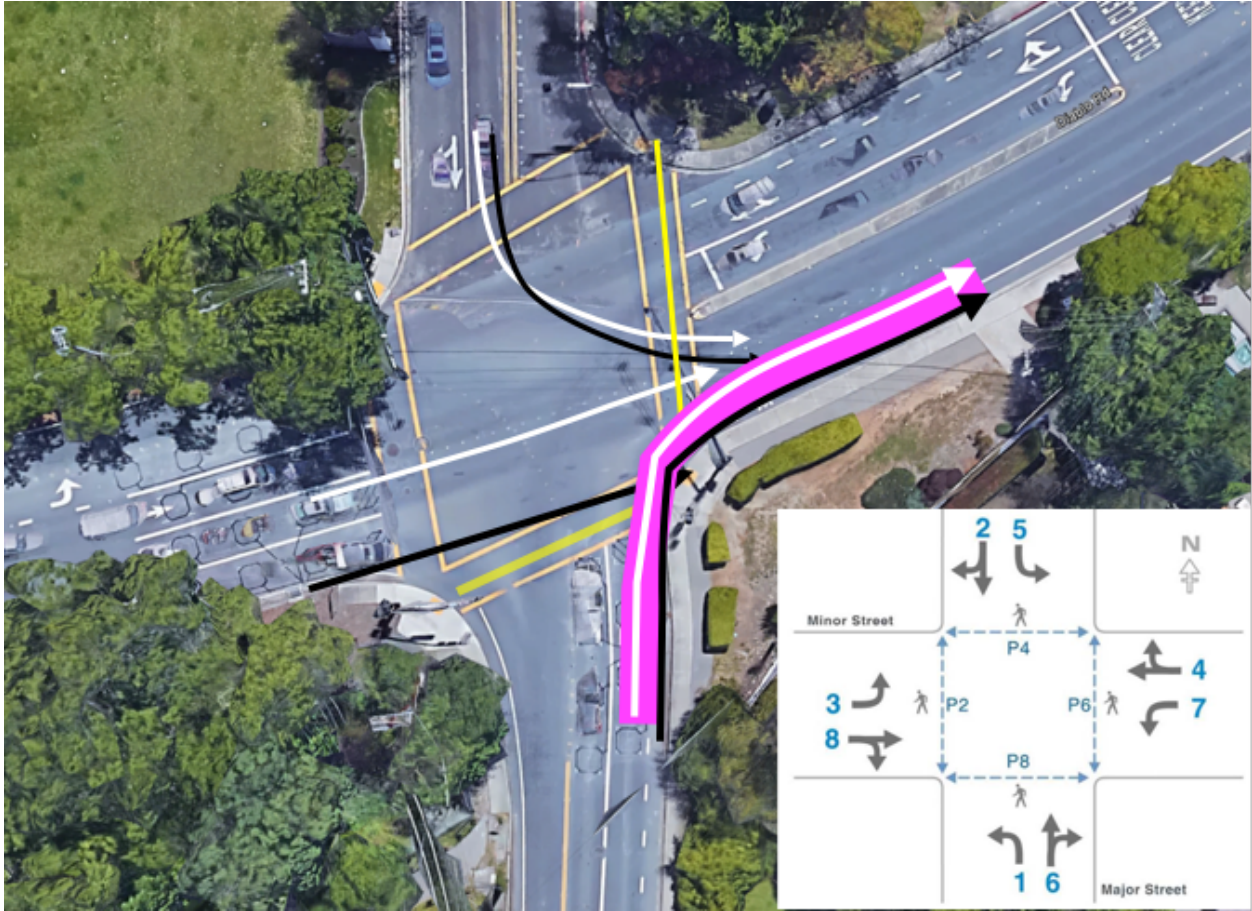
Figure 3.1: A vehicle's right turn trajectory from the south in white. The guideway of all right turn trajectories is in pink. Seven trajectories can conflict with the right turn: two other vehicle trajectories in white, three bicycle trajectories in black, and two pedestrian trajectories in yellow. Trajectories and guideways of non-conflicting movements are not shown. The inset diagram defines the vehicle and bicycle phases $\phi1,...,\phi8$ and the pedestrian phases P2, P4, P6, P8.

attention on the single white trajectory of the vehicle making a right turn from the south in Figure 3.1. Call this the *ego vehicle*. Its trajectory is inside the pink guideway of all right turn trajectories.

The figure shows seven other trajectories that conflict with the ego vehicle's right turn. There are two other vehicle trajectories in white, one making a left turn from the north ($\phi5$), the other making a through movement from the west ($\phi8$). Guideways for bicycles are adjacent to those for vehicles and the figure displays three bicycle trajectories in black, one making a right turn from the south, another making a through movement from the west ($\phi8$), and the third making a left turn from the north ($\phi5$). Pedestrian trajectories are confined to the crosswalks, which form the four pedestrian guideways. Two pedestrian trajectories in yellow are shown (P6 and P8). No bicycle or pedestrian guideway is shown. We will determine the information needed by the ego vehicle's to make its right turn movement safe. The other movements are analyzed similarly.

Guideways may be mathematically specified or empirically constructed. Mathematically, a guideway for a particular movement comprises all possible paths joining its entry and exit lanes, constrained by a reasonable curvature. An empirical construction of a guideway would use GPS traces or videos capturing vehicles or

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bicycles making a particular movement.

Step 2. Identify conflict zones. The seven trajectories–two vehicle, three bicycle and two pedestrian–all intersect the trajectory of the ego vehicle. The intersections of their guideways with the pink guideway identify the seven conflict zones that the ego vehicle must cross. From the inset of Figure 3.1 one can see that the following are all the conflict zones involving the ego vehicle:

1. Conflict with right turn bicycle from south;
2. Conflict with pedestrian on south crosswalk (P8);
3. Conflict with through vehicle from west (ϕ8);
4. Conflict with through bicycle from west (ϕ8);
5. Conflict with left turn bicycle from north (ϕ5);
6. Conflict with left turn vehicle from north (ϕ5);
7. Conflict with pedestrian on east crosswalk (P6).

The conflict zones CZ1, $\cdots$, CZ7 can all be calculated ahead of time from a map of the intersection and the guideways. They are shown in Figure 3.2 as disjoint rectangles for clarity, although in fact they overlap. The ego vehicle must safely cross all seven conflict zones.

Step 3. Resolve conflicts. There are three parts to this step that determines which of the seven conflicts can be resolved. Resolving a conflict means that the ego vehicle establishes sufficiently early whether or not another user will occupy a conflict zone at the same time as the ego vehicle, resulting in a crash. If the ego vehicle determines that another user *will* occupy a conflict zone simultaneously with the ego vehicle, we assume the latter will use a collision avoidance procedure to avoid the accident; if the ego vehicle determines the conflict zone is unoccupied, it ignores this conflict zone. Collision avoidance may simply require slowing down or speeding up without changing the ego vehicle's path [5].

Part 1. Using signal light visible to ego vehicle. Some of the seven conflicts can be resolved by considering the signal light as seen by the ego vehicle, using the fact that two conflicting movements never simultaneously have the green light. Since the signal light may be red or green, the planned movement is either right turn on red (RTOR) or right turn on green (RTOG).

(i) Suppose this is a RTOR movement. So phases ϕ6 and ϕ1 face a red light and P6 has 'dont walk' signal. Hence conflict CZ7 cannot occur, but CZ1, CZ2, CZ3, CZ4, CZ5, CZ6 remain unresolved.

(ii) Suppose this is a RTOG movement. So phase ϕ6 faces a green light and P6 has 'walk' signal, phase ϕ8 faces a red light and P8 has 'dont walk' signal. Hence conflicts CZ2, CZ3, CZ4 cannot occur, but CZ1, CZ5, CZ6, CZ7 remain unresolved.

Part 2. Using ego vehicle's intersection view. The vehicle must decide from its view of the intersection which of the remaining conflicts can be resolved. Figure 3.3 shows a configuration of other potential users in the intersection. (The following analysis must be carried out for the prevailing configuration.) E is the ego vehicle making a right turn. U1, $\cdots$, U7 are the other users whose movements conflict with E: U3, U6 are vehicles, U1, U4, U5 are bicycles, and U2, U7 are pedestrians. O is a vehicle stopped in the left turn lane next to E and obstructs E's view so E cannot see U2, U3, U4 (if they are indeed present) but can clearly see U1, U5, U6, U7. So E can resolve CZ1, CZ5, CZ6, CZ7. However, O prevents E from seeing whether or not U2, U3 and U4 are in fact present and pose a threat, so conflicts CZ2, CZ3, CZ4 remain.

(i) Suppose E is making a RTOR movement. Then the unresolved conflicts are CZ2, CZ3, CZ4.
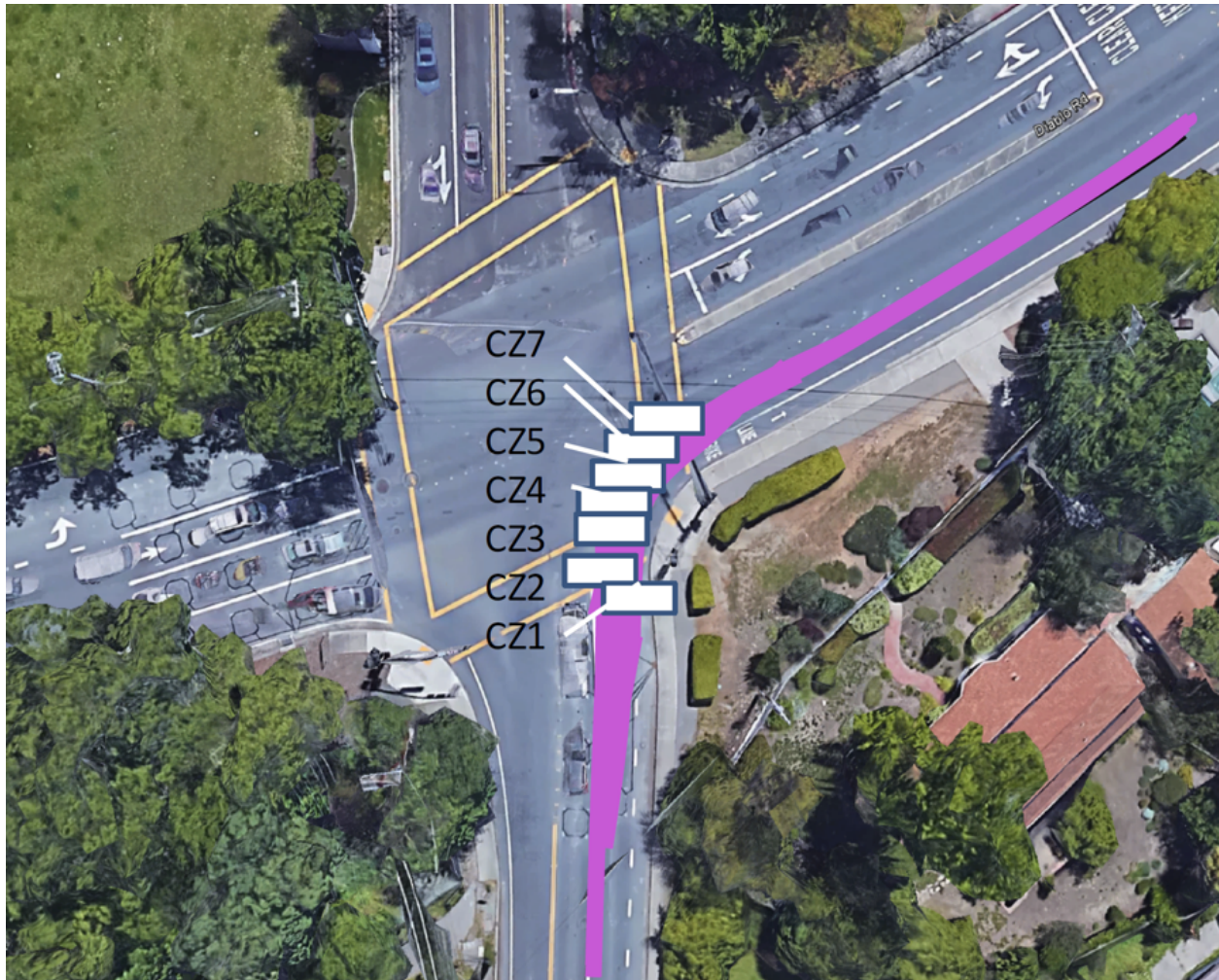
Figure 3.2: The intersection of the seven guideways with the pink guideway yields seven conflict zones, CZ1, ..., CZ7. The conflict zones are shown disjoint for clarity, although in fact they overlap.

(ii) Suppose E is making a RTOG movement. Then all the conflicts are resolved since U2, U3, U4 cannot move, and E can safely complete the right turn.

Parts 1 and 2 delineate the conflicts that can be resolved by drivers and AV systems today.

Part 3. Using signal phase and timing (SPaT) information. An intelligent intersection broadcasts a SPaT message every 100ms. The message consists of the complete signal phase (i.e. the signal phases faced by users at all legs) and an estimate of the time when the phase will change. (In an actuated signal phase durations are not deterministic, and must be estimated [9].) We now see how SPaT information can help resolve additional conflicts.

Suppose E is making a RTOR movement and cannot resolve CZ2, CZ3, CZ4 because of obstruction by O. The red signal seen by the ego vehicIe is compatible with the four possible signal light configurations shown in Figure 3.4. The ego vehicle does not know which configuration prevails, but discovers it from the SPaT message. In configurations I and II West-East movement is permitted, so U2, U3 and U4 all can move and E cannot resolve CZ2, CZ3 and CZ4. In configuration III, only U2 can move, so E cannot resolve CZ2. In
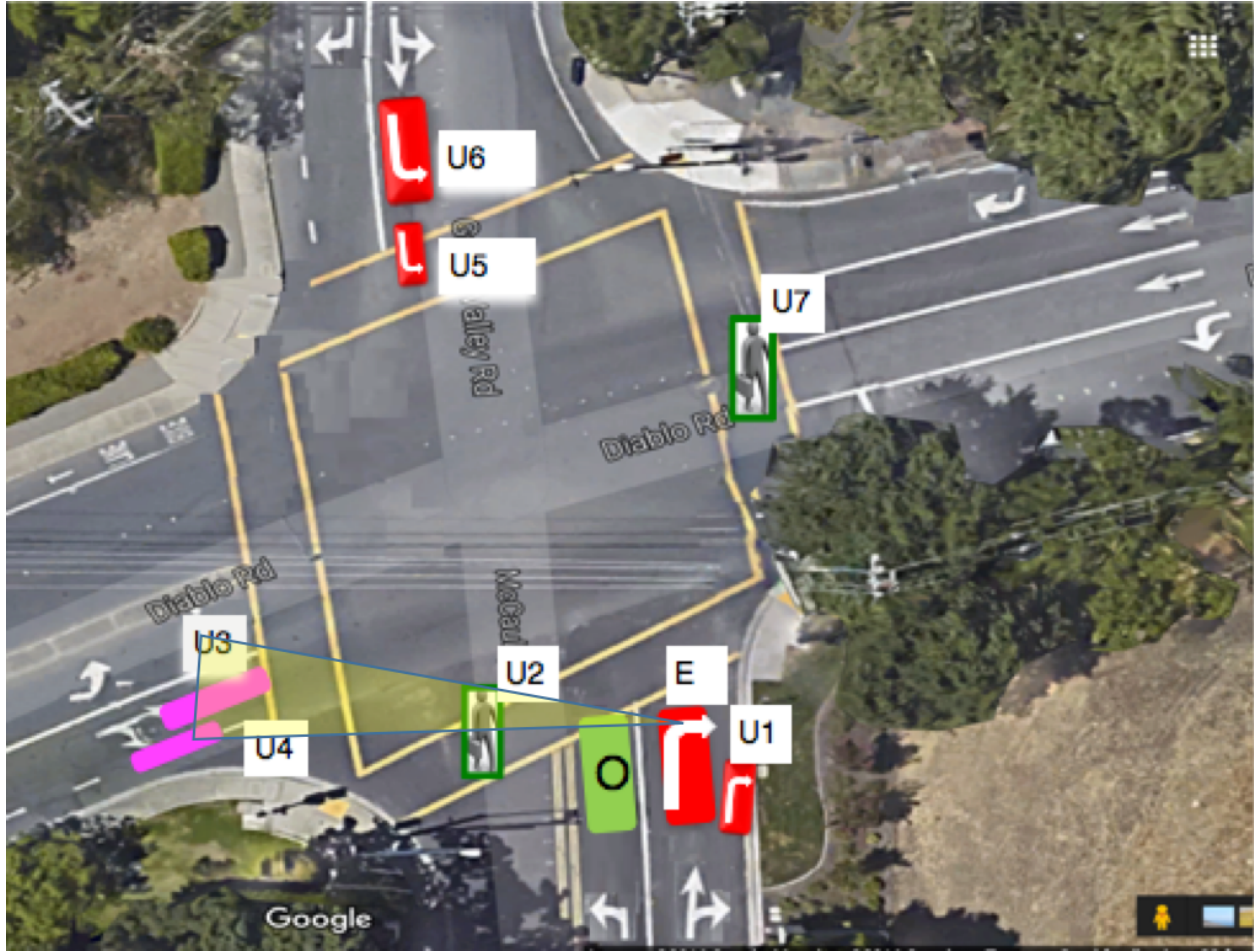
Figure 3.3: The ego vehicle must determine which of conflicts CZ2, CZ3, CZ4, CZ5 can be eliminated from what it sees of the intersection. O obscures the triangular region from the ego vehicle's field of view so it cannot see U2, U3, U4, hence CZ2, CZ3, CZ4 remain.

configuration IV U2, U3 and U4 cannot move, so all the conflicts are resolved, and E can complete the right turn.

Thus upon receiving the SPaT message, it remains for E to resolve either conflict U2 (in configuration III) or conflicts U2, U3 and U4 (in configuration I). This is discussed in Section 3.4.

The SPaT message will also tell the ego vehicle that its signal will change to green in time T. So after T, the vehicle's movement will automatically change from RTOR to RTOG and, as we have just seen, all conflicts will be resolved. T may be as long as the cycle time, up to 2 mins. The ego vehicle may decide it is worth waiting for time T to complete its movement. Many AVs today are programmed not to engage in RTOR movements, e.g. [19, 4]. Ironically, delivery vans are encouraged to avoid left turns and take right turns only [21].

Identification of potential blind zones will complete the definition of the intersection ODD, and is described next.

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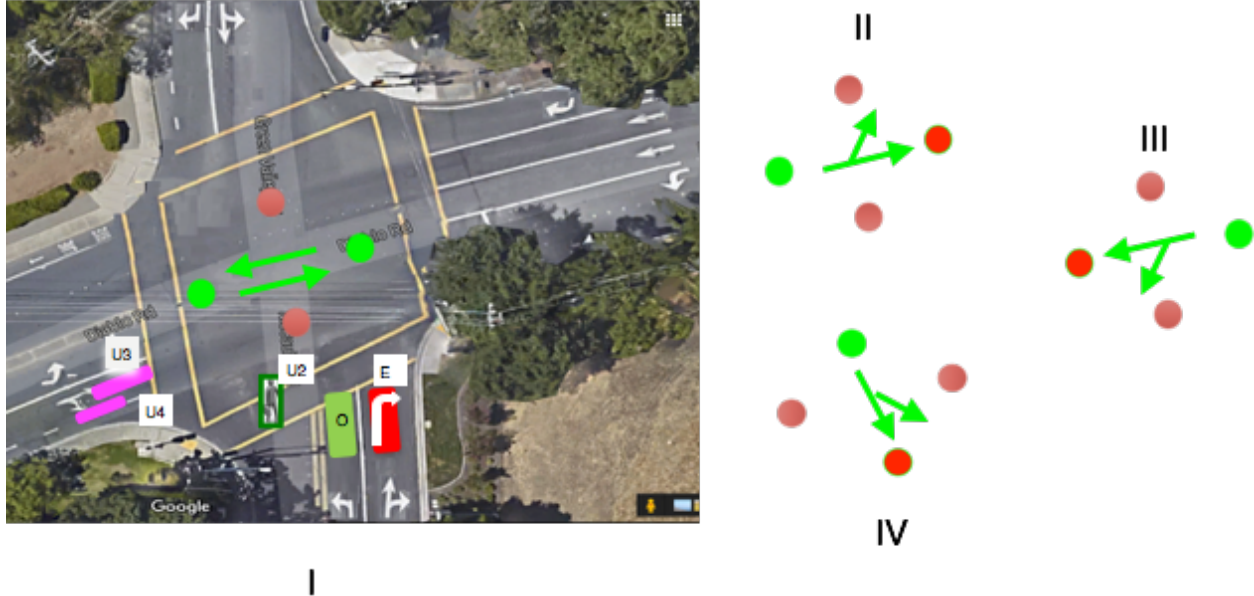
Figure 3.4: The possible signal light configurations (I-IV) compatible with RTOR movement of the ego vehicle.

3.2 Potential Blind Zones

AV safety rests on the proposition that if a vehicle can identify the objects in its field of view and if it can predict how each object will behave, it can safely drive itself. We are now concerned with the situation in which there are objects that are not visible to the AV because other vehicles obstruct the AV's view, leading to the creation of *blind zones*. Such obstruction is commonplace in intersections. Our objective is:

1. Inform a vehicle crossing the intersection about its potential blind zones; and
2. Inform the vehicle about the presence of agents (other vehicles, bicyclists or pedestrians) in those blind zones.

Achieving the first part of the objective would increase vehicle and intersection safety, thus completing the description of the intersection ODD. Accomplishing the second part would improve vehicle and intersection efficiency: when a given blind zone is empty or the agent dynamics in that zone does not lead to a conflict, one can safely proceed at normal speed instead of disengaging, inching forward, or stopping and waiting.

Each potential blind zone is computed for a given guideway with respect to a given conflict zone. Recall the Uber accident described in Section 2.2. We will use it to describe our approach to potential blind zone computation. Consider the conflict zones of the south-to-west left turning guideway, shown in Figure 3.5. CZ1, CZ2 and CZ3 are the conflict zones created by the intersection of this left turn with the three through north-to-south movements. Coincident conflict zones CZ4 and CZ5 are between the left turn and the pedestrian crosswalk.[1] Since the left turn is unprotected at this intersection, all these conflict zones can be active, without any signal violation.

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[1] A crosswalk creates two overlapping guideways going in the opposite directions, south-to-north and north-to-south, hence, formally we have two conflict zones sharing the same area.
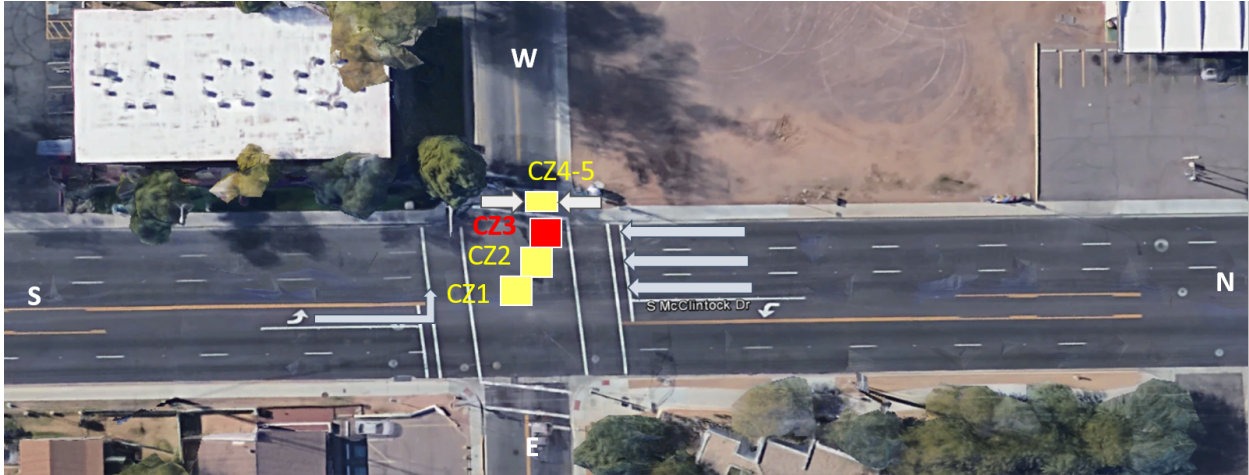
Figure 3.5: Conflict zones of the south-to-west left turning movement at the intersection, where Uber accident occurred.
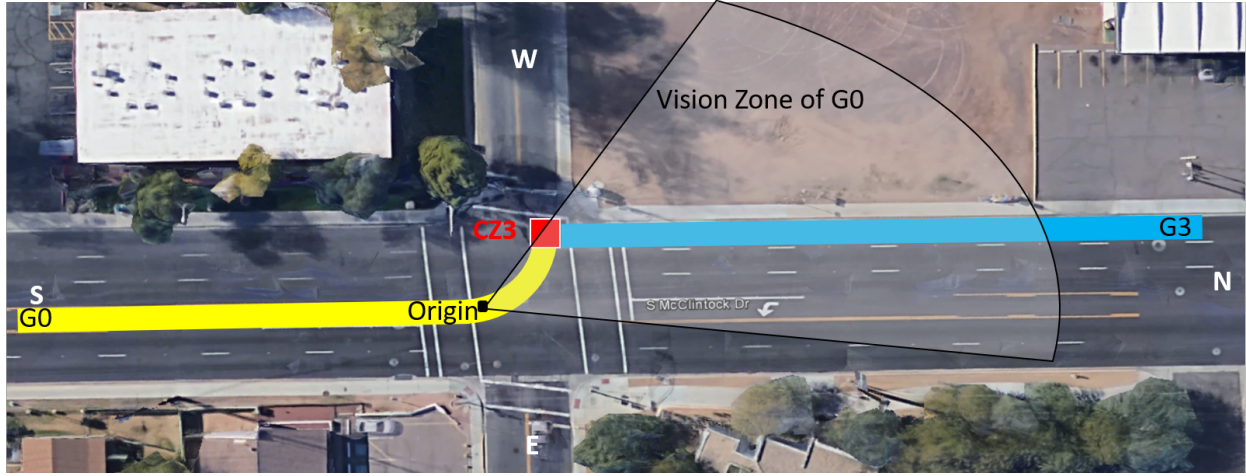
Figure 3.6: Conflict of guideways G0 and G3.

Let us focus on the conflict zone CZ3, where the Uber crash occurred. Denote by G0 the left-turning guideway followed by the Honda CRV, and by G3 the guideway taken by the Uber Volvo. CZ3 is the intersection of these two guideways. We are interested in the parts of these guideways leading to (i.e. upstream of) CZ3 and depicted in Figure 3.6, and want to know if guideway G3 can always be seen from guideway G0 (and vice versa), or if there are potential blind zones. At any particular point in G0 leading to CZ3, we can construct a vision zone defined by given sensor heading, angle and radius.[2] We call this particular point of G0 an *origin*.

Consider the geometric intersection of this constructed vision zone with guideway G3 upstream of CZ3. This geometric intersection can be gridded.[3] Connect each grid node with the origin. These connections are shown as straight gray dashed line segments in Figure 3.7. If such a connecting line segment intersects any

---

[2]Angle and radius are generally defined by the parameters of AV's onboard sensing equipment, i.e. cameras and lidars. However, we can always assume 360 degrees view, and the radius between 100 and 200 meters.

[3]Grid step can be taken to be 1 meter.
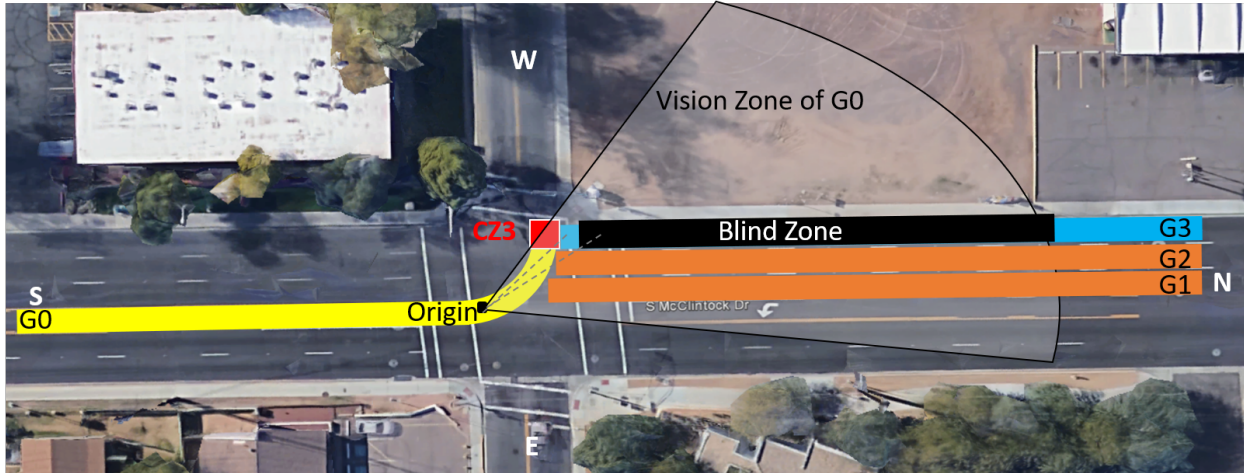
Figure 3.7: Potential blind zone of guideway G0 with respect to guideway G3.

of the guideways other than G0 and G3 upstream of their conflict zones,[4] then we mark this grid node as blind. The reason for this mark is that queued vehicles in the guideways other than G0 and G3 (in our case, these are G1 and G2) can create an occlusion by vehicles queued up upstream of their conflict zones. The union of all blind grid nodes is a potential blind zone of guideway G0 with respect to guideway G3.
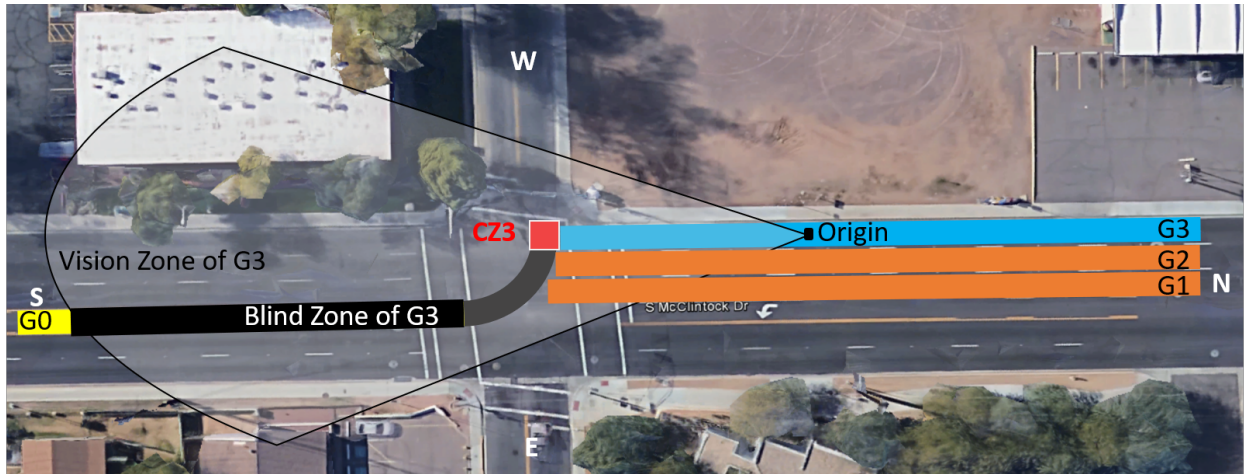
Figure 3.8: Potential blind zone of guideway G3 with respect to guideway G0.

This construction is repeated for guideway G3 with respect to guideway G0, and the potential blind zone of G3 thus obtained is shown in Figure 3.8.

Although the origin can be anywhere in the reference guideway, we recommend placing it at decision points. For G0, the origin can be just before the stop bar, or inside the intersection, where a vehicle (like Honda CRV) is making a decision to wait or to go. For G3, the origin should be placed at the point of no return: given the speed limit of 40 mph (20 m/s), and maximum deceleration of 4 m/s^2, this point will be 50 meters upstream of CZ3.

Having located the blind zones, we can compute the probability that they will be occupied for a given traffic

---

[4]In the example depicted in Figure 3.7, these are guideways G1 and G2.

20

pattern and signal timing, which, in turn, would allow us to estimate intersection safety. We discuss this estimation in the next section.

3.3   Estimating Intersection Safety

For the safety analysis, we will continue using the Uber accident scenario from Section 2.2. We employ the notation summarized in Table 3.1. We consider a typical cycle, with the initial time as the beginning of the green phase for the two conflicting movements (through and permissive left).

Symbol	Description
	Parameters
t_{wait}	average waiting time at the stop bar for a left turning vehicle
$t_{left-turn}$	average left-turn time
t_{buffer}	time-to-collision threshold: collision is 'declared' if the difference between the arrival times of two vehicles in the conflict zone is smaller than t_{buffer}
G	green time of current phase
$n_{through}$	initial queue length (number of vehicles) in the through lane
$n_{left-turn}$	initial queue length (number of vehicles) in the left-turn lane
n_{occ}	initial queue length (number of vehicles) in the lane(s) of potential occlusion
$\lambda_{through}$	vehicle arrival rate at a through guideway (G3)
$\lambda_{left-turn}$	vehicle arrival rate at the left turning guideway (G0)
λ_{occ}	vehicle arrival rate at a guideway of potential occlusion (G1, G2)
$\mu_{through}$	vehicle departure rate of a through movement at full capacity
μ_{occ}	vehicle departure rate of movement in the potential occlusion lane(s) in a jam
$v_{through}$	speed limit in the through movement lane
k_{jam}	vehicle density in the potential occlusion lane(s) in a jam
	Random variables
$X_{through}$	vehicle arrival time in one through guideway at its stop bar
$X_{left-turn}$	vehicle arrival time in the left turning guideway at its stop bar
$H_{through}$	headway of through movement if there is no queue
	Estimated quantities
P_1	probability of a collision danger in traffic state 1 in the presence of occlusion
P_2	probability of a collision danger in traffic state 2 in the presence of occlusion
P_3	probability of a collision danger in traffic state 3 in the presence of occlusion
D_1	expected duration of traffic state 1
L_{occ}	length of queue (in meters) if there is a blind zone (occlusion)
$\tilde{n}_{occ}$	number of vehicles in queue creating the occlusion

Table 3.1: Notation for safety analysis.

Note that the value of $t_{left-turn}$ generally depends on the radius of the left turning guideway that is determined by the size of the intersection. The meaning of traffic states 1, 2 and 3 are explained below.

Occlusion condition
As noted in Section 3.2, blind zones occur from occlusions by queued vehicles. So we start by formulating

the occlusion condition. An occlusion occurs when the queue(s) in the adjacent lane(s) is long enough. The occurrence can be divided into two cases: (1) queues form; and (2) queues dissipate.
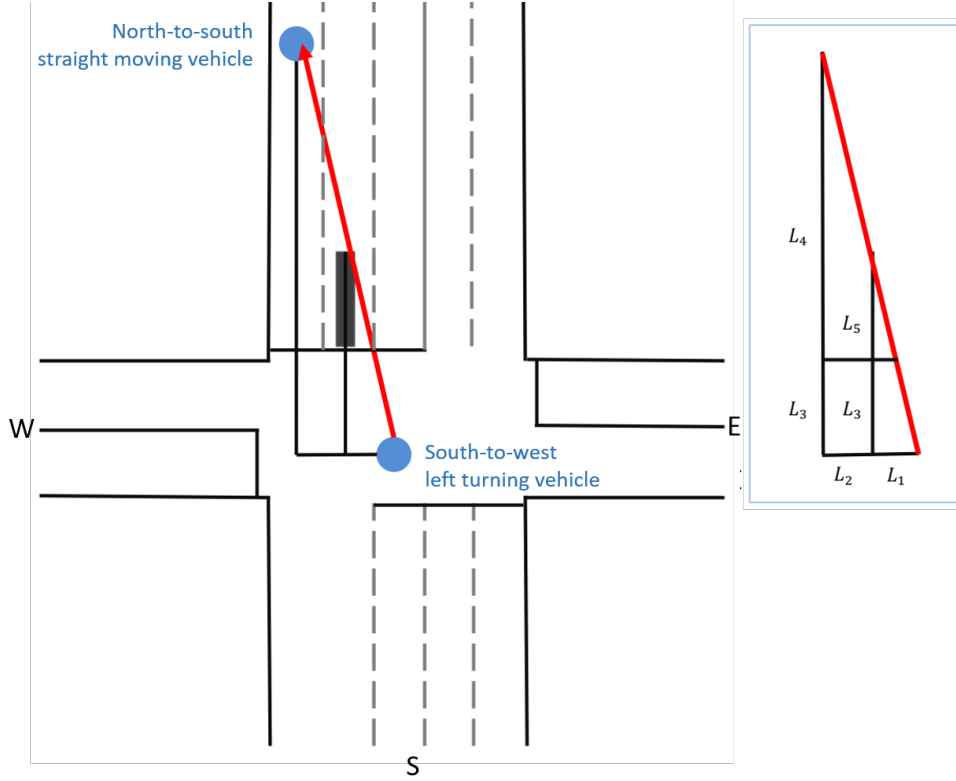
Figure 3.9: Occlusion schematic for the Uber accident scenario.

Figure 3.9 shows the occlusion schematic. L_1, L_2, L_3 can be directly obtained from the geometry of the intersection. We need to estimate L_5, which is the length of the occlusion, L_{occ}. For that, we must compute L_4. Suppose, there is no occlusion and the left turning vehicle decides to go or to wait. It will choose to go if the upcoming through vehicle is far enough from the intersection. Thus, we have:

$$
\begin{aligned}
L_4 &= v_{through} \cdot (t_{left-turn} + t_{buffer}); \\
L_{occ} &= L_5 = \frac{L_4 \cdot L_1 - L_3 \cdot L_2}{L_1 + L_2}; \\
\tilde{n}_{occ} &= \left\lceil \frac{L_{occ}}{k_{jam}} \right\rceil.
\end{aligned}
\tag{3.3.1}
$$

So, given state $\{n_{occ}, \lambda_{occ}, \mu_{occ}\}$, we can compute L_{occ} and $\tilde{n}_{occ}$. Consider the two cases of queue dynamics:

- Queue dissipates if $\lambda_{occ} < \mu_{occ}$. The duration of no-occlusion is:

$$
\max\left\{0, \frac{n_{occ} - \tilde{n}_{occ}}{\mu_{occ} - \lambda_{occ}}, G\right\}.
\tag{3.3.2}
$$

- Queue forms if $\lambda_{occ} \geq \mu_{occ}$. The duration of occlusion is:

$$
\max\left\{0, \frac{\tilde{n}_{occ} - n_{occ}}{\lambda_{occ} - \mu_{occ}}, G\right\}.
\tag{3.3.3}
$$

Since the two expressions above are same, we can use (3.3.3) as the time to change the occlusion status.

Probability of collision danger

The traffic flow pattern during the single green phase of the unprotected left turn can be decomposed into three states, depicted in Figure 3.10. This diagram shows how the signal phase and the traffic state evolves in time, represented by the color-coded horizontal line, where red switches to green, then green switches to yellow. Our focus is on the green phase.
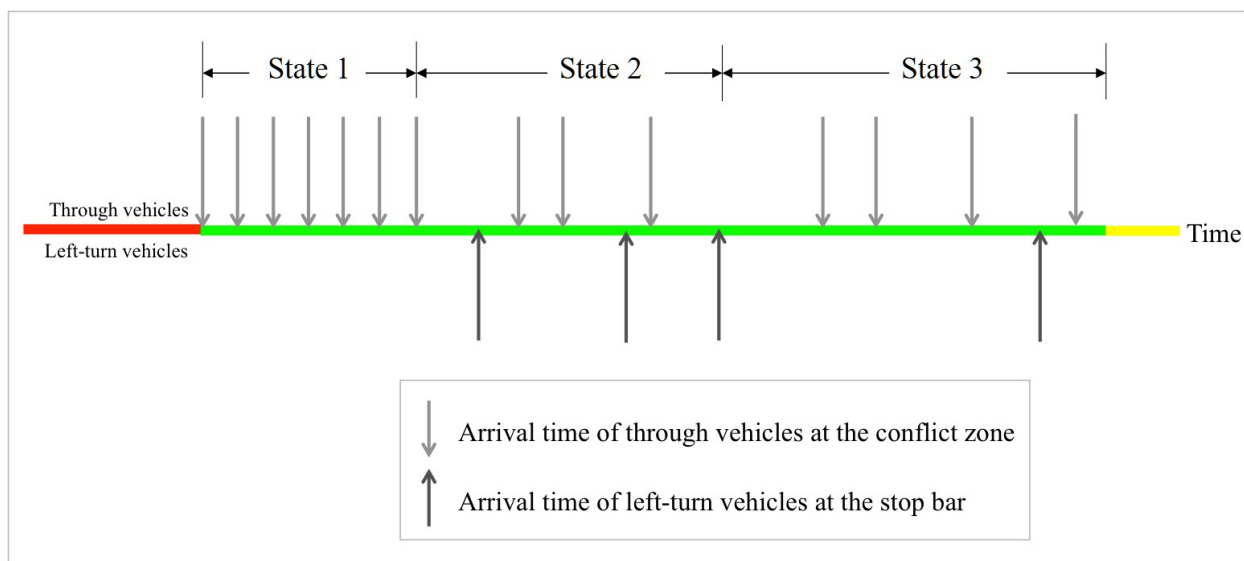
Figure 3.10: The three traffic states during the green phase for unprotected left turn.

State 1: Queues exit in both north-to-south through and south-to-west left-turn lanes. In the beginning of the green phase, the vehicles going from north to south (through movement) will pass the conflict zone at a steady rate with a small headway (e.g., 2 seconds) not letting any left turning vehicles to execute their maneuver. If $D_1 \leq G$, then the original queue in the through lanes will dissipate within the green time, and state 1 will change to state 2. Otherwise, the system will stay in state 1 during the whole green phase. Since in state 1 no left-turning vehicles depart, we have:

$$P_1 \quad = \quad 0; \tag{3.3.4}$$
$$D_1 \quad = \quad \frac{n_{through}}{\mu_{through} - \lambda_{through}}. \tag{3.3.5}$$

State 2: The north-to-south through lanes have no queue, but there is a queue for the south-to-west left-turn. In this case, a left turning vehicle waits for a gap between through vehicles, which would allow it to complete its maneuver. We assume that this left turning vehicle waits for t_{wait} seconds and, if there no through vehicle is coming, proceeds with its movement. Thus, there is a danger of collision if the gap between two through-moving vehicles is shorter than t_{wait} plus the time required for the left turning vehicle

to complete its maneuver. This is formalized in the expression (3.3.6).

$$
\begin{aligned}
H_{through} &\sim \text{Exponential}(\lambda_{through}); \\
K &= \left\lfloor \frac{G - t_{buffer}}{t_{wait} + t_{left-turn}} \right\rfloor \\
P_2 &= \sum_{k=1}^{K} P\left\{ (t_{wait} + t_{left-turn})\, k - t_{buffer} \leq H_{through} \leq (t_{wait} + t_{left-turn})\, k + t_{buffer} \right\}; \\
&= \sum_{k=1}^{K} \left\{ e^{-\lambda_{through}[(t_{wait}+t_{left-turn})k - t_{buffer}]} - e^{-\lambda_{through}[(t_{wait}+t_{left-turn})k + t_{buffer}]} \right\}.
\end{aligned}
\tag{3.3.6}
$$

If the left-turn queue does not vanish, the system will stay in state 2; otherwise, it will switch to state 3.

State 3: There are no queues in north-to-south through or south-to-west left turning lane. In this case, the flows of through-moving and left turning vehicles can be seen as two independent Poisson processes. The probability of collision danger is computed as a probability of an event, when an arrival from through-moving process occurs no more than 1 second before, or no more than 1 second after an arrival from the left-turn process. This is formalized in the following expressions:

$$
\begin{aligned}
X_{through}(X_1) &\sim \text{Poisson}(\lambda_{through}(\lambda_1)); \\
X_{left-turn}(X_2) &\sim \text{Poisson}(\lambda_{left-turn}(\lambda_2)); \\
f_{X_1,X_2}(x_1,x_2) &= \lambda_1 \lambda_2 e^{-\lambda_1 x_1 - \lambda_2 x_2}, \quad x_1 \geq 0, x_2 \geq 0;
\end{aligned}
$$

$$
\begin{aligned}
P_3 &= P\left(x_1 - t_{buffer} \leq x_2 + (t_{wait} + t_{left-turn}) \leq x_1 + t_{buffer} \right) \\
&= \int_0^{\infty} dx_2 \int_{x_2 + t_{wait} + t_{left-turn} - t_{buffer}}^{x_2 + t_{wait} + t_{left-turn} + t_{buffer}} dx_2\, \lambda_1 \lambda_2 e^{-\lambda_1 x_1} e^{-\lambda_2 x_2} \\
&= \frac{\lambda_2}{\lambda_1 + \lambda_2} \left(e^{-(t_{wait}+t_{left-turn}-t_{buffer})\lambda_1} - e^{-(t_{wait}+t_{left-turn}+t_{buffer})\lambda_1} \right) \\
&= \frac{\lambda_{left-turn}}{\lambda_{through} + \lambda_{left-turn}} \left(e^{-(t_{wait}+t_{left-turn}-t_{buffer})\lambda_{through}} - e^{-(t_{wait}+t_{left-turn}+t_{buffer})\lambda_{through}} \right)
\end{aligned}
\tag{3.3.7}
$$

In these probability calculations we made the following assumptions:

- it is the left-turning vehicle's responsibility to find the gap for its maneuver;
- probabilities P_1, P_2 and P_3 are computed for the situation when a blind zone exists;
- traffic violations are not considered, since they are unpredictable.

To summarize, the probability of collision danger can be computed in three steps:

1. determine occlusion condition from expression (3.3.1) – if there exists occlusion, go to step 3, otherwise go to step 2;
2. from expression (3.3.3) estimate the time to occlusion;
3. use expressions (3.3.6) and (3.3.7) to estimate the probability of a collision danger.

Example

Consider the following parameters:

- The left turning vehicle waits for $t_{wait} = 3$ seconds, and if noone appears in the through movement, it performs its maneuver.
- It takes $t_{left-turn} = 2$ seconds to complete the left turn.
- For a safe completion of this maneuver, the through-moving vehicle should arrive no less than $t_{buffer} = 1$ seconds after the left turning vehicle leaves the conflict zone.
- Duration of the green phase is $G = 30$ seconds.
- The queue size in the through guideway at the beginning of the green phase is $n_{through} = 3$ vehicles.
- There are $n_{left-turn} = 2$ vehicles waiting to turn left in the beginning of the green phase.
- The vehicle arrival rate at the through guideway is $\lambda_{through} = 0.25$ vehicles per second (900 vph).
- The arrival rate of the left turning vehicles is $\lambda_{left-turn} = 0.125$ vehicles per second (450 vph).
- As the green phase starts, the vehicle departure rate at the through guideway is $\mu_{through} = 0.5$ vehicles per second (1800 vph).
- Lane width $L_1 = L_2 = 7.5$ meters – see Figure 3.9.
- Speed limit in the through lane is $v_{through} = 15$ mps (≈ 35 mph).
- Vehicle density in the occlusion lane $k_{jam} = 0.2$ vehicle per meter.

Plugging these into equations (3.3.6), (3.3.7) and (3.3.1), we get the results:

- $P_1 = 0$;

- $P_2 = 0.202$;

- $P_3 = 0.048$; and

- $\tilde{n}_{occ} = 4$.

Extending the analysis to other scenarios

In the scenario above, the through movement can be replaced by the right-turn movement. Everything will be the same, except for the arrival rate of the right turning vehicles. Another type of collision scenarios caused by occlusions involves the conflicting movements during the signal phase change.

a) Top-down view: pedestrian and through vehicle are on the collision course

b) View from the through vehicle: cannot see the pedestrian

c) View of the intersection: pedestrian cannot see the danger behind the truck
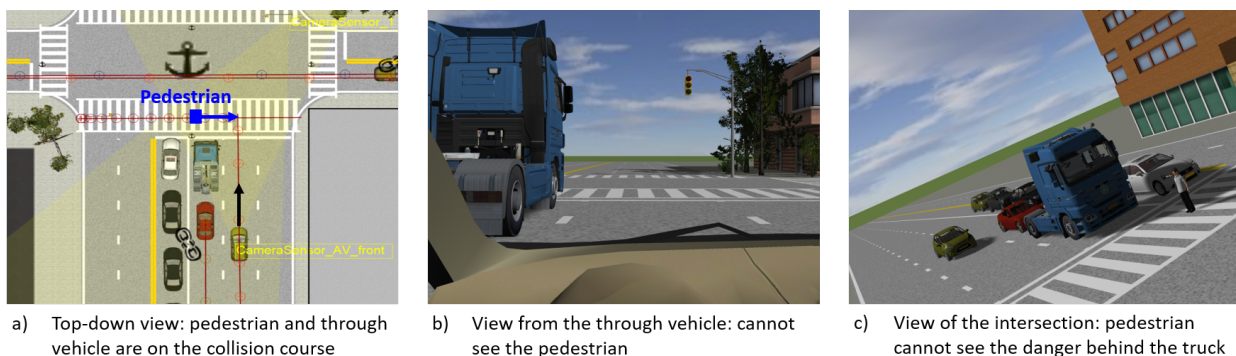
Figure 3.11: PreScan simulation snapshot — 1 second before the vehicle-pedestrian conflict.

Consider the scenario presented in Figure 3.11. A through-moving vehicle approaches the intersection in the right most lane, when its light changes from red to green. So, instead of going to full stop, the vehicle

accelerates. At the same time, a pedestrian is trying to finish the intersection crossing, when he sees his light changing from green (blinking red) to red. Neither the vehicle, nor the pedestian can see each other due to occlusion caused by the queued vehicles. The schematic of this conflict is shown in Figure 3.12. The probability of collision danger in this case is computed similarly to this probability in State 3 discussed above, but with more constraints. The additional notation is summarized in Table 3.2.

Symbol	Description
v_{ped}	pedestrian speed when crossing on yellow
λ_{ped}	arrival rate of pedestrians
L_{ped}	distance to conflict zone from the beginning of the crosswalk from pedestrian's direction

Table 3.2: Additional notation for the pedestrian scenario.
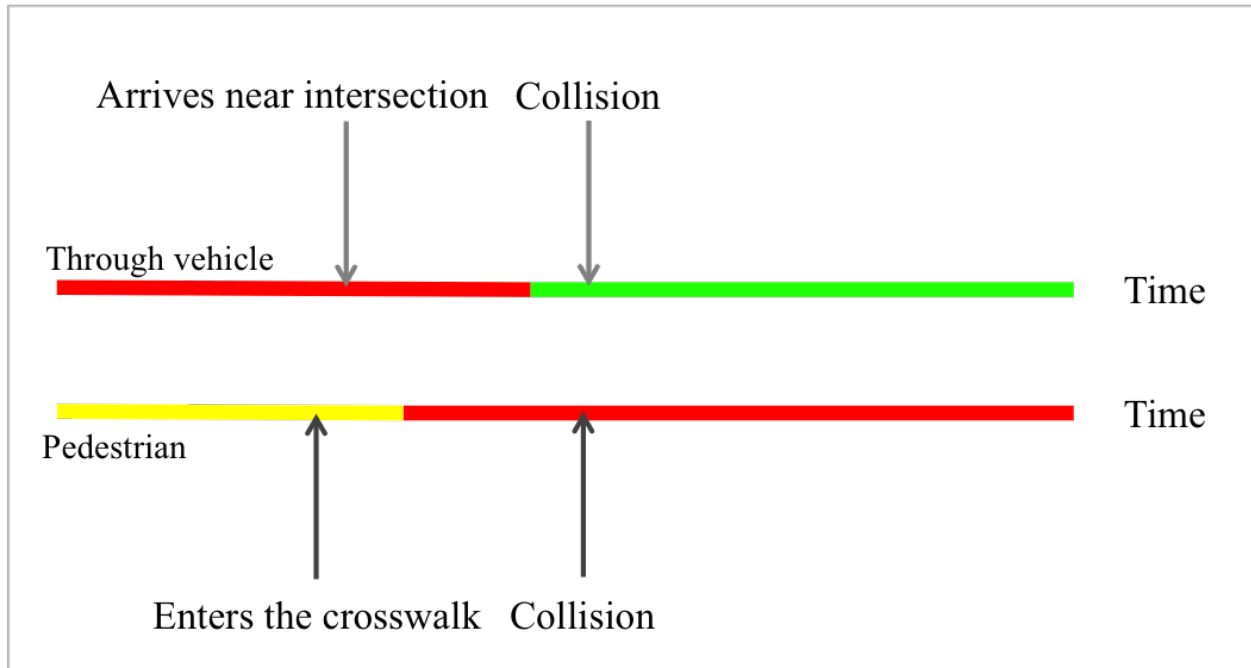
Figure 3.12: Vehicle-pedestrian conflict schematic.

Probability of collision danger can be expressed as follows:

$$
\begin{aligned}
P(\text{pedestrian cannot finish crossing}) &= 1 - e^{-\lambda_{ped}\left(\frac{L_{ped}}{v_{ped}} - 1\right)} \\
P(\text{pedestrian and vehicle arrive simultaneously}) &= \frac{\lambda_{ped}}{\lambda_{through} + \lambda_{ped}} \left(e^{-\left(\frac{L_{ped}}{v_{ped}} - t_{buffer}\right)\lambda_{through}} - e^{-\left(\frac{L_{ped}}{v_{ped}} + t_{buffer}\right)\lambda_{through}} \right) \\
P(\text{collision danger} \mid \text{occlusion}) &= P(\text{pedestrian cannot finish crossing}) \times \\
&\quad P(\text{pedestrian and vehicle arrive simultaneously}). \quad (3.3.8)
\end{aligned}
$$

If $v_{ped} = 2$ mps, $\lambda_{through} = 0.2$ vehicle per second, $\lambda_{ped} = \frac{1}{60}$ pedestrians per second, and $L_{ped} = 12$ meters, then $P(\text{collision danger} \mid \text{occlusion}) = 0.80 \times 0.009 = 0.00075$.

3.4 Detecting Activity in Blind Zones

Detection of activity in the potential blind zones is needed only if the corresponding conflict zones are not eliminated in the three-step process of building the intersection ODD discussed in Section 3.1. If the active conflict zones exist, and the presence of potential blind zones for them is established, we want to put detection into those zones to enable informing vehicles with obstructed vision about potential dangers. Referring to the Uber accident example, Figures 3.13 and 3.14 show zones, where detection is required (desired) for the south-to-west left-turn and north-to-south through movements accordingly. These figures also show a tentative traffic sensor configuration.

Figure 3.13: Desired detection for the south-to-west left turn movement.

Figure 3.14: Desired detection for the north-to-south through movement.

For the left turn, we need to monitor the crosswalk and three north-to-south guideways. Before performing its maneuver, the left-turning vehicle must make sure that there are no pedestrians in the crosswalk. Then, if there is no danger from the visible traffic and nobody is present in the blind zone, the left turn can be completed.

For the north-to-south through movement, the danger comes from the left-turning vehicle(s) that may be present in its blind zone in two forms:

1. left-turning vehicle is in the middle of the intersection, between the stop bar and the exit detectors, waiting for an opportunity to complete the maneuver; and

2. left-turning vehicle is between the approach and the stop bar detectors, but it may be going fast enough to cause a conflict with the vehicle moving from north to south.

The extent of desired detection zones is determined by the assumptions about agent dynamics. The detector placement should satisfy the following requirements:

- the approach detector is far enough to give enough time for the conflicting movement to slow down/stop;

- at the same time, the approach detector is close enough to ensure the prediction is as accurate (the closer the detector, the smaller is the trajectory uncertainty);

- if only one detector can be deployed, it should serve as many movements as possible.
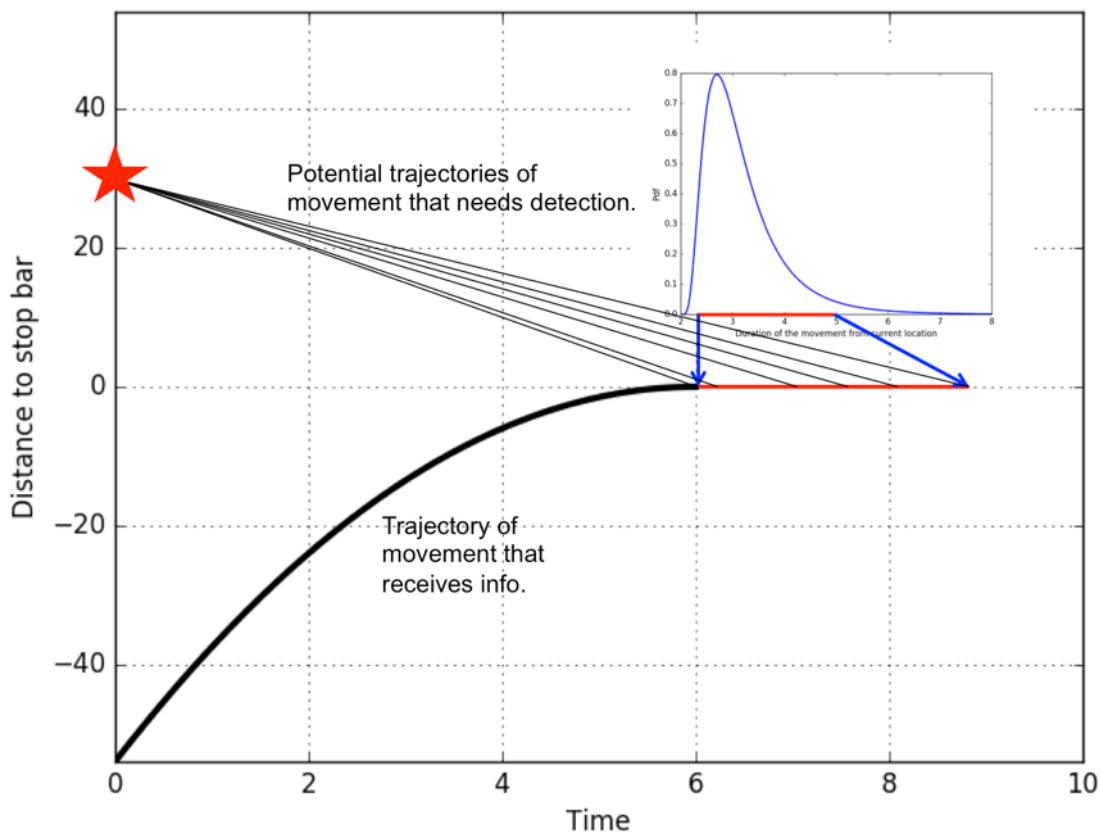
Figure 3.15: Computing desired distance from the approach detector to the stop bar.

The algorithm for placing the approach detectors has five steps:

1. Fix the two conflicting movements.
2. For the movement that needs detector(s), obtain the distribution of the time needed to go from different positions in the guideway to the conflict zone. Identify a reasonable minimum travel time to the conflict zone, as shown in Figure 3.15. We recommend using the value of the mean minus one standard deviation for such minimum travel time.

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3. For the other movement, the one receiving the information from the detector, compute the minimum distance and time to stop right before the conflict zone using the values of speed limit and admissible deceleration.
4. From step 2 and 3, we get the optimal detector location – it is the one, whose minimum time to reach the conflict zone equals the minimum time to stop of its conflicting movement.
5. Repeat steps 1-4 for all active conflict zones to obtain detector placement for all lanes.

Example

Consider the following parameters of a four-legged intersection and vehicle dynamics:

- the size of the intersection is 20 meters by 20 meters;
- radius of the left turn is 10 meters;
- radius of the right turn is 6 meters;
- speed limit is 18 mps (40 mph);
- maximum acceleration is 5 m/s^2;
- comfortable deceleration is 3 m/s^2;
- minimum waiting time for the left and right turns is 1 second.

For such an intersection the placement of the approach detectors is summarized in Table 3.3.

Guideway receiving info	Guideway with detector	Distance to conflict zone
Through	Left turn	10 meters
Left turn	Through	108 meters
Through	Right turn	16 meters
Right turn	Through	88 meters
Right turn	Left turn	10 meters
Left turn	Right turn	16 meters

Table 3.3: Approach detector placement summary.

Chapter 4

Intelligent Intersection

An intelligent intersection implements the intersection ODD analysis, including potential blind zone identification, detects traffic activity and broadcasts signal and traffic information to all connected agents crossing the intersection. Although in this project we only considered connected vehicles (CVs) as *connected* agents, we believe that bicyclists and pedestrians would greatly benefit from the information provided by the intersection infrastructure. Figure 4.1 shows a reference instrumentation that enables intersection intelligence.

The intersection is equipped with approach, stop-bar and departure magnetic sensors to detect vehicles; micro-radars to identify crossing pedestrians and bicyclists; and optional CCTV cameras to enable video monitoring. Wireless sensors transmit their data for processing to the CPU through an access point. CPU is connected to the signal controller with a conflict monitoring card that prevents conflicting signal phases being activated together. This connection provides CPU with access to SPaT information as well as the ability to activate certain phase. Red light violations are identified by the CPU when it detects an agent performing a maneuver prohibited by current signal phase combination. Dedicated short-range communication (DSRC) modem is used to broadcast the state of the intersection (SPaT + information about presence of agents at specific lanes or crosswalks) and warnings about the detected red light violations to CVs. Currently, DSRC is the backbone of I2V and used in connected vehicle and infrastructure deployments [22]. Emergency vehicles and transit can use DSRC to send give-me-green requests. However, the development of cellular technology may render DSRC obsolete. In the recent CV deployment in Washington, DC, Audi relies on 4G LTE in its communications with signalized intersections [7]. Amid the rapidly rising anticipation for 5G, industry believes that this will be the new communication layer used in V2V and I2V applications.

The purpose of the Bluetooth connector is to extend I2V technology presently enabled by DSRC to I2X[1], informing connected agents other than vehicles about the state of intersection and red light violations as well as accepting give-me-green requests from those agents as they approach the intersection. These give-me-green requests are functionally similar to push-to-walk buttons that one encounters at some pedestrian crosswalks. Users will be able to issue give-me-green requests and get updates about the state of intersection through a smartphone application.[2] Data processed by CPU is uploaded to the cloud for long-term analysis and archiving via cellular link.

The format of I2V messages is defined in the SAE J2735 standard [20]. Out of presently defined sixteen J2735 messages, we focus on three:

---

[1] Generalizing the notion infrastructure-to-vehicle (I2V), we refer to the concept *infrastructure-to-anyone* as *I2X*.

[2] Starting in 2020, when the 5G subscription will commence, DSRC and Bluetooth will likely be replaced with 5G.
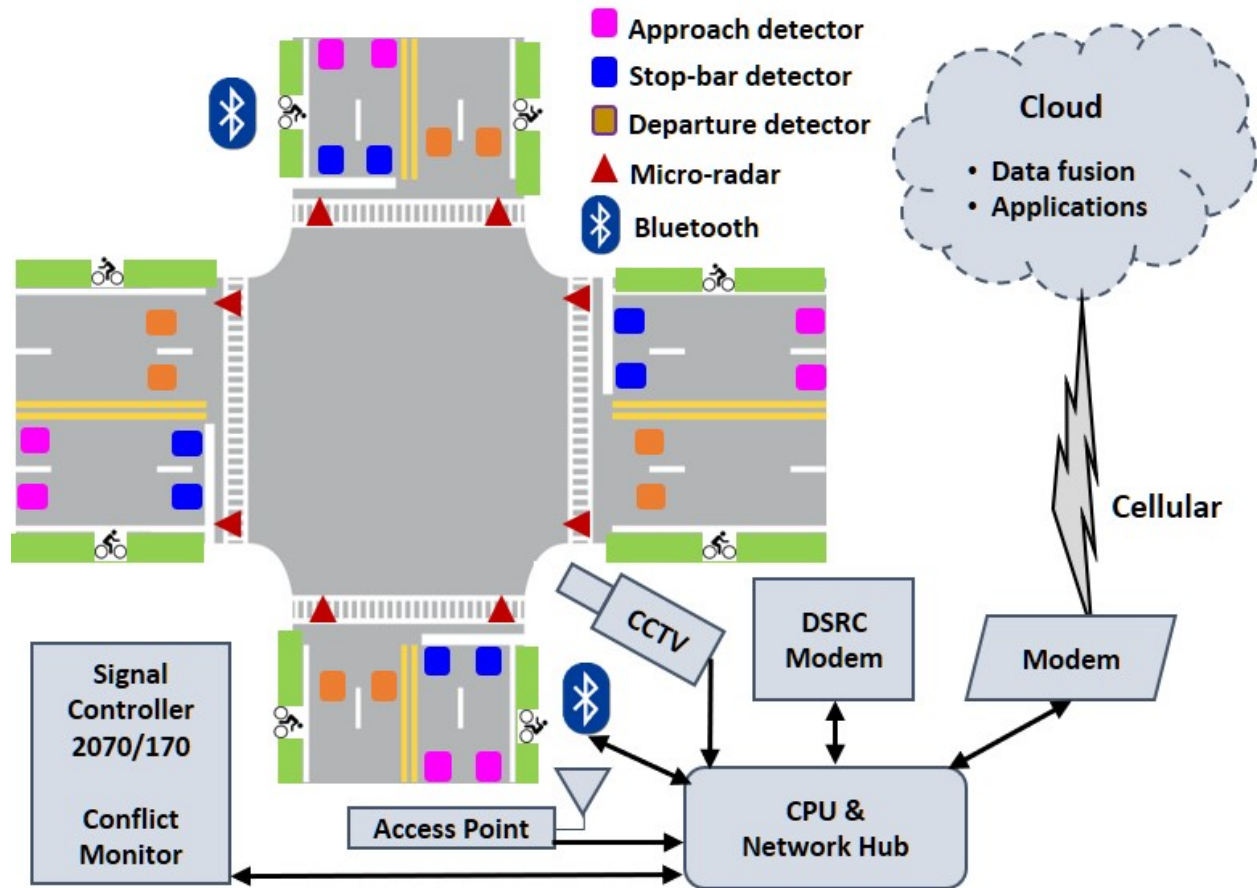
Figure 4.1: Schematic of reference intersection instrumentation.

- *MAP*, used to define the intersection layout. This message describes the intersection geometry by a reference point (geospatial coordinates of the middle of intersection); approaches, including their types – ingress, egress, barrier and crosswalk; and lanes within each approach. Thus, a vehicle getting the MAP message can place itself with respect to the intersection.
- *SPaT*, which, as discussed before, stands for signal phase and timing. This message describes the current signal phases also providing the state of all lanes in terms of vehicles/bicyclists/pedestrians present in them, as well as any pre-emption or priority. Thus, upon receiving the SPaT message, a CV knows the current state of intersection, and what to expect in the next few seconds.
- *ICA*, which stands for intersection collision avoidance. This type of message is typically used in vehicle-to-vehicle communications: a connected vehicle issues this message if it violates the intersection. However, the combination of signal phasing and detector readings provide enough data for the roadside equipment to generate ICA message and broadcast it.

The intersection map is constructed offline. The map may be downloaded by connected vehicles and other users. The intersection software records the signal phase in order to calculate SPaT messages in real time, for example using the algorithms described in [9]. The intersection broadcasts in real time the SPaT message and the occupancy of the blind zones. These broadcasts are received by connected users of the intersection.

An intelligent intersection detects red light violators by combining signal phase and traffic detection data: if the traffic movement is detected in guideways that have no right of way according to the current signal

phase, a violation flag is raised. Figure 4.2 shows three frames of an intersection video camera. The camera is triggered by the detection of the intruding vehicle at a high speed traveling into the intersection during a red signal. The detection took place at least 2 seconds before the vehicle entered the intersection and could warn the vehicle with the right of way. Also shown is a picture of a Google AV after a van crashed into it as it entered the intersection 6 seconds into red. The Google AV could have been programmed to avoid the crash with a 2-second warning.
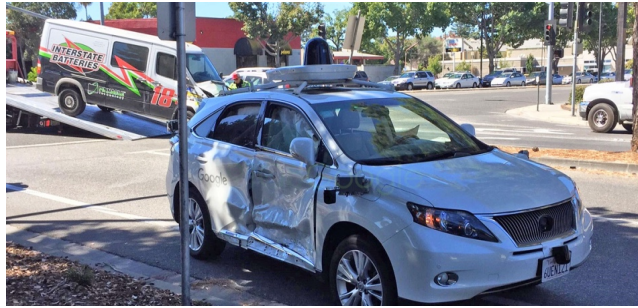

car with ROW   red light violator

Figure 4.2: Intrusion of red-light violator detected by intersection (source: [16]). Above: picture of a Google AV crash by a red-light violator.

In the situation of an Uber accident described in Section 2.2, the intelligent intersection could have broadcasted a SPaT message indicating:

1. the signal phase and its remaining time; and
2. presence of vehicles in guideways G0, G1, G2 and G3 (see Figures 3.7 and 3.8).

Then, everything would depend on whether the left turning Honda, or Uber Volvo, or both, were connected and able to interpret the I2V SPaT message. If neither vehicle were connected the crash scenario would repeat. If the left turning Honda were connected, it would be notified of the presence of danger in G3, which it cannot see, and would wait till Volvo reaches the stop bar and becomes visible. Seeing the Volvo, Honda can make the decision: to let pass, if Volvo goes fast enough, or to go if Volvo stops. If Uber Volvo were connected, it would be informed about the presence of vehicle in G0 in front that it cannot see and about the soon changing signal light. Not aware about the intent of the left-turning vehicle, it will brake to a complete stop before conflict zone CZ3, letting Honda pass. Finally, if both vehicles were connected, Honda would wait for Volvo to become visible, and Volvo would slow down before CZ3 until it can see Honda and predict its intent. Then, if the traffic light is still green, Volvo would proceed through the intersection first, otherwise, it would stop.

Protected intersection

The intelligent intersection also functions as a limited but flexible protected intersection.
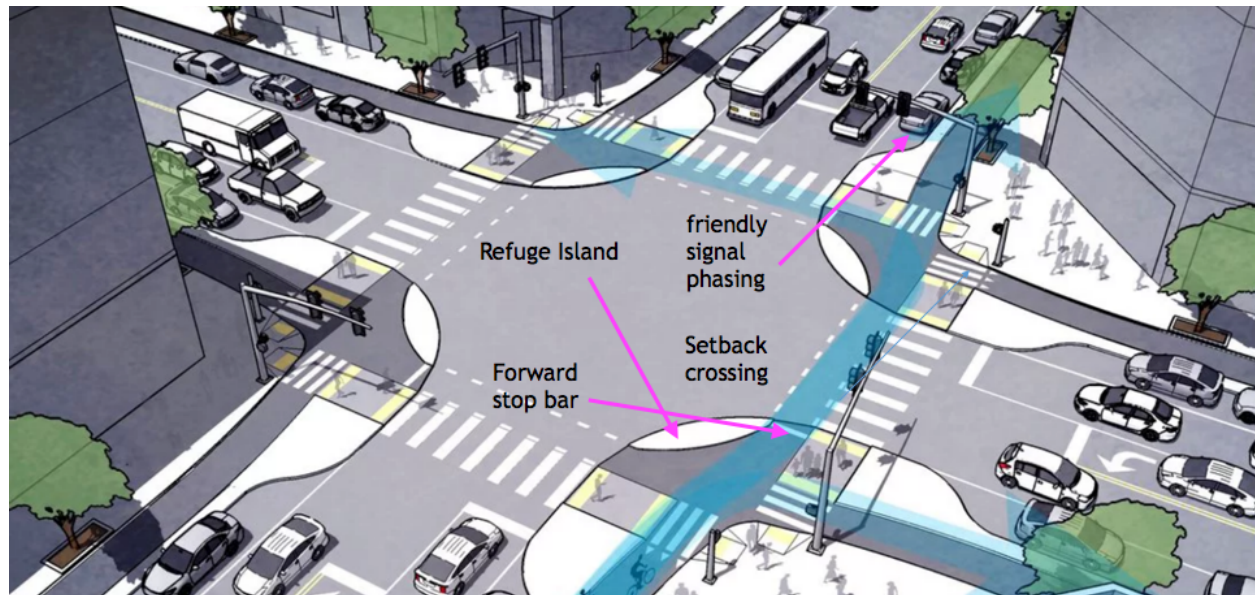

Figure 4.3: Schematic of a protected intersection. Source: [17]

Protected intersections [17] refer to physical modifications designed to improve the passage of cyclists through an intersection. Its key features are (see Figure 4.3):

1. insertion of 'refuge islands' to sharpen turning radius of cars, forcing them to slow down to 5-10 mph when turning right;
2. special bike lane setback as they cross the intersection;
3. forward stop bar for cyclists, far ahead of waiting cars;
4. special cyclist-activated traffic lights;
5. advance green traffic signals for cyclists; and
6. turn restrictions for cars, while all turns allowed for cyclists.

There are now 13 protected intersections in the U.S., each costing between $250K and more than $1M, all built since 2015. The protected intersection at Hopkins Street and The Alameda in Berkeley, CA includes four concrete refuge islands that guide bicycles as they approach the intersection and back towards the traffic lane afterward. Pedestrians have a shorter crossing distance. The result is mixed. Drivers have complained about the increased difficulty turning right. Tire marks have obscured the paint on the outside of some of the islands, as drivers turn too sharply. At one corner tire marks record drivers unwilling to wait in a queue to turn right and go into the bike lane instead. A resident who has been crossing this intersection for 17 years told a reporter that "squeezing the traffic" into a narrower space makes this "a stressful intersection" and irritates drivers [18]. Not all protected intersections incorporate the special bike signals. In Salt Lake City, UT these signals were not added due to the need to install bicycle detection sensors. Similarly, the protected intersection design in Davis, CA omitted bicycle-friendly signal timing, as it would "cause backups and could decrease the safety of other parts of the corridor."

The protected intersection imposes significant mobility cost. As seen in Figure 4.3 the right turn pockets have been eliminated so that right turn and through vehicles must share the same lane; the former will block

the latter as they wait to complete the turn, resulting in a significant reduction in the intersection throughput. This reduction is a permanent imposition even when there is no bicycle traffic or when emergency vehicles need to travel quickly.

An intelligent intersection can be enhanced to provide several safety benefits. Bicyclists could put apps in their smartphones that alert the intersection controller of their location and direction thereby serving as a mobile bicycle sensor. Knowing how many bicycles there are and their desired turn movements, the controller could adaptively set the duration of the bicycle signal to reduce backups. The SPaT calculation could be used to signal to bicyclists that they should speed up or slow down to avoid stopping as in the "Flo" system introduced in Utrecht [12].

The cost of an intelligent intersection is relatively small, estimated at $25K and $100K, depending on the size of the intersection and the extent of preexisting sensing. The safety benefits of an intersection upgrade depends on the traffic demand. From the map of the intersection one can calculate the conflict zones and roughly estimate queues to see how frequently blind zones will occur. On that basis one can rank intersections and target limited funds.

Chapter 5

Intelligent Intersection Toolbox

Implementation of the intersection's intelligence relies on the following algorithm families:

1. analysis of intersection geometry to identify possible maneuvers, conflicts and blind zones;

2. computation of blind zone activation likelihood, given a traffic pattern and signal timing;

3. classification of conflicts and blind zones by their importance;

4. computation of optimal and minimal viable sensor placements in the intersection to ensure desired coverage of blind zones;

5. interpretation of sensor readings to determine traffic presence and dynamics in the blind zones;

6. signal phase prioritization to ensure safe and efficient passage of different travel modes; and

7. prediction of signal phase duration for adaptive and actuated signals.

These algorithms are being implemented in the open source Python package called *Intelligent Intersection Toolbox* (*IIT*) [2]. Presently, we have implemented the algorithms for analysis of intersection geometry, including conflict and blind zone identification and classification.
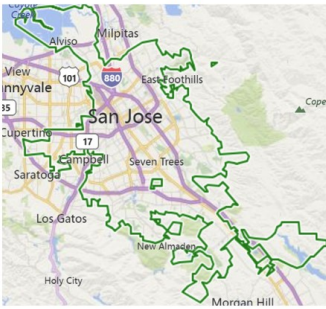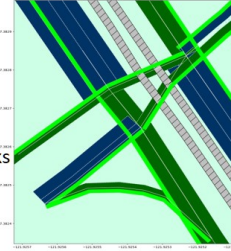
Figure 5.1: Intelligent Intersection Toolbox – workflow.

The workflow of the IIT's intersection geometry analysis is presented in Figure 5.1. IIT uses Open-StreetMap [3] as a source for road geometry and provides the following API:

- `api.get_data()` – one can specify city or given `.osm` file; returns all streets.
- `api.get_intersecting_streets()` – returns list of all intersections.
- `api.get_intersection()` – returns available data about intersection.
- `api.get_guideways()` – returns geometry of vehicle, rail and bicycle guideways.
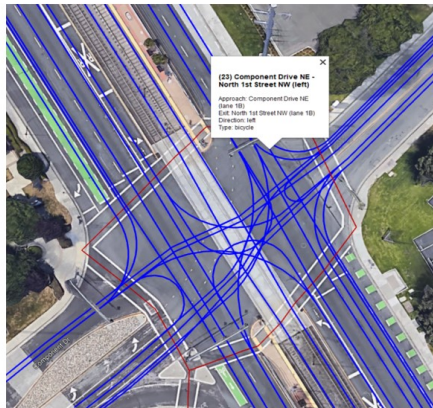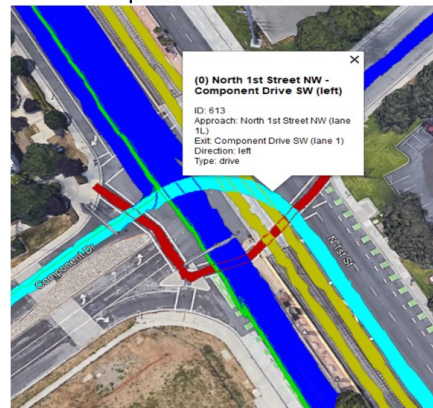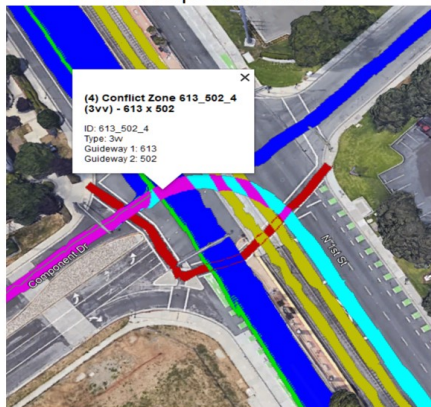
- `api.get_crosswalks()` – returns geometry of pedestrian crosswalks.
- `api.get_conflict_zones()` – returns potential conflict zones for a given guideway.
- `api.get_blind_zones()` – returns potential blind zones for a given guideway and conflict zone.

Chapter 6

Intersection Classification

Heterogeneity of intersections and hazardous conditions can vary significantly, and there is no generally accepted definition of "complexity" of intersections. In light of this, it is necessary to define and categorize the "complexity" of intersection based on their geometric design and layout, operation rules, and traffic. The objective of the intersection classification is to assess the diversity in the complexities of signalized intersections, as different intersections may raise different perception and decision-making challenges from the perspective of AV deployment and testing. Intersection complexity may vary due to differences in number of infrastructure elements (e.g., number of approaches and lanes), type of intersection geometry (e.g., presence of grade, skewness of approaches), and type of signal control operations (e.g., multi-phase signals, lead-pedestrian intervals). While all these intersection attributes are not readily available for a city-level analysis, it is possible to obtain information about the intersection infrastructure from open source databases such as OpenStreetsMap (OSM) [3]. In this section, we will demonstrate the development of a typology for signalized intersections for the City of Berkeley.

To demonstrate a generalizable approach for classifying intersections, we used data from OSM. In particular, we obtained OSM data for the entire city of Berkeley through a Python package developed as part of this project [2]. Using this package, we can query for any city, and obtain location information about all intersections within the city. In addition, we also obtained the following attributes with regards to each intersection:

1. Names of each approach associated with the intersection. For each approach, the following infrastructure elements are also documented:
   - Number of lanes
   - Presence of left-turn channelization
   - Presence of bicycle lanes/tracks
   - Bearing angle and compass of the segment (indicating the directionality of the road)
   - Maximum speed limit
   - Functional classification: motorway, trunk, primary, secondary, tertiary, residential, others

2. Presence/absence of traffic signal control

Collectively, the above-mentioned intersection attributes help us in distinguishing different types of signalized intersections. Moreover, the infrastructure-based attributes provided above are well aligned with the

overarching goals of identifying guideways, conflict zones and blind zones, as variation in number of lanes and presence/absence of bicycle lanes, impact the number of unique movements and interactions that are likely to be observed at an intersection. In addition to these factors, blind zones may also be impacted by skewness of the intersection.

Using OSM, we obtained data associated with 1354 intersections in Berkeley. Out of these, we identified 225 intersections to traffic signals, which were utilized for developing an intersection typology.

Finally, we acknowledge that OSM does not include any operational details about the signal plan, which is also an important determinant when assessing intersection complexity. However, such information can be easily incorporated into the classification approach when available at citywide level.

6.1   Classification Approach

In order to systematically classify signalized intersections, we chose 4 key indicators that we believe to be directly linked to the complexity of the intersection, especially in the context of the number of guideways and conflict zones that can be observed at an intersection.

These indicators are as follows:

1. Number of approaches: The number of road segments leading into the intersection. As the number of approaches increase, the number of associated guideways and conflict zones will also increase.
2. Presence of dedicated left-turn channelization: The presence of dedicated left-turn channelization can act as a proxy for both significant left-turn traffic, as well as potential increase in operational complexity of the intersection (e.g., presence dedicated or permissive left-turns).
3. Presence of bicycle lanes: Presence of a dedicated bicycle lanes implies that both conventional and autonomous vehicles have to be cognizant of cyclists at the intersection, especially when making turns.
4. Maximum difference in number of lanes across approaches: While number of lanes can be correlated with the vehicular throughput of the intersection, differences across approaches with regards to the number of lanes may represent some asymmetry across approaches, such as motorway intersecting with a residential street. In such instances, the complexity of navigating the intersection, especially when approaching from a minor approach to make maneuvers such as right-turns-on-red may be present challenges.

Using the above-mentioned parameters, we proposed the following ten categories of signalized intersections:

1. intersections with more than 4 approaches;
2. intersections with 4 approaches: presence of both left-turn lanes and bicycle lanes along at least one of its approaches;
3. intersections with 4 approaches: presence of left-turn lanes along at least one of its approaches, but no bicycle lanes present;
4. intersections with 4 approaches: neither left-turn or bicycle lanes present, but different number of lanes across approaches;
5. intersections with 4 approaches: other;
6. intersections with 3 approaches: presence of both left-turn lanes and bicycle lanes along at least one of its approaches;

7. intersections with 3 approaches: presence of left-turn lanes along at least one of its approaches, but no bicycle lanes present;
8. intersections with 3 approaches: neither left-turn or bicycle lanes present, but different number of lanes across approaches;
9. intersections with 3 approaches: other; and
10. intersections with 2 approaches.

In the above-mentioned categorization, we hypothesize that more number of approaches per intersection implies greater complexity. In addition, we observe additional differences in other infrastructure elements that may influence the complexity of intersection navigation. Here are some observations pertaining to the above categories:

- Intersections with more than 4 legs may lead to an increase in number of guideways/conflict zones, presence of more skewed approaches, when compared to 2/3/4 approach intersections.
- Among intersections that share the same number of approaches, we argue that presence of left-turn lanes and bicycle lanes lead to more complexity at the intersection, when compared to only one of those attributes present. Please note that this specification only requires that there be at least one left-turn lane channelization and one bicycle lane present along any of the approaches of the intersection.
- In the absence of dedicated left-turn lanes and bicycle lanes, variation in the number of lanes per approach across the different legs of the intersection may also lead to some challenges when navigating through an intersection.
- Lastly, we used a single category to represent all signalized intersections with only 2 approaches. Such intersections may correspond to mid-block intersections, or 3/4-legged intersections involving one-way streets.

Table 6.1 provides some summary statistics associated with signalized intersections pertaining to each category in the city of Berkeley. In addition to the parameters used for intersection classification, Table 6.1 also provides an average minimum skew angle for each intersection category. For instance, we observe that intersections with more than 4 approaches has an average skew angle of 42 degrees, which is significantly lower than what is observed for 2/3/4 approach intersections. We would expect this to be the case since the angle between at least one of the adjacent approaches in a 5+ legged intersection would be less than 90 degrees. For comparison purposes, we would expect an intersection with two perfectly orthogonal streets to have a minimum skew angle of 90 degrees.

Below we describe intersections representing each class.

Figure 6.1 shows a sample intersection at Dwight Way, Dwight Crescent and Seventh Street, which has 5 intersecting approaches. Here, we can observe that the skew angles associated with Dwight Crescent and its adjacent streets would be substantially less than 90 degrees.

Figure 6.2 shows a sample intersection at Hearst Avenue and Oxford Street, which has 4 intersecting approaches. At this intersection, there are left turn lanes along along three of the four approaches, while there is a bicycle lane present along southern leg of the intersection.

Figure 6.3 shows a sample intersection at Ashby Avenue and San Pablo Avenue, which has 4 intersecting approaches with each having a dedicated left turn lane. However, in this instance, there is no bicycle lane intersecting with the intersection.

Figure 6.4 shows a sample intersection at Channing Way and College Avenue, which has a bicycle lane along Channing Way.

Figure 6.1: Sample intersection with 5 or more approaches

Figure 6.5 shows a sample intersection at Martin Luther King Jr Way and Rose Street. This intersection has no left-turn/bicycle lane. However, while Martin Luther King Jr Way has two lanes along both of its approaches, Rose Street comprises of a single lane.

Figure 6.6 shows a sample intersection at Euclid Street and Cedar Street. This intersection has no left-turn/bicycle lane, and all four approaches have identical number of lanes. However, our current classification does not capture the significant vertical grade present along both intersecting streets.

Figure 6.7 shows a sample intersection at Sacramento Street and Delaware Street, which has 3 intersecting approaches. At this intersection, there is a left turn lanes along Sacramento Street, while there is a bicycle lane linking Ohlone Greenway (which is off-street bicycle trail) and Delaware Street.

Figure 6.8 shows a sample intersection at Bancroft Way and Shattuck Avenue, which has 3 intersecting approaches even though it is a 4-legged intersection. In this case, since Bancroft Way is a one-way street, it only corresponds to one approach. This intersection has two left turn lanes.

Figure 6.9 shows a sample intersection at Eunice Street, Henry Street and Sutter Street. It is a 3-legged intersection which a bicycle lane along Sutter Street.

Figure 6.10 shows a sample intersection at Martin Luther King Jr Way and Way. This intersection has no

left-turn/bicycle lane. However, while Martin Luther King Jr Way has two lanes along both of its approaches, Bancroft Way comprises of a single lane.

Figure 6.11 shows a sample intersection at Derby Street and Claremont Boulevard. This intersection has no left-turn/bicycle lane, and all three approaches have one lane each.

Figure 6.12 shows a sample intersection at Dana Street and Durant Avenue. In this case, since both intersecting streets are one-way, even though it is a four-legged intersection, it only has two approaches. While this intersection also has a bicycle lane, the classification for 2 approach intersection did not require its presence.

6.2 Future

Using the proposed intersection classification, we demonstrate the diversity of signalized intersections that are observed even when considering a limited number of infrastructure elements. In addition to the parameters considered in the study, we intend to capture other infrastructure elements such as bus stops and parking spaces as factors which may impact the perception and decision-making of autonomous vehicles at/near intersections. Beyond infrastructure elements, an assessment of different traffic signal control types is also important. Finally, although our choice of parameters for clustering intersections are related to the concept of guideway/conflict zones and crashes, future extensions of this work will also seek to cluster intersections using the number and types of guideways, conflict zones and blind zones as clustering criteria.

Table 6.1: A typology for signalized intersections

Categories	No. of Intersections	Ave. Approaches per Inxn	Proportion of intersections with at least 1 Bike Lane	Ave. Left-Turn Lanes per Inxn	Ave. Lane Difference across Approaches	Ave. Max. Difference across Approaches	Ave. Skewence / Min. Difference across Approaches (in degrees)
5 or more approaches	3	5.3	0%	1.3	1.3		42.1
4 approaches + bike lane + left-turn	18	4.0	100%	2.3	1.3		71.5
4 approaches + left-turn only	32	4.0	0%	2.2	1.5		82.3
4 approaches + bike lane only	17	4.0	100%	0.0	0.8		76.5
4 approaches with different lanes per approach	18	4.0	0	0.0	1.5		82.4
4 approaches (other)	11	4.0	0	0.0	0.0		77.6
3 approaches + bike lane + left-turn	6	3.0	100%	1.8	1.7		96.6
3 approaches + left-turn only	17	3.0	0%	1.4	1.6		90.1
3 approaches with bike lanes	16	3.0	100%	0.0	0.7		77.9
3 approaches with different lanes per approach	30	3.0	0%	0.0	1.7		85.3
3 approaches (other)	35	3.0	0%	0.0	0.0		86.6
2 approaches	22	2.0	45%	0.1	0.3		166.3
Grand Total	225	3.4	30%	0.7	1.0		90.2

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Figure 6.2: Sample intersection with 4 approaches, left-turn lane + bicycle lane
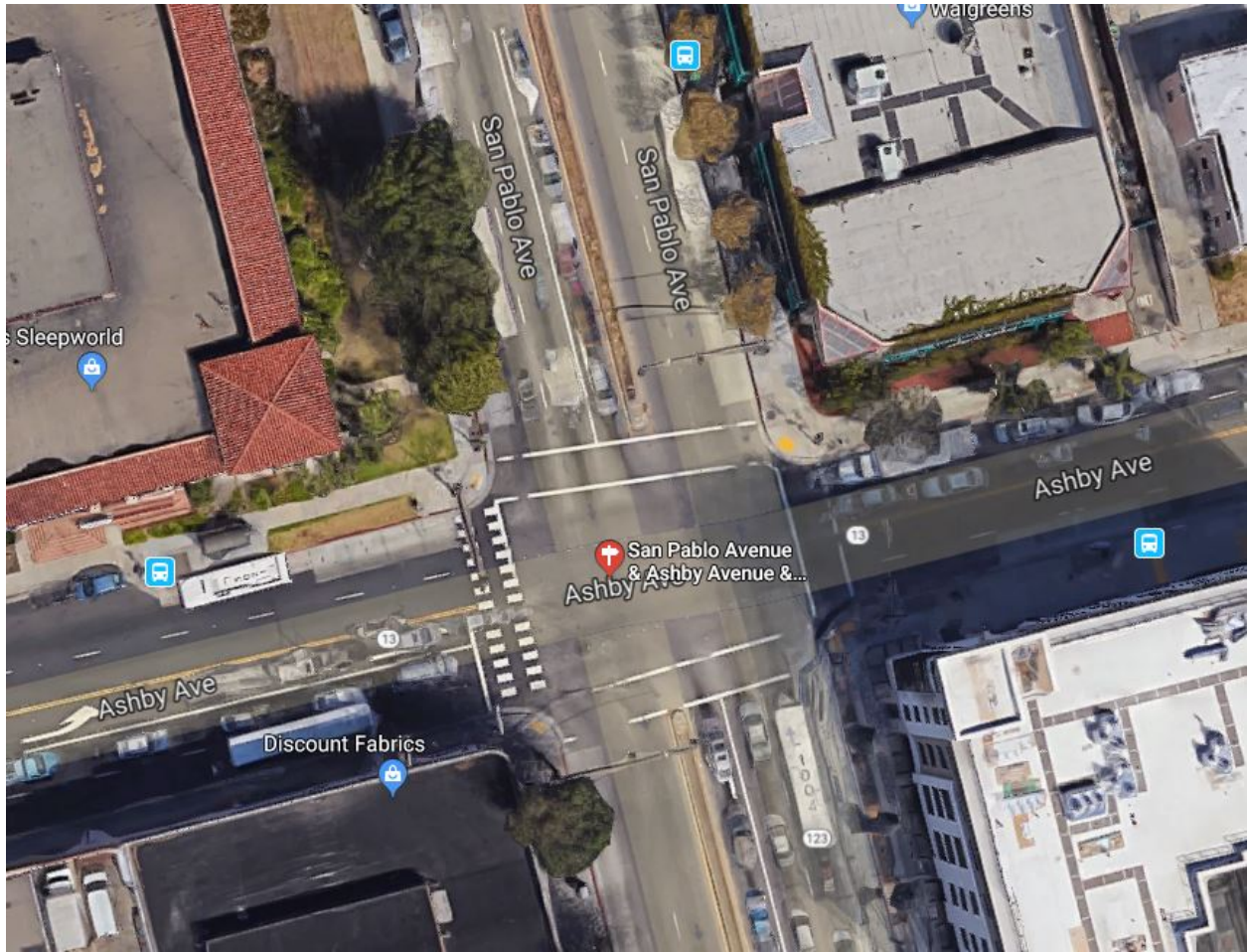
Figure 6.3: Sample intersection with 4 approaches and at least 1 left-turn lane

Figure 6.4: Sample intersection with 4 approaches and at least 1 left-turn lane
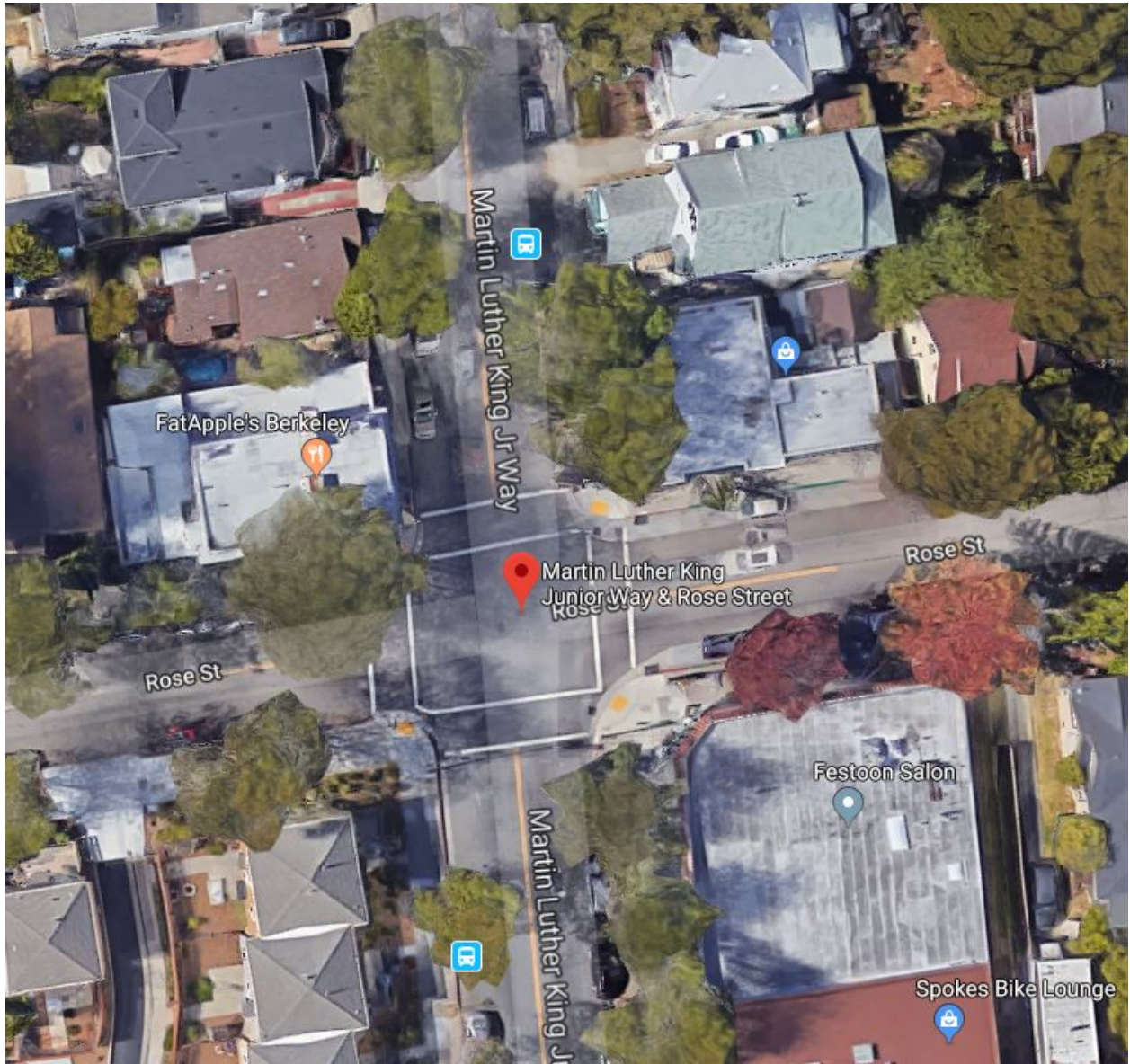
Figure 6.5: Sample intersection with 4 approaches, no bicycle/left-turning lanes, but with variation in number of lanes across the approaches

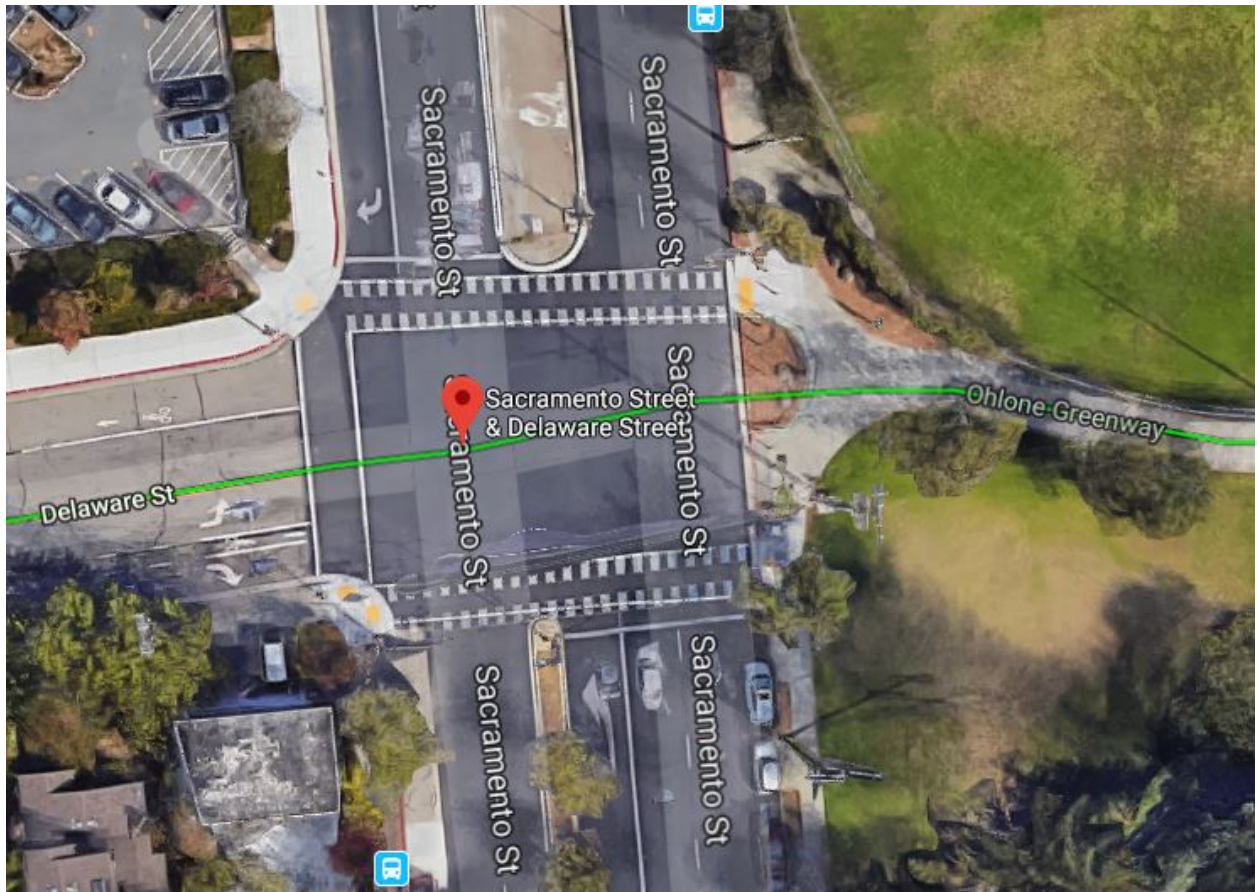Figure 6.6: Sample intersection with 4 approaches (other)

Figure 6.7: Sample intersection with 3 approaches, left-turn lane + bicycle lane

Figure 6.8: Sample intersection with 3 approaches and at least 1 left-turn lane
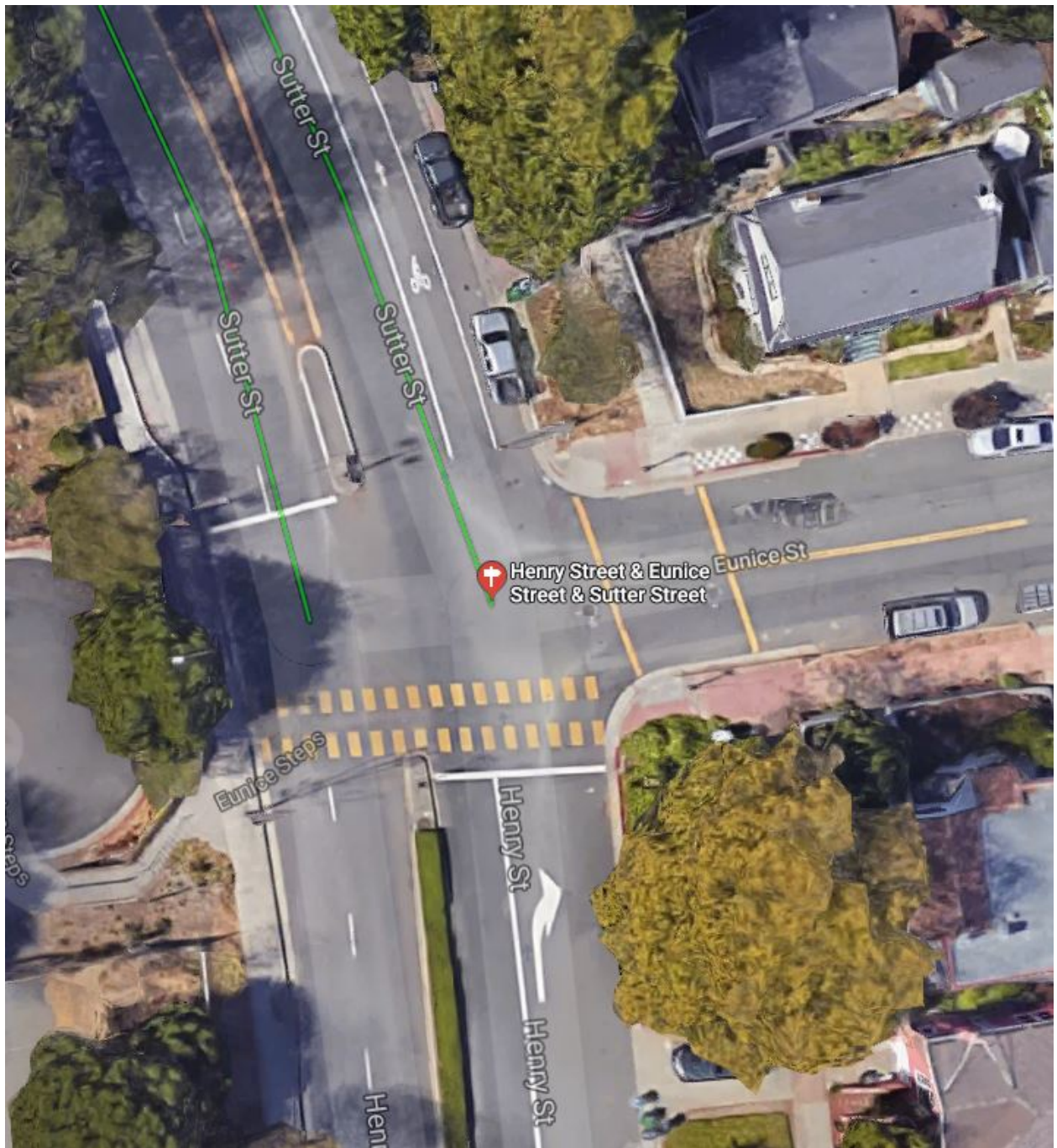
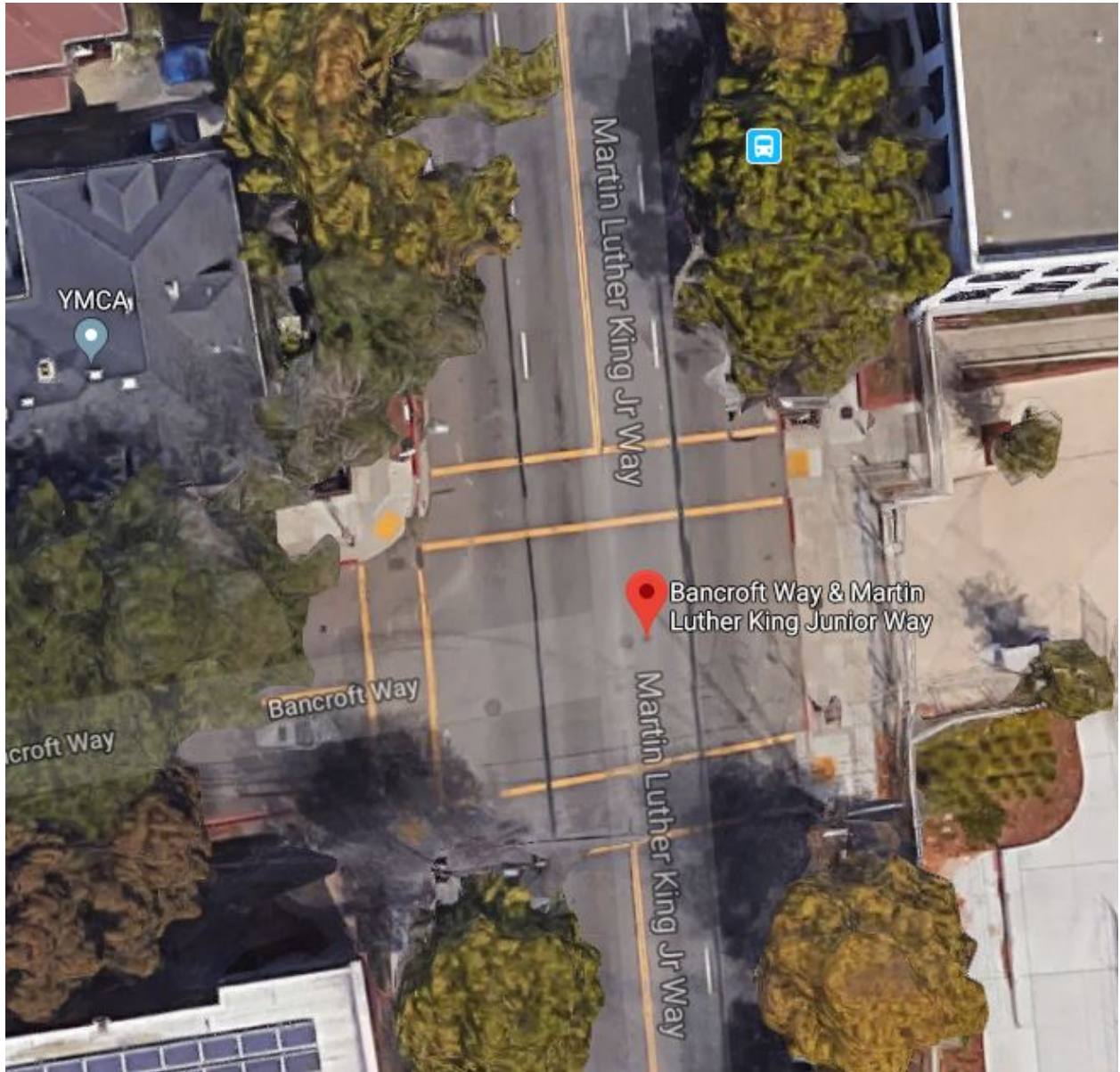Figure 6.9: Sample intersection with 3 approaches and at least 1 left-turn lane

Figure 6.10: Sample intersection with 3 approaches, no bicycle/left-turning lanes, but with variation in number of lanes across the approaches
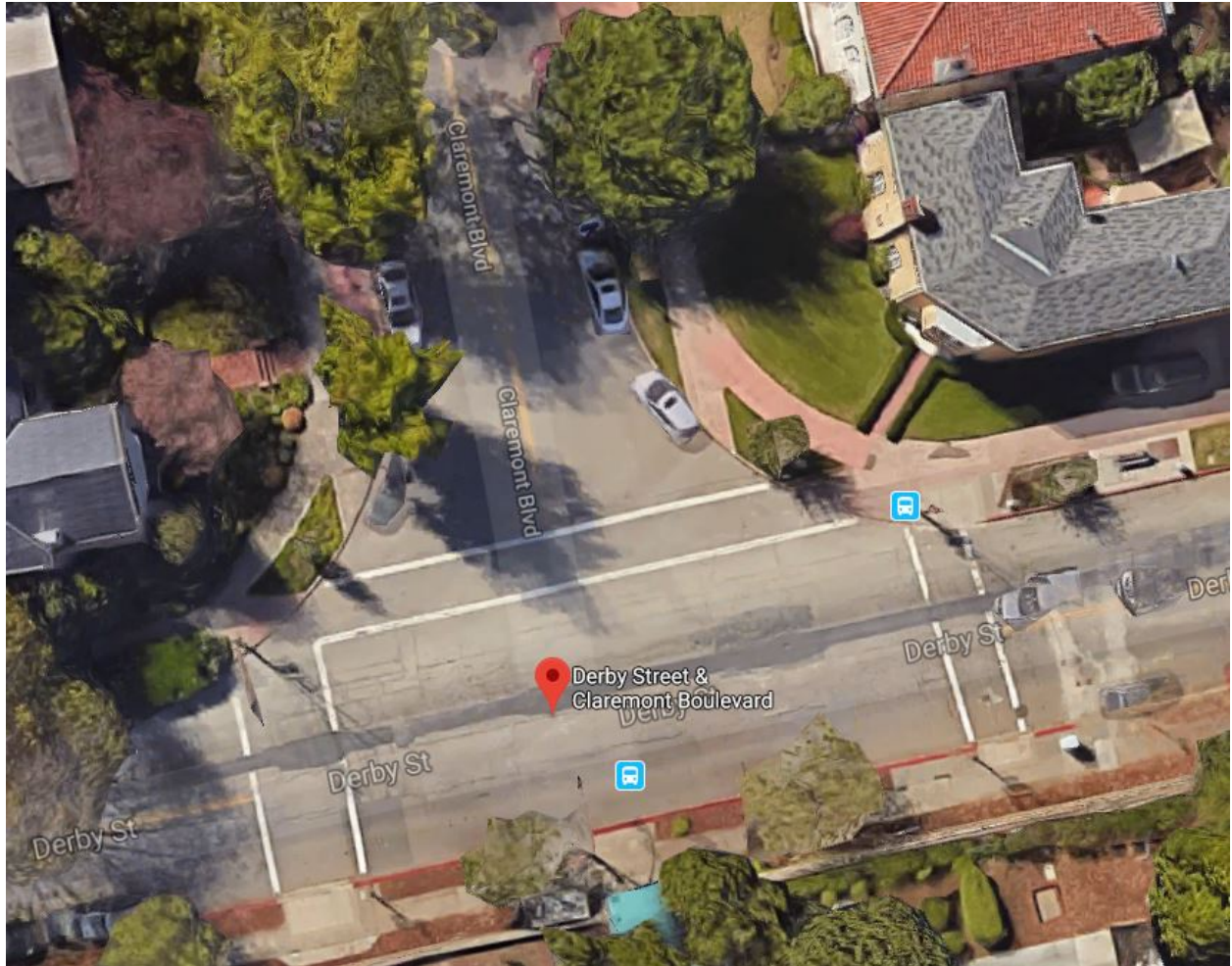
Figure 6.11: Sample intersection with 3 approaches (other)

Figure 6.12: Sample intersection with 2 approaches

Chapter 7

Conclusion

Intersections present a very demanding environment for all the parties involved. Challenges arise from complex vehicle trajectories; the 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 AVs are on freeways; but the full potential of automated vehicles – personalized transit, driverless taxis, delivery vehicles – can only be realized when AVs can sense the intersection environment to safely and efficiently maneuver through intersections. As is evident from intersection incidents with Google [25], Uber [14] and Tesla [6] AVs, their performance can be improved.

AVs are equipped with an array of sensors (e.g., video cameras, RADARs, LiDARs, GPS) to interpret and suitably engage with their surroundings. Advanced algorithms utilize data streams from such sensors to support the movement of AVs through a wide range of traffic and climatic conditions. However, there exist 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, in addition to signal phasing, can be provided to the AV as it approaches an intersection, and incorporated into an improved prior for the probabilistic algorithms used to classify and track movement in the AV's field of vision. Any connected vehicle (CV) with Advanced Driving Assistance System (ADAS) or an AV 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.

We refer to an intersection capable of providing all this functionality as an *Intelligent Intersection*. Intelligent Intersection requires the following algorithms:

1. analysis of intersection geometry to identify possible maneuvers, conflicts and blind zones;
2. computation of blind zone activation likelihood, given a traffic pattern and signal timing;
3. classification of conflicts and blind zones by their importance;

4. computation of optimal and minimal viable sensor placements in the intersection to ensure desired coverage of blind zones;

5. interpretation of sensor readings to determine traffic presence and dynamics in the blind zones; and

6. prediction of signal phase duration for adaptive and actuated signals.

Additionally, we must be able to quantify intersection's safety and mobility performance. All these algorithms will be implemented in an open-source software suite called Intelligent Intersection Toolbox [2] that we started developing in the course of this project. The impacts of this development will include:

- Cities will be given a tool to evaluate performance of their signalized intersections. In particular, compare potential improvements resulting from VZ plans with those provided by Intelligent Intersection.

- Caltrans and DMV are unavoidably getting more engaged in the regulation (i.e. design, testing and modifying the rules of deployment) of AVs in California. In most intersections safe operation of AVs will require augmentation of their capabilities with infrastructure-based sensing. Such sensing capability must be provided by Caltrans and local transportation authorities both because they own and operate the intersection and because this capability will be provided to all AVs. This project is a step towards specifying what these sensing capabilities should be.

- For AV makers it is important to know, which intersections have hidden dangers, such as blind zones. Knowledge of blind zones improves AV's safety. Additional real-time information about presence of agents in blind zones improves AV's efficiency.

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