AUTONOMOUS VEHICLE INTERACTIONS WITH OTHER ROAD USERS: CONFLICTS AND RESOLUTIONS

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Summary: As autonomous vehicles, or AVs, enter the market, other road users will need to interact with them in an effective manner. Currently, in manually-driven cars, the effectiveness of this interaction is based on the rules of the road that define priorities as well as ad-hoc negotiations to resolve conflicts. To formalize the conflict issue, we introduce the concept of *legal zones* showing how the road space can be described as graph of these zones. We also introduce the concept of *operational regions* around a vehicle which must not be infringed upon by others (to avoid safety conflicts). Using these two concepts we show how it is possible to consider new rules for the management of conflict in AV operations. We first briefly describe a new protocol for lane changes and then focus our attention on a protocol for managing conflicts in a pedestrian crossing situation.

INTRODUCTION

Autonomous vehicles are likely to transform not only the current automobile-based transportation system, but also how people move about in urban settings while walking, cycling, or using other motorized vehicles. In implementing autonomy on the road, we need to carefully consider how other users on the road, some of whom are vulnerable, interact with autonomous vehicles. We need to make sure that all road users have secure and accommodating access to road space.

To understand interactions on the road, we begin with an analysis of traffic rules; both formal and informal. Current traffic rules can be broadly divided into two classes: rules that relate to vehicle conduct with respect to the road and the environmental conditions (e.g., obeying speed limits), and rules that deal with interactions with other agents on the road. The second class is the focus of this paper and of special interest in this respect are the necessary interactions among road users aimed at resolving conflicting demands for road space. Traffic rules, aided by the presence of traffic lights, road signs, and the road structure itself, serve a variety of priority schemes aimed at resolving these conflicts.

Nevertheless, while traffic rules attempt to resolve if not prevent conflicts, they do not provide full coverage of all possible road situations. Even when traffic rules are obeyed to the letter, there are situations on the road where one road user can be stuck or blocked by the traffic that has right-of-way for extended lengths of time. Nevertheless, humans have learned, for the most part, how to resolve these conflicts even when there are no formally defined priority rules. What allows for this resolution are informal conventions and ad-hoc negotiations between the parties involved (drivers, cyclist and pedestrians). In these situations, resolution depends on acts of fairness on the road and the willingness to accommodate other road users (especially vulnerable ones). But not only; some road users employ aggression and "gaming," to resolve the situation to their own benefit at the expense of others.

An acute question that is currently becoming relevant, if not urgent, is what will happen when AVs enter the road? How will conflicts be negotiated and resolved when there is no driver to interact with? What kind of mechanisms should be used by AVs to interact with humans? In this paper we address these questions through two examples that show the need for some modification of traffic rules to accommodate AV. However, before we discuss them, we need to define the road space, what formally constitutes a conflict, and some of the current forms of conflict resolution; only then can we begin to address accommodation strategies.

The Road Space

Road users such as cars, trucks, emergency vehicles, cyclists, scooters, and motorcyclists sometimes need to interact among themselves and with pedestrians (Lagstrom & Lundgren, 2015). These interactions primarily involve the transfer of information to prevent a current or future conflict in the shared space. We refer to this shared and physical space that includes roadways, sidewalks, intersections, etc. as the *road spac*e. This is the resource that must be shared by all road users in a safe, efficient and fair manner. Road user separation is imperative for safety and effectiveness. In describing the kinds of interactions that exist between agents in the road space, two concepts are useful: *Legal Zones* and *Safety Regions*:

A *legal zone* is a (unidirectional and typically marked) segment of the road space where a road user has the unqualified and uninterrupted right to move. The only restrictions are the prevailing traffic codes (e.g., speed limits) and safe separation (i.e., maintaining distance) from preceding road users. For example, a lane segment bounded by traffic lights is a legal zone. A marked pedestrian crosswalk is a different type of legal zone where pedestrians have priority over vehicles. Lane segments on opposite sides of a pedestrian crosswalk belong to distinct legal zones. Thus, a route from point A to point B can be thought of as consisting of many legal zones. When legal zones intersect, potential conflicts arise. The intersection of the legal zones of cars (lanes) and the legal zone of pedestrians (crosswalks) may by definition set the stage for a conflict.

Regions of operation define the relations of an agent with the world. These relationships can be with the physical components of the road space (e.g., lanes, curbs, stop lines etc.) as well as with other road users such as pedestrians, cyclists, and other cars. These relations can be envisioned as a dynamic field (Hesse, 1961; Kadar & Shaw, 2000, and Gibson & Crooks, 1938). The concept of operational regions was developed in control theory (Brave & Heymann, 1990; Heymann, Degani, & Barshi, 2007) and the safety sciences domain (Hale, Borys & Else, 2012; van den Top, Jaap, 2010). One immediate dynamic field around the vehicle is its *safety region* around or in the immediate vicinity of the vehicle's physical structure that must be kept clear of other road users. (The formal calculation of the safety region around a vehicle is beyond the scope of the present paper, but see Papakostopoulos, V., Marmaras, N. & Nathanael, D. 2017).

Conflicts and Resolutions

Conflicts arise when two or more road users want to simultaneously access the same physical space, but only one can be in it at any given time (Thomas, 2006). Examples of conflicts on the road abound. When a vehicle switches from one lane to another (change of legal zone) and may infringe on the safety region of a vehicle already in the lane, a conflict arises. Lanes that merge can result in a conflict when there are vehicles in each lane, and paths that require vehicles to cross lanes (e.g., left vehicle to the right lane and right vehicle to the left lane) are inherently conflicting.

Conflicts are resolved in several ways: in a *supervisory* manner (e.g., traffic lights), or in a *partially supervised* manner through traffic signs (e.g., stop sign, yield sign). When a priority is assigned, but there is no specific method of control or guidance, we refer to it as *distributed with priority*. For example, the transition of a vehicle from one legal zone to another is executed without external guidance or supervision. A typical example is a lane change. Finally, there are situations where two or more agents need to change legal zones and are in conflict, but no predefined priority scheme exists; this is a *distributed conflict without priority*. An example is when vehicles coming from opposite directions (South-North and North-South) simultaneously reach a stop sign; priority is undefined. Another example is a "double lane merge" where vehicles that enter from the left lane need to exit on the right and vehicles that enter from the right need to exit on the left (thereby intersecting).

Because of the lack of determinism in resolving situations such as *distributed without priority* and to some extent also *distributed with priority,* as well as the presence of illegal/inappropriate behavior on the road, road users frequently need to negotiate conflicts. These negotiations take many forms. They can involve steps to usurp the space, inactivity, or some bilateral interaction. In the context of negotiations, road users may employ various types of actions to test or "game" other road users to see how the other road users respond. This is, to a large extent, what goes on when one road user infringes on the safety region of another (e.g., a vehicle entering a crosswalk to the detriment of a surprised pedestrian, a jaywalker jumping in front of a vehicle, or a vehicle "squeezing" to merge into a lane packed with other vehicles). Sometimes the aggressor/manipulator succeeds but at other times the aggressor may encounter an even more risk-seeking opponent. When there are two risk-seekers who are unwilling to back down, the situation may degenerate into a deadlock or, worse yet, an accident.

Conflict Management

There are several possible approaches to manage and resolve unsupervised conflicts. One possible protocol to resolve the problem of lane transition in congested traffic is the following: the transitioning vehicle moves toward the boundary of the lane it wants to exit and signals a request to transition lanes (e.g., a turn signal). The immediately affected vehicle in the entered lane makes a random choice (with designated probabilities) between allowing and denying access. If denied, the next vehicle in the entered lane does the same until the outcome *access granted* is obtained. The allowing vehicle signals permission to the requesting vehicle and slows to enable the safe transition. The designated probabilities can be assigned or computed based on such considerations as speed, relative congestion and relative speed of the respective lanes, terrain quality (e.g., visibility), proximity to a highway exit, etc. We call this a *random choice protocol* for conflict resolution.

In interactions between vehicles and pedestrians, the situation is more subtle and prone to ambiguity (Rasouli, Kotseruba & Tsotsos, 2017). Consider the most common interaction: a designated and well-marked road crosswalk. A pedestrian has priority over a vehicle on a designated crosswalk. The vehicle must come to a stop before the crossing and must wait until the pedestrian gets to the other side before resuming motion. Thus, if a pedestrian begins crossing when the vehicle has ample stopping time and distance before reaching the crosswalk, it must slow to a full stop.

But what happens to the pedestrian's priority when the vehicle is already very close to the crosswalk before the pedestrian begins crossing? Is the pedestrian allowed to force the vehicle to stop at a very short distance at a very short warning time? Is the driver responsible for the consequences of a pedestrian leaping into the crosswalk with total disregard for the approaching vehicle (hoping for the best…)? Is the vehicle required to come to a stop even if a pedestrian procrastinates at the curb, or should the vehicle ignore this pedestrian and cross? A chicken game on the part of the pedestrian will generally force an autonomous vehicle to yield. Thus, the simple assignment of priority (always) to the pedestrian can be very problematic from an AV point of view (Millard-Ball, 2016).

Vehicles and Pedestrians in a Crossing Zone

In a conflict, the driver is expected to do whatever possible to avoid hitting a pedestrian, and the tendency is to fault the driver in the case of an accident unless it can be demonstrated without doubt that the driver acted legally and was unable to prevent the accident from occurring due to unlawful behavior on part of the pedestrian. Autonomous vehicles are expected to be designed to behave defensively so that in no circumstances will an accident be attributable to the vehicle (Shalev-Shwartz, Shammah & Shashua, 2017). This raises many issues regarding the interaction of AV with pedestrians.

A case in point is a marked, but un-signaled (no lights) crosswalk. Millard-Ball (2016) examined the case of an unregulated crosswalk from a game theoretic viewpoint. Of the four possible behaviors, *wait/wait, cross/wait, wait/cross* and *cross/cross*, referring to pedestrian/vehicle interaction, *cross/cross* means a potential collision and *wait/wait* means deadlock. Thus, the optimal behavior; i.e., the Nash equilibrium is either *cross/wait* or *wait/cross*. There is no natural choice mechanism between the two and the law gives (essentially unqualified) priority to the pedestrian and requires the vehicle to yield. However, this does not eliminate the potential ambiguity. Specifically, what if a pedestrian starts to cross while the vehicle is already in close vicinity to the crosswalk (i.e., the vehicle's safety zone overlaps the crosswalk)? Clearly, the law cannot resolve the situation within the present legal framework and infrastructure (Bjørnskau, 2015).

Current behavior at crosswalks are strongly governed by cultures. In some countries, drivers are very courteous and tend to yield to pedestrians even when the latter are inconsiderate, while in others, pedestrians are courteous and cautious and tend to yield to approaching vehicles. However, there are many urban environments where neither the drivers nor the pedestrians are overly patient, which frequently leads to near or even actual accidents by trying to force their way into a chicken game with disastrous *cross/cross* outcomes. Since AVs are risk aversive, this will lead to a potential situation where pedestrians, especially in busy and congested situations, will quickly learn that playing the chicken game is a sure winner. Vehicles can be forced to halt with impunity and AVs will be victimized and forced into a slow-motion scenario and possibly be avoided by the public. It is clear that the interaction between pedestrians and vehicles and, in particular, AVs, requires renewed attention with a special focus on the proactive interaction that prevents ambiguity and ensures safe and efficient conduct.

One possible way to alleviate this situation is to introduce a formal interaction protocol between vehicles and pedestrians. Consider the following: A vehicle is approaching a pedestrian crossing at cruising speed. At a specified distance from the crossing, the *active crosswalk region* is entered. The length of the *active crosswalk region* can be determined as a function of vehicle speed, road geometry, visibility, and location (near a school, hospital, etc.). Figure 1 is a sketch of the road, lanes, and crosswalk zones as well as the active crosswalk region.

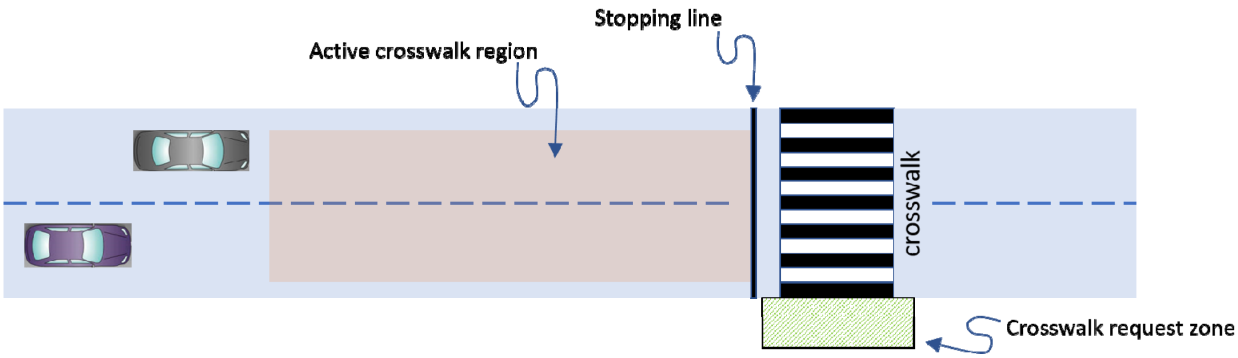

Figure 1. Diagram of the request zone and active crosswalk region.

To resolve the ambiguity, a bilateral interaction protocol with pedestrians and/or other approaching vehicles is initiated in the following manner:

1. Upon entering the *active crosswalk region,* the vehicle transmits a *crosswalk recognition signal* (e.g. through a designated display) and reduces its speed to a legally specified speed.
2. While entering the *active crosswalk region*, if a pedestrian is detected by the vehicle, either in the designated *crossing request zone* or on the crosswalk itself, a *stopping commitment signal* is transmitted by the vehicle to the pedestrian to indicate the commitment to stop. Concurrently, a *stopping commitment signal* is also displayed to other vehicles in the *active crosswalk region*. The vehicle reduces speed and comes to a full stop in front of the crosswalk.
3. All vehicles in the *active crosswalk region* that observe a pedestrian or a *stopping commitment signal* transmitted by another vehicle transmit a *stopping commitment signal* as well and reduce their speed to a full stop ahead of the crosswalk.
4. A pedestrian standing in the *crossing request zone* is obliged to cross, provided that: (1) no vehicle is present in the *active crosswalk region*, or (2) all vehicles in the *active crosswalk region* have either stopped in front of the crosswalk or indicated a stopping commitment signal. (There is also a situation where a pedestrian is not in the crossing request zone but is observed approaching the crosswalk with apparent intent to cross. One possible solution to this problem is that the vehicle must also transmit a stopping commitment signal and come to a stop ahead of the crosswalk, provided it is feasible to stop safely).
5. Vehicles resume their motion only after *all* pedestrians have completely crossed. If at the specified closer distance from the crosswalk no pedestrian is recognized and no *stopping*

commitment signal from other vehicles has been observed, the vehicle may continue its motion at the specified reduced speed through the crosswalk zone, at which point it may resume cruising speed.

It should be noted that this protocol restricts pedestrians' legal status as regards current unconditional priority. This protocol establishes a degree of symmetry between the pedestrians' legal rights and those of the vehicles, with respect to entry into the intersecting zones (driving and crossing). It provides only tentative priority to the pedestrians who, in turn, have obligations toward the approaching vehicles so as to ensure smooth traffic and pedestrian flow. In particular, the pedestrian waiting in the *crosswalk request zone* is not permitted to cross unless either there are no vehicles in the active crosswalk region or *all* the vehicles in the active crosswalk region have indicated a stopping commitment signal. In the case where are vehicles in the active crosswalk region and all of them are displaying the stopping commitment signal, the pedestrian must cross and may not procrastinate.

This protocol assumes implicitly that pedestrians behave rationally and obey the rules of the road. It assumes that pedestrians are familiar with vehicles' communication mechanisms regarding pedestrian crossings and will not cross if approaching vehicles do not transmit the *stopping commitment signal*. It further assumes that all non-traffic-lighted crosswalks are equipped with a recognizable *crosswalk request zone*.

There is an associated problem that can occur when multiple pedestrians (e.g., emerging from a ball game) are streaming through a crosswalk without any reprieve for the waiting vehicles. Conversely, there may be a long stream of vehicles moving through the crosswalk without reprieve for the waiting pedestrians. Today, most drivers will eventually lose patience (aided by the progressively louder honking horns of the line of vehicles) and begin to encroach on the crossing zone with the assumption that at some point the pedestrians will give way. This game is illegal, but since there is no recourse, it is widely employed. In turn, pedestrians employ the same chicken-game to return to the crossing zone. Naturally, such games cannot be tolerated where autonomous vehicles are concerned, thus reinforcing the need to augment the above protocol to better control such crosswalks. This can be done with some supervisory metering control to balance the flow of pedestrian traffic and vehicular traffic.

CONCLUSION

This paper addressed the issue of conflicts, their resolution problems and, in some cases, specific approaches to their potential resolution. To formalize the conflict issue, we introduced the concept of legal zones and showed how the road space can be described as a directed graph of these zones. We also introduced the concept of operational and safety regions which must not be infringed upon by others. Using these two concepts we briefly described a simple protocol for lane change in congested situation and then discussed the problem of AV interaction with pedestrians. The pedestrian crossing example highlights some of the likely changes that will have to take effect when AVs will begin to roam the public space and the kind of regulatory and legal modifications that will need to be considered to accommodate this new technology. These changes will involve not only technological implementations (such as AV lighting signals, Clamann, Aubert & Cummings, 2017), but also more socially focused ones concerning the relationship between vehicles and pedestrians (NHTSA, 2017).

Currently, most efforts in AV technology are focused on solving the problem of how the vehicle drives itself, and finds a trajectory around obstacles and other road users while adhering to traffic rules. Our goal in this paper was to show that the problem of how to interact with other road users when conflicts arise and the need for resolution requires detailed analysis and perhaps some new behavioral protocols. The goal of this paper was to highlight this problem and provide some initial thinking toward the development of protocols and rules for AV behavior.

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