Priority-based Intersection Control Framework for Self-Driving Vehicles: Agent-based Model Development and Evaluation

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***Abstract* - Development of in-vehicle computer and sensing technology, along with short-range vehicle-to-vehicle communication has provided technological potential for large-scale deployment of self-driving vehicles. The issue of intersection control for these future self-driving vehicles is one of the emerging research issues. Contrary to some of the previous research approaches, this paper is proposing a paradigm shift based upon cooperative self-organizing control framework with end-user responsibility. Distributed vehicle intelligence has been used to calculate each vehicle's approaching velocity. The control mechanism has been developed in an agent-based environment. Self-organizing agent's trajectory adjustment bases upon a proposed priority principle. Testing of the system has proved its safety, user comfort, and efficiency functional requirements. Several recommendations for further research are presented.**

Keywords – autonomous vehicle; traffic control; self-organization; agent-based modelling;

I. INTRODUCTION

The development of in-vehicle computer technology [1], vehicle sensors, and short-range vehicle-to-vehicle and vehicle-to-infrastructure communication [2, 3] has created an opportunity for development of the self-driving vehicle in the next decade or two [4]. As a result, in the last level of automation, these vehicles will be able to "perform all safety-critical driving functions and monitor roadway conditions for an entire trip" [5]. In operating a self-driving vehicle, the driver will only be expected to provide destination or navigation input, and not to take over the control of the vehicle at any point during the trip.

This emerging technology is primarily expected to improve traffic safety [6]. In addition to potential decrease in crashes, there should be improvements to mobility for people currently unable to drive or improvements in environmental effects [7, 8]. However, a true potential of this technology is the potential for forming cooperative vehicle systems, where vehicles coordinate their movements with surrounding vehicles [9]. Consequently, the emerging technology of self-driving vehicle has potential for introducing a radical change in the fundamental premises of traffic control principles.

For over a decade, there have been several attempts to develop approaches for intersection control of self-driving vehicles. These previous efforts are grouped according to the underlying operating principles:

1. Queuing principles (e.g., first-in first-out [10])
2. Conventional traffic control principles (e.g., right-hand side rule [11])
3. Economic principles (e.g., auctions [12])
4. Other efforts (e.g., gap adjustment mechanism [13])

These research efforts provided a range of potential control mechanisms. However, we have to note that these mechanisms were primarily developed with a conventional perspective on traffic operations, while neglecting some important behavioral aspects. The approach presented here differs, considering that our design vision tries to include the principles of sustainable development of technology. The main idea is that control technology for self-driving vehicle should be sustainable, thus satisfying current user needs, while not preventing the accomplishment of future user needs. Consequently, sustainable design requires inclusion of economic, environmental, and social aspects, since only a holistic approach can achieve intended results. Our starting premise is that in order to design a sustainable control technology, we need also to consider its effect on distribution of positive and negative effects on social aspects. Specific social aspects under consideration here are fundamental human rights, established by United Nations [14]. For impacting the distribution of effects upon human rights, there is a need for incorporating a social justice framework into technology design. In addition to the sustainable design vision, we are also taking into consideration the utilization of the computational capabilities in each vehicle, linking management scenarios on different network levels, and incorporating lessons learned from conventional traffic control.

Besides theoretical starting point, research team has conducted a survey to investigate users' opinions and attitudes towards operation of traffic control systems. The survey included 239 people total. 96% of subjects recognized the importance of safety at intersections, but identified other factors, especially the concern for respect and morality. In addition, when asked about the impact that traffic control systems have on their fundamental rights, 45% identified impact on right to life, 25% on right to work, and 26% identified impact on all the fundamental rights. On the contrary, only 25% of users declined impact on any of the rights. Finally, when asked if they would accept to pay for the right-of-way through the intersection, only 3% of subjects stated they would accept that.

The focus of this paper, aside from theoretical and empirical foundation of control framework, is on presenting a distributed agent-based model for self-organizing and cooperative intersection control of self-driving vehicles. Second section of the paper provides a description of the background for control framework development. Third section presents the control mechanism developed in agent-based environment. Later paper sections present findings from system testing, conclusions, and recommendations for further investigation.

II. Framework Background

A. *Principles of Social Justice*

The notion of social justice in this research is inspired by the theory of Justice as Fairness, developed by philosopher John Rawls [15]. In essence, Rawls developed his theory as a regulative framework, based on the two principles [16]:

1. Each person is to have an equal right to the most extensive total system of equal basic liberties compatible with the similar system of liberty for all.
2. Social and economic inequalities are to be arranged so that they are both to the greatest benefit of the least advantaged, consistent with the just savings principle, and attached to offices and positions open to all under conditions of fair equality of opportunity.

The first principle above relates to liberty, while the second principle relates to equality. Rawls' notion of social justice argues that every person has inviolability that even the system welfare as a whole cannot override. Consequently, the objective of control is not solely total delay or average total delay, but also the distribution of delay among users or maximum delay. The reason for this shift in performance measures is that the consequences of delay are not the same if person is traveling to a grocery store or to an emergency room. Survey mentioned above has also identified that people would support development of technology with a focus on social justice, since only 8% stated that this approach is not important at all.

B. *Priority System*

Considering underlying social relations from traffic interactions at an intersection, the framework is envisioned as mutually-advantageous long-term and large-scale cooperation that relies upon end-user responsibility. This vision is developed as a Priority System (PS), where each individual user can select a specific Priority Level (PL) for their trip, in addition to the destination or route information for self-driving vehicle. The intention of the PS is to protect fundamental user rights, while simultaneously preventing either user or central control usurpation. As a supporting mechanism to the PS, intended to support cooperation among users, we introduce a structure of non-monetary priority credits. Detailed rules for PL selection and user interaction will be presented elsewhere, considering that the focus of this paper is on presenting the development of the distributed control framework.

C. *Hierarchically Distributed Control Framework*

From a technical standpoint, the mechanism is envisioned as distributed intelligence with cooperative communication and computation performed by individual vehicles. Furthermore, the envisioned dynamic and adaptive nature of the framework relates to the principles of self-organization, allowing for higher computational efficiency, robustness against failure, scalability for expansion, and smaller communication capacity requirements [17, 18]. As a result, vehicle agents will be able to perform domain-oriented reasoning and adapt their own actions to changing environments [19].

Envisioned self-organization framework is expanded using principles of cooperation, in addition to individual vehicle's autonomy. The premise is that setting up individual agent's objective as cooperative versus competitive should result in improved system-wide results. The control framework (Fig. 1) is envisioned to have three cooperation layers: Network, Route, and Intersection [20]. These are not control layers, since all the computation is performed in-vehicle, but are primarily used for cooperative inter-vehicle communication, where vehicles exchange information on their past and current environment.

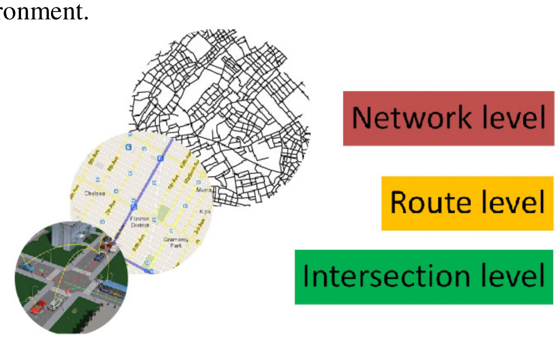

Fig. 1: Hierarchical levels of cooperation

Hierarchically the lowest, but the most important procedure will be happening at the intersection. Intersection level procedure will be focused on ensuring the safety of conflicting directions through the intersection. Furthermore, this procedure will focus on assigning the right-of-way for specific vehicles and platoons, according to their time of arrival and PL (PL values for individual vehicle agents are used for conflict resolution upon simultaneous arrival). Individual vehicles, without the influence of external controller, perform computation of parameters, under uniform rules and using the information sensed or communicated from surrounding vehicles. Self-driving vehicle decides to slow down or stop (assuming acceptable deceleration distance) based on the assignment of the right-of-way. The medium cooperation level (route) enables vehicles to create platoons based on their PL value and routes in the network. Cooperation on this level would be arranged through vehicle leaders at the beginning of the platoon. Each vehicle, while entering the network will be emitting a call to join a platoon with similar PL value and appropriate route. Hierarchically the highest level (network) is envisioned so that central control and individual vehicles can disseminate information on global network events. The role of the central control would be limited only to disseminate information on global network events of high importance. This type of self-organizing decentralization will acquire and maintain structure based on the relationships between the behavior of the individual agents (the microscopic level) and the resulting sophisticated structure and functionality of the overall system (the macroscopic level).

In addition to PL being selected by the user based on the estimated urgency of the trip, this value might also depend on the vehicle occupancy, vehicle type (e.g., emergency vehicle), vehicle's dynamic characteristics (e.g., vehicle's braking capabilities), or constraining intersection characteristics (e.g., approach grade, queuing capacity). However, it is important to emphasize that expanding PS with other information allows for taking into consideration the actual user characteristics. For example, this principle can clearly distinguish vehicles with higher priority, such as emergency or public transportation vehicles. Furthermore, PL principle can allow for development of cooperative platoons of vehicles with similar characteristics on the route level. Stepping further from the reservation first-in first-out principle, the concept of in-vehicle trajectory computation based on PL can accommodate for different user, vehicle, or intersection characteristics.

III. Development of Agent-Based Model

In order to develop decentralized control approach described in the previous section, we have selected agent-based modeling (ABM) approach. This type of modeling is applicable to represent previously described framework since agents can function solely on intelligent interactions with other agents, can detect and respond to changes in the environment, can take actions towards a goal, and can learn and improve [21]. Consequently, using ABM bottom-up approach and defining interaction rules among agents should result in aggregation that establishes a system-level behavior [22]. In addition to capability for modeling decentralized control framework, ABM is useful in this case because we can realistically represent individual vehicle's application for crossing time through the intersection, and individual control commands, but also obtain emerging effects on the macro level and determine consequent influence on user's delay.

A. *Intersection Control Mechanism*

The development presented here is primarily focused on the hierarchically lowest self-organization level at the intersection. As the vehicle agent approaches intersection (Fig. 2), it first encounters cooperative self-organization zone (CSZ). As the vehicle is traversing CSZ, it communicates with all the other vehicles that are simultaneously in CSZ on all other conflicting approaches. Vehicles communicate their PLs and information on their trajectories that relate to occupied space-time of the intersection. In addition, vehicle agent knows conflict areas of the intersection, predefined in the matrix form. As a result, each vehicle can calculate its own and the arrival time at each of the intersection's cells for all the other conflicting vehicles simultaneously in CSZ. Consequently, agent's action space consists in controlling approaching trajectory based on the value of acceleration.

Figure 2 presents two vehicles that are determining their space-time for crossing through the intersection from conflicting approaches. Yellow vehicle coming from the west approach has a higher PL, compared to the blue vehicle coming from the north approach. Higher PL results in right-of-way over blue vehicle. Each of the vehicles knows which intersection cell it will occupy (rows of the matrix in the upper left corner of figure), and at what time step (columns of the matrix in the upper left corner of figure). This way, each vehicle is searching for specific space-time continuum. Once each vehicle finds the new available space-time for traversing through the intersection, each vehicle agent determines the delay (d) it will experience, added to its travel time considering the desired velocity (Fig. 3). While traveling through CSZ, vehicle agent reiteratively computes dynamic parameters, depending on all agents in CSZ in each time step. This iterative computation while traveling in CSZ allows for a vehicle that just entered CSZ to obtain the right-of-way before the vehicle that is already in CSZ on the conflicting approach, if the vehicle farther away has a higher PL.

After CSZ, vehicle agent enters trajectory adjustment zone (TAZ), where it decelerates and accelerates based on the calculated space-time and delay for crossing though the intersection. TAZ is divided into two sections, first for decelerating, and the second for accelerating. The boundaries for these zones depend on communication range, speed limit through the intersection, delay distribution for deceleration or acceleration part of the trajectory, and other constraints. An example presented on Fig. 2 is one potential value for the zone boundaries (200, 130, and 65 m). The objective of trajectory adjustment through deceleration and acceleration is twofold. First, it is to accommodate additional delay in the travel time. Second, it is to reach a terminal velocity for traversing the intersection, based on the movement through the intersection. In addition, the constraint is accommodating trajectory adjustment in a predefined distance before the intersection.

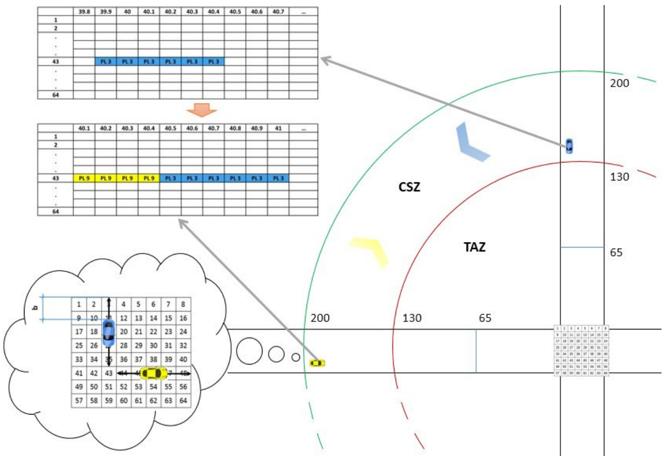

Fig. 2: Self-organization structure

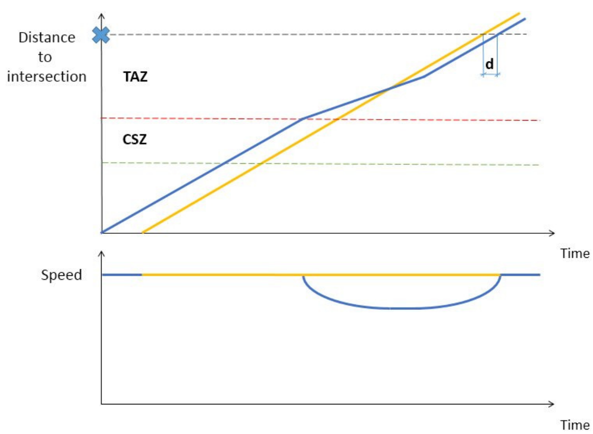

Fig. 3: Example of trajectory adjustment and changes in parameters for two conflicting vehicles

The equations presented below specify vehicle's trajectory parameters during deceleration and acceleration part. Equations 1, 2, and 3 relate to the deceleration part of the trajectory, and equations 4, 5, and 6 relate to the acceleration part of the trajectory. In addition, the zone boundaries and consequent calculation of acceleration value is constrained by several parameters:

- Maximum acceptable acceleration/deceleration rate, which is 3.4 m/s^2 [23];
- Communication range around the intersection, assumed to be 200 m [24];
- Geometry of the road and intersection, which consequently constraints maximum desired velocity through the intersection (for minimum time spent in the intersection conflict area) and braking distance on icy surface;
- Minimum velocity, taking into consideration vehicles with different dynamic characteristics;
- Safety buffers between conflicting vehicles (e.g. based on psychological effect on user);
- Allowed turning lane - in the proposed approach, vehicles will not turn from any lane in the intersection, since this is considered to increase the number of conflicts and it disables potential for platoon formation in the route cooperation level.

$$t_1 = \frac{S_1}{V_0} + d \cdot TAZ_1 \tag{1}$$

$$a_1 = -\frac{(2 \cdot V_0 \cdot t_1) - (2 \cdot S_1)}{{t_1}^2} \tag{2}$$

$$V_1 = V_0 + a_1 \cdot t_1 \tag{3}$$

$$t_2 = \frac{S_2}{V_0} + d \cdot TAZ_2 \tag{4}$$

$$V_2 = V_0 \ OR \ V_3 \tag{5}$$

$$a_2 = -\frac{V_2 - V_1}{t_2} \tag{6}$$

Where:

t_1 – travel time for deceleration part of the trajectory, with portion of the delay included
S_1 – distance travelled during the deceleration part of the trajectory
V_0 – desired velocity before entering VAZ
d – additional travel time required for avoiding conflicts in the intersection
TAZ_1 – delay coefficient used for distributing part of the delay to deceleration part of the trajectory (here, constant value of 0.33)
a_1 – deceleration value for the first part of the trajectory adjustment
V_1 – terminal velocity for the end of the deceleration part of the trajectory
t_2 – travel time for acceleration part of the trajectory, with portion of the delay included
S_2 – distance travelled during the acceleration part of the trajectory
TAZ_2 – delay coefficient used for distributing part of the delay to acceleration part of the trajectory (here, constant value of 0.67)
V_2 – terminal velocity for the end of the acceleration part of the trajectory, and velocity used for traversing through the intersection
V_3 – terminal velocity depending on the turning direction of the vehicle
a_2 – acceleration value for the second part of the trajectory adjustment

B. System Development

The proposed system is developed using application programming interface (API) in VISSIM traffic simulation environment [25]. API bases on C++ programming language. API programming allows development of vehicle agents, integrated with VISSIM using external dynamic link library (DLL). DLL code replaces the internal driving behavior for all the vehicles in the simulation, making them effectively self-driving vehicles. The vehicle agent code has three parts, performing agent's sensing, cognition, and actuation.

1. With the first function, DriverModelSetValue, each vehicle agent receives its current state and state of surrounding agents from VISSIM simulation model (e.g., acceleration, GPS coordinates, simulation time (GPS clock time), route, vehicle length, PL, etc.).
2. Second, using DriverModelExecuteCommand function, each vehicle agent computes new trajectory parameters. This function has four commands: Init (used to initialize DLL parameters), CreateDriver (executed when vehicle enters the network), MoveDriver (executed in every time step), and KillDriver (executed when vehicle leaves the network).
3. Finally, via DriverModelGetValue function, vehicle agent sends new parameters to VISSIM simulation model. As a result, API programming allows execution during simulation initialization, for every

agent initialization, and for every simulation step (simulation frequency used in this research is 10 Hz).

Vehicle agent uses several additional functions to determine the time-space for crossing through the intersection. First, vehicle agent uses Get_Delay function that is searching for available intersection time-space as the vehicle is traveling in CSZ. Available time-space is considered any continuous intersection time-space that vehicle requires based on its length and desired speed, and that is either completely unoccupied or occupied by a vehicle with lower PL. Second function, Revoke_Reservation, is activated for vehicle agent that lost its time-space from the vehicle with higher PL, and while traveling in CSZ. The vehicle with revoked reservation then needs to execute Get_Delay function again. Third function is Finalize_Reservation, which is activated as the vehicle enters TAZ. This function ensures that vehicle agent has assigned a specific time-space, which no any other vehicle agent can override as soon as vehicle is in TAZ. Finally, there is a set of functions that adjust parameters for trajectory profile as the vehicle is traveling in TAZ. A generalized pseudo-code for in-vehicle computations while vehicle is in CSZ and TAZ is as following:

```
WHILE agent in CSZ AND does not have reserved time-space for crossing the intersection
    CALCULATE agent's trajectory AND execute GET_DELAY
        IF conflict exist with lower PL agent
            Execute REVOKE_RESERVATION for lower PL agent
WHILE agent in TAZ
    Execute FINALIZE_RESERVATION AND adjust agent's trajectory
```

C. Model Validation

In order to validate the developed model, research team has decided to test its safety. To test the safety of self-driving vehicle trajectories, research team performed conflict analysis using Surrogate Safety Assessment Model (SSAM) [26]. In order to perform conflict analysis, SSAM uses VISSIM-generated trajectory files from each simulation run. The focus of analysis was on the frequency and character of narrowly averted vehicle-to-vehicle collisions. The parameters used were:

1. Maximum time-to-collision (TTC) - the minimum time to collision observed during the conflict, and its threshold value was set up to 1.5 sec.
2. Maximum post-encroachment time (PET) - the minimum time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. The threshold for PET was set to 5.0 seconds.
3. Conflict angles - an approximate angle of hypothetical collision between conflicting vehicles, based on the estimated heading of each vehicle agent. The threshold for rear angle conflict was set up to 30.0º and for crossing angle conflict to 80.0º.

Both TTC and PET values were selected as the upper limits for time during potential conflicts. For example, SSAM calculated values below the threshold would signify a dangerous vehicle-vehicle conflict, while value of 0 seconds would indicate an actual collision. In addition, conflict angles would determine if trajectory had a rear or crossing angle conflict. After analysis of 1000 simulation runs, no conflict values below the defined thresholds were identified in vehicle's trajectories. Consequently, this is an indication that developed control mechanism and simulation model have fulfilled safety requirements.

IV. Simulation and Results

A. Simulation Setup

The proposed control mechanism has been comparatively tested with conventional state-of-the-art traffic signal control. Testing was performed on a four-leg isolated intersection. The test VISSIM model has desired speed of 50 km/h for through vehicles, with left-turning velocity set to 25 km/h, as generally accepted value for left turning velocity. There were 10 simulation iterations for each volume scenario used, with different random seeds. Each volume scenario was simulated as one hour volume. The exact volumes per scenario are in the left columns of TABLE 1 and Table 2, showing east-west through, east-west left, north-south through, and north-south left traffic volume per hour, respectively. First 300 simulation seconds are not included in the analysis as the network loading time, and simulation would last up to 3800 seconds for measuring a broader impact of control mechanisms. Routing and lane change of the vehicles has been under control of static routing and lane change decisions, made upstream from the intersection (approximately 500 m).

Proposed control mechanism was simulated in three versions. In the first version, vehicle agents were assigned random PL (uniformly distributed). In the second, all the vehicle agents had identical PL, and lastly, in the third version, PL was set to 5 or 10, based on the approach. Conventional traffic signal control was represented using fully actuated ring-barrier NEMA operation [27], with actuation by 15 m long stop bar detectors. NEMA phase configurations included from two to eight phases. Optimized signal timing parameters were converted into minimum and maximum green for through and left turning traffic in different volume scenarios (Table 1). Signal is operating in Free mode, without fixed cycle length, thus allowing for full signal controller flexibility (e.g., gap out, conditional service, etc.). The upper part of Table 1 shows signal timing for the case of equal traffic on all approaches, while the lower part of Table 1 shows signal timing for volume scenarios based on the premise of minor and major approaches.

TABLE 1: Ring-barrier controller signal timing parameters

E+W Through	E+W Left	N+S Through	N+S Left	NEMA	Min Green	Max Green 1	Max Green 2
120	30	120	30	2 ph.	5	15	N/A
240	60	240	60	2 ph.	5	20	N/A
360	90	360	90	8 ph.	5	25	15
480	120	480	120	8 ph.	8	36	15
560	140	560	140	8 ph.	8	65	20

E+W Through	E+W Left	N+S Through	N+S Left	NEMA	Min Green	Max Green 1	Max Green 2	Min Green	Max Green 3	Max Green 4
120	30	60	15	2 ph.	5	10	N/A	5	10	N/A
240	60	120	30	2 ph.	5	10	N/A	5	10	N/A
360	90	180	45	6 ph.	8	15	10	8	15	N/A
480	120	240	60	6 ph.	8	25	10	8	20	N/A
600	150	300	75	8 ph.	8	40	15	8	20	10
720	180	360	90	8 ph.	8	65	20	8	35	15
840	210	420	105	8 ph.	8	110	35	8	65	20

System measures focused primarily on delay, as the difference between the desired and actual travel time through the intersection. We have selected average and maximum delay as the representative measures. Average delay shows the overall system performance, and maximum delay is a measure of potential most significant negative impact on the individual user. Table 2 shows average and maximum delay for proposed mechanism with uniform and random PL distribution, in comparison to actuated signal control. From Table 2 we can see that, in general, proposed mechanism has lower average and maximum delay until volume distribution for scenarios five and twelve. The potential reason for this is that in the cases of higher volume, traffic signal uses queue formation and dissipation for the advantage of forming platoons and reducing gaps between vehicles, thus dissipating queue with a saturation flow rate.

Table 3 shows the results from PL assignment according to approach and volume. This test cases were intended to investigate the impact upon average and maximum delay in the case of major-minor street interaction, under opposing PL assignments and traffic volumes. The information in this table shows that in cases of higher volume with PL 10, system operates with higher average and maximum delay for total traffic, and per PL. Basically, this implies that system operation should encourage smaller use of highest PL, since the greater the number of vehicles uses it, it has negative impact upon delay distribution. This is one of the points that will be considered for development of PL system from the standpoint of user behavior.

Finally, we have investigated the potential of vehicle agent for self-organization as the emerging effect of trajectory adjustment. Figure 4 shows a vehicle trajectory diagram for a group of east bound vehicles as they are approaching the intersection. The distance is measured from the beginning of the link. PL is randomly assigned to each vehicle agent. Space-time diagram for C2 control mechanism shows there is no specific predefined periods when movement through the intersection is allowed, but that each vehicle has its own dedicated time for crossing through the intersection. The figure shows two emerging phenomena:

1. When a platoon is randomly formed in such a way that it cannot pass through the north-south traffic, agents adapt by dispersion to fit within gaps in north-south traffic (red circle),
2. When a relatively dispersed traffic meets large gaps in north-south traffic, agents adapt by forming a dense platoon to pass through large gaps more efficiently (blue circle).

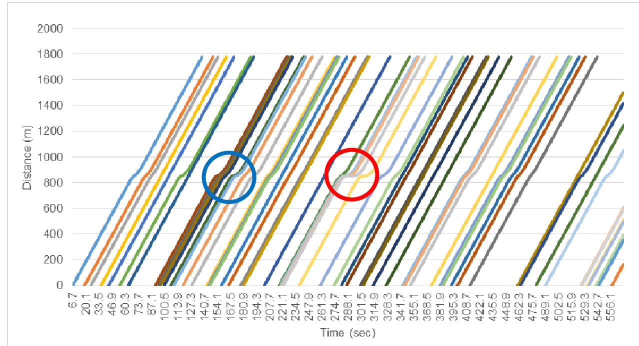

Fig. 4: Vehicle agents' trajectories

We have to note two other things. Testing have shown that if CSZ is lengthier and starts further away from the intersection, delay has lower overall values. The reason might be that vehicles have longer time to organize and determine their best time to cross through the intersection. On the contrary, increasing the safety buffer around the vehicle consequently increases delay, since vehicle agent requires longer space-time continuum through the intersection, thus reducing the effective time available for other agents.

V. Summary and Conclusions

This paper has started with the idea that self-driving vehicle technology, currently under foundational development, should include an aspect of social sustainability. The aspect of social sustainability has been introduces through a framework of social justice, inspired by John Rawls' Theory of Justice as Fairness. Based on this theory, we develop a priority system, intended to protect the inviolability of each user. Priority System also introduces a paradigm shift by introducing end-user responsibility in the control process. In addition, by relying upon cooperative control of self-driving vehicles with increased potential for automation and self-organization in traffic, we propose a decentralized control approach for trajectory adjustment.

Representation of the framework relied upon agent-based modeling approach, where vehicle agents calculate their approach trajectory to the intersection. Vehicle agent performs its actions in a cooperative framework, interacting with other vehicle agents under realistic constraints, and solving control task for trajectory adjustment. The agent-based model has been programmed using C++, and integrated into VISSIM simulation environment.

Table 2: Average and maximum delay per testing scenario

Scenario	Traffic volume (veh/h/ln)				Uniform PL (sec/veh)		Random PL (sec/veh)		Actuated Signal (sec/veh)	
	E+W Through	E+W Left	N+S Through	N+S Left	Average	Max	Average	Max	Average	Max
1	120	30	120	30	0.60	11.30	0.62	10.60	6.49	30.48
2	240	60	240	60	1.55	16.50	1.65	20.20	8.21	44.79
3	360	90	360	90	3.72	28.40	3.49	32.50	21.02	83.19
4	480	120	480	120	10.65	53.40	10.36	59.60	29.03	103.52
5	560	140	560	140	54.69	137.10	59.07	141.30	40.27	168.14
6	120	30	60	15	0.35	7.50	0.39	8.40	5.36	24.60
7	240	60	120	30	0.93	13.70	1.07	14.90	6.44	27.86
8	360	90	180	45	1.78	18.70	2.01	20.50	12.35	59.57
9	480	120	240	60	3.48	35.30	3.49	32.70	15.01	62.90
10	600	150	300	75	6.54	34.60	7.14	55.40	25.28	93.61
11	720	180	360	90	30.15	105.80	29.32	114.10	33.88	137.21
12	768	192	384	96	88.65	221.70	99.66	219.30	41.05	194.75

Table 3: Average and maximum delay for all vehicles, vehicles with PL 5, and vehicles with PL 10

Scenario	North/South (veh/h/ln)	East/West (veh/h/ln)	Total (sec/veh)		Average (sec/veh)		Max (sec/veh)	
	PL 5	PL 10	Average	Max	PL 5	PL 10	PL 5	PL 10
13	135	15	0.12	4.80	0.13	0.02	4.80	2.10
14	270	30	0.30	6.80	0.32	0.06	6.80	2.10
15	405	45	0.54	11.00	0.57	0.07	11.00	4.00
16	540	60	0.82	11.80	0.87	0.14	11.80	5.90
17	675	75	1.22	14.40	1.30	0.22	14.40	7.50
18	810	90	1.97	18.90	2.08	0.75	18.90	11.80
	North/South	East/West	Total		Average		Max	
	PL 5	PL 10	Average	Max	PL 5	PL 10	PL 5	PL 10
19	15	135	0.14	5.00	0.37	0.12	5.00	4.40
20	30	270	0.30	11.80	1.30	0.24	11.80	7.10
21	45	405	0.53	11.60	2.44	0.42	11.60	9.60
22	60	540	0.85	12.10	3.47	0.65	12.10	8.90
23	75	675	1.25	15.00	4.61	0.96	15.00	11.00
24	90	810	1.87	23.20	6.12	1.48	23.20	18.60

Test scenarios involved random arrival of vehicles at an isolated four-way intersection. We have validated the developed control mechanism from the safety perspective. In addition, the proposed framework has showed improved benefits in different measurements of social impact. In addition, experimental results showed the potential of agents to adapt and form high performance streams on the link level, even without explicit coordination mechanism. Conclusively, this framework provides a flexible structure for incorporating social sustainability into the development of self-driving vehicle technology.

A. *Points for Further Investigation*

The research presented here identifies several topics for further research. First, there is a need for comparison with other control approaches for self-driving vehicles, under a common testing procedure and platform. Previously, there have been limited number of research efforts that tried to compare control mechanisms, and they have shown that control principles can be heavily influenced by traffic volume (e.g., FIFO principle has been proven not to work well for high volume situations [28]). This would potentially result in varying different control approaches for different traffic situations or network routes. Second is the need for mechanism for platoon coordination on the arterials, for adjusting the vehicle speeds ahead of the intersection through multi-hop communication, without waiting for each vehicle to be in the communication range of the intersection. The mechanism could operate based on PL, where vehicles with the same PL create platoons on the network links. In addition, the framework can be potentially expanded using knowledge on human decision-making in relation to social justice. Furthermore, there is a potential for investigating optimal trajectory parameters and constraints, which can minimize fuel consumption and emissions. Finally, the ultimate intention of this research is initiating a broader discussion on the objectives and parameters for developing a sustainable future transportation systems, with a self-driving vehicle as its central column.

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