A Fully-Distributed Heuristic Algorithm for Control of Autonomous Vehicle Movements at Isolated Intersections

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ABSTRACT

Optimizing autonomous vehicle movements through roadway intersections is a challenging problem. It has been demonstrated in the literature that traditional traffic control, such as traffic signal and stop sign control are not optimal especially for heavy traffic demand levels. Alternatively, centralized autonomous vehicle control strategies are costly and not scalable given that the ability of a central controller to track and schedule the movement of hundreds of vehicles in real-time is questionable. Consequently, in this paper a fully distributed algorithm is proposed where vehicles in the vicinity of an intersection continuously cooperate with each other to develop a schedule that allows them to safely proceed through the intersection while incurring minimum delay. Unlike other distributed approaches described in the literature, the wireless communication constraints are considered in the design of the control algorithm. Specifically, the proposed algorithm requires vehicles heading to an intersection to communicate only with neighboring vehicles, while the lead vehicles on each approach lane share information to develop a complete intersection utilization schedule. The scheduling rotates between vehicles to identify higher traffic volumes and favor vehicles coming from heavier lanes to minimize the overall intersection delay. The simulated experiments show significant reductions in the average delay using the proposed approach compared to other methods reported in the literature and reduction in the maximum delay experienced by a vehicle especially in cases of heavy traffic demand levels.

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1. INTRODUCTION

Intelligent transportation systems (ITSs) play an essential role towards the optimization of mobility and safety of transportation systems. Two major challenges are facing transportation engineers and ITS researchers.

1. How to manage traffic to avoid or at least to lessen congestion and minimize the wasted delay incurred by commuters? Congestion is currently a real headache in several metropolitan areas around the world. According to Texas Transportation Institute's (TTI's) 2012 urban mobility report [1], the congestion in the US roads accounts for an estimated cost of $121 billion in 2011, with a total travel delay of 5.5 billion wasted hours in congested roads, wasting 2.9 billion gallons of gas, and emitting 56 billion pounds of carbon dioxide with its environmental effect. Although the accuracy of the values and figures just mentioned have been severely criticized [2], there is no doubt that the congestion problem needs more consideration and more innovative solutions to decrease the current losses in time, fuel, and environmental effects.
2. How to avoid or minimize vehicle crashes and make transportation less life threatening? According to the World Health Organization, 1.24 million deaths are caused by vehicle crashes every year. The International Organization for Road Accident Prevention estimates that 90% of accidents are due to human drivers' mistakes. In the US, it is believed that more than half of the car accidents are caused by inadequate driver decisions.

The two challenges can worsen in the near future due to the gap between the growth of vehicle population and the expansion of infrastructure and addition of new roads or lanes. The number of operating vehicles in the world exceeded one billion vehicles in 2010, close to one quarter of those are running in US roads [3]. Researchers and authorities should keep in mind that due to continued population growth, continued economic growth, and continuing urbanization, it is expected that the global vehicle population will increase in the middle of the century to be somewhere between 2.5 billion and 4 billion vehicles [4]. Currently the question being asked and researched is how to enhance transportation system operations and how to ensure that transportation systems continue to function given the fact that the current transportation infrastructure might not be expandable, or might be very expensive to expand in many areas world-wide?

Traffic at intersections contributes significantly to both the congestion and safety problems. The work proposed in this paper focuses on the management of traffic at intersections. Assuming a system of autonomous vehicles, the proposed algorithm models the traffic as a multi-agent system using a fully-distributed protocol where vehicles coordinate to pass through the intersection without collision and with minimum delay at the intersection. This is not only a challenge for autonomous vehicles, even our current transportation system has to deal with such issues. Studies show that about 40% of car accidents in the United States are related to intersections and about half of these accidents are caused by inadequate driver decisions.

The decision to focus on algorithms based on autonomous vehicles is reasonable. Autonomous self-driving vehicles are becoming more real than fiction. These autonomous cars have been demonstrated by Google and other academic institutions such as the Technical University of Braunschweig, and more recently the University of Oxford. It is believed that the current generation of hardware can be used to produce such autonomous vehicles [5]. The rapid progress in research of how to build and operate such intelligent vehicles resulted in getting licensed in the state of Nevada.

However, the researchers in this field are facing challenging issues and problems that need to be solved before such vehicles can find their way to mass production. Among the main challenges are: how to reduce the high cost of sensing devices used by these vehicles, how to guarantee safety in any possible road, weather, or traffic conditions? Besides that, several researchers are working on assessment of how current transportation will be enhanced or optimized when vehicles become smart and autonomous. Studies are evaluating various aspects including minimizing fuel consumption, minimizing delays, avoiding congestions, etc.

The choice of proposing a fully-distributed protocol is also reasonable. In a few years, vehicle-to-vehicle (V2V) communication will be mandated by the US Department of Transportation, as it is viewed to represent the next generation of vehicle safety improvements [6]. It is considered to be the next step after safety belts and air bags. Vehicles will be talking with each other and exchanging trajectory data. It is expected that this will significantly reduce the accidents and crashes especially those caused by human errors, besides alleviating traffic congestion. A protocol requiring vehicles at an intersection to continuously exchange coordination messages, like the one proposed in this paper, will soon be easy to implement in real vehicles on the roads

2. RELATED WORK

Various approaches have been used by several researchers to handle the problem of optimizing the movement of vehicles at intersections. For example, several researchers studied how to minimize the delay at intersections while keeping the current traffic light control system and human-driven vehicles. These research efforts attempted to make the traffic signals smart enough to change their timings to adapt to traffic conditions. An example of a successful algorithm is MARLIN [7, 8]. This algorithm used reinforcement learning to teach a network of traffic signals how to adapt to traffic patterns in real-time. This method was able to reduce delay in a network of sixty intersections in downtown Toronto by 40% at peak hours. However, it relied on a central agent connected to all traffic signals to control their timings; this makes scalability of the system questionable when dealing with larger networks. In addition, maintaining traffic signals and making them smarter is an expensive option. For example, in the case of the MARLIN system, it is estimated that additional equipment need to be added to each intersection that cost between twenty and forty thousand dollars [8].

Similar to the approach presented in this paper, several researchers studied the traffic management at intersections for autonomous vehicles. Traffic signals are not used and vehicles depend solely on communication to coordinate their passing through the intersection without collision. There are two approaches here, depending on a central controlling agent or using a distributed decentralized approach, where vehicles are the only agents without any agents representing the infrastructure in the control system.

One of the key research efforts is the work of Dresner and Stone [9, 10] where a centralized multi-agent reservation-based intersection control protocol was presented. The protocol simply depended on a central management agent that used a First-In-First-Out (FIFO) method to reserve time slots for vehicle agents requesting to pass through the intersection. The importance of the work of Dresner and Stone is that it provided a simple feasible approach and showed how it significantly reduced the delay experienced by traditional traffic signals. Other researchers built on their work, for example Zhu *et al*. [11] also used a centralized reservation-based protocol LICP, but instead of using the FIFO method, they proposed a look-ahead control policy so when a vehicle requests to reserve a time slot, the controller agent predicts the total delay if the request is allocated, and the total delay if it is postponed, and based on these two predicted values the controller makes its decision. The use of LICP can achieve up to 25% performance improvement over the FIFO scheme. However, the reliance on a central agent for traffic control can be a bottleneck when number of vehicles increase in the vicinity of an intersection.

Au *et al*. [5] built on the work of Dresner and Stone in a different way. Instead of limiting the system to autonomous vehicles, they proposed a centralized reservation-based protocol that accommodates human-driven and semi-autonomous vehicles beside the fully-autonomous vehicles. This is the only protocol in literature that enabled smooth interaction between all types of vehicles.

The proposed algorithm in this paper builds on the work of Zohdy *et al*. [12–16] who used centralized multi-agent modeling and proposed and tested a number of techniques to manage the passage of autonomous vehicles through the intersection. In [12], a simulator (OSDI) was built in the central controlling agent that used a heuristic optimization algorithm that continuously adjusted the vehicles trajectories to minimize the occupancy time in areas of conflict in the intersection. The algorithm significantly reduced the delay for a simplified scenario of four-vehicles passing through the intersection zone. In [13–15], a game theory framework and an optimization framework was used to develop a heuristic algorithm for autonomous vehicles equipped with cooperative adaptive cruise control CACC, achieving significant reduction in vehicle delay compared to traditional intersection control schemes such as the use of traffic lights or the use stop signs. This analysis considered mixed flows of autonomous and regular vehicles, lane sharing, and also considered superimposing the logic on the control of roundabouts.

The proposed algorithm in this paper used a fully-distributed approach depending solely on V2V communication. Centralized approaches form a communication and control bottleneck and may not prove scalable for application in real-life situations where tens or hundreds of cars may be in the vicinity of the intersection concurrently and may flood the central controller.

Few research efforts have proposed a distributed algorithm to address this problem, such as the work of Makarem [17] which required each vehicle to communicate with all other vehicles in the intersection. In the proposed algorithm in this paper, the focus is on how communication exchanged in each time step can be minimized. Besides that the heuristic approach is much easier to implement and allows for better optimization of traffic to avoid long queues of waiting cars.

VanMiddlesworth et al. [18] proposed a fully distributed V2V control scheme based on pure peer-to-peer communication to coordinate the passage of autonomous vehicles in small intersections. Their objective was to replace the stop signs in a cost-effective way with no requirement of any infrastructure at the intersection. Unlike the algorithm proposed here, they required every vehicle to communicate with every other vehicle at each time step.

3. PROPOSED ALGORITHM

This section provides a detailed description of the proposed intersection automated vehicle control algorithm.

3.1. Overview

In this paper, a heuristic distributed coordination algorithm is proposed for the management of vehicles traversing an intersection. The algorithm exploits the fact that drivers approaching an uncontrolled intersection typically make rational decisions while proceeding or yielding without having complete information about all oncoming vehicles from all approaches. Considering an intersection of four approaches, each a single lane, the proposed algorithm assumes the four leading vehicles communicate with each other at each time step to schedule their entry time to the intersection. In each time step, one of the four vehicles will be responsible for updating the schedule if needed. If the scheduling agent identifies a conflict that may lead to a collision between two or more vehicles, the arrival times of some of the vehicles are altered by sending messages from the scheduler to update their trajectory to ensure they arrive at the correct time. Priority is always given to vehicles on the more congested lanes when a conflict is identified by the scheduler. Other than the four leading vehicles, a vehicle communicates only with its two neighboring vehicles (the one preceding and the one following it) at each time step.

The goal of the proposed system is to optimize the movement of autonomous vehicles traversing an intersection. The solution proposed in this paper focuses on how to achieve this in a realistic and feasible manner. The proposed algorithm uses a fully-distributed approach: There is no central agent controlling the traffic approaching the intersection; instead each vehicle in the proximity of the intersection is modeled as an agent. All agents cooperate using a heuristic distributed coordination algorithm. A distributed algorithm seems to be more reasonable in real-world applications for a number of reasons, as follows:

a. The use of a central agent to control traffic may lead to excessive stress onthe communication network as the volume of traffic increases in the intersection vicinity. For example an intersection in a downtown area of a big city during the peak period may have hundreds of vehicles heading to the intersection from different approaches at the same time. The ability of a central infrastructure controller to scale well and be able to communicate with all vehicles and schedule their passage in an efficient manner is questionable.
b. A technique requiring installing some device at each intersection to control the traffic is much more expensive compared to a distributed approach. It is reasonable to assume that state and city transportation officials are less enthusiastic to approve or test a traffic control system that requires the installment of hardware at each intersection. Furthermore, both central and distributed approaches will require a vehicle to be equipped with almost the same communication devices whether they need to communicate with infrastructure agent or with other vehicles in close proximity to them.

c. Another important reason to favor distributed systems is related to safety issues and how the system will respond to failures in the central agent unit. Distributing the traffic control among the vehicles themselves allows for a truly fault-tolerant system.

Focusing on the wireless communication limitations due to the complexity of the traffic control at an intersection, most research efforts in this field focused on the modeling of the control problem while ignoring the communication constraints. It was noticed that several approaches implicitly assumed that communication is guaranteed to be successful and that a packet is always transferred in trivial time compared to the processing time of the control strategy. Unfortunately, the current state of wireless communication used for vehicle-to-vehicle communication cannot guarantee or support these assumptions. The scalability and feasibility of an approach that requires dozens of vehicles in an intersection area to exchange their states such as their positions and speeds every fraction of a second is highly questionable. In this paper, the order was reversed, starting from the communication restrictions such as the transmission errors, delays, interference, and consumed power, the focus is to propose a protocol that can function well in such a non-ideal environment. So for this algorithm, trying to minimize communication between vehicles is a first priority, followed by finding a way to control the traffic within the communication limits.

Applying a priority scheme to avoid forming queues at the intersection rather than scheduling the passage of vehicles on a first-come first-serve fashion (FIFO), the proposed algorithm gives priority to vehicles that may form a longer queue if required to slow or stop at the intersection. The goal is to minimize the overall delay incurred by vehicles trying to pass the intersection. The scheduling technique will be discussed in more detail later.

3.2. Modeling Agent States

Every vehicle is modeled as an agent that has a role in coordinating with other agents (vehicles) to order the passage of all vehicles without collisions and with the minimum possible delay. As summarized in Figure 1, a vehicle passes through a number of states until it successfully passes the intersection safely.

1. A vehicle that is far from the intersection zone (more than 200 m away from intersection) is in state "Out". It simply proceeds without any actions related to intersection traffic control.
2. As the vehicle passes the edge of the intersection zone (within 200 m from the intersection), it moves to state "Last".
   a. As soon as it enters this state, a vehicle calculates the time it could reach the intersection if it continued to travel at its current speed if not delayed by other conflicting vehicles.
   b. It sends its properties and the time it calculated in a broadcast message to cars ahead of it in the lane.
   c. The vehicle later receives a reply from the vehicle preceding it so it knows the agent it will be following, each time step the vehicle is updated with any change of the properties of the preceding car so it can follow without colliding.

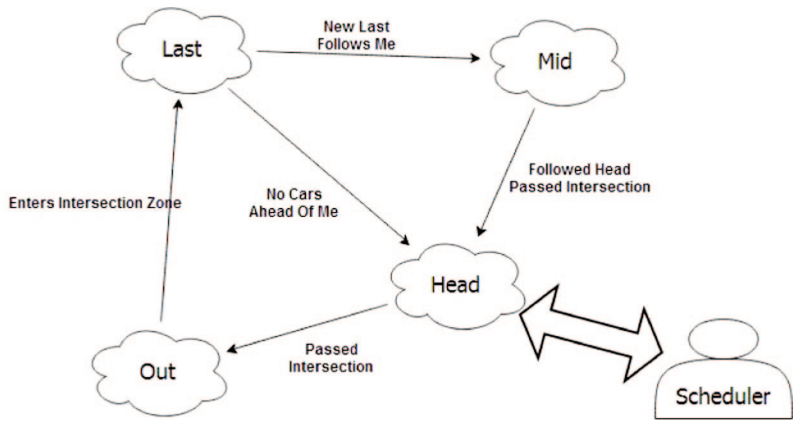

Figure 1. Agent state diagram

3. A vehicle moves from "Last" state to "Mid" state when it receives a message from a vehicle announcing it is the new last in the lane, it receives the properties of the new car following it and replies with its properties so the new last can follow it. Meanwhile, the "Mid" agent still follows the vehicle in front of it. So, at every time step, every vehicle in a lane updates the vehicle immediately following it, so at each time step, each vehicle needs to receive from the one ahead of it and check if it needs to change its properties (for example if it needs to decelerate) and then sends its possibly updated properties to the vehicle following it.
4. A vehicle becomes in "Head" state when it receives from the vehicle preceding it that it passed the intersection.
   a. The new "Head" communicates with other "Head" agents in other approaches.
   b. It listens to any messages from every newly arriving "Last" so it knows all vehicles behind it.

Every time unit, one of the "Head" vehicles from the different approaches of the intersection becomes the "Scheduler" that is responsible to make sure that all vehicles in the intersection zone arrive and pass the intersection at different non-conflicting times. Only the "Heads" communicate with each "head" gives the most updated arrival times of vehicles following it.

3.3. Scheduling Algorithm

The scheduling of vehicles is designed to minimize the overall average delay of vehicles in the intersection area by avoiding forming queues of waiting vehicles. To achieve this in a distributed manner, the following algorithm is executed every time step.

1. For each approach, the "head" vehicle checks based on the current time if it is its turn to be the scheduler for this time step.
2. Each "head" sends the partial schedule it holds for vehicles behind it in the lane. Any vehicle in a lane that alters its speed and time to reach the intersection conflict

area sends a message with its new arrival time to the head, so each head knows the number of vehicles in its lane and holds a sorted list of times when these vehicles will reach the intersection.

3. The current scheduler receives the messages from the other heads, these messages gives a complete picture of the expected times of arrival of all vehicles from all approaches.
4. The scheduler agent performs the following steps:
   a. Merge the sorted lists of various approaches into a global list of arrival times of all vehicles of the intersection
   b. Extract the traffic surges or waves; a traffic surge is a continuous flow of vehicles in the intersection conflict area from different approaches without any gaps of free traffic. The efficiency of scheduling depends on the capability of distinguishing traffic surges and identifying which approach has more vehicles needing to proceed, delaying one vehicle in such an approach results in delaying all vehicles following it in the same lane.
   c. For each traffic lane, the number of vehicles in each approach is determined; approaches with more vehicles are given higher priorities. Starting with highest priority approach, scheduler reserves time slots for vehicles.
   d. When a vehicle from a less priority approach conflicts with a vehicle that already reserved time slots from a higher priority approach, the scheduler reserves the slot for the less priority vehicle at the earliest possible time.
   e. The scheduler sends to each head an array with values representing how much delay is required from each vehicle in each approach. For example, the value zero for a vehicle means the scheduler does not require this vehicle to slow down as it was given priority to pass or no conflict was discovered at the time of its arrival to the intersection. On the other hand, a value of 5 for example associated with a vehicle by the scheduler means that the scheduler figured out that this vehicle need to delay its arrival to the conflict area of the intersection by 5 seconds.
   f. Each head receives the partial schedule sent by the scheduler for its approach, the head identifies if there are any nonzero values associated to any vehicles, if such values exist, the head forwards the delay orders from the scheduler to the vehicles that need to delay. Each of these vehicles receives the order and decelerates to a speed that will allow it to enter the intersection at the time reserved for it.

The next time step, another “head” will be responsible for scheduling. The previous steps are repeated. It may take a vehicle few time steps to receive its final permitted time of entry to the intersection based on the traffic in all lanes.

3.4. Communication Requirements

Compared to the distributed approach in [17] which requires vehicles to communicate their states every time step, the proposed algorithm in this paper reduces the required communication in the following manner:

1. A vehicle entering the intersection zone will broadcast a message once to reach all vehicles in its lane (200 m). In this manner the "head" and the previous "last" vehicles will know a new "last" is in the lane. The old "last" will reply to inform the new "last" of the car ahead of it, the distance between the two vehicles is typically small, and the power used for this reply message can be assumed to be small.
2. Every time step, a vehicle in a lane only receives a message from the car ahead of it, and sends to the car behind it, this way the vehicles in a lane can adjust their speeds to follow each other. This minimizes interference and communication transmission power as a vehicle knows where the neighbor vehicles are located.
3. The exception from the previous point is when a vehicle is "head" of its approach. In this case, it sends a sorted array of arrival times of vehicles in its lane to the scheduler. In case the scheduler wants to delay some vehicles, a reply is broadcast to other "heads" with the vehicle ids and amount of time to slow down. In most time steps, no updates are made to the schedule or minimal changes may be expected, so even this communication is not a significant.

Only when a "head" leaves the intersection, it sends a special message to the vehicle following it to become a new "head".

4. SIMULATED EXPERIMENTS AND RESULTS

The proposed algorithm was implemented in Matlab and the following experiments were performed.

4.1. Experiment Set 1

A two-lane cross-intersection was simulated. Each approach is a single lane heading towards the intersection. It was assumed that all vehicles are autonomous and that a vehicle entering the intersection zone will not accelerate. It either proceeds with its speed until it passes the intersection if no conflict exists from traffic of other approaches, or it slows down and may stop for some time to obey scheduling orders from peer vehicles ahead of it that are responsible of scheduling.

For this experiment, it was assumed that all vehicles enter the intersection zones with speeds varying between 30 and 40 mi/h (approximately 12 to 18 m/s). Intersection traffic was randomly generated allowing for a maximum gap of 10 seconds between two consecutive vehicles in a lane. It was assumed that all lanes have similar traffic so number of simulated vehicles was evenly divided among the four lanes.

The experiment was started by simulating four vehicles (one vehicle per lane), and running two algorithms, the distributed approach discussed in this paper, and the FIFO centralized approach discussed in the related work section. The average delay and the maximum delay of both approaches were obtained for the four-vehicle scenario. The experiment was repeated ten times and the overall average delay and maximum delay for the two compared algorithms were recorded.

The number of vehicles considered in the simulation was increased in steps. Each step involved ten runs of randomly generated traffic of vehicles when the number of vehicles was increased by four (one added vehicle to each lane). The last ten runs included one hundred vehicles.

The results of this experiment are summarized in Figure 2 and Figure 3. Figure 2 shows how the average delay (s/veh) experienced by a vehicle decreased using the distributed prioritized scheme compared to the central FIFO approach. The reduction in the average delay increased gradually until it reached about 40% at the 100-vehicle simulations.

Comparing the maximum delay experienced by a vehicle on the other hand did not show the same significant reduction as can be seen in Figure 3. Larger number of vehicles still shows that the distributed prioritized approach is better than the central FIFO approach.

4.2. Experiment Set 2

In order to assess the effect of heavier traffic on both approaches, the same set of simulated experiments was repeated with heavy traffic. Instead of allowing for a 10 seconds gap between two consecutive cars, the maximum allowed gap was reduced to range between one and five seconds.

The same trend was noticed for the average delays resulting from both approaches as shown in Figure 4. The maximum delays seen in this experiment is much reduced for the proposed distributed approach as can be noticed in Figure 5.

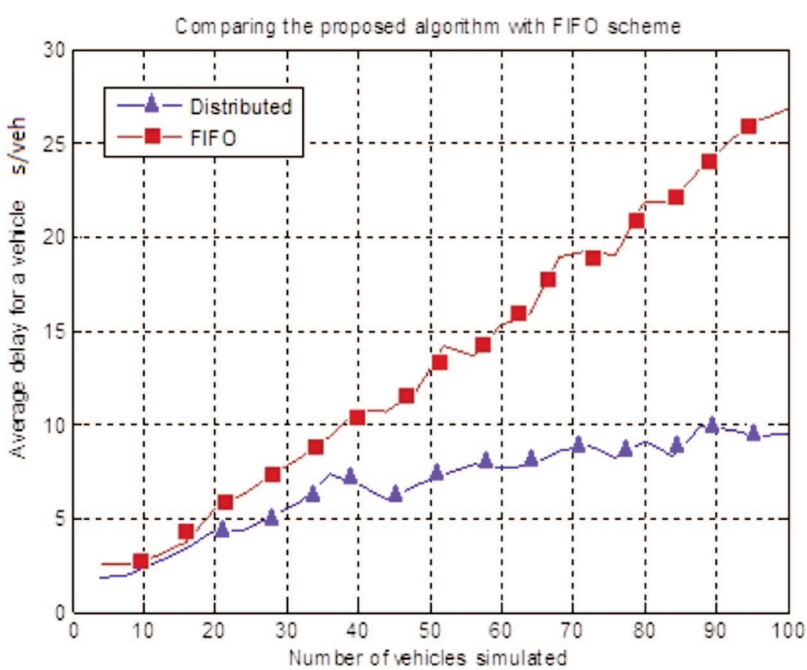

Figure 2. Average delay of proposed algorithm compared to FIFO

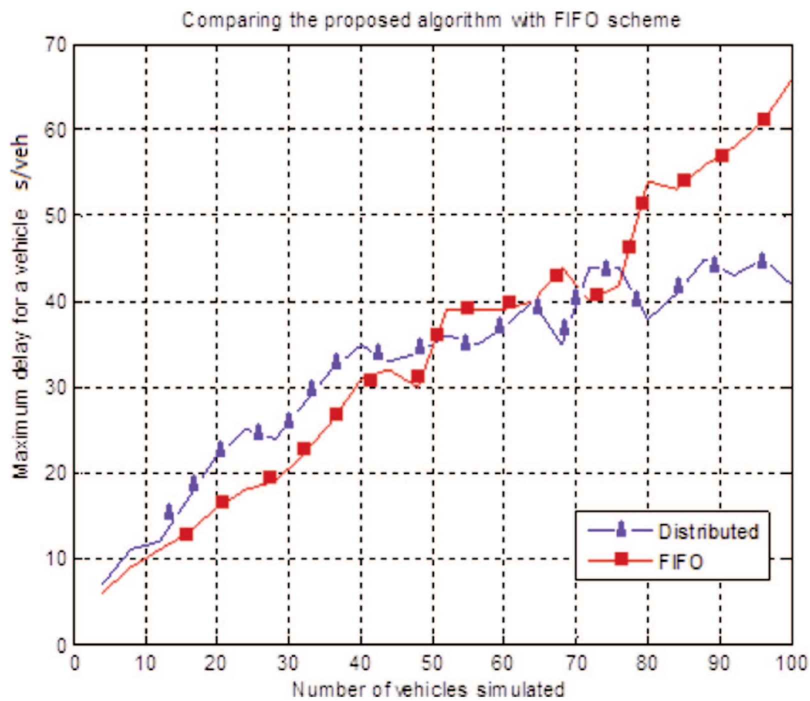

Figure 3. Maximum delay of proposed algorithm compared to FIFO

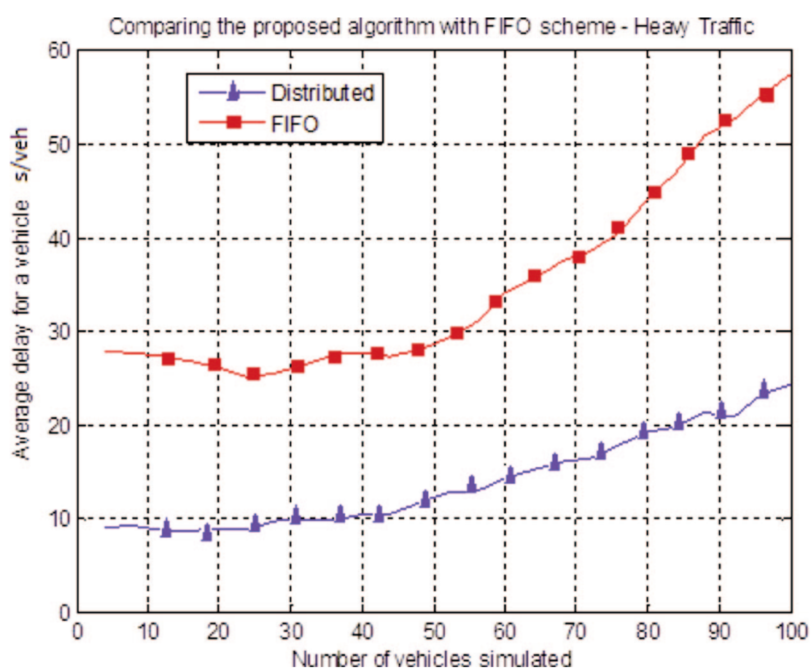

Figure 4. Comparing average delay of two methods with heavy traffic

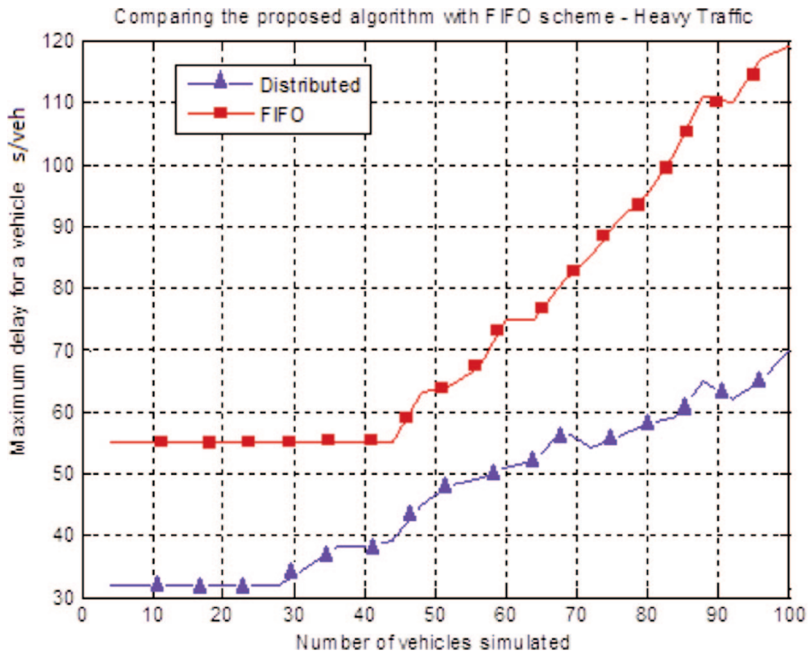

Figure 5. Comparing maximum delay of two methods with heavy traffic

5. CONCLUSIONS AND FUTURE WORK

From the results shown in section 4 and the discussion of the communication protocol in section 3, the following contributions can be summarized:

1. The proposed distributed algorithm was successfully implemented and simulated for various numbers of vehicles in each lane. The rotating scheduling processing was successful without any collisions in any of the experiments.
2. The concept of prioritizing the assignment of time slots to vehicles based on identifying surges and preferring lanes with more crowded vehicles in each surge proved powerful when compared to the centralized FIFO method. The average delay reduction is clearer when more vehicles are simulated and when time spaces between vehicles become tighter.
3. The maximum delay experienced by a vehicle is also significantly reduced with heavier traffic compared to FIFO.
4. The communication requirements for the use of the proposed algorithm in real-life intersections are affordable. The proposed solution does not require installing any infrastructure devices.

Among the future considerations is to study the robustness of the proposed algorithm by modeling the communication limitations such as error rates and transmission delay to see the effect on the scheduling process and if it may result in any collisions, and if this is the case, how to modify the algorithm to guarantee fault-tolerance.

Another future direction is to extend the algorithm to multiple-intersections, so vehicles can better cooperate to avoid congestion

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] D. Schrank, B. Eisele, and T. Lomax, "TTI's 2012 URBAN MOBILITY REPORT," Texas A&M Transportation Institute December 2012.

[2] T. Litman, "Congestion Costing Critique, Critical Evaluation of the "Urban Mobility Report"," 13 June 2014.

[3] J. Sousanis, "World Vehicle Population Tops 1 Billion Units," WardsAuto Aug 15 2011.

[4] "Transport Outlook 2012: Seamless Transport for Greener Growth," International Transport Forum.

[5] T.-C. Au, S. Zhang, and P. Stone, "Semi-autonomous intersection management," presented at the Proceedings of the 2014 international conference on Autonomous agents and multi-agent systems, Paris, France, 2014.

[6] E. Nawaguna. (2/3/2014). *U.S. may mandate 'talking' cars by early 2017*. Available: http://www.reuters.com/article/2014/02/03/us-autos-technology-rules-idUSBREA1218M20140203

[7] S. El-Tantawy and B. Abdulhai, "Multi-Agent Reinforcement Learning for Integrated Network of Adaptive Traffic Signal Controllers (MARLIN-ATSC)," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, 2012, pp. 319–326.

[8] S. El-Tantawy, B. Abdulhai, and H. Abdelgawad, "Multiagent Reinforcement Learning for Integrated Network of Adaptive Traffic Signal Controllers (MARLIN-ATSC): Methodology and Large-Scale Application on Downtown Toronto," *Intelligent Transportation Systems, IEEE Transactions on,* vol. 14, pp. 1140–1150, 2013.

[9] K. Dresner and P. Stone, "A multiagent approach to autonomous intersection management," *J. Artif. Int. Res.,* vol. 31, pp. 591–656, 2008.

[10] K. Dresner and P. Stone, "Traffic intersections of the future," presented at the proceedings of the 21st national conference on Artificial intelligence - Volume 2, Boston, Massachusetts, 2006.

[11] Z. Minjie, L. Xu, H. Hongyu, K. Linghe, L. Minglu, and W. Min-You, "LICP: A look-ahead intersection control policy with intelligent vehicles," in *Mobile Adhoc and Sensor Systems, 2009. MASS '09. IEEE 6th International Conference on*, 2009, pp. 633–638.

[12] I. Zohdy and H. Rakha, "Optimizing Driverless Vehicles At Intersections," in *19th ITS World Congress,* Vienna, Austria, 2012.

[13] I. H. Zohdy, R. K. Kamalanathsharma, and H. Rakha, "Intersection management for autonomous vehicles using iCACC," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, 2012, pp. 1109–1114.

[14] I. H. Zohdy and H. Rakha, "Game theory algorithm for intersection-based cooperative adaptive cruise control (CACC) systems," in *Intelligent Transportation Systems (ITSC), 2012 15th International IEEE Conference on*, 2012, pp. 1097–1102.

[15] I. H. Zohdy and H. A. Rakha, "Intersection Management via Vehicle Connectivity: The Intersection Cooperative Adaptive Cruise Control System Concept," *Journal of Intelligent Transportation Systems,* pp. null-null, 2014.

[16] H. A. Rakha, I. H. Zohdy, and R. K. Kamalanathsharm, "Agent-Based Game Theory Modeling for Driverless Vehicles at Intersections," Mid-Atlantic University Transportation Center VT-2010–02, February 19 2013.

[17] L. Makarem and D. Gillet, "Fluent coordination of autonomous vehicles at intersections," in *Systems, Man, and Cybernetics (SMC), 2012 IEEE International Conference on*, 2012, pp. 2557–2562.

[18] M. VanMiddlesworth, K. Dresner, and P. Stone, "Replacing the stop sign: Unmanaged intersection control for autonomousvehicles," in *AAMAS Workshop on Agents in Traffic and Transportation*, pp. 94-101, Estoril, Portugal, May 2008.