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Abstract

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Cooperative, Connected and Autonomous Mobility: Coordination at Intersections using Reservation-based Mechanisms

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***Abstract*— Road transportation is fundamental for the movement of individuals and goods, also contributing to economic development. A significant contributor to urban road congestion is poor intersection control using conventional traffic signals. In this work, we present a decentralized multi-agent system mechanism for road intersection management for connected autonomous vehicles, including the coordination of platoon formations. We propose a reservation-based mechanism able to maximize the overall vehicle throughput at intersections. The study introduces $i)$ auctions as an alternative to the First-Come-First-Serve policy for assigning reservations to vehicles and $ii)$ a method for resolving disputes between conflicting reservations. The results demonstrate the benefits of using platooning for improving throughput and the average delay in intersection control. The distributed nature of the approach increases scalability by shifting the majority of the computing burden from the intersection manager to the driving agents.**

I. Introduction

Transportation is fundamental for the movement of individuals and goods, also contributing to economic development. Road transportation is one of the major transportation modes in most parts of the world. During the last decades, an increase in vehicle usage has been also observed. This growth leads to higher road congestion, fuel consumption, and travel times. A significant contributor to urban road congestion is poor intersection management using conventional traffic signals. Despite recent developments, typical traffic disruption events, such as accidents [1] or uncontrolled traffic wave propagation, are not taken into consideration.

At the same time, advancements in vehicular networks allow for explicit collaboration via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Cooperation emerges in this setting through event-driven or periodic static and dynamic data interchange. Only lately has the concept of Connected Automated Vehicles (CAV) gained traction. Platooning is a prime example of CAV cooperative driving, in which a group of vehicles follows a leading vehicle regulating longitudinal and lateral positions using local sensor information and V2V data. Platooning is a viable method for decreasing traffic congestion and boosting safety [2]. In [3] current issues and challenges in platoon scheduling and planning are discussed, namely the assumption that V2X communications occur without e.g. delay or bandwidth constraints, thus ignoring real-world issues.

Works in the Multi-Agent Systems (MASs) community try to tackle issues in the coordination of traffic flow in the CAVs context. For instance, Dresner and Stone [4] designed a multi-agent system assisted by V2I communications to efficiently guide vehicles through an intersection with the improved network. A main research area for intersection management is the designs of resource scheduling mechanisms using different forms. Regarding negotiation mechanisms, market-based strategies have been studied in traffic research but only to some extent [5]. Not only that, but some other scenarios such as intersection management have not yet been explored to their fullest potential. The state-of-the-art vastly explored market-based negotiation strategies (e.g. auctions) for intersection management. However, most research works focused on managing independent vehicles or platoons in an intersection, overlooking co-existence scenarios.

We argue that MAS-based reservation mechanisms can achieve consensus in collective decision-making in an intersection management context, while considering both individual vehicles and platoon formations, under realistic settings and constraints. We present a decentralized trajectory reservation intersection management mechanism based on auctions, that reduces the reliance on the intersection manager (IM) to compute the vehicles' paths. Another key enabler is vehicular networks for data exchange between vehicles and the IM, i.e. vehicles send to the IM both operational data (e.g. trajectory) and requests messages to reserve time-space slots of the intersection. Due to the competitive nature of accessing intersections, the reservations are accompanied by a bid determined using a first-price, sealed-bid approach. We assess the proposed method using a hybrid simulation platform, comparing also our solution to traditional traffic lights intersection management and a First Come First Serve (FCFS) approach. The main contributions of this paper are:

i) We discuss the viability of auction-based reservation mechanism for intersection management considering both individual vehicles and platoon formations,
ii) We evaluate the proposed use case resorting to a multi-resolution and multi-domain simulation framework

The remainder of this paper is organized as follows. Section II presents the relevant related work. Section III describes the methodological approach for intersection management. In Section IV, we present and discuss the main results. Section V presents the conclusions and future work.

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II. Related Work

Eliminating the high impact of intersection bottlenecks in the traffic flow has always been one of the major research concerns. Current mechanisms (e.g. stop signs or traffic lights) were designed with human drivers in mind. Research is now shifting towards autonomous driving agents to achieve higher levels of efficiency, which forces rethinking some of the system's coordinating elements [6], [7]. CAV technologies can be further improved with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity (e.g. [8]). For instance, Dresner&Stone [4] developed a multi-agent approach to guide vehicles through an intersection in a more efficient way. Their approach uses an intersection manager that receives requests from incoming vehicles attempting to reserve space-time blocks.

Worrawichaipat et al. [9] presented a decentralized agent-based mechanism for road intersection management of CAVs. Their work focuses mainly on solving delays caused by road obstructions, at the entrance or in the middle of an intersection through a decentralized approach. An intersection Cooperative Adaptive Cruise Control (iCACC) was proposed by Zohdy and Rakha [10], allowing multiple vehicles to go through the intersection. Simulation results show that delays may be cut by 90% when compared to stop sign control. In [11] a multiagent approach is considered for implementing a traffic light control system.

Market-based approaches. Cabri et al. [12] analyzed the benefits of using auctions to regulate intersections, including competitive and collaborative strategies in an environment of both autonomous and human-driven vehicles. Furthermore, an enhancement mechanism considers in the auction process the number of vehicles in lanes to reduce longer queues. Carlino et al. [13] proposed a decentralized auction-based autonomous intersection management. Vehicles automatically bid credit through a "wallet agent" for crossing intersections sooner or later, depending on their value of time. The study mitigates two problems: i) a steady stream of wealthy vehicles competing against others without enough funds and ii) evenly distributed auction winners causing a stop sign-like behavior. Vasirani and Ossowski [14] proposed a distributed, market-inspired approach for intersection management in urban road traffic networks based on the reservation-based model proposed in [4]. Following a similar approach, a vehicle reserves space-time slots before crossing. In [15] is presented a queue-based and lane-based model to determine users' expected waiting time during traffic intersection auctions that take into account the probability of future arrivals at intersections. Contrary to [4], reservations are not assigned using an FCFS policy, but - instead - bids are placed by vehicles, and the winner is chosen based on bid values. [16] discusses the concept of green time negotiation.

Game-theory and econometrics. A different perspective for assigning priority to intersections has been proposed by Lin and Jabari in a series of studies. In [17] they consider direct transaction-based systems that have the benefit of immediately compensating vehicles for giving up precedence. In [18], [19] a technique based on the concept of transferable utility has been given. Vehicles with diverse values of time participate in games, where they trade intersection priority for direct monetary reward. However, the fact that the framework doesn't provide direct communication might be a concern. Wei et al. use game theory in [20] to determine the course of action with the fewest conflicts. In [21] authors propose a game-theory framework based on a karma mechanism that fosters coordination for resource allocation in competitive settings.

Platooning. The advantages of creating platoons among crossing vehicles were investigated in [22]. In order to reduce communication complexity, the study recommended deploying platoon commanders to communicate on behalf of followers. [23] introduced a reservation policy that minimized delay or optimized schedules. [24], [25] explores the use of collective decision-making mechanisms in platoon coordination.

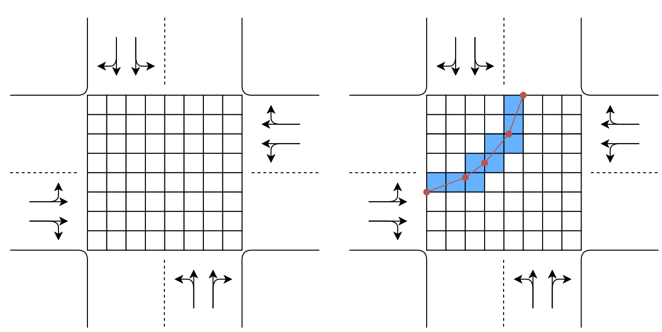
III. Intersection Management Mechanism

We present a decentralized trajectory reservation (auction-based) intersection management mechanism, that reduces the reliance on the intersection manager (IM) to compute the vehicles' paths. The basis of this approach is to have vehicles communicate with an intersection manager and make reservations of the time-space slots to cross the intersection. We designed an intersection coordination strategy that relies on a reservation-based mechanism. This strategy is inspired by the First-Come-First-Serve (FCFS) approach by Dresner and Stone's [4]. Due to the competitive nature of accessing intersections, the reservations are accompanied by a bid, i.e. the value that the vehicle must pay to cross the intersection, describing the urgency to transverse the intersection.

A. Traffic Model

The two main traffic model entities (i.e. *intersection* and *vehicles*) are described in more detail in the following.

Intersection. The intersection is represented as an occupancy grid (Fig. 1a), where vehicles reserve a sequence of time-space slots (cells) to cross it. Each reservation tile of the



a) Intersection model b) Bresenham's algorithm

Fig. 1: Intersection modeled as a matrix of reservation tiles

matrix then holds a list of all current reservations. A reservation is characterized by the following parameters:

- *begin-time:* time-step at which a vehicle/platoon enters a reservation-tile
- *end-time:* time-step at which a vehicle/platoon leaves a reservation-tile
- *bid:* value of the vehicle/platoon's bid for its reservation
- *vehicle id:* identifier of the vehicle or platoon leader

Vehicles. We consider three different types of agents, namely (i) *independent vehicles*, (ii) *platoon leaders*, and (iii) *platoon followers*. A vehicle's behavior depends on its type. Independent vehicles only communicate with the IM. Platoon leaders have the responsibility of sharing the best interest of the platoon to the IM, as such, platoon leaders communicate with both their followers and the IM. Platoon followers only communicate their interests to their respective leaders. We consider that all vehicles have the same computational capabilities.

B. Bidding Protocol

Bids are related to the urgency of a vehicle to cross an intersection. High bid values mean that crossing the intersection as fast as possible is very important for a vehicle, while low bid values mean that a vehicle can wait longer at an intersection. These bids, once a vehicle starts crossing an intersection, are paid to the IM. In this work, we consider a first-price, sealed-bid approach.

We consider a Belief-Desire-Intentions (BDI) architecture to represent a human-like decision-making process for estimating the bidding value of a reservation request. A BDI agent is defined by the following functions:

- *Beliefs:* represent the agent's estimations about the system's state. In this case, the Maximum Time of Arrival (MTA) and Estimated Time of Arrival (ETA) is the agent's estimation about its approaching an intersection. These estimations are used in its bidding decisions.
- *Desires:* represent the short-horizon goal(s) of the agent, i.e. crossing an intersection
- *Intentions:* represent the course of actions that are necessary for the agent to reach its goals, i.e. the computations of the bidding values that allow the agent to cross an intersection.

Bid Estimation. Four parameters must be known for the planning strategy of a vehicle, namely 1) Maximum Time of Arrival (MTA); 2) Estimated Time of Arrival (ETA); 3) Number of intersections still to transverse (nI); 4) Wallet credits for bidding (W). The MTA and ETA metrics are estimated assuming constant velocity. Only vehicles with some sort of credit are eligible to bid. We consider a *non-uniform* credit distribution between vehicles that follows a normal distribution with a given mean (e.g., 250 credits) and standard deviation (e.g., 100 credits).

These four parameters are used in the bid calculation process in two different ways. The first approach focuses on the difference between the ETA and MTA values. The smaller the difference, the greater the urgency of a vehicle, i.e. bids increase exponentially as the ETA gets closer to the MTA.

$$Bid = \frac{W}{nI} * \frac{1}{MTA - ETA} \tag{1}$$

A second approach is obtained by making the quotient between the ETA and MTA values, effectively resulting in the percentage of available credits used for bidding. Since the ETA is always smaller or equal to the MTA, their quotient is always less than 1, i.e. less than 100% of the available bidding credits. The bid increases linearly as the ETA and MTA values become similar.

$$Bid = \frac{W}{nI} * \frac{ETA}{MTA} \tag{2}$$

In a platooning context, each vehicle still calculates its own bid using the previous process. A platoon bid is represented as the average of its vehicle's individual bids. For instance, a platoon vehicle in a hurry increases the platoon's bid as its individual bid is higher.

Bid Payments. For the bid payment approach, we resort to the first-price rule [26]. If a vehicle wins a reservation with a bid of x credits, it pays the IM x credits. However, that is not the case for platooning vehicles. Since every vehicle of the platoon benefits from successfully crossing an intersection, every vehicle must pay fairly. This prevents vehicles from overbidding credits that they do not possess. That could be the case if, for example, only the platoon leader paid the bid to the IM. Two different bid payments were studied for platoon bids:

- *Non-Weighted:* every vehicle pays the same share of the final bid ($finalBid/platoonSize$).
- *Weighted:* The share of each vehicle depends on how much the vehicle contributed to the final bid. Vehicles that contribute more to the final bid also pay more. The payout of each vehicle is calculated as follows:

$$share_n = \frac{bid_n}{\sum_{n=1}^{plat_{size}} bid_n} * bid_{plat} \tag{3}$$

where $share_n$ is share bid paid by the n^{th} platoon vehicle, bid_n is the bid of the n^{th} vehicle, $plat_{size}$ is the size of the platoon, and bid_{plat} is the platoon's final bid. The latter method can be seen as a more fair-minded payment method as vehicles that have more available time are not harmed.

C. Intersection Reservation Mechanism

Dresner and Stone [4] proposed an intersection management solution wherein the IM has a proactive role, i.e. the IM is responsible for assigning time-space reservations based on the information received from vehicles. Herein, to decrease the IM's computational load, we consider a decentralized approach (e.g. for trajectory computation). Fig. 2 the depicts message flow between vehicles and the intersection manager. This design choice implies that i) the IM shares with vehicles

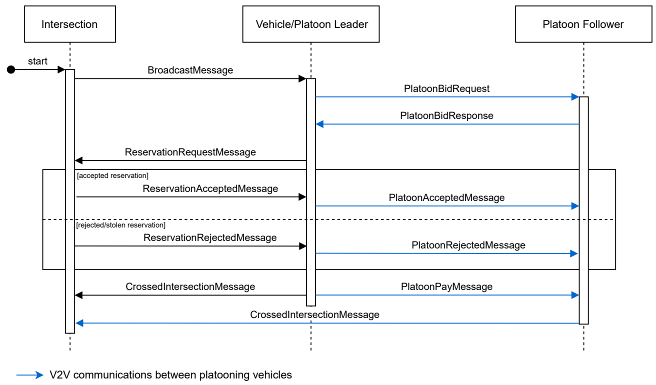


Fig. 2: V2X message flow of the intersection reservation mechanism

(i.e. periodic broadcast) *global* information on the intersection state and ii) the vehicle is responsible for computing all required information (i.e. conflict-free trajectory and bid) to include in the reservation request.

Upon arriving at an intersection, the vehicle (asynchronously) starts the reservation request (*ReservationRequestMessage*). Vehicles require up-to-date information on the intersection state (stored by the IM) for the reservation process, i.e. the IM must broadcast - with a given frequency (e.g. every 100 ms) - the current reservation map as well as the different routes vehicles take (i.e. *BroadcastMessage*). Upon receiving such information, the following four main stages must be completed to successfully perform a reservation request. The vehicle discards subsequent broadcast messages until the IM's reservation reply is received.

- *path prediction*: compute the reservation map tiles intersected by the vehicle when crossing the intersection. Furthermore, calculate the respective timestamps that the vehicle enters and leaves each reservation tile.
- *conflict detection*: evaluate the computed trajectory with the reservation map by comparing whether or exists tiles and their respective timestamps that generate conflicts (i.e. potential vehicle collisions).
- *conflict resolution*: re-calculate the reservation timestamps to delay the vehicle's departure if any conflict has been detected in the previous stage.
- *bid calculation*: calculate the bid value based on the bidding protocol.

After evaluating the vehicle request, the IM transmits a positive (*ReservationAcceptedMessage*) or negative (*ReservationRejectedMessage*) reply. If the reservation was accepted, the vehicle (or platoon leader) stores the message and starts transversing the intersection at the designated start time and informs the IM that the intersection is empty (*CrossedIntersectionMessage*).

The mechanism is slightly adjusted for platoon formations. First, the platoon leader exchanges information (e.g. ETA) with the followers so that their bids are taken into account in the platoon's final bid (*PlatoonBidRequest* and *PlatoonBidResponse* messages) Second, the platoon leader informs its follower whether the reservation was accepted (*PlatoonAcceptedMessage*) or rejected (*PlatoonRejectedMessage*), with the followers taking the appropriate measures. Lastly, the platoon leader request followers to pay its share of the bid according to the previously defined payment method (*PlatoonPayMessage*), with followers withdrawing credits from its wallet W.

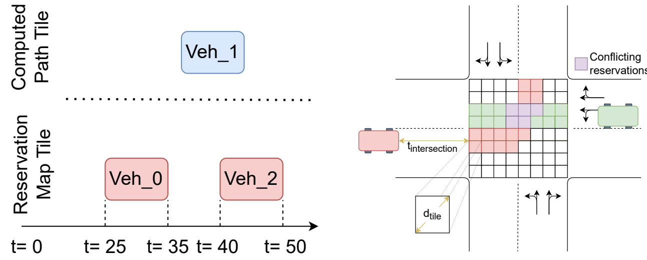


Fig. 3: Reservation tile conflict detection

Path Prediction. To determine which reservation tiles are intersected by a vehicle's predetermined path we use an adaptation of Bresenham's algorithm [27]. Bresenham's algorithm determines the points of an n-dimensional raster that should be selected in order to form a close approximation to a straight line between two points. Fig. 1b depicts the result of applying Bresenham's algorithm.

As soon as the vehicle finishes calculating all of the reservation tiles in its path, a time interval for each tile needs to be determined. Such time interval specifies the time steps at which a vehicle enters and leaves a specific reservation tile. For this computation, a constant velocity is considered (e.g. free-flow). We assume the diagonal of the tile in the grid as traveled distance to estimate the travel time for a vehicle to cross a reservation tile. This approximation slightly decreases performance but also increases safety as each vehicle will end up reserving each tile for a longer period than required. Whenever in the presence of a platoon, this time interval is multiplied by the number of vehicles in the given platoon. The time interval required to cross a reservation tile is calculated using Eq. 4, where d is travel distance, v is velocity, and $plat_{size}$ is platoon size (set to 1 if an independent vehicle).

$$t_{tile} = \frac{d}{v} * plat_{size} \tag{4}$$

A vehicle/platoon needs also to specify the timestep at which it will start crossing the intersection to be able to compute its reservation tiles' time intervals.

Conflict Detection. Once a vehicle finishes calculating its path through the intersection, it will test its validity against the reservation map sent by the IM. This evaluation takes each reservation tile from the computed path and checks if the corresponding reservation tiles in the reservation map already contain reservations during the requesting reservation timestamps. Fig. 3 depicts a conflict scenario in a given reservation tile that may occur during the conflict detection phase. For a vehicle's computed path to be eligible for a reservation request, its reservation tiles must all be available during the specified time intervals in the reservation map. If at least one conflicting reservation-tile occurs, then the path is invalid as this would mean a collision at the intersection.

Conflict Resolution. The proposed conflict resolution strategy consists in delaying the departure of the vehicle until no conflicts occur. The core concept for this approach lies on the following premise: if a conflict occurs with a duration time of t, regardless of the reservation tile, at least a delay of t time needs to be added to the departure time in order for the conflict to disappear. In the presence of multiple conflicts, t is used to represent the conflict with the largest duration.

Bidding. Once a vehicle concludes the first three stages, it will calculate a bid using the bidding protocol (see subsection III-B). Upon a vehicle's initialization, the MTA parameter is stored in its belief base. After the vehicle concludes the path prediction, conflict detection, and conflict resolution stages, it updates the ETA value in its belief base. The update of the ETA parameter triggers the bid calculation plan. After calculating the bid value, a valid reservation request - containing the computed trajectory, reservation timestamps, and bid value - is sent.

D. Intersection Manager Protocol

The IM validates incoming requests and updates the reservation map. In the presence of conflicts, the IM assesses whether to accept or reject these requests. The criterion for the conflict resolution is based on the bid value:

- **No conflicts occur:** the requesting reservation is added to the reservation map.
- **Conflicts occur:**
  A. *request's bid is higher than all conflicting bids*: the reservation is granted to the requesting vehicle/platoon, and all other conflicting vehicles/platoon(s) in the reservation map lose their respective reservations. The IM notifies both the requesting (winning) vehicle and the losing vehicles.
  B. *request's bid is not higher than all conflicting bids*: the request is rejected and no changes are made to the reservation map.

IV. Results

To evaluate how platoons can impact the performance of vehicle coordination at intersections, we consider a single intersection scenario with both individual vehicles and platoon formations. In both cases, besides analyzing the performance of the solution according to several metrics, a comparison is made between the designed approach and two other traffic regulation methods: traffic lights and an FCFS approach.

A. Simulation Framework

To assess the proposed solution, we have developed a hybrid simulation framework (Fig. 4) based on Eclipse MOSAIC [28] and integrating the following components. Eclipse MOSAIC[1] is a multi-scale/multi-domain simulation platform following the High-Level Architecture (HLA) paradigm for co-simulation.

[1]https://www.eclipse.org/mosaic/

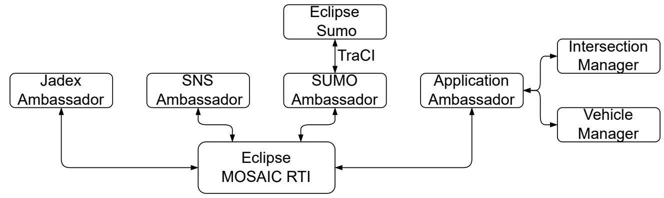
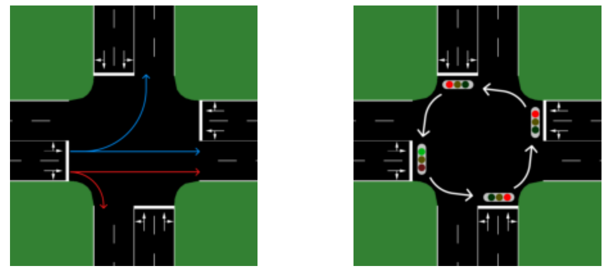


Fig. 4: System architecture



a) Trajectories b) traffic light phases

Fig. 5: Intersection

- **an agent-oriented platform** for emulating the vehicle's decision-making process. We resort to the *Jadex Active Components Framework* [29]) for the definition of the BDI agent behaviors and for the high-level decision-making (i.e. bidding).
- **a microscopic traffic simulator** (*SUMO* [30]) to simulate the vehicular traffic dynamics while satisfying all the requirements of traffic simulation (e.g. kinematics).
- **a network simulator** (*MOSAIC SNS*) to simulate the communication between vehicles and infrastructure (e.g. traffic light controller).

The interactions between the three presented federate components are synchronized by the MOSAIC's run-time infrastructure module.

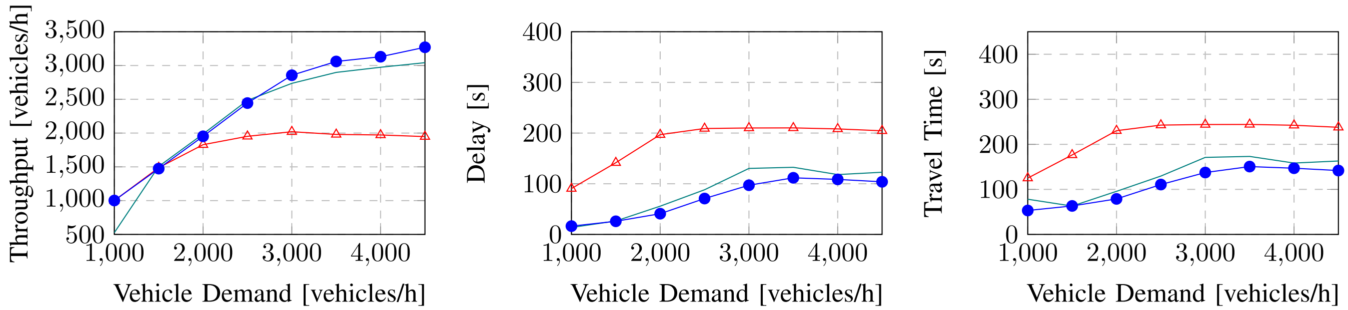
B. Evaluation metrics

In order to thoroughly assess the performance of the designed solution, the following metrics were selected:

- **Throughput** (in $vehicles/h$): measures the rate at which vehicles cross any given intersection.
- **Average Delay** (in s): the average waiting time experienced by the vehicles at an intersection. Only vehicles that crossed a given intersection are taken into account for computing the average delay.
- **Travel Time** (in s): the time taken by a vehicle to complete its route.
- **Bid Value** (in $credits$): the bid value sent by a vehicle to the intersection manager. Only values regarding successful reservations are considered.
- **Reservation Time** (in ms): time taken for a vehicle to successfully schedule a reservation, i.e. the time interval between the moment a vehicle receives IM information and it receives a (successful) reservation confirmation.

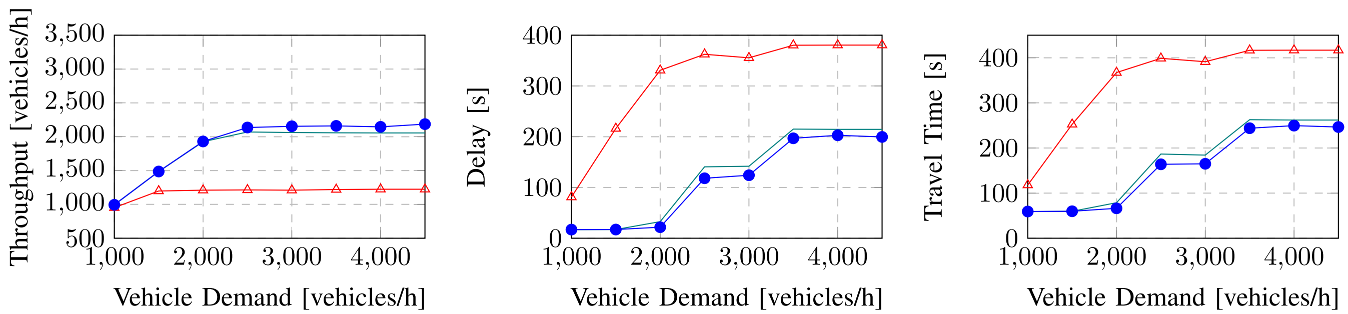
C. Experimental Setting

Scenario. The scenario consists of a four-way intersection (Fig. 5a) with each road/edge being composed by two lanes for each travel direction. Thus, the intersection has eight



a) Throughput b) Delay c) Travel Time

Fig. 6: Platooning Use Case (TL, FCFS, RB)



a) Throughput b) Delay c) Travel Time

Fig. 7: Non-platooning Use Case (TL, FCFS, RB)

incoming and eight outgoing lanes in total. The length of the lanes is 150 m long to allow bigger platoons to be fully inserted into the simulation prior to its leader handling any information from the intersection manager. Vehicles are 4 m long with a maximum speed of 10 m/s. The minimum safety gap between vehicles is 2 m, which corresponds to the distance between stopped vehicles when waiting at the intersection. The vehicle trajectories are also presented in Fig. 5a. Two different trajectories were defined for the two different existing lanes of every incoming edge. The defined behavior is standard to today's road design. The inner lane allows a vehicle to turn left whilst the outer lane allows it to turn right. To continue straight a vehicle can select any lane. This definition allows any incoming vehicle to continue its path through any of the three possible outgoing edges.

Different vehicle demands were generated to emulate low, moderate, and high traffic volume environments, ranging from 1000 $vehicles/h$ to 4500 $vehicles/h$ with increments of 500 $vehicles/h$.

Benchmark. We compare the proposed coordination strategy with a traditional intersection management system. For the reservation-based strategy, an intersection map with a granularity of 5 was used (i.e. reservation map consists of a 5 by 5 matrix). For the traffic light system, since any incoming vehicle is able to choose from one of the three different outgoing edges, in order to avoid conflicts, at most one edge can have a green phase at any given time. This traffic light definition means that access to the intersection is exclusive to the edge that has been given a green light. Fig. 5b depicts the round-robin scheme of how traffic light phases change over time with a default green light phase length of 20 s. Moreover, regardless of the strategy used, all experiments emulate a total of 30 min of simulation time.

We also compare the system performance with and without platooning capabilities in two cases:

- **Non-platooning:** All simulation vehicles act as individual vehicles.
- **Platooning:** 50% of the simulation vehicles act as individual vehicles, whilst the other 50% form platoons.

D. Evaluation & Discussion

Throughput. Fig. 6a and Fig. 7a depict the intersection throughput as a function of vehicle demand in a platooning and non-platooning scenario, respectively. In both scenarios, as expected, the throughput increases for higher vehicle demands until the intersection capacity is reached. This *plateau* is especially evident for the non-platooning use case that is reached in the worst case for 2500 $vehicles/h$. In both cases, our reservation-based method outperforms the conventional traffic lights and the FCFS methods; note that the gain of our method is much larger when compared with the conventional traffic lights benchmark, demonstrating the advantages of autonomous approaches.

For low traffic demands, the performance difference is not very significant between the autonomous approaches and the traditional approach as the traffic light's green phase is long enough to flush all of the waiting vehicles in an intersection edge with time to spare. However, when increasing the traffic demand it is clear that the traffic light strategy cannot effectively handle vehicle demands higher than 2500 $vehicles/h$, i.e. 20 s of green phase are not enough

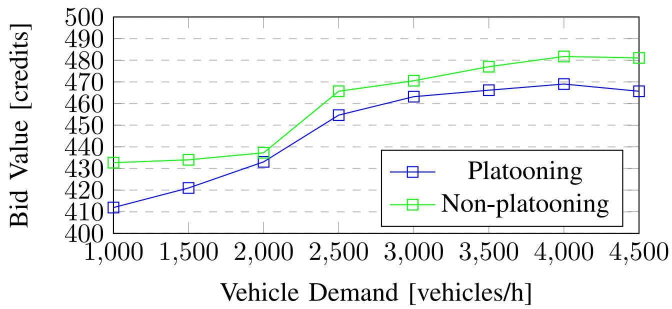


Fig. 8: Average bid value

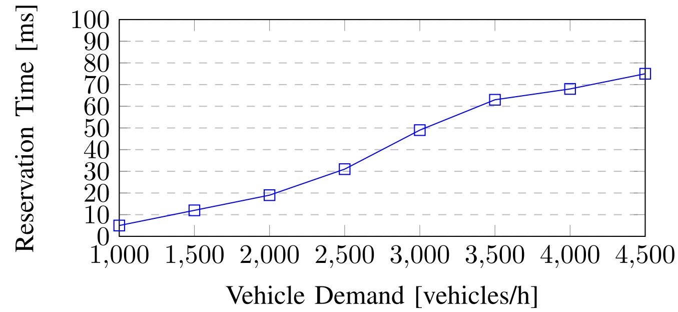


Fig. 9: Time to acquire reservation

to flush all waiting vehicles in a given intersection edge due to vehicle build-up. On the other hand, the designed reservation-based approach shows a better ability to handle higher vehicle demands by allowing vehicles from multiple lanes to cross at the same time, which results in a much smaller queuing of vehicles. A throughput improvement of up to 75.8% when compared to the traffic light management system is obtained. The comparative analysis between the negotiation-based approach and the FCFS approach shows very similar throughput for increasing vehicle demands. The same behavior is present when observing the average delay. The improvements provided by the negotiation-based approach are the result of a lower number of conflicts.

Fig. 7a depicts the intersection throughput in a non-platooning scenario. Even though a similar behavior can be observed, having a distinct performance gap between the autonomous and traditional approaches, the throughput values are significantly lower in all three cases. For a vehicle demand of 4500 $vehicles/h$ the platooning approach improves the vehicle throughput by 59.15%, 49.59%, and 47.96% for the traffic-light, reservation-based, and FCFS approaches, respectively. Analysing Fig 6a and Fig. 7a the same can be inferred for other vehicle demands. Thus, the usage of platoons allows for maximizing vehicle throughput.

Average delay. Our reservation-based approach shows promising results by reducing, at least by half, the average delay experienced by the vehicles when compared with conventional traffic light systems. The analysis of Fig.6b and Fig. 7b shows a direct correlation between the average delay and throughput experienced at an intersection in the reservation-based approach due to the increasing vehicle build-up at the intersection.

Comparing the results of the platooning scenario (Fig. 6b with the non-platooning scenario (Fig. 7b)we observe that the former greatly outperforms the latter also in terms of the delay experienced at the intersection. Platooning scenario reduces average intersection delays since a vehicle only waits as long as the leader (i.e. the first vehicle in an intersection edge) when in a platoon. On the other hand, in a non-platooning scenario, once a vehicle has finished its bidding process and crosses the intersection, its successor must perform the same steps as the vehicle before, and thus wait until its bid is approved so it can safely cross the intersection.

Travel time. The analysis of the average travel times (Fig. 6c and Fig. 7c) shows similar behavior to the experienced delay since the scenario consists of a single intersection, i.e. the vehicle average delay and travel time are directly correlated to each other. Thus, the analysis of the vehicle delay described previously can be applied to the average travel time experienced at an intersection. Once again, the platooning scenario in Fig. 6c shows greater performance regarding the average travel time when compared to the non-platooning scenario depicted in Fig. 7c.

Bid value. Fig. 8 depicts the average bid value received by the IM as a function of the demand for the platooning and non-platooning cases. A slight increase in the average bid is observed for higher vehicle demands as a result of the increasing delay experienced by the vehicles waiting at an intersection. As time goes by the vehicle's urgency to cross the intersection increases resulting in higher bids. Average bids are similar in the platooning and non-platooning cases since the only difference in the bid calculation process between the two approaches is that the platoon's bid is the average of its vehicles' bids. Lastly, we observe that the average delay (Figs. 6b 7b) and the average bid (Fig. 8) show an exponential relation. An exponential correlation was chosen instead of a linear or polynomial correlation since it posed a better approximation to the true delay values.

Reservation time. Fig. 9 depicts the average reservation time real estimation of the vehicle demand. The results show that even at high traffic demands, the average reservation time takes less than 100 ms to perform both the vehicle's and IM's protocols. This metric helps to assess whether the developed solution is feasible in real-time. Results show that even in high volumes of traffic demand, the network is able to deliver reasonable reservation time values. The small reservation times result from the developed lightweight process and due to few requests being rejected, regardless of the traffic demand. Furthermore, since only the first vehicle of a lane is allowed to perform reservations, the messages exchanged are fairly limited. For instance, for the reference scenario at most 8 vehicles can perform reservation requests concurrently.

V. Conclusions

We discuss a decentralized auction reservation-based approach for intersection management in the presence of both individual and platoon vehicles. The obtained results demonstrate superior performance when compared with traditional intersection management systems. The designed solution can significantly increase throughput while maintaining lower average delays, regardless of the vehicle demand. Platooning delivers a considerable performance improvement when compared with individual vehicles, exhibiting higher throughput values with lower experienced delays.

Despite the performance gains, improving the designed bidding protocol, regardless of whether it boosts the mechanism's performance or not, is critical to ensure that a correct, fair, and consistent bidding strategy exists within the implementation. Future research will address fairness aspects to ensure a balanced flow and distribution of reservations throughout the intersection's incoming edges. For additional fairness, the mechanism should also consider the waiting time of vehicles that have been outbid in order to grant them priority over the new coming vehicles. One of the limitations in the existing experimental setup is that the ETA and MTA are computed assuming constant velocities. A more robust setup will take into consideration traffic conditions and congestion. Furthermore, we plan to perform experiments considering a network of intersections and assess the fitness of our approach.

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References

[1] A. E. Retallack and B. Ostendorf, "Relationship between traffic volume and accident frequency at intersections," *International Journal of Environmental Research and Public Health*, vol. 17, no. 4, 2020.

[2] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE communications surveys & tutorials*, vol. 18, no. 1, pp. 263–284, 2016.

[3] J. Hou, G. Chen, J. Huang, Y. Qiao, L. Xiong, F. Wen, A. Knoll, and C. Jiang, "Large-scale vehicle platooning: Advances and challenges in scheduling and planning techniques," *Engineering*, 2023.

[4] K. Dresner and P. Stone, "A multiagent approach to autonomous intersection management." *J. Artif. Intell. Res. (JAIR)*, vol. 31, pp. 591–656, 01 2008.

[5] M. Khayatian, M. Mehrabian, E. Andert, R. Dedinsky, S. Choudhary, Y. Lou, and A. Shirvastava, "A survey on intersection management of connected autonomous vehicles," *ACM Transactions on Cyber-Physical Systems*, vol. 4, no. 4, pp. 1–27, 2020.

[6] M. C. Figueiredo, R. J. F. Rossetti, R. A. M. Braga, and L. P. Reis, "An approach to simulate autonomous vehicles in urban traffic scenarios," in *12th IEEE Conf. Intelligent Transportation Systems*, 2009, pp. 1–6.

[7] R. J. F. Rossetti, P. A. F. Ferreira, R. A. M. Braga, and E. C. Oliveira, "Towards an artificial traffic control system," in *11th IEEE Conf. on Intelligent Transportation Systems*, 2008, pp. 14–19.

[8] S. Zhang, J. Chen, F. Lyu, N. Cheng, W. Shi, and X. Shen, "Vehicular communication networks in the automated driving era," *IEEE Communications Magazine*, vol. 56, no. 9, pp. 26–32, 2018.

[9] P. Worrawichaipat, E. Gerding, I. Kaparias, and S. Ramchurn, "Resilient intersection management with multi-vehicle collision avoidance," *Frontiers in Sustainable Cities*, vol. 3, p. 44, 2021.

[10] 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*, vol. 20, no. 1, pp. 17–32, 2016.

[11] C. Vilarinho, J. P. Tavares, and R. J. F. Rossetti, "Design of a multi-agent system for real-time traffic control," *IEEE Intelligent Systems*, vol. 31, no. 4, pp. 68–80, 2016.

[12] G. Cabri, L. Gherardini, and M. Montangero, "Auction-based crossings management," in *EAI Int. Conf. on Smart Objects and Technologies for Social Good (GoodTechs)*, 2019, p. 183–188.

[13] D. Carlino, S. D. Boyles, and P. Stone, "Auction-based autonomous intersection management," in *IEEE Int. Conf. on Intelligent Transportation Systems (ITSC)*, 2013, pp. 529–534.

[14] M. Vasirani and S. Ossowski, "A market-inspired approach for intersection management in urban road traffic networks," *Journal of artificial intelligence research*, vol. 43, pp. 621–659, 2012.

[15] D. Rey, M. W. Levin, and V. V. Dixit, "Online incentive-compatible mechanisms for traffic intersection auctions," *European Journal of Operational Research*, vol. 293, no. 1, pp. 229–247, 2021.

[16] C. Vilarinho, J. P. Tavares, and R. J. F. Rossetti, "Intelligent traffic lights: Green time period negotiaton," *Transportation Research Procedia*, vol. 22, pp. 325–334, 2017, "19th EURO Working Group on Transportation Meeting, EWGT2016, 5-7 September 2016, Istanbul, Turkey".

[17] D. Lin and S. E. Jabari, "Comparative analysis of economic instruments in intersection operation: A user-based perspective," in *IEEE Int. Conf. on Intelligent Transportation Systems*, 2020, pp. 1–6.

[18] D. C. Lin and S. E. Jabari, "Transferable utility games based intersection control for connected vehicles," in *IEEE Intelligent Transportation Systems Conference (ITSC)*, 2019, pp. 3496–3501.

[19] D. Lin and S. E. Jabari, "Pay for intersection priority: A free market mechanism for connected vehicles," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 6, pp. 5138–5149, 2022.

[20] H. Wei, L. Mashayekhy, and J. Papineau, "Intersection management for connected autonomous vehicles: A game theoretic framework," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2018, pp. 583–588.

[21] A. Censi, S. Bolognani, J. G. Zilly, S. S. Mousavi, and E. Frazzoli, "Today me, tomorrow thee: Efficient resource allocation in competitive settings using karma games," in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*. IEEE, 2019, pp. 686–693.

[22] M. Bashiri and C. H. Fleming, "A platoon-based intersection management system for autonomous vehicles," in *2017 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2017, pp. 667–672.

[23] M. Bashiri, H. Jafarzadeh, and C. H. Fleming, "Paim: Platoon-based autonomous intersection management," in *IEEE Int. Conf. on Intelligent Transportation Systems (ITSC)*. IEEE, 2018, pp. 374–380.

[24] Z. Kokkinogenis, M. Teixeira, P. M. d'Orey, and R. J. F. Rossetti, "Tactical level decision-making for platoons of autonomous vehicles using auction mechanisms," in *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2019, pp. 1632–1638.

[25] M. Teixeira, P. M. d'Orey, and Z. Kokkinogenis, "Autonomous vehicles coordination through voting-based decision-making," in *International conference on agreement technologies*. Springer, 2018, pp. 199–207.

[26] Y. Han, Z. Zhou, A. Flores, E. Ordentlich, and T. Weissman, "Learning to bid optimally and efficiently in adversarial first-price auctions," *CoRR*, vol. abs/2007.04568, 2020.

[27] J. E. Bresenham, "Algorithm for computer control of a digital plotter," *IBM Systems Journal*, vol. 4, no. 1, pp. 25–30, 1965.

[28] K. Schrab, M. Neubauer, R. Protzmann, I. Radusch, S. Manganiaris, P. Lytrivis, and A. J. Amditis, "Modeling an its management solution for mixed highway traffic with eclipse mosaic," *IEEE Transactions on Intelligent Transportation Systems*, 2022.

[29] A. Pokahr and L. Braubach, "The active components approach for distributed systems development," *International Journal of Parallel, Emergent and Distributed Systems*, vol. 28, no. 4, pp. 321–369, 2013.

[30] P. A. Lopez, M. Behrisch, L. Bieker-Walz, and et al., "Microscopic traffic simulation using SUMO," in *IEEE Int. Conf. on Intelligent Transportation Systems (ITSC)*, 2018, pp. 2575–2582.