

A Two-class Priority Preservation Scheme for CAV-only Zones

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Abstract—Recent research has demonstrated the potential benefits of connected, autonomous vehicles (CAVs) to the performance of urban networks. Specifically, several proposals have been made for policies and related technologies that either perform more efficiently when the proportion of CAVs is relatively high or that exclude human driven vehicles (HDVs) altogether. This same body of research has also identified several challenges faced by such networks, especially in the context of shared autonomous vehicles (SAVs). We propose a lane-use policy for networks of exclusively CAVs with the goal of preserving priority within any two-class, arbitrary priority assignment regime. We investigate the merits of such a policy by adopting a simple occupancy-based, two-class priority scheme in a network of SAVs. We will demonstrate that by granting and preserving priority for occupied vehicles, average travel times and speeds for passengers are improved with limited degradation in these measures for other, i.e. unoccupied, vehicles. The proposed lane-use policy is developed on realistic physical limitations of the street network and without the need for trajectory reservations.

I. Introduction

Recent research has demonstrated the potential benefits of connected, autonomous vehicles (CAVs) to the performance of urban networks. Among these is the promise of complex, high-frequency adaptive tolling and congestion pricing mechanisms that assign priority to vehicles in the network ([1], [2], [3], and [4], among others). Central to the effectiveness of such schemes is the ability to honor priority, once granted, either to preserve its value as a tradable asset or to achieve the objective of the priority granting regime.

Two works in particular illustrate the state of the art for such priority schemes. [1] proposes trajectory-reservations for networks of autonomous vehicles with autonomous intersection management (AIM) (AIM was first introduced in [5]). [1] assigns priority by auction, but its methodology also supports any arbitrary priority assignment function. Priority is preserved by rationing capacity in the space-time network and assigning mandatory arrival times at each intersection, i.e. assigning trajectories. The work demonstrates that the proposed scheme reduces travel times for high-bidding users. However, due in part to first-in-first-out (FIFO) behavior in the links, priority is preserved only for trajectories as determined by an initial or periodic auctions, and it may not be possible to incorporate new trips within the network. That is, some capacity would need to be held in reserve for vehicles to get out of the way of a new, high-priority user.

The second work [2] proposes queue sorting within

links. Users trade tokens with the others in the link and move ahead or behind in the queue accordingly. In theory, this method also could be adapted for arbitrary priority functions. Practically, however, it is unrealistic as it presumes that vehicles are always capable of passing each other even within a single lane. Furthermore, this scheme only addresses priority within links; it is unclear how it could be extended to incorporate new trips as they arise.

What is needed then is an approach that combines queue sorting within links and takes advantage of AIM to extend some measure of priority preservation to trajectories to allow changes to priorities as new travelers enter the network. To this end, we propose a lane-use policy that supports any arbitrary, two-class priority assignment scheme. This is accomplished by segregating each class of vehicle into separate lanes and preferentially granting reservations to the high-priority vehicles at AIM intersections. In contrast to [2], we retain the traditional assumption that two lanes are necessary for queue sorting and that vehicles only move forward. As such, we propose a feasible mechanism for queue sorting in that high-priority vehicles are always able to pass low-priority vehicles. Also, our proposal partially relaxes the FIFO constraint of [1] in that high-priority vehicles are not subject to delays in the low-priority queues. Although our proposal does not guarantee arrival times, it does potentially preserve end-to-end priority for two-class schemes throughout an entire network. Our proposal is analogous to existing applications related to bus lanes, bus signals, and bus queue-jumping lanes. Also, there is a body of work in queuing theory that considers the general features of two-class priority queuing networks. However, to our knowledge, this work is the first to propose a scheme that supports any arbitrary, two-class priority-assignment regime for every vehicle in contiguous areas of urban networks.

One possible application of such a two-class scheme is in the context of networks of autonomous taxis or shared autonomous vehicles (SAVs). SAVs have the potential to significantly reduce the number of vehicles in the network [6]. However, large numbers of autonomous vehicles engaged in empty repositioning trips can increase congestion. It may be possible to mitigate the effect of this congestion by preserving priority for occupied vehicles. To demonstrate the effectiveness of our proposed lane-use policy for preserving the priority of occupied vehicles, we simulate its implementation in a network of SAVs and passengers. We show that by granting

and preserving priority for occupied vehicles, passenger experience improves with limited degradation in service measures for others.

In Sections II and III, we describe the relevant literature and our proposed policy in greater detail. This is followed by Sections IV and V in which simulation-based numerical experiments are described and results are analyzed. Finally, in Section VI, we conclude with our analysis and considerations for future work.

II. Related Literature

Beginning with [5], many works have explored the potential merits of reservation-based AIM technologies for improving urban traffic at intersections. AIM systems replace traditional, vehicle-actuated intersection signals with a controller agent that manages vehicle trajectory conflicts by granting or denying space-time reservations to approaching vehicles. Since then, much research has focused on various methods of reservation assignment. While a first-come-first-served policy has been shown to be inferior to traditional signal control [7], other policies show greater promise. These include auction-based ([8]) and optimization-based ([9]) assignment, as well as systems that emulate some elements of traditional signals while adding improvements for CAVs [10]. One key aspect of AIM systems is their general requirement that participating vehicles be CAVs. Although important proposals have been made for protocols that accommodate human-driven vehicles as well as CAVs [11], AIM's full potential lies in managing high proportions of autonomous vehicles.

In addition to intersections, lanes have also been considered for policies directed at leveraging the capabilities of CAVs. These proposed policies include dedicated lanes for CAVs ([12], [13]) and dynamic lanes for transit [14]. While dedicated-lanes for various classes of vehicle are already in use for HDVs, dynamic lane policies, such as rush-hour contraflow lanes that accommodate human drivers, are limited to time-of-day or signalized segments that are chosen during planning, marked, and thereafter fixed. These policies are also limited by the frequency with which use-class or direction may be changed, and are typically limited to two or four periods per day. More advanced policies such as dynamic lane reversal ([15], [16], [17]) are the CAV-only analogs of existing lane reversal policies that potentially effect any lane in the network at any time. Moreover, they may be changed with relatively high frequency in response to network conditions.

If CAVs are personally owned, empty repositioning trips have the potential to increase congestion. While there is some evidence that allowing empty repositioning may still net benefits in lower congestion, this outcome relies on all vehicles being CAVs and significant improvements to the efficiency of FIFO, reservation-based intersection controls [18]. Networks comprised of

autonomous taxis or SAVs have the potential to significantly reduce the number of vehicles in the network and lower the distance traveled during empty repositioning trips, albeit at the cost of increased total distance traveled as compared with the non-SAV case. [6]

As discussed in the previous section, [2] implements congestion pricing with vehicle-to-vehicle transactions that allocate network priority without a central controller. It also implements sortable queues by assuming that vehicles are always able to pass each other in a single lane. This assumption could be construed as the state of affairs where CAVs are able to use single, standard lanes as two CAV lanes. In this case, the solution amounts to reserving half the capacity of the link for queue sorting. However, this sorting is only possible if all vehicles are moving or otherwise are able to adjust their rear and forward gaps. This work identifies several means of providing 'differential priority,' including lane restrictions for vehicles and/or passengers of different classes that can meet this goal. [1] presents a space-time trajectory auction. Priority is established with a centralized auction and preserved by preventing vehicles from entering links until their reserved time. Priority, though, is fixed by the auction and cannot be adjusted since the model assumes FIFO behavior in the links, and because priority is guaranteed by limiting volume on the links. The author suggests that reserved capacity might address this issue.

III. Proposed Lane-Use Policy

We adopt a two-class priority assignment scheme where vehicles occupied by one or more passengers are given priority over unoccupied vehicles engaged in empty repositioning or otherwise moving unoccupied through the network. Specifically, the policy requires that, on links with two or more lanes in the relevant direction, unoccupied vehicles are strictly prohibited from using the inside lane. Hereafter, we refer to this lane as the occupied vehicle (OV) lane. Consequently, unoccupied vehicles will not be granted reservations to enter an intersection if the requested trajectory would place them in the OV lane. Occupied vehicles, on the other hand, are permitted to enter a link in any lane and merge to the OV lane if necessary. As such, occupied vehicles in the OV lane comprise a high priority queue that is not subject to delays caused by unoccupied vehicles in the link.

Delays for occupied vehicles in the OV lane are further reduced by requiring that intersection controllers honor the priority scheme while granting reservations. Specifically, a reservation for an unoccupied vehicle that has not yet entered the intersection will be revoked if an occupied vehicle requests a conflicting trajectory that, if the unoccupied vehicle were not present, could otherwise be granted. That is, an occupied vehicle will have priority over any unoccupied vehicle not already in the intersection. As a consequence, unoccupied vehicles

can not enter an intersection if doing so would cause delays for an occupied vehicle.

Similar to [2], this policy preserves priority in a link by ensuring that vehicles are able to overtake those with a lower priority. Here, though, overtaking is limited by the physical presence and capacity limits of a second lane. This differs from their work in that they reserve half the capacity in a single link model for overtaking. Here, we retained the potential full use of the available capacity while preserving priority for a two-class priority scheme. As compared to [1], our proposal relaxes the FIFO constraint in the links to the extent that links under the policy support separate queues for each priority class. This decentralized methodology enables new travelers to enter the system at any time without reservation.

IV. Simulation

Numerical experiments were conducted on a hypothetical network with 81 intersections to demonstrate the proposed two-regime priority scheme and assess its viability and performance. For this purpose, a traffic model was developed using concepts from microscopic cellular automata based on [19] with additional rules for behavior at intersections. The model was implemented in MASON ([20], [21]) and is a general framework for agent-based modeling. Implemented in Java, its prior applications have been in biology, robotics and economics. Such a framework was useful for generating large numbers of repeatable, stochastic scenarios with differing behavior for different classes of vehicles.

In the experiments, vehicle desired speed is limited to two cells per step where the cell length is 7.5 m and step length is 1 s or 54 km/h. Vehicle forward motion inside an intersection is the same as outside, but turning is allowed. Vehicles may make 90-degree turns in a single cell provided they slow to a complete stop. While a somewhat over-simplified model of turning motion, it suffices to capture the sequence of space-time trajectory conflicts which are the target of the priority policy.

The test network takes the form of a Manhattan grid with alternating two- and four-lane roads, each having an equal number of lanes in each direction. Each intersection in the network is controlled by a reservation-based, AIM protocol that always grants reservations preferentially to occupied vehicles both with and without the proposed lane-use policy in effect.

Demand in the network is the result of a Poisson process at each intersection. New travelers spawn at their respective origin intersections with a destination chosen uniformly from the remaining intersections. They enter the first unoccupied vehicle that arrives at their origin and leave it upon arriving at their destination, where they are removed from the network. Their previously occupied vehicle is now unoccupied and remains in the network, available for a new traveler.

Vehicle trajectories through the network are stochastic and their specific route-choice behavior varies depending

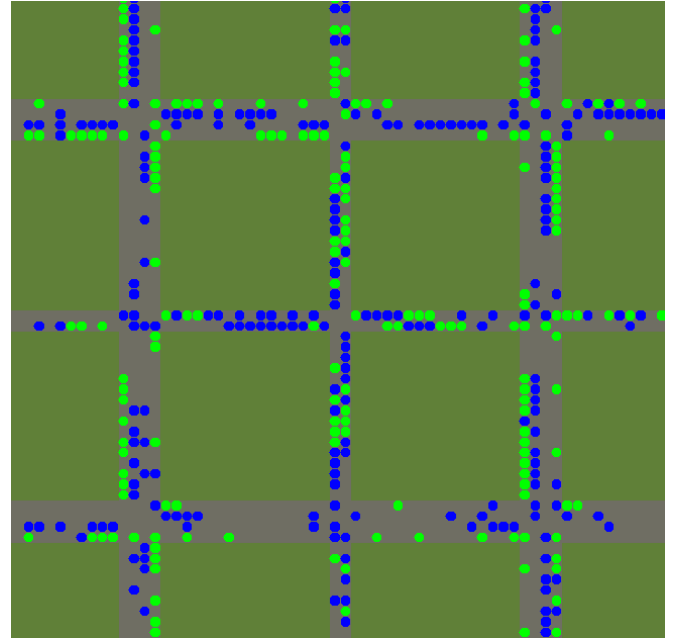


Fig. 1. A portion of the network during simulation with the proposed lane-use policy in effect. Blue points represent occupied vehicles, while green points represent unoccupied vehicles.

on their occupancy status. At each intersection, unoccupied vehicles choose a direction randomly by choosing uniformly from all lanes comprising the downstream legs. This direction-choice behavior is applied with or without imposing a priority scheme in that vehicles will weight lane options uniformly even if it is not permitted to use some subset of the lanes. In the event that a vehicle's intersection reservation request is denied due to congestion in the requested downstream lane, this process will repeat until a viable direction is chosen. This behavior has the effect of distributing unoccupied vehicles uniformly about the network with respect to the network's available capacity. Occupied vehicles behave in a similar manner with the single difference that they do not consider downstream legs in directions away from their intended destination. Consequently, occupied vehicles have either one or two direction choices at each intersection. This approach to unoccupied vehicle behavior is conservative in the sense that these vehicles are always moving and represent worst-case scenario with respect to over-all demand. On the other hand, unoccupied vehicles move away from congested links, reducing local concentrations of demand perhaps less conservatively. An alternative approach to modeling path decisions by unoccupied vehicles might be used, but their empty repositioning objectives may permit more loitering and more circuitous route choices.

The analysis was conducted as a Monte Carlo simulation of scenarios varying by vehicle density, traveler demand rate, network size, and policy enforcement. For a network with 81 (9x9) intersections, two, one-hour scenarios were simulated for each joint sample of traveler

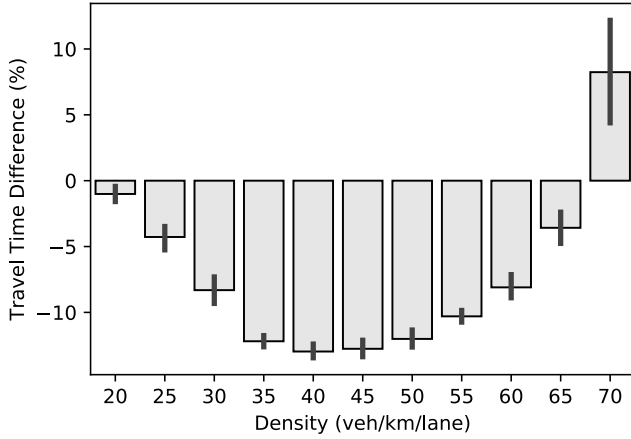


Fig. 2. Average travel time improvements due to the proposed lane-use policy for a network with 81 intersections and a passenger spawn rate of $\lambda = 0.04$. Travel time values are averaged over the first sixty (60) minutes for 128 scenarios

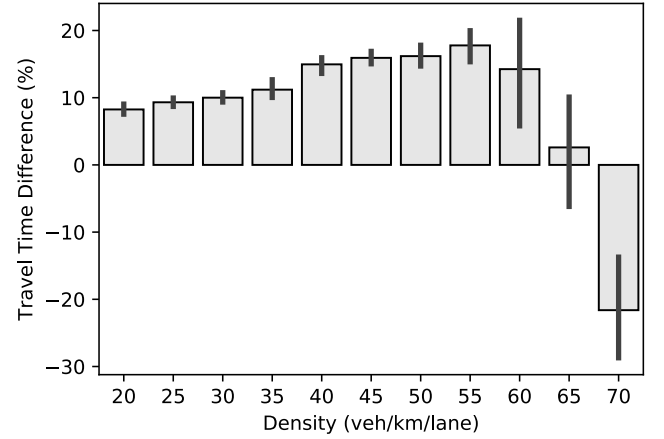


Fig. 3. Average travel time improvements due to the proposed lane-use policy for a network with 81 intersections and a passenger spawn rate of $\lambda = 0.1$. Travel time values are averaged over the first sixty (60) minutes for 128 scenarios

demand rate and vehicle density; one with and the other without enforcement of the priority policy. Vehicle densities varied uniformly from 10 to 80 veh/km/lane, while the mean traveler spawn rate, λ , at each intersection varied uniformly from 0.0 to 0.1 travelers per step or up to six trips per minute per intersection. From the resulting data, policy and non-policy scenarios were compared to determine the effect of the policy on average trip times and average speeds for occupied vehicles in the network.

V. Results and Analysis

For the test network, the proposed lane-use policy decreases travel times for occupied vehicles by about 15% for densities around 40 veh/km/lane as compared with the same set of scenarios without the policy (recall that intersections always preferentially grant priority to occupied vehicles). At very low densities (below 25 veh/km/lane), the policy does not greatly affect travel times. At the highest densities (greater than 70 veh/km/lane), the policy increases travel times. As illustrated by Fig. 2, the trend is such that travel-time improvements increase with density from very low densities to an optimal density (≈ 40 veh/km/lane). As density increases from the optimum, improvement continues with diminishing returns until reaching a critical density (≈ 70 veh/km/lane), above which the policy increases travel times. These general features do not vary significantly for demand rates below five (5) trips per minute per intersection ($\lambda < 0.08$). However, at higher demand rates ($\lambda > 0.08$), this trend is reversed. Under such high demands, the policy increases travel times for occupied vehicles until the critical density, above which travel times are reduced by up to 25%. See Fig. 3.

Travel-time improvements for occupied vehicles, however, do come at a slight cost in total network travel de-

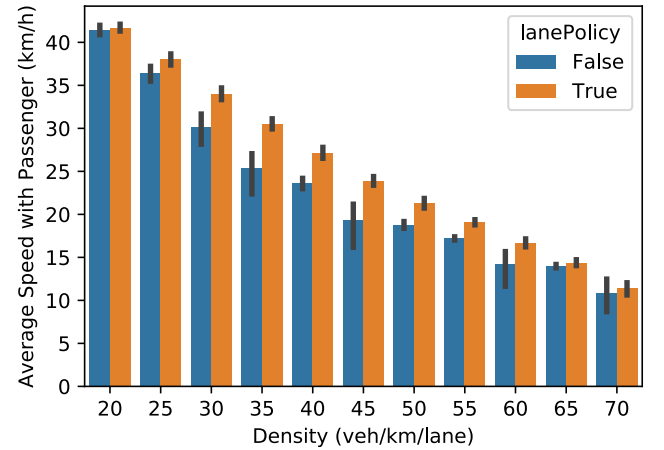


Fig. 4. Average speeds for occupied vehicles with and without the proposed lane-use policy for a network with 81 intersections and a passenger spawn rate of $\lambda = 0.04$. Travel time values are averaged over the first sixty (60) minutes for 128 scenarios

lays. That is, enforcement of the policy slightly decreases the average speed over the whole network. However, this cost is born by unoccupied vehicles. As shown in Figs. 4 and 5, near the optimal density (≈ 40 veh/km/lane) average speeds for occupied vehicles increased by about 5 km/hr, while average speeds for unoccupied vehicles were reduced by about 3 km/hr. Moreover, this effect follows the same trend seen with travel times. In fact, at low densities (< 20 veh/km/lane) the policy has little effect and the optimal density for both travel time and speed is nearly identical (≈ 40 veh/km/lane).

VI. Discussion and Future Work

We introduced a policy of segregating occupied and empty SAVs in specific lanes by restricting empty vehicles to curb-side lanes. This policy takes advantage of autonomous intersection management by creating, in

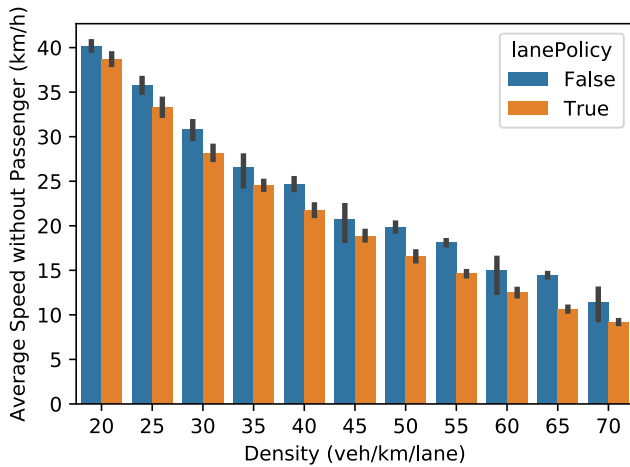


Fig. 5. Average speeds for unoccupied vehicles with and without the proposed lane-use policy for a network with 81 intersections and a passenger spawn rate of $\lambda = 0.04$. Travel time values are averaged over the first sixty (60) minutes for 128 scenarios

effect, separate queues for occupied and empty vehicles. Of course, occupied (higher priority) vehicles can be assigned to either queue if beneficial. We simulated the performance of this policy with a microscopic, cellular automata-based model on a hypothetical network under varying density and demand scenarios. The analysis shows that the proposed lane-use policy improves travel times and speed for travelers under certain demand and vehicle-density scenarios with limited degradation in these measures for other, i.e. unoccupied, vehicles. The proposed lane-use policy is developed on realistic physical limitations of the street network and without the need for trajectory reservations.

Thus far, the policy has only been applied on 4-lane roadways (2-lanes in each direction). Additional considerations may be required for lane-based implementations of the priority scheme with greater or fewer lanes or for networks with variable numbers of lanes across links. Future demand in SAV zones is likely to be the result of ride-hailing mechanisms. Thus, three or more level priority schemes will be required to give unoccupied vehicles with a waiting passenger priority over unoccupied vehicles, but less priority than a vehicle with a passenger on board. Such multi-level schemes will also enable prioritization of vehicles with greater numbers of passengers. Commonality with transit-specific geometries and intersection designs, including for example queue-jumping lanes and bus signals have been noted. Indeed, the two classes of priority suggested in this work could be construed as transit and non-transit classes. However, multi-level priority schemes could incorporate transit as a separate priority class. In addition to carrying greater numbers of passengers, inclusion of this mode could require a new category of lane and alternative lane usage mechanisms. Also of immediate interest are selective and dynamic policy enforcement strategies that

could operate by link, intersection or zone. Finally, additional experiments could be undertaken to assess the importance of varying demand patterns, pick-up and delivery locations, traffic characterization and network layout.

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