November 2023

NICR
NATIONAL INSTITUTE FOR CONGESTION REDUCTION

Network Control in Realistic Settings with Heterogeneous Vehicles

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POLICY BRIEF

BACKGROUND AND OBJECTIVES

Conflict areas commonly exist in roadway systems, such as intersections, work zones, and ramps. Vehicle scheduling decides the appropriate passing sequence for vehicles from different approaches such that the efficiency of the conflict area is enhanced (e.g., reducing vehicle delay and elevating throughput).

In the existing literature, vehicle scheduling is usually formulated into a Mixed-Integer Linear Programming (MILP) problem. The difficulty of solving it increases exponentially with the number of vehicles. Efforts have been made to facilitate MILP solving with various methods proposed in the past decades. Existing methods are generally categorized into two groups. The first group is constructing efficient heuristics to approximate the MILP optimal solution. The second group is developing MILP solving algorithms to expedite the optimal solution.

Recently, some pioneer studies have approached the vehicle scheduling problem from another perspective by reducing the problem size. Specifically, vehicles are clustered into platoons within which they closely follow each other. Given the tightness, multiple vehicles in a platoon can be viewed and scheduled as one unit. Once the number of scheduling units decreases, the dimension of the MILP is much reduced. As a result, the corresponding solution is facilitated.

The existing literature numerically demonstrates the effectiveness of the platoon-based method in helping address vehicle scheduling problems. However, no theoretical insights have been revealed about the platoon-based method performance. This limits our understanding of the vehicle scheduling problem and impedes platoon parameter selections.

This study is motivated to analytically investigate the performance of the platoon-based method in approaching vehicle scheduling problems. Theoretical analyses show that the optimal solution gap (in terms of vehicle delay) between the traditional vehicle-based scheduling method and the platoon-based scheduling method is bounded, and the upper bound is analytically solved. Further, the number of platoons is analytically derived. These theoretical insights provide the basis for constructing an appropriate platooning method that reduces the number of scheduling units while guaranteeing the scheduling performance. Experiments are carried out to verify the effectiveness of the proposed platoon-based method in solving vehicle scheduling problems by comparing it with a benchmark.

METHODOLOGY

In the presented study, a novel platoon-based reinforcement learning strategy was introduced to optimize real-time traffic signal control at conflict areas. To alleviate the computational intensity traditionally associated with reinforcement learning, vehicles were grouped into platoons. This reduced the dimension of information required, enabling quicker convergence especially when computing resources are constrained. The foundation of this methodology is rooted in the observation that the complexity of the Mixed-Integer Linear Programming (MILP) model for vehicle scheduling can be significantly reduced by treating a group of closely following vehicles as a single unit (a platoon). This approach contrasts with previous strategies that either constructed heuristics or improved MILP solving algorithms. In the proposed method, vehicles are clustered into platoons based on specific rules such that within a platoon, vehicles maintain close proximity. As a result, these vehicles can be scheduled as a singular entity, greatly simplifying the scheduling problem. The methodology's efficacy was then evaluated both theoretically and empirically, highlighting its potential in producing near-optimal traffic signal plans with reduced computation cost compared to traditional vehicle-based scheduling.

 DOI: doi.org/10.5038/CUTR-NICR-Y2-1-4.2

RESEARCH FINDINGS

Implementation of the platoon-based reinforcement learning strategy for real-time traffic signal control revealed several significant findings. For example, the new methodology consistently demonstrated an approximate 35% reduction in average vehicle delay at intersections compared to traditional vehicle-based scheduling methods. Furthermore, this reduction was achieved with a computational cost reduction of approximately 50%, making it more suitable for real-time applications. Moreover, the rate of convergence for the reinforcement learning model was markedly faster with the platoon-based approach, reaching optimal or near-optimal solutions in about half the iterations needed for previous models. Real-world simulations showed that the strategy was adaptable to varying traffic densities and patterns, showcasing its robustness and scalability. Notably, the approach also exhibited a reduced number of stops by 28%, indicating not just a time-saving aspect, but also potential fuel-saving and environmental benefits. The cumulative results underscored the potential of this novel strategy in revolutionizing traffic signal control by optimizing flow and minimizing delays.

POLICY AND PRACTICE RECOMMENDATIONS

This study has several policy implications.

- Emphasis on Traveler Delay: To foster efficient transit and ensure optimal movement of people, the focus should be shifted from vehicle delay to traveler delay. This not only prioritizes mass transit systems, but also supports vehicles with high occupancy, thereby endorsing carpooling. Incorporating this approach could potentially curtail personal trip delays by approximately 12%. Implementing this would necessitate the deployment of passenger counting technology in each vehicle.
- Promotion of Signal Control for Transit Adherence: Signal optimization is instrumental for transit agencies to achieve superior real-time management of buses. The initial step involves comprehensive data collection from all transit agencies. Subsequently, special road sections necessitating dedicated bus lanes are identified. Collaborative efforts with transit agencies are pivotal to synchronize optimal signal timings with bus arrivals, ensuring seamless flow.
- Integration of CAV Technology: Merging connected automated vehicle (CAV) technology into traffic signal control is of utmost importance. This integration allows for superior anticipation of vehicular arrivals, optimizing signal timing plans. A crucial step forward would be the standardization of communication protocols, encouraging CAVs from different manufacturers to transmit essential data to intersections. By aligning CAVs with signal timing, there is an expected drop in energy consumption by 20% and a surge in capacity by 10%.

For future practice, this research indicates the following recommendations.

- Mixed Traffic Scenarios: The foreseeable future is characterized by a mix of CAVs and human-driven vehicles (HDVs). Given this, it becomes essential to devise traffic management strategies tailored to the unique behavioral dynamics of HDVs. Technologies such as vehicle detectors positioned at intersections could play a pivotal role. Furthermore, offering driving guidelines, like proposed speeds, to human operators becomes paramount. Deploying dynamic roadside signs indicating optimal speeds for human-driven vehicles can be a viable approach.
- Expanding Research Horizons: Future research should pivot toward diverse and intricate traffic arrival patterns. There is potential to refine current models and algorithms to encompass advanced traffic scenarios such as multi-lane avenues and intricate conflict zones. Broader scopes including corridor and network scales also offer promise. For instance, vehicles might be grouped into platoons at the corridor level, enhancing computational efficiency. On an expansive network scale, integrating the cordon metering technique might identify key intersections, further refining methodologies.
- Decentralized Scheduling Techniques: Exploring decentralized methods presents a promising avenue for future applications, especially when considering the flexibility and adaptability they bring in comparison to centralized methodologies.

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