Decentralized trip-based traffic signal control

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Abstract

This article proposes a traffic signal control strategy that incorporates the remaining travel distance of each vehicle in the network to clear vehicles faster, reduce congestion, and increase network throughput. The objective of the proposed strategy is to prioritize vehicles with shorter remaining travel distances. By swiftly clearing these vehicles, we free up space for other traffic and alleviate pressure on congested areas. This approach introduces a computational burden due to the need to process individual vehicle data in real-time. To address this, a decentralized, pressure-based control strategy is designed that operates at each intersection and relies on local information. The pressure-based controller dynamically adjusts phase durations based on local phase pressures, maximizing network throughput and stabilizing traffic flows. Simulation results using an AIMSUN model of the Barcelona network, with 1500 links and 600 intersections, show that our approach outperforms strategies based only on links' queue information.
Keywords: Pressure-based control, Remaining travel distance, Decentralized control.

1 Introduction

Urban traffic congestion has become a significant challenge due to the rising demand for mobility. To mitigate traffic congestion and improve efficiency, various control strategies have been investigated, including centralized and decentralized algorithms. However, the real-time implementation of centralized algorithms in large-scale urban areas faces significant challenges, primarily due to scalability issues. This has led researchers to focus on developing decentralized algorithms.
In Pedroso & Batista (2021), a decentralized traffic control approach based on the store-and-forward model is proposed. In this approach, a decentralized linear quadratic regulator is designed to enable each intersection to independently compute the green times for its signal phases. The objective is to reduce the computational and communication burden in large-scale networks. Similarly, in the approach presented in Chow et al. (2020), the network is first partitioned into multiple vertices or groups of vertices. Then, a decentralized algorithm is devised comprising two loops. The inner loop ensures the convergence of the iterative algorithm within each vertex or group of vertices, while the outer loop ensures convergence across the network.
The pressure-based traffic signal control strategies P_0 and Max Pressure (MP) represent significant research work in decentralized traffic control. The local MP controller investigated in Varaiya (2013) relies on queue lengths in adjacent links at an intersection. The controller selects the phase with the highest pressure, computed as the difference in queue lengths between upstream and downstream links. Smith et al. (2015) investigated the accumulation-based P_0 control method, which is also based on the length of queues in the network links. This method takes into account variable route choices and maximizes network capacity under specific conditions. These conditions include demand being within network capacity and no spillback occurring. The research in Le et al. (2015) proposed a decentralized backpressure traffic signal control approach. The term *backpressure* is used because the local controllers consider the impact of traffic conditions on the downstream links of approaching links at individual intersections. Li & Jabari (2019) proposed a position-weighted backpressure traffic signal control approach. This decentralized approach captures the spatial distribution of vehicles along links and addresses spillback conditions. Their results showed that the proposed approach outperforms both standard and capacity-aware backpressure methods, especially under higher levels of demand.

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This paper contributes to the literature by proposing a trip-based P_0 controller based on the remaining travel distance of each vehicle in the network. In this approach, a weight is assigned to the vehicles proportional to the inverse of their remaining travel distance. By doing so, a vehicle with a shorter remaining travel distance has a higher weight and, thereby, a greater influence on the pressure of the corresponding phase.

2 Methodology

The decentralized pressure-based traffic signal control in this paper is based on the remaining travel distance of each vehicle in the network. This section explains the dynamics of the remaining travel distance and formulates the trip-based P_0 controller. The objective is to determine the green times for all phases at an intersection so that the pressures of all phases are equalized.

Trip-based P_0 controller

Consider an urban traffic network in which the links are denoted by $z \in \mathcal{Z}$ and the signalized intersections are denoted by $j \in \mathcal{J}$. The traffic signal control strategy at intersection j, is based on a set of phases, belonging to the set $\mathcal{F}_j$. Furthermore, $r_{n,z}(k)$ denotes the remaining travel distance of vehicle n on link z at the discrete time instant k. In other words, $r_{n,z}(k)$ represents how much distance vehicle n requires to travel in the network to reach the destination. To capture the movement of vehicles, we update $r_{n,z}(k)$ at each time step k based on the vehicle's speed $v_{n,z}(k)$ and sampling interval Δt. The dynamic of the remaining travel distance of vehicle n on link z is formulated as follows:

$$r_{n,z}(k+1) = \max\Big(0,\, r_{n,z}(k) - v_{n,z}(k)\,\Delta t\Big), \tag{1}$$

where the term $v_{n,z}(k)\Delta t$ relates to the distance traveled by vehicle n during the sampling interval Δt. The maximum operator ensures that the remaining travel distance does not become negative, which would indicate that the vehicle has completed its trip and arrived at its destination.
Next, we define a weight $w_{n,z}(k)$ associated with vehicle n on link z at time k. This weight is calculated by taking one divided by the remaining travel distance $r_{n,z}(k)$ as follows:

$$w_{n,z}(k) = \frac{1}{r_{n,z}(k)}. \tag{2}$$

According to (2), vehicles that are closer to completing their trip and reaching their destination receive higher weights. This weighting scheme is advantageous for applications where vehicles nearing trip completion have a greater influence on subsequent control or decision-making processes. Subsequently, the total weight of link z at time k is calculated as the summation of the individual vehicle weights on that link in the following form:

$$W_z(k) = \sum_{n \in \text{link } z} w_{n,z}(k). \tag{3}$$

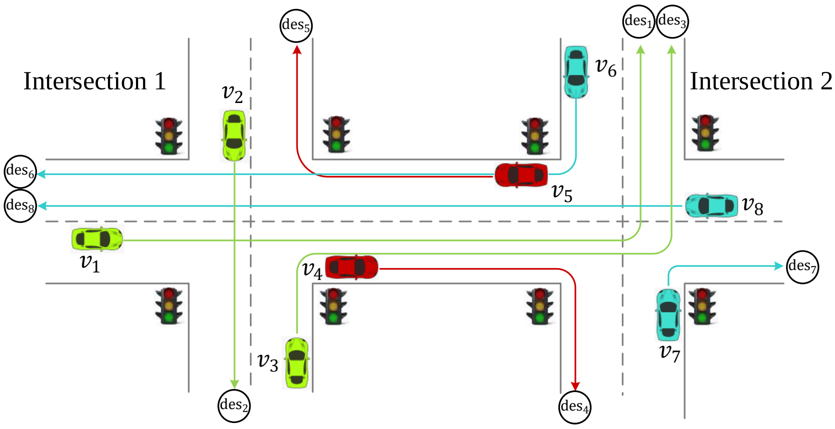

Figure 1: Signalized network with two intersections

Figure 2: AIMSUN model of the Barcelona network

Afterwards, by taking into account that the weight of phase i at intersection j is calculated as $W_{j,i}(k) = \sum_{z \in \text{phase } i} W_z(k)$, the pressure on phase i at intersection j is formulated as follows:

$$\gamma_{j,i}(k) = \frac{W_{j,i}(k)}{P_{j,i}(k)}, \tag{4}$$

where $P_{j,i}(k)$ is the green time proportion of phase i at intersection j. As shown in Figure 1, at intersection 1, vehicle v_2 is nearly at its destination and therefore contributes a higher weight to the phase that controls its movement. At intersection 2, a similar situation applies to vehicle v_7. The main goal in the P_0 controller is to equalize the pressure across different phases of the intersection. To this end, it is assumed that there exists a constant $\alpha > 0$ such that the pressure on all the phases of the intersection j is equal. Thus, we have

$$\frac{W_{j,i}(k)}{P_{j,i}(k)} \;=\; \alpha, \quad \forall i \in \mathcal{F}_j. \tag{5}$$

Equivalently, we can rewrite (5) as $P_{j,i}(k) = \frac{W_{j,i}(k)}{\alpha}$. Moreover, in order for a control policy to be feasible, the green time proportions of all the phases at intersection j must satisfy the constraint, $\sum_{i \in \mathcal{F}_j} P_{j,i}(k) = 1$. Taking these points into account, we have

$$\sum_{i \in \mathcal{F}_j} P_{j,i}(k) = \sum_{i \in \mathcal{F}_j} \frac{W_{j,i}(k)}{\alpha} = \frac{1}{\alpha} \sum_{i \in \mathcal{F}_j} W_{j,i}(k). \tag{6}$$

Since the left-hand side of (6) is 1, the constant α is calculated as follows:

$$1 \;=\; \frac{1}{\alpha} \sum_{i \in \mathcal{F}_j} W_{j,i}(k) \quad \Longrightarrow \quad \alpha \;=\; \sum_{i \in \mathcal{F}_j} W_{j,i}(k). \tag{7}$$

Hence, the green time proportion of phase i at intersection j can be formulated as

$$P_{j,i}(k) = \frac{W_{j,i}(k)}{\sum_{i \in \mathcal{F}_j} W_{j,i}(k)}. \tag{8}$$

Finally, the green time of phase i at intersection j can be obtained as follows:

$$G_{j,i}(k) = P_{j,i}(k)\left(C_j - L_j\right), \tag{9}$$

where C_j and L_j are the cycle time and lost time of signalized intersection j, respectively.

3 Results and discussion

The simulations are carried out in the AIMSUN microsimulation environment. To evaluate the performance of the proposed trip-based P_0 approach, a portion of Barcelona's urban network spanning $12\,\text{km}^2$ is utilized. As depicted in Figure 2, this network comprises approximately 1500 links and 600 intersections. In the simulations, drivers exhibit adaptive behavior, and vehicles continuously update their routes in response to real-time traffic information. For the sake of brevity, we exclude detailed information on lost times and cycle times of intersections. The simulation was conducted for 45 minutes using the demand profile depicted in Figure 3, which represents the maximum feasible demand. During the initial periods, the number of vehicles entering the network remains approximately constant. Subsequently, the demand increases sharply, followed by a gradual decline throughout the remainder of the simulation period.

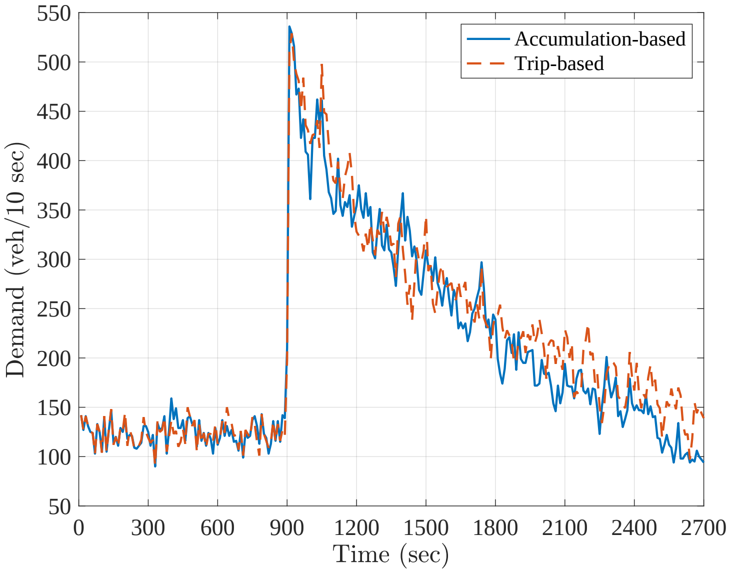

Figure 3: Demand profile for accumulation-based and trip-based P_0 controllers

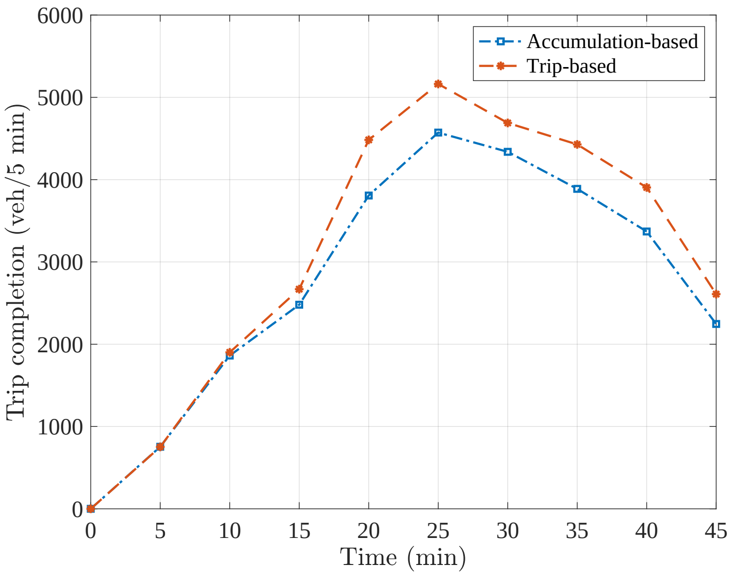

Figure 4: Flow of exiting vehicles every 5 minutes

In the accumulation-based approach, a total number of 51650 vehicles entered the network, while in the trip-based approach, this number increased to 53029. The results indicate that the trip-based approach allows an additional 1379 vehicles to enter the network and helps prevent the creation of virtual queues in the AIMSUN software. In the following, we compare the performance of the proposed controller with the controller proposed in Smith et al. (2015), in terms of delay time (sec/km), average travel time (sec/km), density (veh/km) and flow (veh/h).

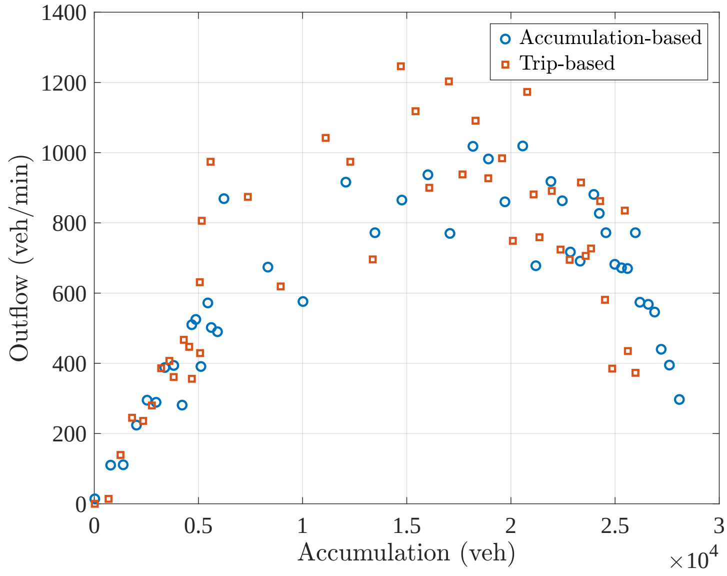

Figure 5: Macroscopic fundamental diagram for Barcelona urban network

Table 1: Network of Accumulation-based with Trip-based P_0 controller

	Delay time (sec/km)	Average travel time (sec/km)	Density (veh/km)	Flow (veh/h)
Trip-based	312.79	377.99	26.77	40798.67
Accumulation-based	351.17	416.52	28.38	36422.67
Improvement	10.93%	9.25%	5.67%	12.01%

According to Table 1, the trip-based controller performs better in terms of delay time and average travel time, indicating its efficiency in reducing delays and average travel durations. The lower density observed with the trip-based controller reflects reduced congestion and contributes to smoother traffic flow across the network. Furthermore, the higher flow achieved by the trip-based controller highlights its ability to manage a larger volume of vehicles, which ensures better utilization of the road infrastructure and improved overall system performance.

In Figure 4, we compare the flow of exiting vehicles over time for accumulation-based and trip-based strategies. The trip-based approach achieves a higher flow, especially during peak periods (20–35 minutes), with a maximum flow of 5163 vehicles compared to 4573 for the accumulation-based method. Both strategies perform similarly in the early times (5–15 minutes), but the trip-based approach maintains better performance under peak demand. In conclusion, the results show the effectiveness of the trip-based strategy in improving network throughput and allowing better queue clearance in high traffic volumes.

In Figure 5, the macroscopic fundamental diagram of the Barcelona urban network is illustrated. As it is shown, under undersaturated conditions, both methods perform similarly. However, as traffic approaches saturation and nears critical accumulation, the trip-based method achieves higher outflows more quickly than the accumulation-based method. In the oversaturated regime, both approaches exhibit a decrease in outflow as the number of vehicles increases.

4 Conclusions

In the present work, a decentralized trip-based P_0 controller is proposed, which is based on the remaining travel distance of the vehicles in the network. Firstly, a weighting scheme is introduced in which greater weights are assigned to vehicles that are closer to their destinations. Secondly, the phase pressure is calculated as the total weight of vehicles with the right-of-way during that phase. Subsequently, the green time proportion for a phase at an intersection is determined as the proportion of the phase weight to the total weight of all phases at the intersection. The simulation results for a part of Barcelona city, modeled in the AIMSUN microsimulation environment, illustrate a 12.9% increase in the flow of vehicles completing their trips. Furthermore, using the trip-based P_0 controller, the delay time, average travel time, and density decreased by 10.93%, 9.25%, and 5.67%, respectively.

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