Rhythmic Control for Automated Intersections: Concept and Properties

Xiangdong Chen[a] Meng Li[a] Xi Lin[a] Yafeng Yin[b] Fang He[c*]

[a]*Department of Civil Engineering, Tsinghua University, Beijing 100084, P.R. China*

[b]*Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA*

[c]*Department of Industrial Engineering, Tsinghua University, Beijing 100084, P.R. China*

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1 Introduction

Connected vehicle (CV) technologies are capable of building an interconnected network of moving vehicles and infrastructures, where vehicle-to-vehicle and vehicle-to-infrastructure communications can be realized in a collaborative and real-time manner. Fully automated vehicles (AV) are capable of gathering information, autonomously performing all driving functions, and monitoring roadway conditions for an entire trip (NHTSA, 2013). From a traffic operations perspective, the capabilities of AV technologies, integrated with CV systems, can further enable more responsive traffic controls, which imply a tremendous opportunity to more efficiently allocate right of way (ROW) at intersections.

In the literature, several studies have been conducted to improve intersection control under a fully connected and automated vehicle (CAV) environment. In a broad sense, related studies could be categorized into two groups, i.e., "signal-free" and "signalized" schemes. "Signal-free" schemes explicitly optimize the sequence of each CAV passing through an intersection (Levin and Rey, 2017; Lee and Park, 2012; Wu et al., 2012; Xu et al., 2018; Muller et al., 2016), whereas "signal schemes" organize non-conflicting movements into groups/phases, then form platoons in each movement direction, and finally optimize the phase sequences (Li et al., 2014; Yu et al., 2018; Feng et al., 2018). Both schemes formulate the problem of passing sequence optimization as mathematical programs. However, exactly solving the optimization problems is undoubtedly highly exigent, as the size of passing sequences grows exponentially with the number of incoming vehicles. Nevertheless, it is always difficult to theoretically guarantee the solution quality of the above heuristics.

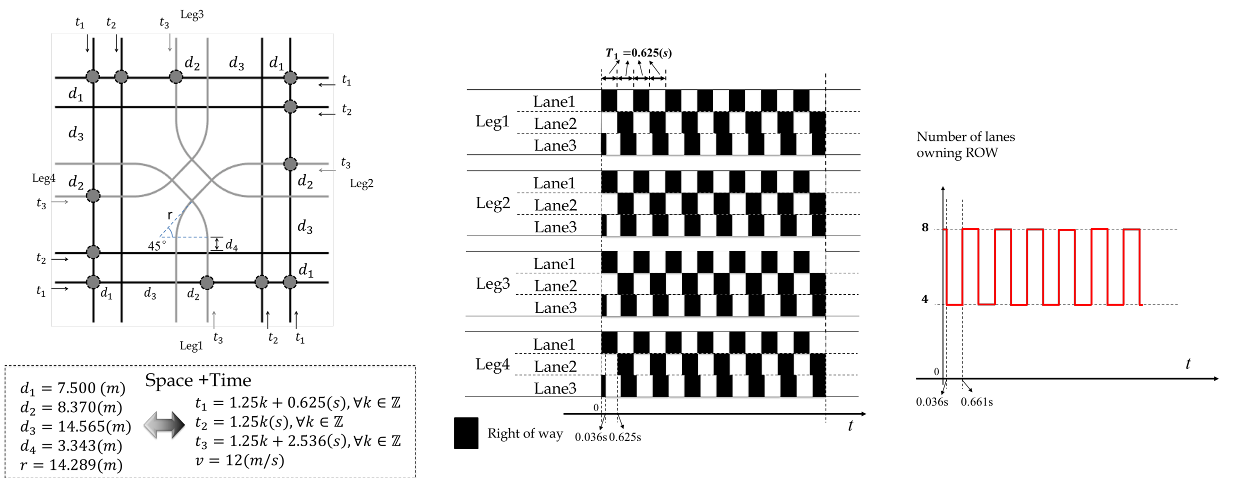
To address the aforementioned research question, we propose a computationally cheap control which is capable of breaking the limitation that right of way can only be allocated to non-conflicting movements at a time, thus significantly improving the performance of intersection

*Corresponding author. E-mail address: fanghe@tsinghua.edu.cn.

control. Moreover, it relies on a preset rhythm, rather than dynamically controlling the movements of vehicles/platoons to avoid conflicts, as this latter method requires complicated computational efforts and possibly massive amounts of accelerations/decelerations. Finally, the performance of the proposed rhythmic control is tested in the simulations with both stationary and non-stationary vehicle arrivals at both symmetric and asymmetric intersections.

2 Rhythmic control scheme

The idea of rhythmic control is to untangle the intersection conflicts and then enable CAVs to proceed within the intersection at a constant speed without any stop, by letting them follow a preset and coordinated rhythm. The rhythm assigns regularly recurring vehicle entry times for each lane such that the vehicles pass through each conflicting point in an alternating way.



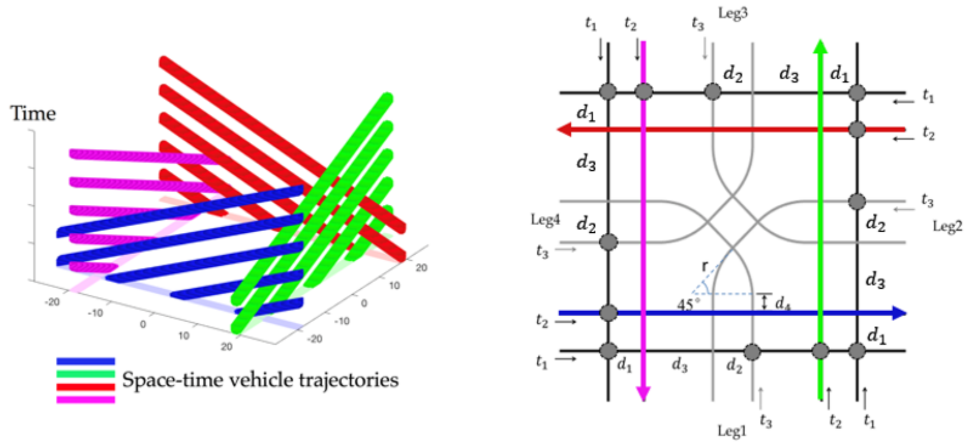
(a) Intersection layout

(b) Right of way for lanes

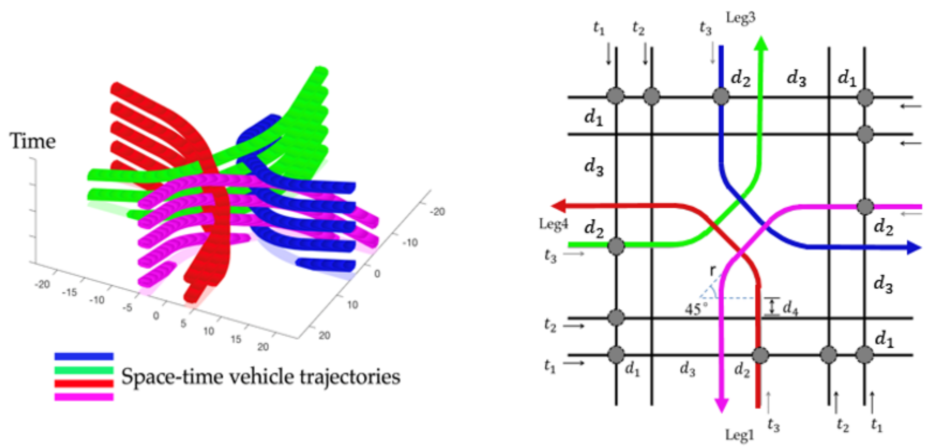
(c) Number of lanes owning ROW

Figure 1: Right of way allocation under rhythmic control

Specifically, the rhythmic control first designs the spatial placement of conflicting points through re-designing the intersection layout, as shown in Fig.1(a). Then, it sets the rhythm, i.e., assigning the times of vehicles on each lane entering the first conflicting points, showed by the dotted circles in Fig.1(a). Under the rhythmic control, vehicles on lanes 1, 2 and 3 of each leg periodically enter the corresponding first points at pre-determined times. Then, they will cross the intersection at a constant speed without any stop. It can be proved that this design totally resolves all the inter-vehicle conflicts. Fig.2 provides the designed vehicular space-time trajectories under rhythmic control within the intersection to demonstrate the conflict-free properties of rhythmic control. Fig.1(b) shows the temporal distribution of ROW on each lane under rhythmic control, whereas Fig.1(c) depicts the number of lanes owning ROW over time. It can be observed that the number of lanes owning ROW under rhythmic control is always higher than (sometimes even two times higher than) that under Traffic signal control(TSC), which intuitively confirms the rhythmic control's capability of utilizing the intersection more sufficiently. Finally, we extend the methodology as Figs.1-2 demonstrates to resolve all inter-vehicle conflicts at a generic intersection.



(a)



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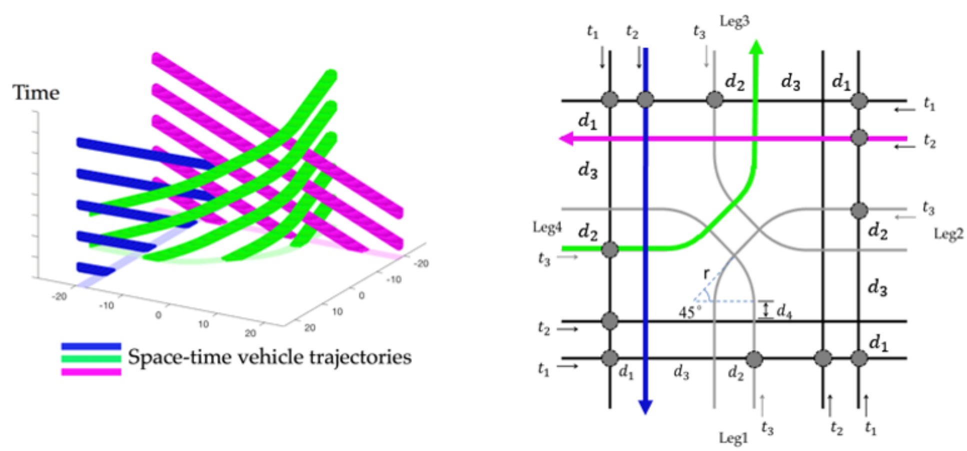


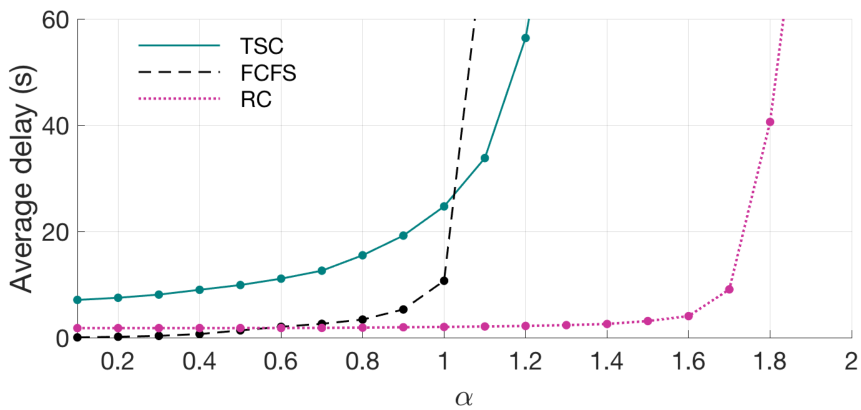
(c)

Figure 2: Space-time trajectories at the isolated intersection in Figure 2(a).

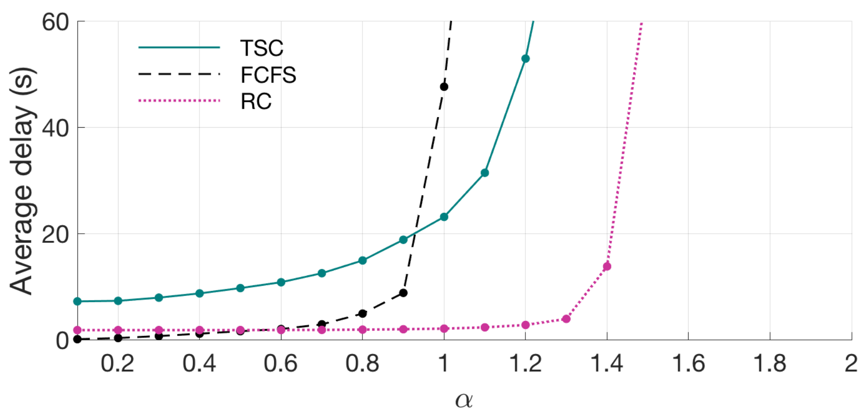
3 Numerical experiments

To demonstrate the performances of the the rhythmic control in various scenarios, we conduct several simulation experiments; the benchmarks include the TSC and reservation-based scheme in the first-come-first-serve protocol (FCFS; Dresner and Stone, 2004).

First, simulation tests at a symmetric intersection with balanced demand pattern ($\mathbf{d}_b$) and imbalanced pattern ($\mathbf{d}_i$). We assume that the vehicle arrival process follows a time-invariant process with a headway that obeys a shifted exponential distribution. The simulation results in the two demand patterns are given in Figs.3(a)-(b).



(a)



(b)

Figure 3: Comparison of average delay in stationary vehicle arrival. (a) Balanced demand case. (b) Imbalanced demand case

We can obtain that for low-demand cases , both FCFS and RC are all capable of achieving a practically zero delay. This is a major advantage for automated intersection control schemes as claimed by several publications in literature. In both balanced and imbalanced demand patterns, as the demand increases, RC is the last to become over-saturated among the three control schemes. That reflects the superior performance of the rhythmic control on the intersection capacity.

Also, we conduct tests for non-stationary vehicle arrival scenario and asymmetric intersection, and the performances of the rhythmic control for these extended scenarios are considerably similar to those in the symmetric intersection; this proves the applicability of the proposed control schemes in more general settings.

4 Conclusions

This research proposes an innovative intersection control scheme, the rhythmic control, in a fully CAV environment. Utilizing an appropriately designed layout of conflicting points at an intersection, the rhythmic control assigns predetermined time spots in a rhythmic way for vehicles entering intersection from each lane. It can fully coordinate the complicated conflicting relationships at the intersection under given conditions. Finally, The results of extensive numerical experiments show that the rhythmic control, even when it is compared to the advanced TSC in CAV environment, can significantly reduce vehicle delays and increase intersection capacity. Among the considered three control schemes, TSC in CAV environment, FCFS, and the rhythmic control, the proposed the rhythmic control has the largest admissible demand set and introduces the least average vehicle delay in most cases.

There are extensive further investigations following the line of the proposed rhythmic control framework. Demonstrating the effectiveness of the proposed scheme at a generic isolated intersection is the first step. Further exploration is needed to generalize the rhythmic control into a road network, which inevitably requires further coordination among the rhythms at the intersections of the network. Furthermore, extremely imbalanced demand situations shall be handled when the design of an intersection layout possesses more freedom. Lastly, in practical implementations, there are always some unexpected control errors and vehicle dysfunctions that may threaten the safe operation of rhythmic control. We need to design backup control protocols for handling emergencies.

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