Integrated Control of Internal Boundaries and Signal Timing at An Isolated Intersection for Lane-free Traffic of CAVs

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1 INTRODUCTION

Signal timing at intersections has been studied and applied for a long time to improve urban traffic efficiency. It aims to allocate the entire intersection capacity temporally, and road resources are equally assigned for traffic in the opposite directions. However, in case of unbalanced traffic demands, the above problem is related to the road resource assignment, and goes beyond the scope of conventional traffic signal timing. Nevertheless, relevant efforts have been made over the past decades via the concept of reversible lanes (Zhao, et al., 2015). With respect to urban areas, variable guidance lanes are applied to accommodate the unbalanced bi-direction mobility and also tackle the imbalance of through and left-turning traffic (Wong, et al., 2011). The essence of applying reversal or variable guidance lanes is to transfer the redundant capacity for the uncongested direction to the congested direction in a "dynamic" manner. The aforementioned studies address the "lane based" traffic mode which restricted the traffic efficiency.

A novel concept "TrafficFluid" was recently proposed for traffic flow of CAVs (Papageorgiou, et al., 2021). One typical feature of TrafficFluid is lane-free traffic, CAVS can drive anywhere on the 2-D surface of the road. A novel traffic control measure of internal boundary control has been proposed (Malekzadeh, et al., 2021). The main idea of IBC is as follows: the currently rigid boundary between the bi-directional traffic can be softened for the lane-free traffic of CAVs. Thus, the resulting virtual internal boundary can be regulated by a roadside controller in real-time to respond to the unbalanced bi-directional traffic flows. In other words, the bi-directional road capacity can be shared between the two opposite directions according to their demands, and the assignment can be managed in real-time to maximize road space utilization for improved traffic efficiency. Later Quadratic Programing (Malekzadeh, et al., 2021), Linear Quadratic regulators (Malekzadeh, et al., 2021) and overlapping decentralized control (Malekzadeh, et al., 2023) schemes were employed to implement IBC more practically on freeways. Jin et al. (2022) combined ramp metering and IBC for improved traffic control results that ramp metering or IBC alone cannot achieve.

The above studies show the profound potential of IBC in better utilizing the existing infrastructure and improving traffic efficiency on freeways. However, the potential of IBC in urban traffic control is still unknown. This paper studies the integrated control of internal boundaries and signal timing at an isolated intersection in the lane-free traffic of CAVs. To discover the essence of IBC for urban traffic flow management, two issues are of particular interest for this paper: (1) how much can signal control efficiency be improved via IBC; and (2) under what circumstances.

2 METHODOLOGY

Figure 1 shows an isolated intersection with the through movement in each direction for lane-free traffic of CAVs. The intersection controller unit (ICU) regulates the intersection's signal timings and the internal boundary of each road linked to the intersection so as to optimize the traffic flow efficiency. It is displayed in Figure 1 that four traffic streams towards the intersection are considered in this work, each indicated by $i \in I = \{1,2,3,4\}$. The core of ICU is a joint optimization model that addresses both signal timing optimization and internal boundary control. The road resources are allocated temporally via signal timing optimization, and spatially via IBC. The signal cycle C is fixed at 60s, and each cycle is split into a number of time steps each of 5s. The signal timing is optimized every time step, while IBC is conducted once per cycle.

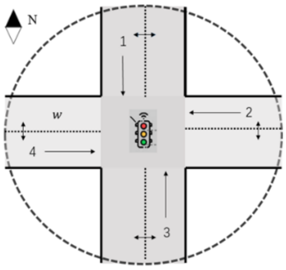


Figure 1 – *The considered intersection*

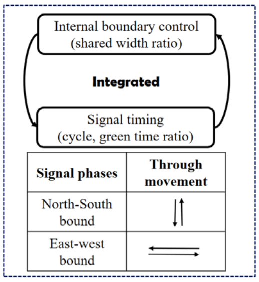


Figure 2 – *The framework of the integrated control with intersection controller unit*

2.1 Signal Timing Model

Since the cycle length is fixed, we focus on the optimization of the effective green times for all approaches, with the upper and lower bounds of the green times considered.

$$g_{min} \leq T \cdot \sum_{n=1}^{N} \delta_{i,m,n} \leq g_{max}, \ \forall\, i, m \tag{1}$$

where $\delta_{i,m,n}$ is a binary variable for the signal status in approach i at time step n of the m-th signal cycle. $\delta_{i,m,n} = 1$ means the traffic light is green, $\delta_{i,m,n} = 0$ means that traffic light is red.

Equations (2) - (5) represent the basic phase constraints, with reference to Figure 2:

$$\delta_{1,m,n} = \delta_{3,m,n} \tag{2}$$

$$\delta_{2,m,n} = \delta_{4,m,n} \tag{3}$$

$$\delta_{1,m,n} + \delta_{2,m,n} = 1 \tag{4}$$

$$T \cdot \sum_{n=1}^{N} (\delta_{i,m,n} + \delta_{i',m,n}) = C, \ \forall\, m, i \in \{1, 3\}, \ \ i' \in \{2, 4\} \tag{5}$$

Equations (6) - (8) set the phase sequence constraints:

$$\delta_{1,m,0} = \delta_{3,m,0} = 1 \tag{6}$$

$$\delta_{2,m,0} = \delta_{4,m,0} = 0 \tag{7}$$

$$if\ \delta_{2,m,n-1} = \delta_{4,m,n-1} = 1, \ \ \delta_{2,m,n} = \delta_{4,m,n} = 1 \tag{8}$$

2.2 Internal Boundaries Control Model

In the paradigm of the lane-free traffic of CAVs, CAVs are drive anywhere on the 2-D surface of the road, respecting the road boundaries. Approaches 1 & 3 or Approaches 2 & 4 in Figure 1 that occupy the same channel share the road resources (road width) to meet the possibly unbalanced traffic demands in the opposite directions. With reference to Figure 1,

$$w_{1,m} + w_{3,m} \leq 1 \tag{9}$$

$$w_{2,m} + w_{4,m} \leq 1 \tag{10}$$

where $w_{\mathrm{i},m}$ are the space shared ratios of approach i at cycle m.

Consider the smoothness of the IBC, $w_{\mathrm{i},m}$ should change gradually in a step-by-step manner, i.e.

$$0 < w_{min} \leq w_{i,m} \leq w_{max} \leq 1 \tag{11}$$

$$\left|w_{i,m} - w_{i,m-1}\right| \le w_0 \tag{12}$$

The time-delay issue is considered for the urban IBC. The attention should be given only to the traffic direction that is being widened, while the direction that is narrowed should promptly adopt the determined smaller width. In this work, the above idea is implemented via the following:

$$w^c_{i,m} = \min\{w_{i,m}, w_{i,m-1}\} \tag{13}$$

2.3 Store-and-forward Model of Vehicle Traffic

The model can be expressed as follows:

$$L_{i,m,n+1} = L_{i,m,n} + T(q^{in}_{i,m,n} - q^{out}_{i,m,n}) \tag{14}$$

$$q^{out}_{i,m,n} = min\{q^{in}_{i,m,n} + \frac{L_{i,m,n}}{T},\ q^{cap}_{i,m,n}\} \tag{15}$$

$$q^{cap}_{i,m,n} = \mathrm{Q} w^c_{i,m} \delta_{i,m,n} \tag{16}$$

where $L_{i,m,n}$, $q^{in}_{i,m,n}$, $q^{out}_{i,m,n}$, $q^{cap}_{i,m,n}$ denote the vehicular queue length, traffic demand, outflow, capacity at the intersection in approach i at cycle m in step n, respectively. Q represents the total capacity of the intersection. (14) formulates the queueing model, (15) delivers the outflow that is determined with the demand and the supply, and (16) determines approach i's outflow capacity with the total capacity Q, the signal status $\delta_{i,m,n}$ and road width ratio $w^c_{i,m}$.

2.4 Objective Function

The cost criterion to be minimized is defined as follows: The first term represents the average delay. The second/third term aims to smooth the temporal/spatial allocation of road resources over cycles.

$$J = \frac{\sum_{i=1}^{4}\sum_{m=1}^{M}\sum_{n=1}^{N}\frac{T}{2}(L_{i,m,n} + L_{i,m,n-1})}{\sum_{i=1}^{4}\sum_{m=1}^{M}\sum_{n=1}^{N} T \cdot q^{in}_{i,m,n}} + \lambda_1 \sum_{i=1}^{4}\sum_{m=1}^{M}\sum_{n=1}^{N}(\delta_{i,m,n} - \delta_{i,m-1,n})^2 + \lambda_2 \sum_{i=1}^{4}\sum_{m=1}^{M}(w^c_{i,m} - w^c_{i,m-1})^2 \tag{17}$$

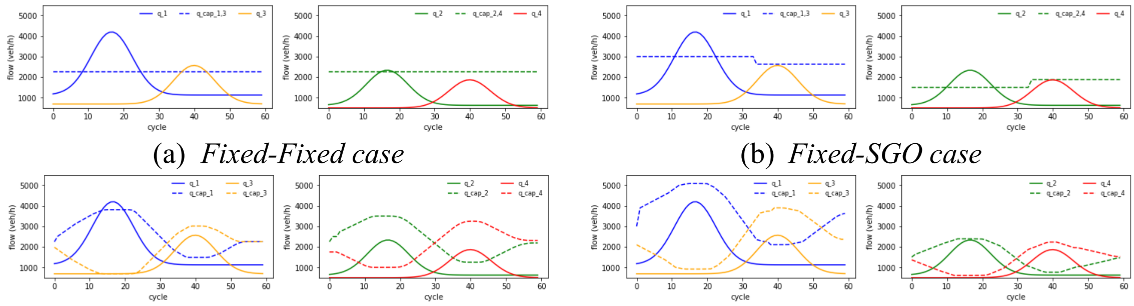
3 RESULTS

After linearizing the nonlinear formulae, this task can be formulated as a MIQP problem. The proposed problem was solved by GUROBI and PYTHON on a personal computer with a quad-core processor running at 3.4 GHz with 8 GB memory. This scenario was designed such that neither SGO nor IBC alone suffice but the combination of the two can handle the problem (Figure 3).

(a) (b)

Figure 3 – *Demand profiles for simulation scenario*

The simulation study results for this scenario are shown in Figure 4 with the four control methods considered. More specifically, each sub-figure displays the average demand and average capacity allocated for each approach over cycles Firstly, purely the SGO case (Figure 4b) could not accommodate the traffic demands in approaches 1 and 2. Secondly, purely IBC (Figure 4c) was not able to fully handle the demand in approach 1. Thirdly, the integrated IBC and SGO satisfactorily tackled the problem. Note that the total capacity in Figure 4b (the sum of the two dashed curves in two sub-figures for any cycle) is equal to 1/2*Q, the total capacity in Figure 4c (the sum of the two dashed curves in each sub-figure for any cycle) is equal to 1/2*Q, and the total capacity in Figure 4d (the sum of the fourth dashed curves for any cycle) is equal to Q.



(a) *Fixed-Fixed case* (b) *Fixed-SGO case*

(c) *IBC-Fixed case* (d) *IBC-SGO case*

Figure 4 – *Demands and capacities over cycles for simulation scenario*

4 DISCUSSION

The possibility of regulating urban roads' internal boundaries between opposite directions is investigated for lane-free traffic of connected automated vehicles. Particularly, the coordinated optimization of internal boundaries and signal timing for an isolated intersection has been studied. The optimization task problem is formulated as a binary-mixed-integer-quadratic-programing problem and solved using the standard branch-and-bound technique. The obtained results show that the joint optimization can better deal with traffic situations at an intersection, particularly those not tractable via signal timing optimization alone. Signal timing optimization can be applied to allocate the road capacity temporally to address unbalanced incompatible traffic demands in the opposing directions, while the internal boundary control assigns the road capacity spatially to deal with unbalanced compatible traffic demands in the opposite directions. The two control measures are both significant and irreplaceable. The co-utilization of both measures leads to the traffic efficiency improvement that either measure alone cannot achieve.

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