Emission based signal control optimization on arterials

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1 INTRODUCTION

The increasing transportation demand in urban areas has led to challenging issues including congestion and vehicular emissions on transportation networks. Efficient traffic control design is promising to provide solutions and address these challenges.

There is a plethora of research studies that have developed real-time signal control systems using various objectives functions in their optimization, many of which are targeted at minimizing the environmental impacts of traffic operations. Such signal control systems have utilized NO_x and HC emissions (Khalighi & Christofa, 2015), CO_2 emissions (Zhao *et al.*, 2021), CO, NO_x and HC emissions (Fan *et al.*, 2023) as their objective functions when optimizing signal settings. Often these objectives have been combined in multi-objective optimization models with delay (Lv *et al.*, 2013), travel time (Osorio & Nanduri, 2015), delay and capacity (Zhang *et al.*, 2022), delay, number of stops, and fuel consumption (Al-Turki *et al.*, 2020), as well as fuel consumption and noise (Balta & Özcelik, 2018). However, most of the studies do not account for oversaturated traffic conditions, emissions released from transit vehicles or the feasibility of implementing these signal control systems in real time.

To address these research gaps, this study develops a mathematical model that minimizes total emissions of both automobiles and transit vehicles at a single intersection that is part of a signalized arterial, i.e., vehicles arrive in platoons, when optimizing signal control settings. In addition to minimizing emissions of two modes, this research contributes by accounting for emissions by driving mode, i.e.,acceleration, deceleration, idling, and cruising, therefore, obtaining more accurate estimates of emissions, and providing a flexible and efficient real-time signal control system that can be implemented at real-world intersections. Lastly, the proposed signal control can handle both undersaturated and oversaturated traffic conditions.

2 METHODOLOGY

The mathematical model is formulated based on the assumption that there is no platoon dispersion from the upstream signalized intersection. The auto arrivals of the vehicles are deterministic since the time that the first vehicle of the platoon arrives at the intersection is known.

These platoons arrive at capacity as they have left the upstream intersection at capacity, assuming that the upstream intersection has the same capacity and characteristics (e.g. number of lanes, speed) with the downstream one.

This model can be applied in both undersaturated and oversaturated conditions, under the constraint that all vehicles are served within two cycles. In total, six different cases for auto vehicle delay and four cases for transit vehicle delay are considered. An example of an auto vehicle delay case is shown in Figure 1. In this case, the green time is not enough to fully discharge the residual queue. Therefore, some of the vehicles of the residual queue and the new platoon will become residual for the next cycle. Signal cycle length, phase sequence, and yellow times are constant.

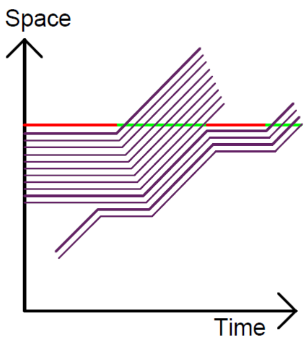

Figure 1 – *Case for auto vehicle delay.*

The mathematical program minimizes the auto and transit vehicle emissions for two consecutive cycles, T and $T+1$, by optimizing the green times of each phase i, i.e., $g_{i,T}$, for the current cycle T. The green times of the next cycle, i.e., $g_{i,T+1}$, are considered as equal to the optimal green times of the previous cycle, $T-1$. The objective function is shown in (1). Lower (2) and upper bounds (3) for green times are set so that no phase is skipped. The sum of the green times of all phases and the lost time sum up to the cycle length (4).

$$min \sum_{j=1}^{J} \sum_{l=1}^{L} \sum_{m}^{M} e_m^a t_{l,m,j}(g_{i,T}) + \sum_{b=1}^{B} \sum_{n=1}^{N} \sum_{m}^{M} e_m^b t_{n,m,b}(g_{i,T}) \tag{1}$$

$$s.t.\ \ g_{i,T} \geq g_{i,min} \quad \forall i \tag{2}$$

$$g_{i,T} \leq g_{i,max} \quad \forall i \tag{3}$$

$$\sum_{i=1}^{I} g_{i,T} + L = C \tag{4}$$

where:
J: total number of autos that arrive at the intersection during cycle T and $T+1$
L: number of auto cases
M: total number of operating modes, i.e., acceleration, deceleration, idling, cruising
B: total number of buses present at the intersection during cycle T
N: number of transit cases
m: operation mode index, i.e, acceleration, cruising, deceleration, idling
l: auto case index
n: transit case index
j: lanegroup index

i: phase index
$e_m^{a/b}$: emission factor for auto vehicles (a) or buses (b) in operation mode m [mg/sec]
$t_{l,m,j/b}$: time spent in each operating mode m, in case l, for auto lanegroup (j) or bus (b)
C: signal cycle length [sec]
T: cycle index
L: total lost time during each cycle [sec]
$g_{i,T}$: green time allocated to phase i during cycle T [sec]
$g_{i,min/max}$: minimum/maximum allowable green time allocated to phase i [sec]

3 Test Site

The intersection of University and San Pablo Avenues in Berkeley, CA has been selected as the study site to evaluate the emission-based signal control system with real world geometric, traffic, and signal timing data. The intersection signal operates on a 4-phase cycle and has a flow ratio of Y=0.73. Traffic volumes and signal settings for the evening peak hour (4pm-5pm) have been obtained from previous studies (Christofa, 2012). The cycle length C is 80 seconds and the lost time is L is 14 seconds. The intersection has five conflicting transit routes. Information about the bus routes has been obtained from the Alameda and Contra Costa Transit website.

4 EVALUATION

Deterministic and stochastic arrival tests are preformed to evaluate the performance of the emission-based signal control system. Deterministic arrival tests assume constant acceleration and deceleration rates and perfect information about the auto and transit vehicle arrival times. In each cycle T, the green times of the previous cycle $T-1$, i.e., $g_{i,prev}$, are updated with the optimal values and the residual queues for the next cycle $T+1$ are estimated based on the vehicles that were not served in cycle T. Stochastic arrival tests are performed with the microsimulation software AIMSUN, where stochasticity is introduced in platoon sizes, as well as auto and bus arrival times. The acceleration and deceleration rates are considered to be 3 m/s^2 and 4 m/s^2 respectively. An average cruising speed of 45 km/h and 30 km/h is considered for auto and transit vehicles respectively.

Three scenarios are tested for both deterministic and stochastic arrival tests: a) vehicle-based, b) person-based, c) emission-based optimization. The tests are conducted for different intersection flow ratios, Y, varying from 0.4 to 1.2 so that the system is evaluated under both undersaturated and oversaturated conditions.

The emission rates are obtained from a previous study (Khalighi & Christofa, 2015) for which were estimated using the Vehicle Specific Power mode for both auto and transit vehicles. The focus is on gasoline cars and diesel buses which have the hydrocarbon (HC) and nitrogen oxide (NOx) respectively as the main pollutants.

5 RESULTS

Figure 2 illustrates preliminary results on the reduction in auto NOx emissions from the vehicle-based to the emission-based scenario for deterministic arrival tests for the first two consecutive cycles of the peak hour. The highest auto emission reduction is 19% and is achieved under intersection flow ratio Y=0.4. The emission reduction is higher in lower intersection flow ratios due to the flexibility in the cycle in allocating green times to different phases to reduce emissions.

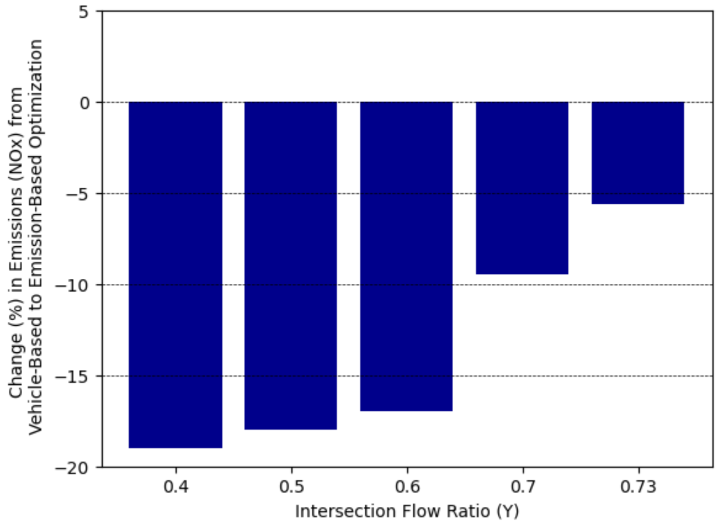

Figure 2 – *Percent change in auto NOx emissions for various intersection flow ratios from vehicle-based to emission–based optimization (deterministic arrival tests).*

6 CONCLUSION

The study presents a real-time signal control system that minimizes auto and transit vehicle emissions at an intersection that is part of an arterial, i.e.vehicles arrive in platoons. A sensitivity analysis with respect to intersection flow ratios is conducted. The results on emission reduction show improvement on auto vehicles for undersaturated traffic conditions, while the reduction is higher in lower intersection flow ratios. The presentation will also include results on deterministic arrival tests that minimize both transit vehicle and auto emissions as well as on the corresponding stochastic arrival tests in both undersaturated and oversaturated traffic conditions.

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