

ADAPTIVE PERSON BASED SIGNAL CONTROL SYSTEM IN ISOLATED CONNECTED VEHICLE JUNCTION

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1 ABSTRACT

2 Urban person delay and congestion have becoming an increasing important issues. Connected ve-
3 hicle (CV) technologies offer opportunities for managing urban traffic efficiently to reduce vehicle
4 delays. The adaptive signal controls in CV environments are vehicle based controls, ignoring the
5 importance of reducing person delay and improving person mobility in urban areas. This paper
6 proposes an innovative Adaptive Person Based Signal Control Algorithm (APBSCA) to minimize
7 person delay at isolated urbans. APBSCA is able to explore flexible phase combinations and stage
8 sequences to find optimal signal timing solutions in certain prediction horizon. The vehicle in-
9 formation including positions, speeds and occupancy levels are collected through CV technology
10 as data sources. A three-level dynamic programming approach is adopted in APBSCA to update
11 the predictive departure time of every vehicle surrounding junctions, which is affected by network
12 environments and signal decisions. APBSCA figures out optimal signal timing parameters that
13 yield highest person delay saving values indicators at isolated junction over the prediction period
14 and implement the corresponding signal timings. The results indicate that APBSCA have better
15 results in reducing average person delay in vehicle in terms of high occupancy vehicles. APBSCA
16 offers significantly average person delay reduction up to 55%. The proposed APBSCA indicates
17 that person based controls have potential benefits in reducing person delay to consistent the future
18 urban goals of improving person mobility over vehicle based controls by better utilizing CV data
19 incorporating occupancy levels.

20

21 *Keywords:* Connected Vehicles, Adaptive Signal Controls, Dynamic Programming approach

1 INTRODUCTION

2 The increasing traffic delay and congestion is a growing problem in urban areas caused by dra-
3 matically rising passenger vehicle miles travelled (1). INRIX (2) research estimated that total
4 congestion cost across US, UK and Germany almost reaches to 461 billion dollars in 2017, which
5 is mainly attribute to time losses of drivers and passengers in vehicles.

6 Traffic signal control system plays a crucial role in urban signalized junctions and can po-
7 tentially mitigate urban congestion through fully response to dynamic traffic flow demands. Urban
8 Traffic Control (UTC) systems have experienced tremendous developments from pre-determined
9 fixed-time controls based on historical recorded data (e.g. TRANSYT (3)), actuated control to
10 more sophisticated traffic responsive control based on sensors at fixed locations (e.g. SCOOT (4),
11 OPAC (5)).

12 Recent advancements of Connected Vehicle (CV) technology can potentially remedy the
13 limitations of existing UTC systems. Many adaptive urban signal controls in CV environments are
14 developed to figure out new signal decision optimization paradigms based on better understandings
15 of road network states from connected data (6, 7). Most common of adaptive signal researches are
16 vehicle based controls, whose optimization algorithms are processed by reducing average vehicle
17 delays or vehicle travel times (8).

18 The importance of improving person mobility in urban networks are highlighted in future
19 urban traffic strategies (9). The average time loss of every person in vehicle rather than vehicle
20 itself largely determines the direct costs of congestion and this value is predicted to be 106 hours
21 per year in 2050, three times higher than time loss level in 2018 (10). Therefore, it is critical to
22 explore how the urban person based signal controls with the objective of reducing person delay in
23 urban signalized junctions will implement as realistic meanings of person congestion reduction.

24 This paper focus on developing person based urban signal controls in CV environments.
25 CVs are assumed to be 100% connected and capable of transferring vehicle status and occupancy
26 information to junction controller. The vehicles on road are awarded with different priority levels
27 according to their occupancy levels. The flexible phase combinations and stage sequences signal
28 schemes are adopted to explore optimal solutions of reducing person delay from all feasible possi-
29 bilities. This is inspired from bus priority strategies applying flexible signal timing plans to ensure
30 bus priority (11).

31 This paper proposes an Adaptive Person Based Singal Control Algorithm (APBSCA) to
32 minimize person delay at isolated urbans. The contributions of this paper are as follows:

- 33 • A three-layer dynamic programming person based signal control system called APBSCA
34 are proposed in CV environment at isolated junctions. The approach is capable of appro-
35 priately assigning signal priorities to vehicles according to passenger occupancy for the
36 objectives of minimizing person delay.
- 37 • A hypothesis urban isolated junction environments for the implementation and evaluation
38 of proposed APBSCA and three benchmarking models (fixed-time, actuated and vehicle
39 based connected) is constructed in simulation.
- 40 • The average person delay of APBSCA is collected in simulation and compared to other
41 three benchmarking models and its performance in reducing average person delay is
42 validated.

43 The proposed APBSCA approach develops a three-layer dynamic programming system to min-
44 imize average person delay in certain prediction period. The positions, speeds and occupancy
45 levels of CVs are absorbing in APBSCA as inputs. The upper level uses a forward recursion DP

1 to calculate the optimal person based performance measure based on the signal plans and vehicle
2 departure time in current stage and records optimal solutions. The middle level of process explores
3 all of the possible signal timing strategies for next stage following rules of signal adjacent list. It
4 also updates vehicle predictive departure time of all lanes for next stage combining state variables
5 and decision variables. At lower level, the algorithm finds the optimal person based performance
6 measure at the end of planning horizon and uses a backward recursion DP to search for signal
7 timing plan resulting in maximum value function.

8 This paper is organised as follows: The first section discusses the motivations and literature
9 regarding UTC systems and existing adaptive signal controls in CV environments. Second part
10 exhibits the whole structure of proposed APBSCA to explain how it works in each part. In third
11 part, the simulation procedure, evaluation settings and benchmarking models are outlined; the
12 performances of four signal controls are presented and discussed. Finally, conclusions and future
13 works are highlighted.

14 BACKGROUND

15 A great number of urban signal controls have been developed with the objective of smoothing
16 vehicle trajectories and reducing vehicle delays. The existing UTC systems experience three stages
17 as better reactive to traffic conditions through sensors: fixed time, actuated, traffic response UTCs.

- 18 • **Fixed-time controls** operate with stationary stage sequence and phase duration deter-
19 mined by local historical traffic data for different times of day (6). As a result, they have
20 poor flexibility and are not sensitive to traffic flow fluctuations during a day (12).
- 21 • **Actuated controls** collect real-time traffic data using sensors, such as loop detectors,
22 radar. They adjust signal cycle lengths, phase durations and signal sequences by applying
23 simple logics like extending unit green time (13).
- 24 • **Traffic response UTCs** use similar information resources as actuated control to acquire
25 data (e.g., speed and acceleration) from upstream urban road, with the advantages of
26 estimating short period incoming traffic flows and attempting to reach to maximum or
27 minimum objective functions by figuring out the optimal timing strategies.

28 Traffic response UTCs are most advanced traffic signal controls among three categories.
29 Table 1 summarizes the key features of common used traditional traffic response UTCs. However,
30 there are two limitations existed degrade the performances of traffic response UTCs.

31 It can be seen from Table 1 that the traffic data collection sensors (e.g. inductive loops
32 embedded under roads) adopted in most common UTCs are point detectors, which can only provide
33 a briefly snapshot of vehicles crossing it (14). It is challenging for UTC system to realize the
34 accurate state of vehicular environments and accordingly make signal timing decisions.

35 The second limitation is they are all vehicle based signal control system (seen in Table 1).
36 However, the number of people (including drivers and passengers) in different vehicles are varying
37 and most of cost metrics caused by urban road congestion are measured by person rather than
38 vehicle. Those control optimizations result in unfair treatments of high occupancy vehicles and
39 people inside without the consideration of real vehicle occupancy levels (8).

40 With the advancement of CV technology, new data sources are available to offer detailed
41 information for signal control optimization by accessing road and vehicle states (15). CV tech-
42 nology gathers abundant real time information describing vehicle states (e.g. positions, speeds,
43 accelerations, sizes) from variety kinds of most advanced data sensing technologies in Intelligent
44 Transport System (ITS) (16). It also enables information exchange among infrastructure and con-

TABLE 1: Key features of current coordinated traffic response control strategies

Control strategy	Objectives	Means of collecting data	Types of Data collected	Optimization system
SCATS (17)	Improving vehicular throughput, reducing congestion	Inductive loops	Vehicle flow, road occupancy	3-level hierarchical architecture
OPAC (5)	Minimize total vehicle delay	Inductive loops	Queue length (assumed), vehicle flow	Dynamic programming algorithm
SCOOT (4)	Minimize average vehicle delay	Inductive loops	Vehicle flow, Occupancy	On-line computer
RHODES (18)	Minimize average vehicle delay	Inductive loops	Traffic flow	3-level hierarchical architecture
PRODYN (19)	Minimize total vehicle delay	Inductive loops	Vehicle presence time, queue length (assumed)	Dynamic programming algorithm
MOTION (20)	Improve traffic flow performance	GPS	Traffic volumes	Adaptive Signal Control Technique
ALLONS-D (21)	Minimize average vehicle delay	Inductive loops	Vehicle arrivals	Branch and Bound algorithm
REALBAND (22)	Minimize total vehicle delay	Inductive loops	Traffic flow	3-level hierarchical architecture
CRONOS (23)	Minimize total vehicle delay	Video sensors	Queue length, number of stopped vehicles	CRONOS algorithm

TABLE 2: Key summary of adaptive urban signal controls in CV environments

Literature	Key information of control approach
(24)	<ul style="list-style-type: none"> • Predictive microscopic simulation algorithm (PMSA) in decentralized isolated junction • Predicting future traffic conditions using data received from CVs including positions, headings, and speeds • Deploying microscopic simulator to simulate vehicles and calculates the objective function of total vehicle delay directly every 15 seconds
(13)	<ul style="list-style-type: none"> • Real-time adaptive traffic control algorithm in isolated junction • Proposing a two-level dynamic programming approach to minimize total vehicle delay and queue length • An EVLS algorithm to estimate vehicle status of unequipped vehicles in three regions: queuing, slow-down, and free-flow region
(25)	<ul style="list-style-type: none"> • Cumulative travel-time responsive(CTR) real-time control algorithm • Updating the cumulative travel time (CTT) of every vehicle on respective approach and determining the highest CTT phase • Applying KF technique to estimate traffic states for CTT under imperfect connected vehicle penetration rates
(26, 27)	<ul style="list-style-type: none"> • Platoon-based Arterial Multi-modal Signal Control with Online Data (PAMSCOD) is proposed • A headway based platoon recognition algorithm is developed to identify pseudo-platoons based on vehicle probe data • Phasing sequence and start time of phases for the next considered cycle optimization • 40% penetration rate is critical for ensuring the performance of developed signal control approach
(28)	<ul style="list-style-type: none"> • Dynamic Programming (DP) and Complete Enumeration (CE) applied for 20 seconds predicted horizon • Integrating queue length estimation (ql-estimation) [40] into the proposed control algorithm using vehicle speeds and positions every 5 seconds • The objective is to determine the optimal phase sequence for the aim of minimizing queue length
(29)	<ul style="list-style-type: none"> • A traffic signal control algorithm utilizing the information from CV technology • Optimizing sequences of vehicles discharging from junction to minimize total vehicle delay
(30, 31)	<ul style="list-style-type: none"> • An intelligent traffic light controlling (ITLC) algorithm based on VANETs • Vehicular ad hoc networks technology is utilized to gather the real-time traffic information • Collecting real-time information at each signalized junction to optimize the sequence phases according to traffic flow characteristics
(32)	<ul style="list-style-type: none"> • A bi-level optimization model adopted to minimize total vehicle delay • Bidirectional V2I communication and integrating trajectory design for automated vehicles into signal control schemes
(33)	<ul style="list-style-type: none"> • An integrated framework for joint control of traffic signals and vehicle trajectories • A two-stage optimization model is developed where traffic signals and vehicle trajectories are optimized sequentially • DP is applied to the signal control problem with the objective to minimize vehicle travel time delay

1 nected vehicles (V2I, V2V) via wireless communication. Abundant of innovative adaptive signal
2 controls in urban areas incorporating connected information are developed (7).

3 Table 2 outlines key literature papers of urban adaptive signal controls adopting CVs, some
4 of which are summarized their details in (6). It describes how these proposed signal controls
5 implement and use forms of CVs data incorporated. The information provided in Table 2 indicates
6 that adaptive signal controls are all vehicle based controls as the objectives and performances of
7 vehicle based systems are measured by vehicles, which is not consistent with the target of reducing
8 person congestion.

9 There is a critical gap that no research attempts to investigate how person based traffic
10 signal timing schemes and traffic vehicular systems works if only consider the passenger cars
11 but different occupancy levels in urban intersections. Furthermore, the adaptive controls do not
12 explore the traffic signal adjustments by predicting the person based performances of different
13 signal timing choices without the constraints of fixed stage sequences and non-conflicting phase
14 combinations at every decision inspired by public transport approaches.

15 **SYSTEM OVERVIEW**

16 This section presents general framework of innovation person based signal control paradigm APB-
17 SCA for isolated urban junction. The structure of APBSCA is illustrated in Figure 1. The APBSCA
18 incorporates data inputs collection and process part, signal timing and phase plan optimization
19 part and signal timing decision execution part. A three-level dynamic programming signal tim-
20 ing optimization algorithm is developed as core principle of APBSCA to calculate person delay
21 measurements.

22 The APBSCA is researched to be implemented in four-leg isolated signalized junction
23 layout and phase allocations are illustrated in Figure 2.

24 The position, speed, occupancy and ID of every CV received by APBSCA are origi-
25 nated from BSM data framework under SAE J2735 message set, which broadcasts at 10HZ fre-
26 quency (13). BSMs are through IEEE 802.11p communication protocol which describes the hi-
27 erarchy of Dedicated Short-Range Communication (DSRC) designing for high speed vehicular
28 movements. The time step of proposed adaptive signal timing approach is set as 1s. The connected
29 intersection control region is defined as 250m as far enough reliable communication range, where
30 the messages can be received accurately under IEEE 802.11p DSRC networks (34).

31 **ADAPTIVE PERSON BASED DYNAMIC PROGRAMMING**

32 In this chapter, the details of proposed APBSCA is introduced to minimize average person delay
33 in urban isolated junction. APBSCA describes the controller decision making operational mech-
34 anism of associating traffic signal plans with corresponding person based performance measures,
35 considering occupancy level of each vehicle according to real time information from interaction
36 of junction controller and CVs. Dynamic programming is adopted to divide whole optimization
37 problem into sub-problem in every time step with recursive structure.

38 In a certain planning step the upper level of three-level DP optimization algorithm can
39 capture an optimal value function to a special traffic situation and remove any other strategies to
40 avoid recalculation from initial stage. The performance measure value function at every time step
41 should be calculated by combining junction policy and instantaneous environmental vehicle states.
42 Junction controller awards traffic green light to discharge vehicles or traffic red light to stop and
43 obstruct vehicle queues. In order to calculate performance measure, the middle level of three-level

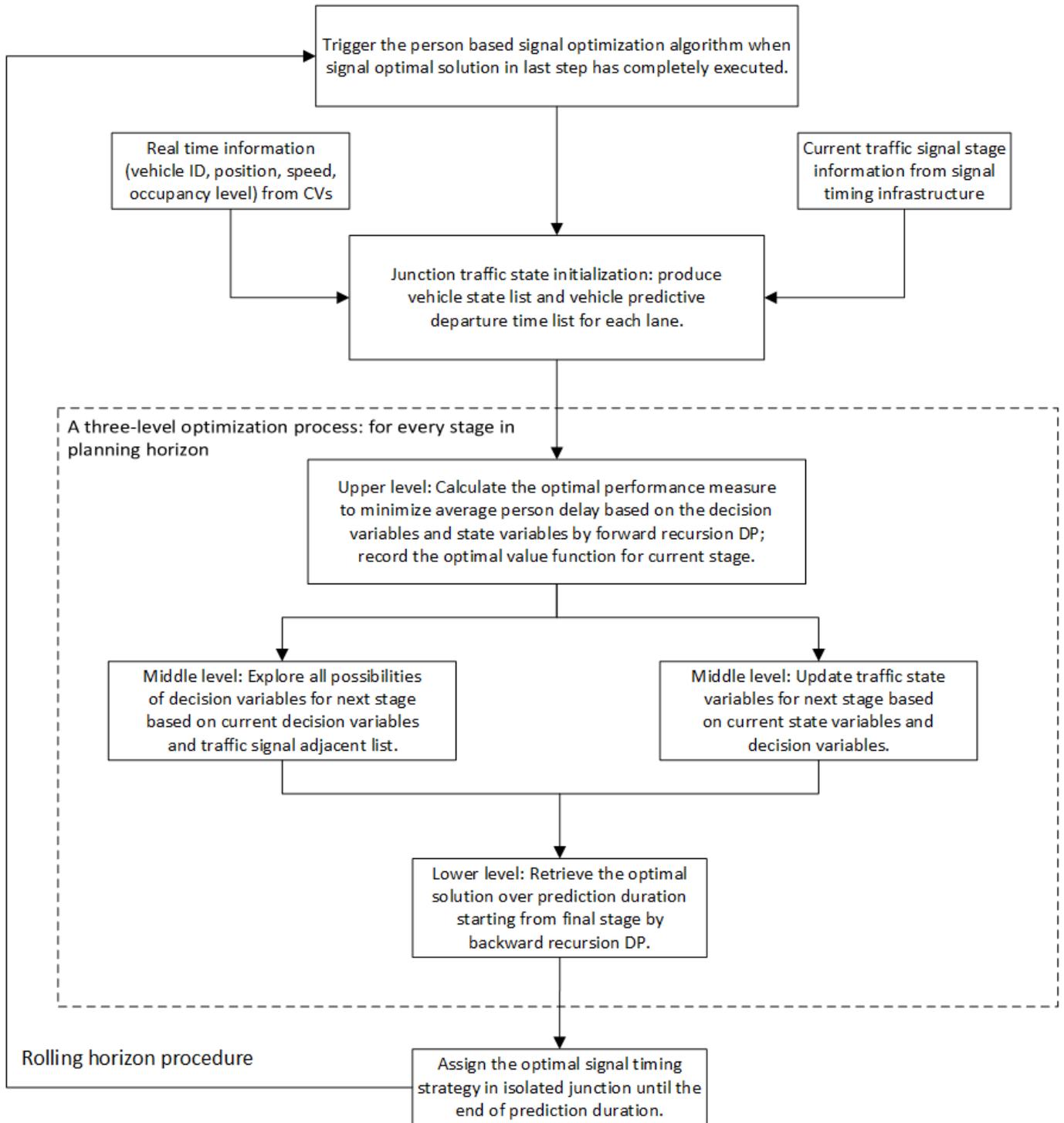


FIGURE 1: Conceptual framework flowchart of APBDP.

1 DP optimization algorithm updates the vehicle departure time list in every stage. The middle level
 2 also explores all kinds of possible signal plans based on flexible traffic light state machine in (35)
 3 rather than fixed stage sequence, such as a standard NEMA ring barrier signal timing structure
 4 in (13). At lower level, the algorithm finds the optimal person based performance measure at
 5 the end of planning horizon and uses a backward recursion DP to search for signal timing plan
 6 resulting in this value function.

7 All sets, variables and parameters used to formulate APBSCA are defined as follows:

8
 9

10 T : Set of all stages in the planning horizon, expressed in form of time step.

11 P : Set of all phases in an isolated junction.

12 D : Set of all possible traffic signal plans in a junction.

13 $D_t(s_t)$: Set of feasible control decisions at time stage t , given state variable s_t .

14 S_t : Set of possible traffic light phase states at stage step t .

15 L : Set of state transition linkage allowing junction state transfer between two stages.

16 $E(p)$: Set of all compatible phases given phase index t in isolated junction.

17 p : Index of phases in phase set P .

18 t : Planning time stage index in time step set T , expressed in form of time step.

19 i : Index of a vehicle in a specific lane at a specific time step, counting from the vehicle
 20 nearest stop line.

21 d_t : Control variable denoting traffic control decision made to time stage t from last stage.

22 m_t^p : Traffic light state in phase p at time stage t , represented by binary variables. 0 if red
 23 and 1 if green.

24 $\langle s_{t-1}, s_t \rangle$: Decision made by junction controller transition from state s_{t-1} to state s_t .

25 $f(t, s_t)$: Function value which represents the accumulated person based performance mea-
 26 sure for current stage and all of the previous stage, given state variable s_t .

27 $c_t(s_t, d_t)$: Performance measure for person delay at time stage t , given state variable s_t and
 28 control variable d_t .

29 s_t : State variable denoting current state of traffic light phase at time stage t , which value is
 30 represented by (p_t^1, p_t^2) .

31 $A(i, p)$: Occupancy level of vehicle i in phase p at beginning time stage.

32 $Tc(i, p)$: Time spent for vehicle i in phase p at beginning time stage when it crosses the
 33 stop line. Value equals to $T' + 1$ if it fails to cross in planning duration.

34 $Vc_t^p(i, s_t)$: Predictive departure time of vehicle i in phase p at time stage t , given state
 35 variable s_t assuming constant green light given for the phase in following stages.

36 $Sc_t^p(i, s_t)$: A binary variable represents predictive status, 1 represents free travelling status
 37 and 0 represents queuing/slow-down status.

38 $l_0^p(i)$: Instantaneous distance of vehicle i from stop line to its location in phase p at initial
 39 time stage 0 in meters.

40 $v_0^p(i)$: Instantaneous speed of vehicle i from stop line to its location in phase p at initial
 41 time stage 0 in meters per second.

42 F : Intergreen time interval in seconds.

43 α : Start-up lost time in seconds.

44 h_s : Saturation headway in seconds.

45 T' : Planning duration in seconds.

- 1 i_p : Number of vehicles in phase p at the beginning of planning.
 2 p' : Total number of phases in junction.
 3 A_0 : Occupancy limit of passenger vehicles.
 4 Δp : Time needed for first index of queuing vehicle ($i = 1$) discharging from stop line with
 5 constant green light in seconds.
 6 Δv : Speed threshold judging whether vehicle is free travelling status or queuing/slow-down
 7 status.

8 Data collection and process

9 The purpose of data collection and process is to adjust each piece of BSMs to vehicle information
 10 lists sorted by phase index. Every CV can only send real time information about its individual
 11 characteristics and trajectories to junction management infrastructure. The distance from those
 12 connected vehicles travelling within in range of detection region and approaching towards inter-
 13 section center to cross line of each lane can be calculated corresponding to location information.
 14 The connected vehicles recognized by their IDs are then sorted according to their distance from
 15 intersection, as well as their speed statuses and occupancy levels.

16 The APBSCA then predict the initial departure time of connected vehicles in each lane. The
 17 vehicle departure times are predicted supposing that the next stage for this lane will be constantly
 18 activated with green lights. The travel times of connected vehicles are subject to two variable situ-
 19 ations: number of vehicle in front of it and current green active/ red inactive state of the specified
 20 lane (36). In most congested road situations, the vehicle flow will be discharged following satu-
 21 rated flow rates, which can be observed when vehicle queues are given green priority. Otherwise
 22 the vehicle travel time equals to the distance to the cross line divided by current speed. The predic-
 23 tive departure time of first vehicle and following vehicles in a lane are modified from (31), shown
 24 in formula 1 and 2:

$$Vc_t^p(1, s_0) = \begin{cases} \alpha + h_s - g_p & \text{if } v_0^p(1) = 0 \text{ and } g_p < \alpha + h_s \\ \min[\alpha + h_s - g_p, l_0^p(1)/v_0^p(1)] & \text{if } 0 \leq v_0^p(1) \leq \Delta v \text{ and } g_p < \alpha + h_s \forall p \in P \\ l_0^p(1)/v_0^p(1) & \text{if } v_0^p(1) > \Delta v \text{ or } g_p \geq \alpha + h_s \end{cases} \quad (1)$$

$$Vc_t^p(i, s_0) = \begin{cases} Vc_t^p(i-1, s_0) + h_s & \text{if } v_0^p(i) \leq \Delta v \\ \max[Vc_t^p(i-1, s_0) + h_s, l_0^p(i)/v_0^p(i)] & \text{if } v_0^p(i) > \Delta v \end{cases} \quad \forall p \in P, i \geq 2 \quad (2)$$

25 The travelling status of each vehicle when it leaves from the approaching lane is defined by
 26 binary variables. The calculation of first vehicle and following vehicles in lane counted from stop
 27 line are expressed in formula 3 and 4 respectively:

$$Sc_t^p(1, s_0) = \begin{cases} 1 & \text{if } v_0^p(1) > \Delta v \\ 0 & \text{if } v_0^p(1) \leq \Delta v \end{cases} \quad \forall p \in P \quad (3)$$

$$Sc_t^p(i, s_0) = \begin{cases} 1 & \text{if } v_0^p(1) > \Delta v \text{ and } Vc_t^p(i, s_0) > l_0^p(i)/v_0^p(i) \\ 0 & \text{other cases} \end{cases} \quad \forall p \in P, i \geq 2 \quad (4)$$

1 Upper level of three-layer DP

2 The objective of APBSCA is to minimizing the average person delay of the isolated urban in-
 3 tersection. The vehicle delay is calculated by the difference value of vehicle predicted departure
 4 time and virtual departure time from the downstream place of junction. A mixed integer linear
 5 programming model is developed in APBSCA maximizing the total number of person discharging
 6 time savings. The occupancy level factor is incorporated into objective function to assign fairly
 7 priorities to vehicle users and their vehicles. The objective function is formulated in equation (5-5):

$$\max \sum_{p=1}^{p'} \sum_{i=1}^{i_p} A(i, p) [T' + 1 - Tc(i, p)] \quad (5)$$

8 *s.t.*

$$0 \leq A(i, p) \leq A_0 \quad i = 1, 2, \dots, i_p, \forall p \in P \quad (6)$$

$$0 \leq Tc(i, p) \leq T' + 1 \quad i = 1, 2, \dots, i_p, \forall p \in P \quad (7)$$

$$0 \leq \sum_{p=1}^{p'} m_t^p \leq 2 \quad \forall t \in T \quad (8)$$

$$Vc_t^p(i, s_t) < Vc_t^p(i+1, s_t) \quad i = 1, 2, \dots, i_p - 1, \forall t \in T, \forall p \in P, \forall s_t \in S_t \quad (9)$$

$$d_t \in D_t(s_t), s_t \in S_t \quad \forall t \in T \quad (10)$$

9 Constraints 6 and 7 limit the value ranges of occupancy level parameter in each vehicle
 10 and prediction departure time of each vehicle. Equation 8 constraints the number of green traffic
 11 light phases in a certain time, which should be no more than 2 to obey the rules of non-conflicting
 12 phases in standard 8-phases isolated junction to avoid vehicle collision. Constraint 9 sets out the
 13 relationships of departure time among those vehicles in the same lane.

14 At upper level, the multi-stage DP applies a forward recursion to solve the signal timing
 15 optimization problem in certain planning horizon. Forward recursion calculates the performance
 16 measure based on the state variables and decisions then records the optimal value function for each
 17 stage. The forward recursion of DP is on the basis of assigning signal phase plans to each stage as
 18 time step.

1 All of the feasible states s_t and junction decisions d_t at time step stage t are derived from the
 2 sets of possible states S_t and control decisions $D_t(s_t)$. The determinations of state set and control
 3 decision set depend on phase transition regulation and state set in last stage, which are represented
 4 in equations 11 and 12 respectively.

$$S_t = \{s_t | \langle s_{t-1}, s_t \rangle \in L, s_{t-1} \in S_{t-1}\} \quad \forall t \in T \quad (11)$$

$$D_t(s_t) = \{ \langle s_{t-1}, s_t \rangle | \langle s_{t-1}, s_t \rangle \in L, s_{t-1} \in S_{t-1} \} \quad \forall t \in T \quad (12)$$

5 The details of forward recursion are described as follows:

6

7

8 Step1: set $t = 1$ and $f(0, s_0) = 0$:

9 Step 2: for each of $s_t \in S_t$:

$$10 \quad f(t, s_t) = \max_{s_t} \{c_t(s_t, d_t) + f(t-1, s_{t-1}) | d_t \in D_t(s_t)\}$$

11 Record $s_{t-1}^* = O^*(s_t)$ as optimal solution for state variable s_t at time stage t .

12 Step 3: If $t < T' : t = t + 1$, repeat from step 2.

13 Else record optimal state $s_T'^*$ reaching to maximum performance measure at final time

14 stage T' , where: $f(T', s_T'^*) = \max\{f(T', s_T') | s_T' \in S_T'\}$, stop.

15

16 The forward recursion in upper level starts the optimization at stage 1 by assigning cumulative
 17 value representing person based objective function to 0. For each stage, the upper level of DP
 18 calculates the performance measure of passenger discharging benefits, determining and recording
 19 the optimal solution $O^*d_t(s_t)$ combining with cumulative value function in last stage for each state
 20 variable s_t . At final stage, the optimization algorithm compares function values of different state
 21 to decide the optimal signal timing plans with highest objective function value.

22 Vehicle departure time update and flexible signal state mechanism

23 The departure times of vehicles for one lane are predicted assuming traffic green light is always
 24 given for current phase in following stages. The different traffic phase sequences and combinations
 25 in varying state will result in different vehicle status, affecting time spent to arrive at the stop
 26 line. The vehicle environments are essential to be updated at every stage corresponding to every
 27 generated state in state set given green or red traffic light. If the traffic phase stage is green at
 28 stage t , the renovation of predictive departure time for each vehicle in each lane is expressed in
 29 equation 13:

30 $I f g_i^p = 1$:

$$Vc_t^p(i, s_t) = \begin{cases} Vc_{t-1}^p(i, s_{t-1}) - 1 & \text{if } Vc_{t-1}^p(1, s_{t-1}) > 1, i = 1, 2, \dots, i_p \\ Vc_{t-1}^p(i+1, s_{t-1}) - 1 & \text{if } 0 < Vc_{t-1}^p(1, s_{t-1}) \leq 1, i = 1, 2, \dots, i_{p-1} \end{cases} \quad \forall p \in P, \forall t \in T \quad (13)$$

31 The green traffic light guarantees the smooth passage of vehicles and reduces the expected

1 arrival time of all vehicles to stop line. If junction controller allocates red traffic light to planned
 2 phase in present stage, the proceedings of vehicle discharging will be obstructed and none of the
 3 vehicles in this lane is able to leave, which is expressed in equation 14 and 15.

4 $I f g_t^p = 0$:

$$Vc_t^p(i, s_t) = \begin{cases} \max[Vc_{t-1}^p(i, s_{t-1}) - 1, Vc_{t-1}^p(i-1, s_{t-1}) - 1 + h_s] & \text{if } Sc_{t-1}^p(i, s_{t-1}) = 1 \\ Vc_{t-1}^p(i, s_{t-1}) & \text{if } Sc_{t-1}^p(i, s_{t-1}) = 0 \end{cases} \quad i \leq 2, \forall p \in P, \forall t \in T \quad (14)$$

$$Vc_t^p(1, s_t) = \begin{cases} \max[Vc_{t-1}^p(1, s_{t-1}) - 1, \alpha + h_s] & \text{if } Sc_{t-1}^p(1, s_{t-1}) = 1 \\ Vc_{t-1}^p(1, s_{t-1}) & \text{if } Sc_{t-1}^p(1, s_{t-1}) = 0 \end{cases} \quad \forall p \in P, \forall t \in T \quad (15)$$

5 In middle level of DP optimization algorithm, the set for all feasible traffic signal phase
 6 state is produced in each stage depending on signal state set in last stage and phase transition
 7 linkages allowing junction state transfer from last stage to current stage. As for phase transition
 8 linkages, the theoretical flexible traffic light state machine proposed in (35) is adopted in this
 9 research as it allows exploring all of the flexible phase transition linkage situations efficiently by
 10 obeying the rules of avoiding conflicting vehicle flow collision and eliminating unnecessary or
 11 meaningless linkages. To elaborate the feasible adjacent relationships, several criteria need to be
 12 satisfied meanwhile to ensure junction travelling safety and limited green time resource utilization:

- 13 • At any state in isolated junction, junction controller assigns green traffic lights to at most
 14 two non-conflicting phases to ensure the vehicle flow can safety cross junction center
 15 area without collision.
- 16 • The transitions between two states need to experience complete inter-green interval du-
 17 ration, each of which incorporates two non-conflicting phases with green light and all of
 18 them are completely different. However, if one of the green light phases in one state is
 19 same as one of those green light phases in another state, this phase should keep green
 20 lights during the inter-green time.
- 21 • The traffic signal phase state with two non-conflicting phases cannot transfer to itself after
 22 an intergreen duration. This criterion is to ensure maximizing use of green resources.

23 Lower level of three-layer DP

24 In lower level, a backward recursion is applied to retrieve the optimal policy for whole planning
 25 duration starting from the final stage operating backwards. After all of optimal decisions reacting
 26 to every state made in all stages, the optimal decision of each stage can be retrieved by backward
 27 recursion described as follows:

28

29

30 Step1: set optimal policy = [] and insert $s_T'^*$ into list;

31 Step 2:for $T = T', T' - 1, \dots, 2$:

32 find $s_{t-1}^* = O^*(s_t)$, insert s_{t-1}^* as first element in optimal policy list;

33 Step 3: If $t = 2$: stop, else repeat from step 2.

1
2 A rolling-horizon approach is applied for APBSCA where the problem is solved again when one
3 stage (barrier group) is executed in order to include more recent vehicle data from CVs. The
4 proposed approach collects data at a certain time step, predicts traffic state for a future duration
5 constituted by a number of time steps, and finds solution parameters with highest objective function
6 values, implementing it in isolated intersection over the prediction period.

7 **SIMULATION AND EXPERIMENTS**

8 To validate the performances of APBSCA, a hypothesis isolated junction and vehicular environ-
9 ments are constructed in microscopic simulation to test whether the APBSCA offers improved
10 measures compared to benchmarking models. The SUMO microsimulation environment is se-
11 lected applied to preform how models work because of its open source, space-continuous and
12 multi-model features (37). SUMO simulation can be controlled by a Python API which can inter-
13 face with SUMO to develop new complicated logistic managements proposed by researchers. The
14 model uses discrete time steps of 1s.

15 **Benchmarking models for validation**

16 To identify how the performances of APBSCA improve on the basis of new signal control paradigm
17 of person based rather than vehicle based and additional occupancy level information from CVs,
18 three different benchmarking models are defined and compared:

- 19 • **Fixed-time control algorithm (FTCA):** the phase sequence and green durations of sig-
20 nal control algorithm are fixed from historical recorded traffic flow data.
- 21 • **Inductive loop actuated control algorithm (ILACA):** signal control decisions for green
22 duration are variable, partly response to real time data collected from inductive loops.
- 23 • **Vehicle based adaptive CV signal control (VBACVSC):** A vehicle based adaptive sig-
24 nal control assign green duration to each stage based on the queue length and arriving
25 vehicle information from CVs.

26 **Junction settings**

27 To validate those control algorithms, an isolated crossroad intersection is designed as experiment
28 road network environment and built in SUMO micro simulation, which is shown in Figure 2. Each
29 direction contains two approaching lanes respectively for straight-right driving vehicles and left-
30 turn vehicles, and two discharge lanes. Each lane in this intersection is set as urban major arterial
31 road, operated at 50km/h vehicle speed limit.

32 **Control algorithm parameters**

33 The start time loss at the start of green time and saturated flow for each lane is observed to be
34 1.8s and 1400 veh/h separately in this intersection. Therefore the time needed to clear 1 vehicle in
35 queue is estimated to be 2.6s. For ILACA, each approach lane installs inductive loops at 6m and
36 18m from their stop lines (38) so that the vehicle flows can be detected. If vehicle flow is greater
37 than 80% of the saturated flow ($0.81400\text{veh/h} = 1120\text{veh/h} = 3\text{s/veh}$), the vehicle can be detected
38 less than 3s from the last detection time between detectors. Thus the unit extension time will be
39 extended for this lane corresponding to high vehicle demand. The typical values of extension time
40 is suggested to be a range from 0.1s to 2s in (39), so 1s extension time will be accepted here to
41 related to time step. A minimum green time of 15s will be adopted for each stage. A maximum

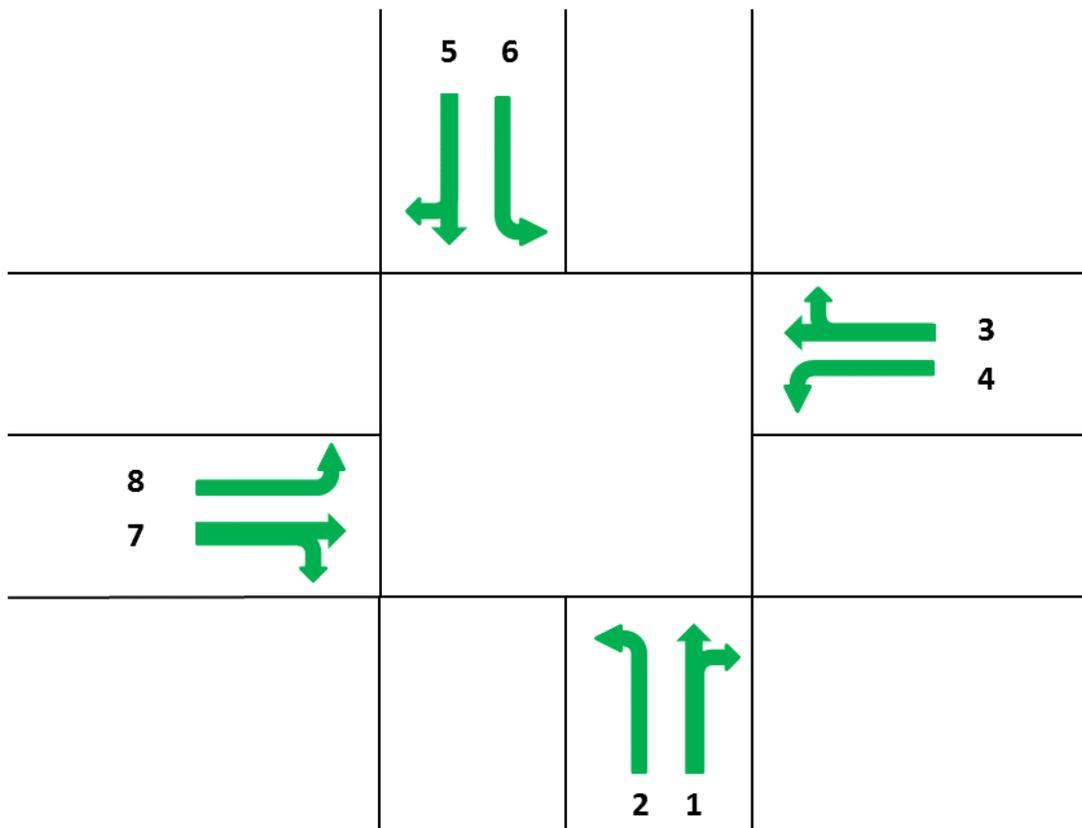


FIGURE 2: Isolated junction layout and signal phase diagram.

1 green time of 60s will be adopted for ILACA to improve the flexibility and variability of traffic
 2 responsive algorithm. The 60 s maximum green time will also be used in VBACVSC, makes it
 3 comparable to ILACA.

4 The Krauss microscopic car-following model is selected to describe the behaviors of ve-
 5 hicles driving in the road network because its parameters ensure vehicle flows to be stable and
 6 collision-free. Vehicles in different intersection routes are generated randomly for each simulation
 7 model experiment following the probability of vehicles driving along the specified route with same
 8 vehicle arrival distribution. The vehicle demands are generated at rates of 2400veh/h, operating
 9 for 20 minutes for the whole network.

10 Performance Indicators

11 Average person delay is selected for validation in this research to measure the delay suffered of
 12 passengers in vehicles. Delay is described as the excess time of one vehicle takes to complete its
 13 travelling routes compared to the free-flow travel time. The delay of one vehicle equals to actual
 14 travel time minus free-flow travel time. The delays of all passengers inside the vehicle are same as
 15 the value of vehicle delay. Therefore, the total delay of passengers in one vehicle equals to number
 16 of passengers multiply vehicle delay.

1 Different planning duration values will be adopted in APBSCA evaluation, which is in-
 2 cremented from 10s to 60s with a step of 10s to test the influences of planning horizon towards
 3 APBSCA.

4 **Results and discussions**

5 Table 3 shows the changes in average person delay for APBSCA and benchmarking models cate-
 6 gorized by different vehicle occupancy levels. The numbers expressed as percentages in Table 3
 7 represents the reductions of average person delay, across each of operating signal control approach
 8 by selecting FTCA as a baseline.

Control strategy	1-occupancy	2-occupancy	3-occupancy	4-occupancy	Summation average
FTCA	0%	0%	0%	0%	0%
ILACA	14%	13%	13%	15%	14%
VBACVSC	48%	43%	46%	42%	44%
APBSCA	42%	46%	48%	55%	50%

TABLE 3: Comparison of average person delays (s/per) sorted by different vehicle occupancies under different signal controls (FTCA, ILACA, VBACVSC, APBSCA). The values represent the percentage reductions of average person delay in APBSCA and other two benchmarking models against FTCA as a baseline.

9 It can be found from Table 3 that the average person delay is decreased by 14%, 44% and
 10 50% in ILACA, VBACVSC and APBSCA respectively compared to FTCA on certain degrees.
 11 The proposed APBSCA shows the greatest delay reduction effectiveness among these four deci-
 12 sion making algorithms, a 11% average person delay reduction is achieved even separately com-
 13 pared with VBACVSC. From Table 3 it can be found that adaptive signal control algorithms using
 14 CV data (VBACVSC and APBSCA) offer significantly delay reduction, above 42% in all levels
 15 of vehicle occupancies. The CV data inputs are highlighted to provide more accurate estimation
 16 of vehicle crossing time than infrastructure sensors such as inductive loops or pre-determined off-
 17 line signal optimization. In addition to reducing average person delay, adaptive CV signal control
 18 (VBACVSC and APBSCA) reduce the delay variability experienced by vehicle users and passen-
 19 gers in all occupancy levels from the box plots in Figure. The discrepancy of average person delay
 20 and delay variability between ILACA and VBACVSC/ APBSCA can be attribute to imprecise es-
 21 timation of road conditions, queue length discharging time, stage switching and green extension
 22 by inductive loop sensors.

23 The comparisons of VBACVSC and APBSCA in different occupancy levels in Table 3
 24 show that the proposed APBSCA can reduce average person delay up to 13% in 4 occupancy
 25 vehicles taking FTCA as a benchmarking. The average delay of passengers in 2 and 3 occupancy
 26 vehicles are slightly lower than those in VBACVSC. It can be seen from the results in Figure 3 (b),
 27 (c), (d) that the variants of person delay in APBSCA outperform than those in VBACVSC in the
 28 cases of 2, 3 and 4 occupancy vehicles. Additionally, the person delay in 1 occupancy vehicles does
 29 not significantly degrade (6% higher than VBACVSC) the performances of proposed APBSCA.
 30 The box plot in Figure 3 (a) indicates that the variability of person delay in 1 occupancy vehicles

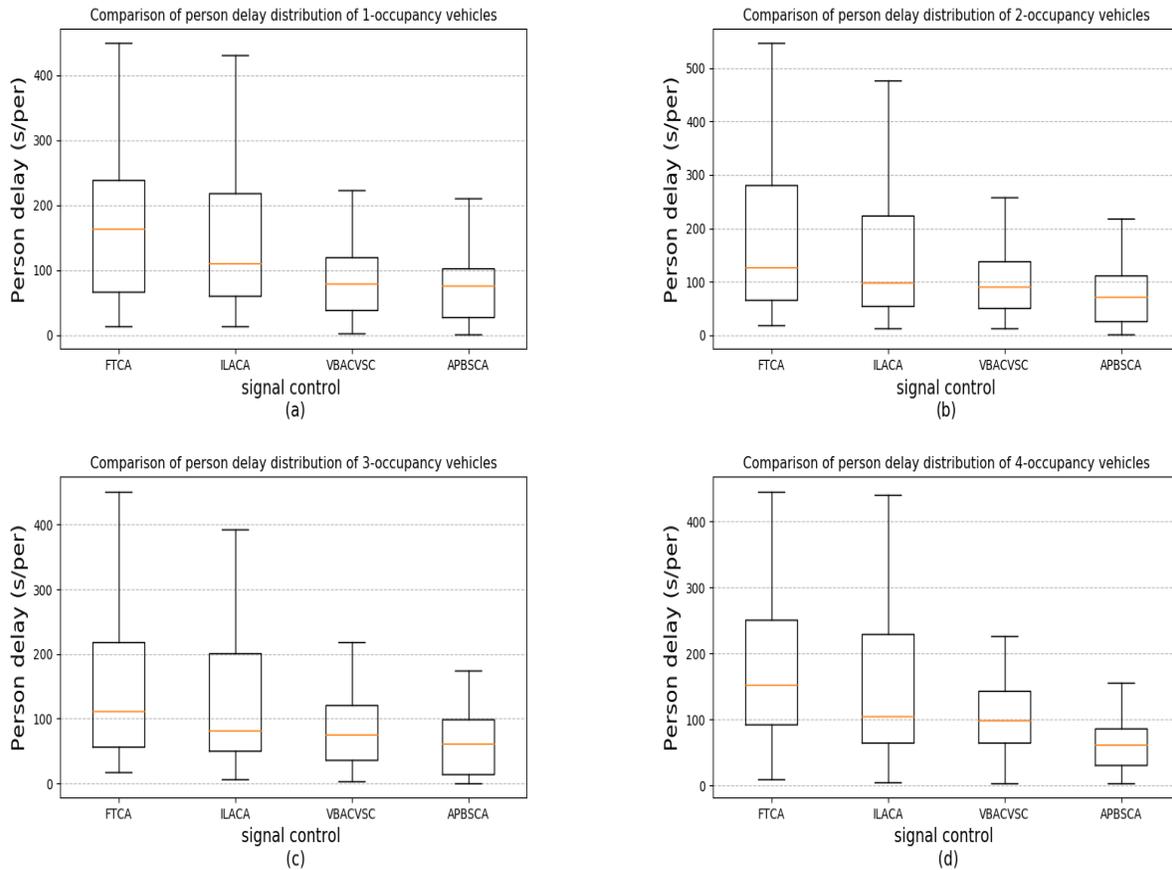


FIGURE 3: Box plots of 5th, 25th, 50th, 75th and 95th percentiles of delay per person (s/per) during simulation sorted by different vehicle occupancy levels (1, 2, 3, 4) under different signal controls (FTCA, ILACA, VBACVSC, APBSCA).

1 follows the similar pattern with those in VBACVSC. These results find that APBSCA performs
 2 to be much better in reducing average person delay than VBACVSC in terms of those vehicles
 3 with higher occupancy, on the premise of not significantly degrade the behaviors of low occupancy
 4 vehicles.

5 The results in Figure 4 indicates that in most cases of planning horizons, the higher occu-
 6 pancy vehicles (3 and 4 people in each vehicle) and passengers inside experience less delay than
 7 lower occupancy vehicles (1 and 2 people in each vehicle). This evident the person based signal
 8 control mechanism in APBSCA to assign higher priority and right of way to those vehicles with
 9 higher occupancy. The 30s planning horizon will be chosen for optimization approach among
 10 all tested scenarios in order to avoid both biased function value calculation in too short planning
 11 period and over/under estimation of vehicle travelling time without newest CV data in too long
 12 period.

13 CONCLUSIONS AND FUTURE WORKS

14 This paper develops an innovative predictive person based signal control APBSCA in urban roads.
 15 The objective of APBSCA is to minimize average person delay. Positions, speeds and occupancy

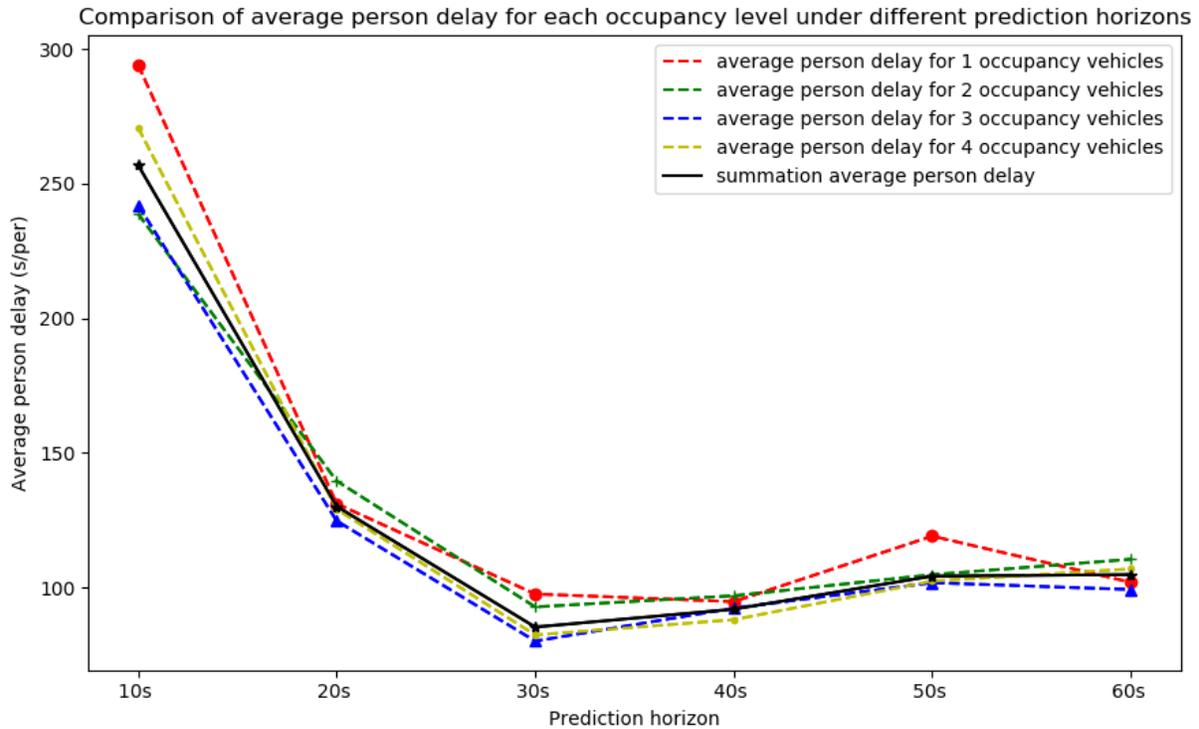


FIGURE 4: Line chart of average delays per person (s/per) in different occupancy level vehicles (1, 2, 3, 4) and summation average value in different DP prediction horizons (10s, 20s, 30s, 40s, 50s, 60s) in APBSCA. Each color represents a kind of vehicle occupancy level and black color represents summation average person delay.

1 levels of each CV from interaction of junction controller and CVs through wireless communication
 2 are required as data sources of signal timing decision optimization. An innovation three-level
 3 dynamic programming signal optimization algorithm is developed as the core of APBSCA after
 4 collecting and processing connected vehicle data. The three-level DP approach is able to explore
 5 all of the possible signal timing strategies in a certain planning horizon and efficiently figure out
 6 their person based value function for determining optimal solutions.

7 An experiment and evaluation framework to validate the performances of APBSCA in hy-
 8 pothesis urban isolated junction with three benchmarking models is also built in this paper. The
 9 results indicate that APBSCA have better performances in average person delay in terms of high
 10 occupancy vehicles. APBSCA offers significantly average person delay reduction up to 55%. The
 11 APBSCA also outperforms than vehicle based adaptive CV signal control in average and high oc-
 12 cupancy vehicles person delay, which highlights its effectiveness in dealing with reducing person
 13 delay in passenger vehicle environments.

14 Future works will be done to extend the junction scales of person based approach in CV
 15 environments into coordinated junctions. Some realistic scenarios, such as imperfect CV penetra-
 16 tion rates, variety flow demand and real world case study will also be considered to constructed
 17 to test the performances of proposed person based control. The functions of APBSCA should be
 18 supported in those cases if necessary.

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