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Developing a dynamic utilisation scheme for exclusive bus lanes on urban expressways: an enhanced CTM-based approach versus a microsimulation-based approach

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Abstract: In the current practice of bus rapid transit (BRT) system, under-utilized exclusive bus lanes (EBL) could negatively impact the system efficiency, particularly when traffic congestion occurs on regular vehicle lanes during peak period. In this paper, we propose an EBL sharing scheme to dynamically control the usage of the EBL by regular vehicles based on connected vehicle technologies without disturbing normal operation of the BRT system. An enhanced cell transmission model (CTM)-based approach and a simulation-based approach are proposed to model the traffic dynamics of a BRT section currently running in Chengdu, China. The optimal entry/exit proportion of regular vehicles are derived by minimizing total car delay on both the EBL and regular lanes given fixed bus service. The performance of the proposed dynamic sharing control scheme is evaluated under-saturated and over-saturated conditions. The sensitivity of the BRT service frequency and the average bus waiting time on the performance of the control scheme is also analysed. The results show that when traffic becomes over-saturated, delays on regular lanes can be significantly reduced by allowing optimized proportion of regular vehicles to use the EBL. However, it is unnecessary to use the EBL where traffic demand on regular lanes is low.

1 Introduction

The increase of traffic demand on urban networks has caused severe congestion particularly in metropolitan areas across the world. One strategy of mitigating traffic congestion is to attract more travellers to use public transport instead of private cars, e.g. travelling by bus, metro or tram. Therefore, transit priority measures such as dedicated/exclusive bus lanes (DBL/EBL) [1, 2], transit signal priority [3–8] and combination of both [9–11] have been widely applied in practice. These measures have effectively improved transit reliability and reduced running times when transit buses share the road space with regular urban traffic. The DBL/EBL system which can be implemented based on the existing road infrastructure is considered to be a cost-effective approach for providing a high-quality transit service [12]. However, allocating a dedicated lane to transit buses leads to the reduced road space for regular traffic and increased level of traffic congestion on regular lanes. Intuitively, the dedication of permanent bus lanes unfairly competes with regular lanes in the cases with a low frequency of transit services.

In order to better utilise the capacity of road space as well as provide priority for buses, Viegas and Lu [13–15] first introduced the concept of an intermittent bus lane (IBL). The basic idea is that an IBL is divided into sections which are open to general traffic when no buses are in use. Once a bus is approaching such a section, the status of the IBL is changed to the bus-only lane. When the bus leaves the section, it becomes a lane for regular traffic. Such operation scheme could work effectively when bus service frequency is low such that regular traffic will not suffer much delay, which has been analytically investigated by Viegas and Lu [15] and tested by some field experiments conducted in Lisbon, Portugal [16] and Melbourne, Australia [17]. In order to assess different transit priority measures, Zhu [18] proposed the cellular automata-based approach to investigate different scenarios of the DBL, the IBL and ordinary lanes and found that the IBL strategy performs best in terms of the trade-off between bus flows and regular traffic. Different from IBLs where vehicles already in the bus lane do not have to leave the lane, Eichler and Daganzo [19] proposed the IBL variant, termed bus lanes with intermittent priority 'BLIP' where regular traffic has to leave the lane reserved for the bus to ensure no regular vehicle queues exists in the bus lane, resulting in shorter travel times to buses. Both analytical models and simulation approaches have been developed to evaluate the feasibility, traffic condition requirements and benefits of implementing BLIP [19–21], the impact on the road capacity and travel times [22, 23], as well as advantages of new communication technologies (e.g. infrastructure-to-vehicle or connected vehicle (CV) communications) on the performance of the BLIP strategy [24].

While the focus of the IBL and the BLIP is using the existing urban road infrastructure to provide intermittent priority for buses to improve their level of service at the meantime have no significant impact on regular traffic in terms of delay or congestion, a more attractive alternative called bus rapid transit (BRT) system has been rapidly implemented in the cities around the world. A BRT system as a high-quality bus-based transit system could deliver fast, comfortable and cost-effective services at metro-level capacities. Such a system provides dedicated lanes with busways and modern stations to high capacity buses to assure fast and frequent operations [25]. Despite the advantages of the BRT system, it can be frequently observed in field operation that no transit bus is running at a certain section of the busway whereas traffic is congested on regular lanes, for instance, the BRT system on the elevated expressway in Chengdu, China. This under-utilisation of BRT lanes is unfavourable especially in an urban road network with limited space. Therefore, in this paper, we propose a control scheme to dynamically utilise the spare capacity of the

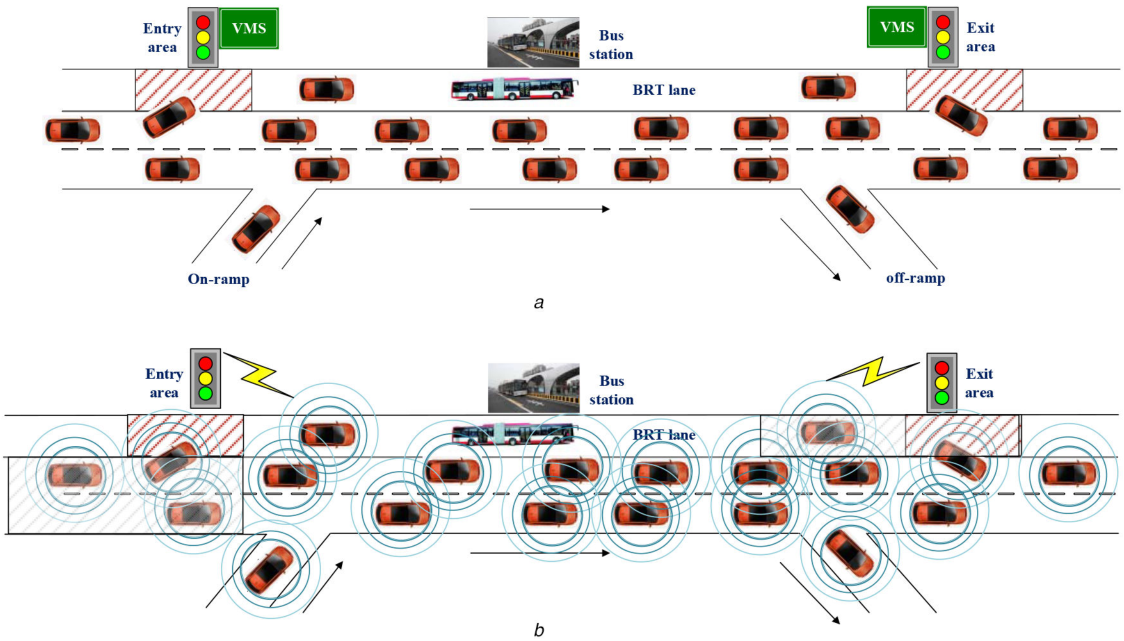

Fig. 1 *Illustration of dynamic usage control of the EBL*
(a) Control scheme 1: via signal control, ***(b)*** Control scheme 2: via CV technologies

EBL/BRT lanes in such a way that regular traffic can use the EBL as long as an uninterrupted BRT service is assured.

The rest of the paper is organised as follows. Section 2 introduces the problem specification of the BRT system in the city of Chengdu, China. Based on the dynamic EBL-sharing control scheme developed in our previous work [26], a new control scheme using CV technologies is proposed. In Section 3, we propose an enhanced cell transmission model (CTM)-based optimisation approach and a simulation-based approach to derive optimal control strategies such that the optimal entry/exit proportion of regular vehicles can be calculated for our specific scenario. Section 4 presents case studies including numerical and simulation-based examples to evaluate the performance of the proposed dynamic-sharing control scheme under different traffic conditions. Section 5 concludes the paper including a discussion of future research needs.

2 Problem setting and control scheme

The scenario we investigate in this paper is the second elevated expressway in the city of Chengdu, China. The expressway is a two-way road without intersections. For each direction, it consists of two lanes for regular traffic and one dedicated lane for buses known as the EBL or BRT Lane. Currently, the EBL of the elevated expressway cannot be used by regular traffic, which prohibits any regular vehicles from interrupting transit vehicles. However, it is frequently observed in this system that no transit bus is present on certain sections of the EBL while heavy traffic exists or congestion occurs on regular traffic lanes, at the upstream of the bottleneck (e.g. on-ramp) during peak-hours. It leads to not only inefficient capacity utilisation of the EBL but also cost ineffective considering the high construction cost of the elevated BRT system. Therefore, clear improvement opportunities exist to increase the utilisation of the EBL.

In [26], we have proposed an operation scheme to dynamically utilise the EBL as illustrated in Fig. 1*a*. The sharing system as defined previously consists of different entry and exit areas on the EBL to allow regular vehicles to enter or exit at those designated area guided by dynamic message signs or traffic signals. The signal at the entry/exit area controls whether a regular vehicle can enter/exit the EBL or not depending on green/red signals. The control parameter is the proportion of regular vehicles that can enter/exit the EBL like the concept of the green split in the signal control. Such an operation scheme is relatively low cost to be implemented in practice. In the proposed new control scheme, CV technologies are employed to dynamically control the entry/exit as shown in Fig. 1*b*. The system calculates the optimal proportion of regular vehicles that can enter/exit the EBL for a given time interval and disseminate the control messages (e.g. enter/exit the EBL or lane keeping) to the vehicles equipped with vehicle-infrastructure communication devices instantly. In this way, the system dynamically controls the proportion of CVs entering/exiting the control area according to traffic conditions both on the EBL and regular lanes. This is a step-further control scheme suitable for the CV environment that is widely believed to be implemented in near future. Nevertheless, there remain several questions to be investigated: (i) How to determine the optimal proportion of regular vehicles to enter/exit the EBL under different traffic conditions? (ii) How efficient is the proposed control scheme under different traffic conditions? (iii) How to evaluate the proposed dynamic EBL-sharing control scheme? To address these questions, we propose two approaches, namely an enhanced CTM-based approach for heterogeneous traffic and a microscopic simulation-based approach considering stochastic driving behaviour (e.g. lane changing behaviour) to model the operation of the dynamic EBL control scheme. The optimal control strategy is formulated by minimizing the total car delay on the EBL and regular lanes have given that the bus services on EBL are not interrupted. We further investigate the performance of the proposed scheme under different traffic conditions.

3 Methodology

3.1 Enhanced CTM-based approach

3.1.1 CTM for homogeneous traffic: In order to investigate how the proposed dynamic EBL-sharing scheme works, the traditional CTM [27] is applied to model the traffic dynamics of the system. In the traditional CTM formulation, traffic flow is assumed to be homogeneous. The road section is divided into cells with a fixed length of Δx and the time is divided into a fixed time interval of Δt (e.g. $\Delta t = 1$). The propagation of traffic flow can be described by equations:

$$n_i(t+1) = n_i(t) + q_i(t) - q_{i+1}(t) \tag{1}$$

$$\begin{aligned} q_i(t) &= \min\{S_{i-1}(t), R_i(t)\} \\ &= \min\{n_{i-1}(t), Q_i(t), \delta(N_i(t) - n_i(t))\} \end{aligned} \tag{2}$$

With $S_{i-1}(t) = \min\{n_{i-1}(t), Q_i(t)\}$

$$R_i(t) = \min\{Q_i(t), \delta(N_i(t) - n_i(t)\}$$

where $n_i(t)$ represents the number of vehicles in cell i at time step t, $q_i(t)$ is the number of vehicles flowing into a cell i at time step t, $Q_i(t)$ is the capacity of cell i at time step t, $N_i(t)$ is the maximum number of vehicles that cell i can accommodate at time step t, δ is the ratio of the backward speed and the free-flow speed given by w/v, $S_i(t)$ is the maximum number of vehicles can be discharged by cell i at time t and $R_i(t)$ is the maximum number of vehicles can be received by cell i at time step t.

3.1.2 Enhanced CTM for heterogeneous traffic mixed with buses and cars: The original CTM assumes homogeneous cells, which can be modified to consider heterogeneous cells. For instance, Levin and Boyles [28] proposed a modified CTM model to include a varying number of lanes in space and time in their dynamic lane reversal application with automated vehicles. In our specific scenario with the proposed dynamic control schemes, we need to model the traffic for the EBL and regular lanes separately, where mixed traffic with BRT buses and regular vehicles exist on the EBL. Therefore, it is necessary to develop a model which could describe the dynamics and the interaction among different types of vehicles. In order to model different characteristics of buses and cars, we introduce the passenger car equivalent (PCE) parameter γ_e as discussed in [22] to convert heterogeneous cells to homogeneous cells in terms of occupancy. The equivalent number of cars in cell i at time step t can be calculated as

$$n_i^{eq}(t) = n_i^{car}(t) + \gamma_e n_i^{bus}(t) \quad (3)$$

The number of vehicles in each cell for each time step is updated by applying the conservation equation of the CTM as

$$n_i^{eq}(t+1) = n_i^{eq}(t) + q_i^{eq}(t) - q_{i+1}^{eq}(t) \quad (4)$$

A new vector called 'sequence vector (SV)' is also introduced to track the sequence of individual buses and cars within the cell. We denote $P_i(t)$ the vehicle SV of cell i at time t. The conservation equation for $P_i(t)$ is given by:

$$P_i(t+1) = \left[P_{i-1}^{out}(t+1) \quad P_i^{r}(t+1)\right] \quad (5)$$

$$\text{with} \quad P_i^{out}(t+1) = P_i(t)\Big|_{n_i^{*}(t)}^{n_i^{eq}(t)} \quad (6)$$

$$P_i^{r}(t+1) = P_i(t)\Big|_1^{n_i^{*}(t)} \quad (7)$$

$$n_i^{*}(t) = n_i^{eq}(t) - q_{i+1}^{eq}(t) \quad (8)$$

where $P_i^{out}(t)$ is the outflow SV of cell i at time step t, $P_i^{r}(t)$ is the SV of remaining vehicles in cell i at time step t; $\boldsymbol{P}|_x^y$ represents the sub-vector from xth to yth of P.

3.1.3 Optimal control of entry/exit traffic: Fig. 2 shows the representation of the proposed dynamic EBL-sharing scenario using the enhanced CTM. There are two main links including one for the EBL/BRT lane and the other for (two) regular lanes. The lane-changing behaviour between two regular lanes is not explicitly considered. Thus, these two lanes are combined to a single link of cells. Apart from main links, there are also an on-ramp link and an off-ramp link. For this specific network, we have three types of CTM links: ordinary links merges and diverges. The bus station is regarded as a special ordinary link. We assume that all the buses must stop at the bus station. The traffic flow for different types of links can be calculated by applying the method proposed by Daganzo [29].

The control variables are the proportion values $(\beta_1(t), \beta_2(t))$ of regular vehicles that are allowed to enter/exit the EBL. The purpose of the dynamic control is to maximise the capacity utilisation of the EBL such that traffic congestion on regular lanes can be reduced while do not interrupt the normal operation of the BRT system. The objective function of this control problem is given by:

$$\min D = \sum_{t=1}^{N_B}\{D_{EBL,car}(\beta_1(t), \beta_2(t)) + D_{MRL,car}(\beta_1(t), \beta_2(t))\} \quad (9)$$

$$D_{EBL,car}(\beta_1(t), \beta_2(t)) = \sum_{i=1}^{N} n_{EBL}^{i}(\beta_1(t), \beta_2(t), t)\Delta t \quad (10)$$

$$D_{MRL,car}(\beta_1(t), \beta_2(t)) = \sum_{i=1}^{N} n_r^{i}(\beta_1(t), \beta_2(t), t)\Delta t \quad (11)$$

subject to

$$q_{EBL,out}^{j-1}(t) + q_{r,out}^{j-1}(t)\beta_1(t) \le R_{EBL}^{j} \quad (12)$$

$$q_{EBL,out}^{k}(t)\beta_2(t) + q_{r,out}^{k}(t) \le R_r^{k+1} \quad (13)$$

$$\beta_1(t) = 0 \text{ if } \quad L \le L_B \quad (t \in \{1, 2, \ldots, N_{TB}\}) \quad (14)$$

where $D_{EBL,car}$ is the total car delay on the EBL, $D_{MRL,car}$ is the total car delay on the main regular lanes (abbreviated as MRL), N_{TB} is the total number of time steps which is defined as the bus departure time interval T_1 divided by the simulation time interval Δt, N is the total number of cells for the EBL/regular lanes, L is the distance between the entry control area and the position of the bus upstream, L_B is the minimum headway distance between the bus and the downstream vehicle on the EBL to assure that regular vehicles do not affect the normal operation of the bus, $q_{EBL,out}^{j-1}(t)$ is the outflow of cell b_{j-1} on the EBL at time step t, $q_{r,out}^{k}$(t) is the outflow of cell r_k on regular lanes at time step t and R_{EBL}^{j} and R_r^{k+1} represent the maximum inflow of cell b_j on the EBL and cell r_{k+1}

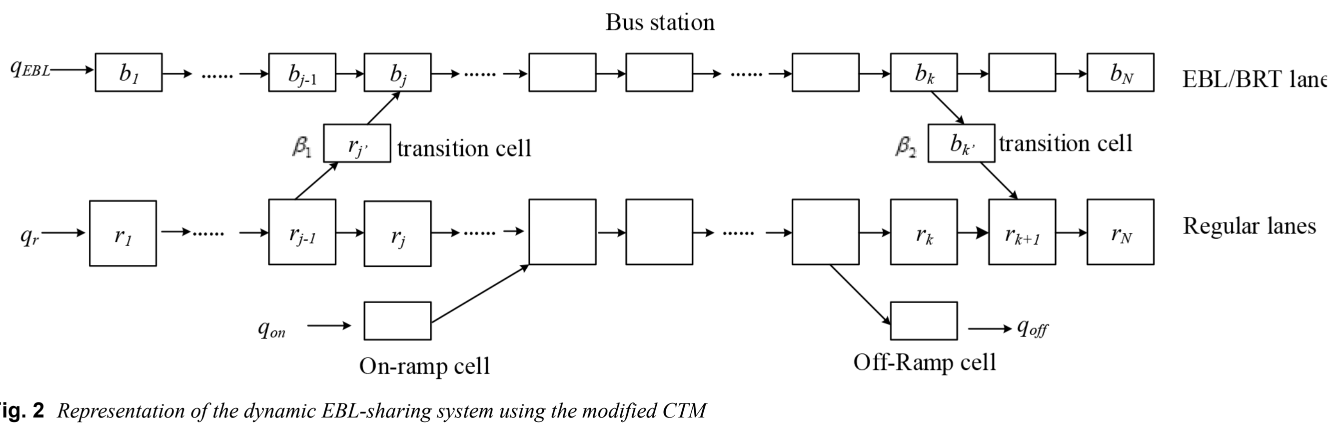

Fig. 2 *Representation of the dynamic EBL-sharing system using the modified CTM*

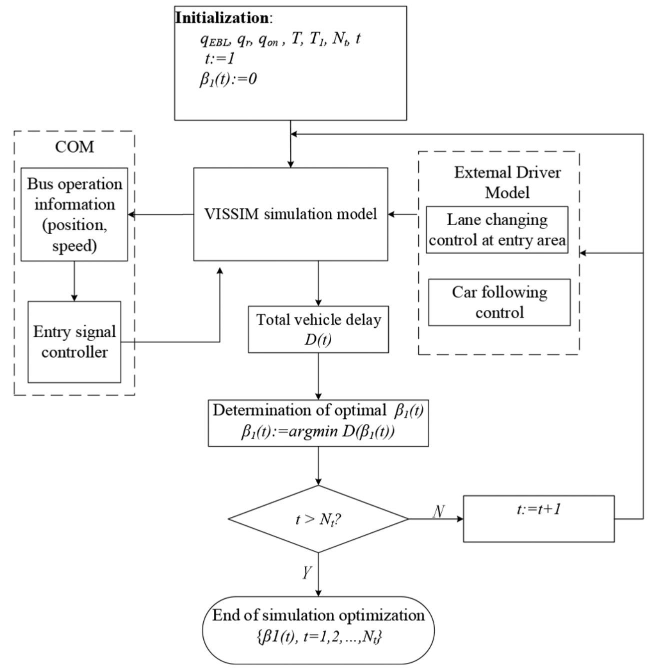

Fig. 3 *Simulation-based optimisation approach for the proposed dynamic EBL system*

on regular lanes, respectively; (12) and (13) ensure that regular vehicles are not allowed to use the EBL when the BRT service is very high (near capacity) or the traffic is congested at the immediate upstream of the exit area on the regular lanes; $n_{\text{EBL}}^i(t)$ and $n_r^i(t)$ represent the number of vehicles (in PCEs) in cell b_i on the EBL and cell r_i on MRLs at time step t, respectively. For the entry control area illustrated in Fig. 2, traffic dynamics for three types of links can be described as below.

Ordinary links: $n_{\text{EBL}}^i(t)$ is updated using (1) and (2).

Merges: Merges exist in the entry control area, the exit control area and on-ramps as shown in Fig. 2. e.g. the outflow of cell b_{j-1} on the EBL and the transition cell $r_{j'}$ are calculated according to

$$\text{if } R_{\text{EBL}}^j \geq S_{\text{EBL}}^{j-1}(t) + S^{j'}(t)$$
$$\begin{cases} q_{\text{EBL,out}}^{j-1}(t) = S_{\text{EBL}}^{j-1}(t) \\ q_{\text{out}}^{j'}(t) = S^{j'}(t) = \beta_1(t) q_{\text{r,out}}^{j-1}(t) \end{cases} \quad (15)$$

else

$$\begin{cases} q_{\text{EBL,out}}^{j-1}(t) = \text{mid}\left\{S_{\text{EBL}}^{j-1}(t), R_{\text{EBL}}^j - S^{j'}(t),\ p_{j-1} R_{\text{EBL}}^j\right\} \\ q_{\text{out}}^{j'}(t) = \text{mid}\left\{S^{j'}(t), R_{\text{EBL}}^j - S_{\text{EBL}}^{j-1}(t),\ p_{j'} R_{\text{EBL}}^j\right\} \\ p_{j-1} + p_{j'} = 1 \end{cases} \quad (16)$$

where p_{j-1} and $p_{j'}$ are the merge portion which can be explained as a priority for different lanes. In this paper, we assume that all the lanes have the same priority with $p_{j-1} = p_{j'} = 0.5$. In addition, the function mid { } is the middle of the three value.

The inflow of cell j can be calculated as

$$q_{\text{EBL,in}}^j(t) = q_{\text{EBL,out}}^{j-1}(t) + q_{\text{out}}^{j'}(t) \quad (17)$$

Therefore, the number of vehicles in cell b_j is updated by

$$n_{\text{EBL}}^j(t+1) = n_{\text{EBL}}^j(t) + q_{\text{EBL,in}}^j(t) - q_{\text{EBL,in}}^{j+1}(t) \quad (18)$$

Diverges: In case of diverges, e.g. the outflow of cell r_{j-1} on regular lanes can be calculated as

$$q_{\text{r,out}}^{j-1}(t) = \min\left\{S_r^{j-1}(t), \frac{R^{j'}}{\beta_1(t)}, \frac{R_r^j}{(1-\beta_1(t))}\right\} \quad (19)$$

The number of vehicles in cell $j-1$ is updated according to

$$n_r^{j-1}(t+1) = n_r^{j-1}(t) + q_{\text{r,in}}^{j-1}(t) - q_{\text{r,out}}^{j-1}(t) \quad (20)$$

where $q_{\text{r,in}}^{j-1}(t)$ is the inflow of cell r_{j-1} on regular lanes at time step t and $q_{\text{r,out}}^{j-1}(t)$ is the outflow of cell r_{j-1} on regular lanes at time step t given by (19).

Since the objective function of (9) is a time-dependent nonlinear function of the entry/exit control proportion, we apply the dynamic optimisation approach to convert the problem into discrete time steps with the same time interval defined in the CTM and derive the optimal values of β_1 and β_2 for each step.

3.2 Simulation-based approach

The CTM-based analytical optimisation approach considers deterministic behaviour of traffic flow and lane-changing behaviour is not considered in the model, which has advantages of fast implementation and efficient computation. In this section, we model the same dynamic EBL-sharing scenario using VISSIM microscopic simulation to consider the heterogeneous (stochastic) behaviour of vehicles in the system and propose a simulation-based approach to optimise the proportion of regular vehicles to enter/exit the EBL. Fig. 3 shows the algorithm flow of the proposed simulation-based optimisation approach for our specific network scenario modelled in VISSIM.

First of all, the network input flows of the EBL q_{EBL}, regular lanes q_r and the on-ramp q_{on}, the BRT bus departure time interval T_1, the total simulation time T are initialised. The number of optimisation steps is given by $N_t = T/T_1$. Apart from the VISSIM internal simulation model, two external components are introduced in our proposed model as shown in Fig. 3 with dashed boxes.

We use the COM interface to derive the real-time bus operation information, e.g. position and speed. If the distance between the entry control area and the current position of the bus upstream is smaller than the minimum distance L_B, the entry signal (controlled by the external signal controller) is set to be red such that no regular vehicles can enter the EBL. This consideration is to ensure the normal operation of BRT buses in the same sense as it is in the CTM approach. For each entry control proportion $\beta_1(t)$ at a time step $t (t \in \{1, 2, \ldots N_t\})$, we randomly select $\beta_1(t)$ of vehicles at the entry control area on regular lanes and use the external driver model to control the lane changing (from regular lanes to the EBL) and car-following behaviour. The car following control scheme is based on the vehicle kinematic dynamics considering the relative speed and spacing between the vehicle and its preceding vehicle, the desired speed and minimum safety distance. The detailed process is described in Fig. 4.

For the lane changing control, we focus on determining whether it is possible for a vehicle to perform lane changing considering the relative speed and the longitudinal distance between the current vehicle and adjacent vehicles on the upstream and the downstream of the EBL. The detailed lane changing motion control is carried out by VISSIM. Fig. 5 shows the lane changing control process.

For each optimisation step t, we calculate the total delay $D(t)$ of the EBL and regular lanes. The optimal $\beta_1(t)$ is determined with minimum total delay from the VISSIM simulation output.

4 Case study

In this section, we investigate the performance of the dynamic EBL-sharing control scheme (as shown in Fig. 1) using the enhanced CTM-based approach and the simulation-based approach. The total length of the road segment is 2.4 km. The simulation time period is set to be 1 h. We consider mixed demand (both buses and regular vehicles) at the origin of the EBL, where we set the $q_{\text{EBL,car}} = 360$ pce/h. The parameters of the CTM are

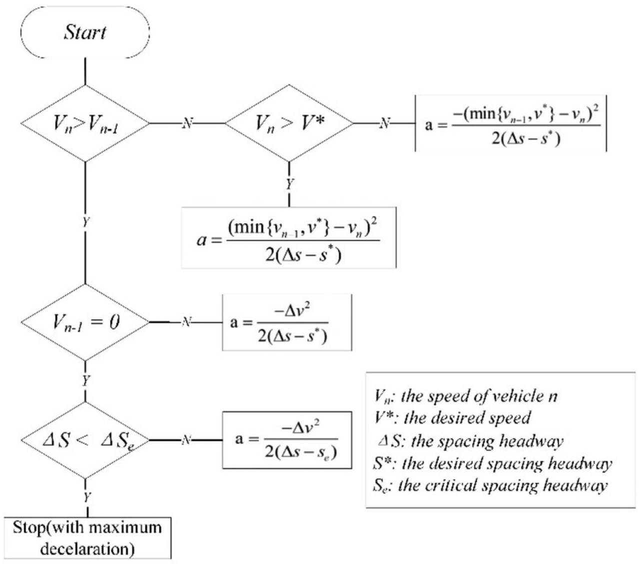

Fig. 4 *Car following control process use the external driver model in VISSIM*

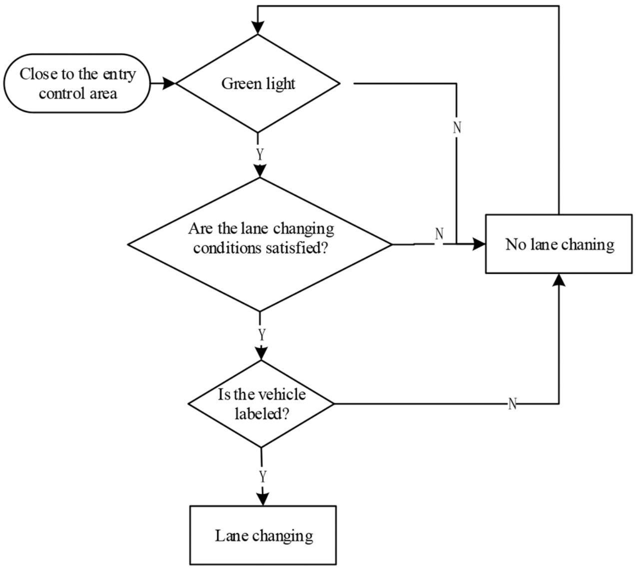

Fig. 5 *Lane changing control process use the external driver model in VISSIM*

Table 1 Parameters of the CTM in the numerical experiments

Parameters	Value
free flow velocity v_f	20 m/s
length of the cell l_c	200 m
time step Δt	10 s
capacity per lane Q	1800 pce/h
jam density k_j	125 pce/km
PCE value for BRT buses γ_e	2
backward wave speed w	5 m/s
bus departure time interval T_1	120 s
average waiting time for transit buses at the bus station τ_B	20 s

given in Table 1. Similar settings (including the road network and parameters) are used in the VISSIM simulation as well.

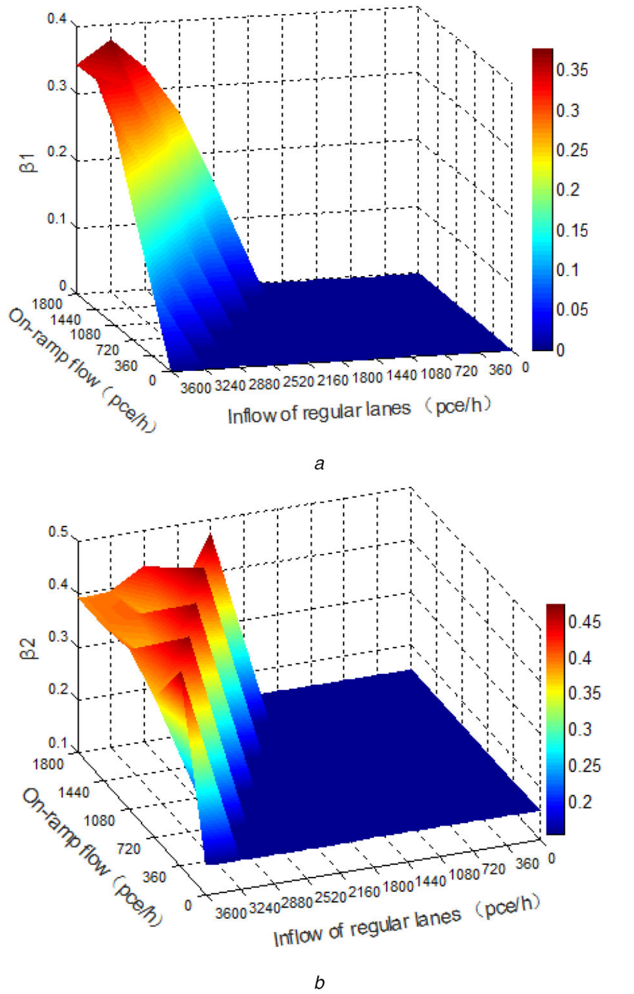

Fig. 6 *Optimal entry/exit control proportion as a function of the MRL inflow and the on-ramp flow*
(a) Entry control proportion β_1, ***(b)*** Exit control proportion β_2

4.1 Numerical results from the enhanced CTM-based approach

4.1.1 General performance analysis: Fig. 6*a* shows the optimal entry control proportion β_1 for bus departure time interval T_1 under different combinations of the MRL flow and the on-ramp flow. The off-ramp flow is set to be one-third of the flow on the MRL upstream the bottleneck (the off-ramp). When the total traffic flow of the MRL and the on-ramp is lower than the capacity of the bottleneck (3600 pce/h), no congestion occurs and the optimal entry control proportion is 0 which means no need to use the EBL in this case. When the traffic condition becomes saturated, e.g. the total flow is larger than the capacity of the bottleneck, congestion will occur at the bottleneck and propagates upstream if no EBL entry control is applied. It can be observed that the optimal entry control proportion increases with the increase of the traffic demand on regular lanes; meanwhile, the optimal control proportion varies for different combinations of the MRL inflow and the on-ramp flow, even the total flow upstream the bottleneck is the same. For the fixed total flow upstream the bottleneck, the entry control proportion increases with the increase of the on-ramp flow in the case of over-saturated conditions (degree of saturation (DS) > 1.0). Fig. 6*b* illustrates the exit control proportion from the EBL to the MRL, which depends on the traffic condition upstream the merge area of the MRL as well as respects the merge conditions described in the CTM.

Fig. 7 shows the optimal entry control proportion β_1 under different degrees of saturation at the bottleneck with the fixed on-ramp flow of 1800 pce/h. When the inflow of the MRL increases (e.g. the DS increases from 1 to 1.4), the control proportion β_1 increases ranging from 0.15 to 0.38. A slight decrease of β_1 can be

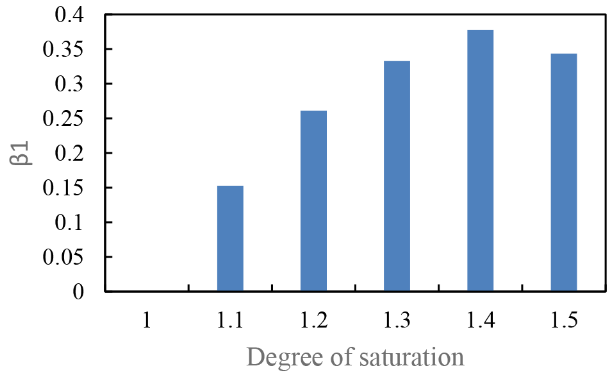

Fig. 7 *Optimal entry control proportion β_1 as a function of DS at the bottleneck (on-ramp flow is fixed to be 1800 pce/h)*

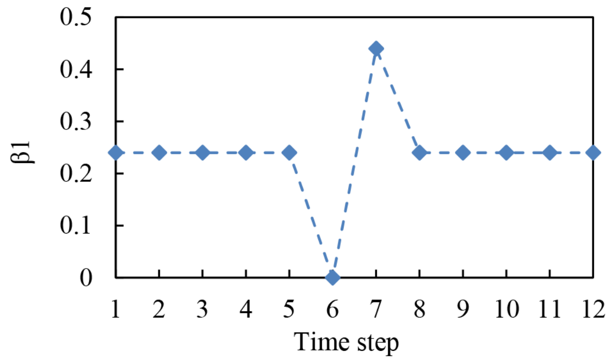

Fig. 8 *Entry proportion $\beta_1(t)$ as a function of the time step t for one bus departure time interval T_1*

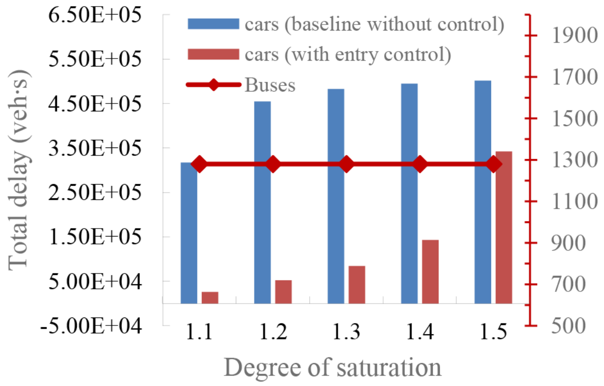

Fig. 9 *Total delay under different DS*

observed for the case of DS = 1.5, where both the MRL and the on-ramp are operating at the capacity flow. As we discussed in Section 2, the proposed CTM-based approach is able to explicitly trace the position of the bus in the cell using the SV. Therefore, the entry control proportion for each time step is optimised taking into consideration of the bus position on the EBL. Fig. 8 illustrates an example of the entry control proportion $\beta_1(t)$ for each time step ($\Delta t = 10$ s) during one bus departure time interval ($T_1 = 120$ s). When the distance L between the bus position and the entry control area is smaller than the predefined minimum safety distance (L_B = 200 m), vehicles on the MRL are not allowed to enter the EBL which leads to $\beta_1(t) = 0$ as can be seen in Fig. 8 at time step $t = 6$. After the bus leaves the entry control area, more vehicles can enter the EBL such that the congestion can be reduced on the MRL.

Fig. 9 shows the total car delay on the EBL and the MRL with the proposed EBL control scheme and without under different traffic conditions. The on-ramp flow is fixed to the capacity flow of 1800pce/h. It can be clearly observed that vehicle delays are reduced significantly by applying the optimal control scheme for different degrees of saturation. The bus delay is fixed for different traffic conditions since the prerequisite of the control scheme is

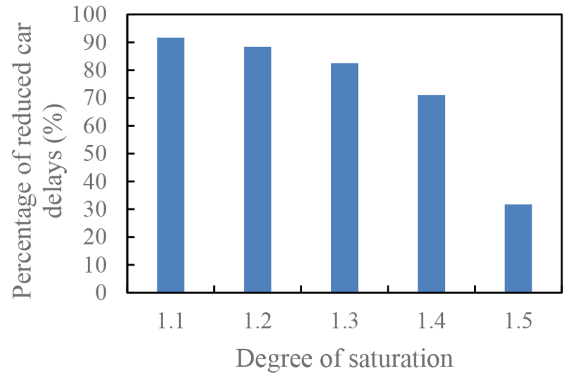

Fig. 10 *Percentage of reduced car delays under different DS*

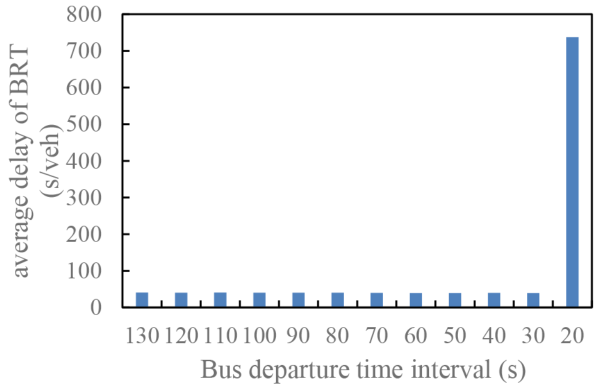

Fig. 11 *Average delay of the BRT bus as a function of the bus departure time interval*

that the normal operation of the BRT system is not disturbed. The percentage of reduced car delays ranges from 31.8 to 91.6% as illustrated in Fig. 10. When traffic is slightly congested on the MRL (e.g. DS = 1.1), applying the optimal entry control scheme could improve the traffic condition substantially with delay reduction up to 91.6%. When the traffic condition is highly oversaturated (e.g. DS = 1.5), the performance improvement becomes less significant with delay reduction of 31.8%.

4.1.2 Sensitivity analysis of bus departure time interval: Fig. 11 shows the relation between the average delay of the BRT and the bus service frequency. As can be seen from the figure, when the bus departure time interval is >30 s, the average delay of the BRT does not increase. In this case, the BRT operation is not interfered by the regular vehicles on the EBL. When the bus departure time interval decreases to 20 s (the same as the bus waiting time at the BRT station), the average delay increases significantly, which indicates that the regular vehicles have caused an extra delay to the BRT bus. Thus, it is unfavourable to allow regular vehicles to use the EBL when the bus service frequency is high.

4.1.3 Sensitivity analysis of bus waiting time: Fig. 12 illustrates the reduced percentage delay for regular vehicles as a function of the average waiting time for the BRT buses under different traffic conditions (v/c at the bottleneck is ranging from 1.1 to 1.5). When the traffic condition is slightly oversaturated ($v/c = 1.1$), the delay of regular vehicles is reduced significantly for different average waiting time of BRT buses at the bus station. When the traffic becomes more oversaturated (e.g. v/c is between 1.2 and 1.4), the percentage reduction of delays decreases with the increase of average bus waiting time. In the case that the traffic condition is highly oversaturated, e.g. v/c = 1.5, the control scheme does not help to reduce the delay for regular vehicles when the average waiting time is larger than (including) 30 s. The reason is that in this case, the queue on the EBL spills back to the entry control area where regular vehicles cannot enter the EBL anymore.

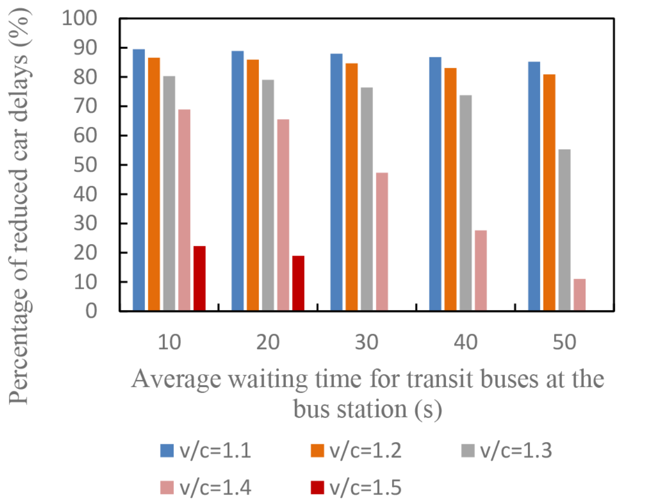

Fig. 12 *Percentage of reduced car delays with different waiting time for transit buses*

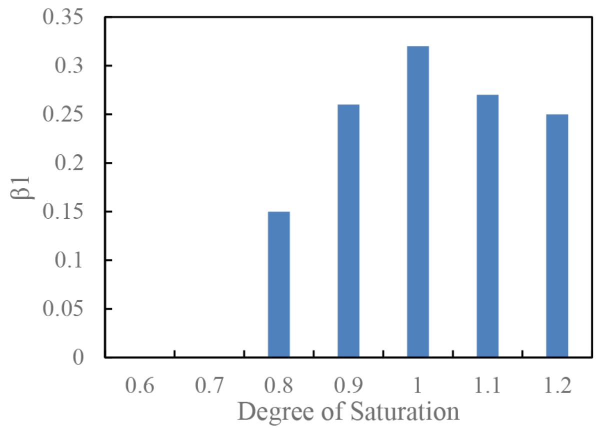

Fig. 13 *Optimal entry control proportion β_1 as a function of DS at the bottleneck derived from the simulation-based approach (On-ramp flow is fixed to 720 pce/h)*

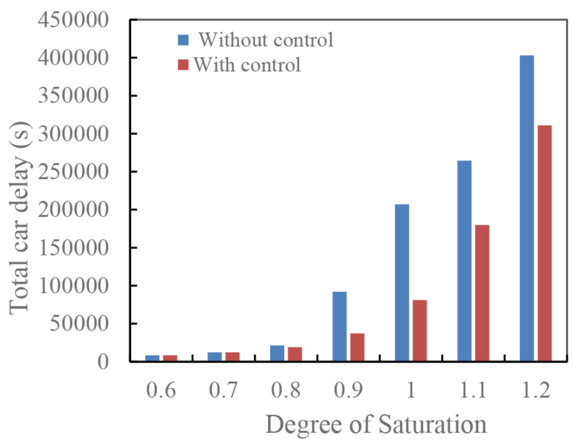

Fig. 14 *Total car delay under different DS for the simulation-based approach*

4.2 Results from the simulation-based approach

To evaluate the performance of the VISSIM simulation-based approach, we consider different traffic conditions at the bottleneck from the under-saturated condition (DS = 0.6) to the over-saturated condition (DS = 1.2). The inflow of the on-ramp is fixed to 720 pce/h. Fig. 13 shows the optimal control proportion of regular vehicles that are allowed to enter the EBL under different DS derived from the VISSIM simulation-based approach. When the total traffic demand is very low at the bottleneck (e.g. DS = 0.6 or 0.7), the optimised control proportion is 0 which is consistent with that of approach 1. When the traffic demand increases to (near) saturated condition (e.g. DS = 0.9 or DS = 1.0), vehicles experience delays at the bottleneck due to frequent (stochastic) lane changes. In this case, the optimal control proportion increases from 0 to 0.32. Compared with the CTM-based approach which gives the optimal control proportion of 0 when DS is <1.0, the simulation-based approach could capture the microscopic driver behaviour and produces more realistic results, in particular when the traffic condition is close to the saturated condition.

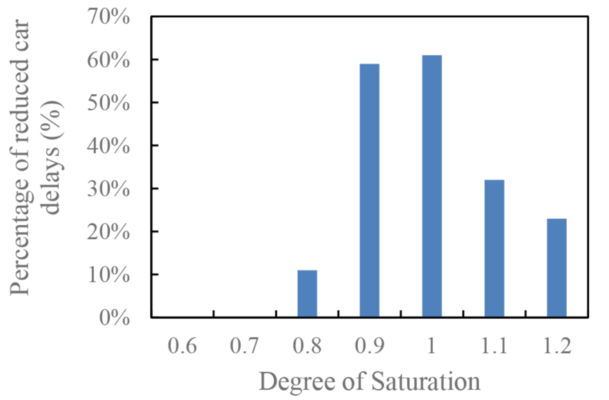

Fig. 15 *Percentage of reduced car delays under different DS for the simulated-based approach*

Fig. 14 illustrates the total car delay on the EBL and the MRL with and without the control scheme under different traffic conditions. It can be observed that the total car delay is reduced substantially using the EBL-sharing control scheme. The percentage of reduced car delays increases significantly from 0 to 61% when the DS increases from 0.6 to 1.0. Afterwards, the increase in the percentage of reduced delays becomes less significant as shown in Fig. 15. In comparison with the CTM-based approach, the simulation-based optimisation approach is much more computationally intensive and thus suitable for offline optimisation and evaluation. Nevertheless, the microsimulation-based approach considers individual driver behaviour and can capture traffic dynamics more realistically than the CTM-based macroscopic approach.

5 Conclusion

The BRT system has been well recognised for its fast and high-quality service to transit passengers. However, it is frequently observed that the EBLs are under-utilised when limited transit buses operate on the dedicated lane while long queues occur on regular vehicle lanes during a certain period, e.g. the BRT system in the city of Chengdu, China. In this paper, we propose a dynamic EBL-sharing scheme to allow regular vehicles to use the EBL via entry/exit control by the traditional signal control or via CV technologies at designated areas. The enhanced CTM-based analytical approach for heterogeneous traffic and the microscopic simulation-based approach considering individual driver behaviour is proposed to model traffic dynamics of the EBL-sharing scenario. The optimal enter/exit proportion of regular vehicles is derived by minimizing the total car delay on the EBL and the MRL. Based on the optimisation results, the entry/exit proportion at different time scales (e.g. per departure time interval or per time step) can be obtained for implementation.

Case studies are conducted to evaluate the performance of the proposed dynamic EBL control scheme. The results show that delays can be significantly reduced by allowing the optimised proportion of vehicles to use the EBL in over-saturated conditions at the bottleneck (on-ramp) on condition that there is no congestion at the immediate upstream of the exit area on regular lanes. The sensitivity analysis of the BRT departure time interval on the system performance indicates that the BRT delay increases substantially when the bus service frequency is high (e.g. the departure time interval is 20 s). In this case, it is unfavourable to implement the control scheme to allow regular vehicles using the EBL. Thus, the proposed control scheme could work effectively in the situation when the EBL lane and the immediate upstream of the exit area on regular lanes are uncongested.

The comparison between the enhanced CTM-based approach and the simulation-based approach indicates that the former is more efficient in the computation perspective and suitable for real-time control implementation. However, the CTM-based approach is deterministic that cannot consider the individual (lane-changing) behaviour of vehicles, especially at the merges and diverges. This could lead to the underestimation of congestion at the bottleneck, thus the optimal entry proportion is lower than that derived from the VISSIM simulation approach, where the stochastic lane changing behaviour is explicitly modelled.

Though the specific scenario analysed in this study is on an urban expressway, the proposed dynamic utilisation scheme of EBL could be generalised to different scenarios where EBL/BRT lanes are not physically isolated. Besides, the proposed control optimisation approaches (both the analytical approach and the simulation-based approach) could be applied or combined with signal control optimisation (in case of intersections) to other EBL scenarios in the urban area as well.

Apart from the performance evaluation and implementation scope of the proposed dynamic EBL-sharing scheme, there remain several issues to be investigated for practical considerations. For instance, the location and length of the entry/exit area could have an impact on the performance of the control scheme. For the entry/exit control, we assume full compliance of drivers which might be too idealistic for real-world situations. It could be interesting to investigate in future the impact of driver compliance on the performance of the proposed dynamic EBL-sharing control scheme. Furthermore, testing the effect of perturbations would be advisable before implementing the proposed control scheme on the road.

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