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Optimal Multimodal Travelway Design for an Urban Street Network

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ABSTRACT This study introduces a bi-level model for optimal travelway design of an urban street network by successively executing a lower-level model for traffic assignments and an upper-level model for network travel time minimization. A computational experiment is conducted for optimal travelway design of a 4-square-km urban street network containing 25 signalized intersections, 80 street segments, and 5 bus routes that accommodates 62,640, 43,200, and 33,120 person-trips per hour in AM/PM peak, adjacent-to-peak, and off-peak periods, respectively. Model execution results indicate that adopting a higher number of narrow lanes for auto use only and auto/bus shared use could potentially lead to increases in auto mode share and savings of network total travel time. More narrow lanes for auto use could raise auto speeds, but the auto/bus shared use of narrow travel lanes could slightly fluctuate bus speeds. Further converting narrow lanes for shared use by autos and buses to exclusive bus lanes (EBLs) could enlarge bus mode share, reduce network total travel time, slightly elevate auto speeds, and drastically increase bus speeds. The proposed model could be augmented to incorporate optimization of networkwide intersection signal timing plans, bus signal priorities, and bus dispatching frequencies into optimal travelway design.

INDEX TERMS Multimodal, optimization, street network, travelway, urban area.

I. INTRODUCTION

The population growth and economic development have resulted in increases in travel demand especially in urban areas worldwide. With the pace of travel demand escalation significantly surpassing the level of transportation system capacity expansion, urban street networks in many countries are currently operated near or at capacities especially in daily AM/PM peak periods. The ever-enlarging gap of capacity shortage has exacerbated more severe and prolonged recurrent traffic congestion. Owning to land scarcity in urban areas and prohibitively high costs of road work, capacity expansion measures for congestion mitigation become technically and economically infeasible. Over the years, researchers have developed alternative solutions in the context of travel demand management, multimodal integration, and efficient capacity utilization to slow down the deteriorating trend of urban traffic conditions [1]–[5]. For integration of multimodal travel, emphases have been given to integrated scheduling, seamless transfers, vehicle bridging, demand-responsive riding, and streamlined fare, payment, and yield management between auto and transit modes. At present, measures of system operations integration have not been implemented in conjunction with those of facility design integration such as considering alternative configurations of auto and transit travelways based on the available cross-sectional clearance of streets to achieve the far-reaching benefits of congestion mitigation.

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A. ALTERNATIVE TRAVELWAY CONFIGURATIONS

Adopting narrow travel lanes within the available width of a street for exclusive use by autos or high-occupancy vehicles (HOV), or shared use by autos and buses offers opportunities to potentially increase the number of travel lanes resulting in capacity expansion and to integrate multimodal travel. As an example, Figure 1 presents the cross-section of a 15-meter wide urban street. With the allowable lane width varying in the range of 2.87-3.75 meters, the following travelway configurations are feasible: a) four 3.75-meter wide auto lanes; b) three 3.75-metter wide auto lanes and one 3.75-meter wide exclusive bus lane (EBL); c) five 3-meter wide auto lanes; d) four 2.87-metter wide auto lanes and one 3.52-meter wide EBL. Of which, options (a) and (b) are typically deployed in

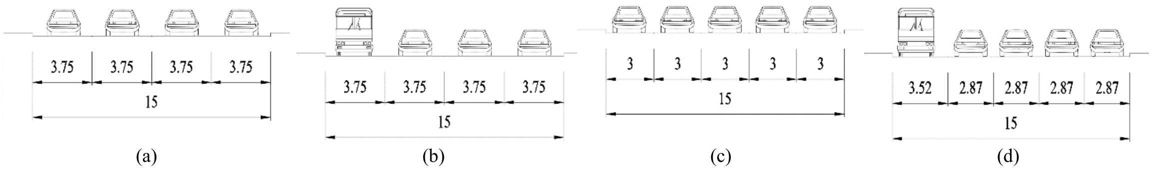

FIGURE 1. Alternative travelway configurations for a 15-meter wide urban street. (a) Four travel lanes without an EBL. (b) Four travel lanes with an EBL. (c) Five travel lanes without an EBL. (d) Five travel lanes with an EBL.

the field. As a result, the potential for capacity expansion in urban areas might have not been fully attained.

Historically, narrow travel lanes have been used in various countries. For instance, during reconstruction of I-94 in Milwaukee, Wisconsin, USA, the two-way 12-ft wide six-lane Interstate highway was delineated to a two-way eight-lane Interstate highway [6]. Similarly, travel lane widths of M6 and M62 motorways in the United Kingdom were reduced during the road work season from 3.65 meters to 3.25 meters for segments with a significant portion of truck traffic and to 3.0 meters for the remaining segments [7]. Also, a new geometric design standard was adopted in Hangzhou, China to allow for decreasing the urban street width from 3.75 meters to 3.25 meters, making it possible to convert some urban streets from four lanes to six lanes. Average vehicle volumes after the lane width adjustments increased by 3.1-21.4% [8]. Although the use of narrower travel lanes could potentially reduce vehicle running speeds, it might help keep more consistent speeds attributable to more attended driving behavior. A study using data on 60 streets containing varying narrow lane widths of 2.73-3.97 meters in Shanghai, China revealed that stable speeds along those streets could be maintained [9].

B. MOTIVATION

The problem of alternative travelway configurations falls into the category of the multimodal travelway design problem that involves two decision-making processes. On one hand, the transportation agency strives for providing optimal capacity to minimize total travel time for all multimodal users. On the other hand, travelers aim to minimize their origin-destination (O-D) travel times via shared network usage. In current practice, the two processes are largely treated independent of each other. This motivates introducing a new model that could integrate them to arrive at truly optimal network travelway design.

The remainder of this article is organized as below. Section 2 briefly describes literature review on travelway design. Section 3 elaborates on the proposed bi-level model. Section 4 covers solution algorithms. Section 5 focuses on a computational experiment for model application. Finally, Section 6 draws conclusion and provides future research directions.

II. RELATED WORK

A. TRAVELWAY DESIGN WITH NARROW LANES

In the United States, unlike the principal arterials such as Interstate highways that are typically designed with the standard lane width of 3.6 meter (12 ft), narrower travel lanes are often used for lower classes of highways with comparatively lower speed limits and more so for urban streets [10]–[20]. In Europe, legally allowed lane widths are 2.75-3.5 meters for arterial roads and 2.5-3.25 meters for local roads [21]. In China, typical travel lane widths of urban streets are 3.25-3.50 meters for autos only reducible to 2.70-2.80 meters wide in high density areas, and 3.50-3.75 meters for trucks only or shared use by autos, trucks, and buses [22].

One potential adverse impact of delineating narrow lanes is traffic safety consequences. References [23]–[27] show that changes of crash frequencies from the use of narrow lanes were statistically insignificant. Another study used data associated with urban streets in Tokyo, Japan and Toronto, Canada for safety impacts assessment of varying lane width [28], which concluded that the crash rate would be at the lowest for lane widths of 3.0-3.25 meters and would increase for narrower or wider widths.

B. TRAVELWAY DESIGN WITH EBLS

Another option of travelway reconfigurations is adopting EBLs along arterials, which is typically used along with delineating narrow travel lanes for use by autos according to available roadway width. Extensive research has been conducted to assess impacts of traffic mobility along arterial corridors [29], impacts extending beyond the physical range of EBLs [30], orientation of one-way street segments and signal settings [12], bus service frequencies [31]–[34], continuity of bus priority lane along consecutive street segments [35], [36], policy impacts of bus line settings [37], [38], effects of intermittent priority [2], [39]–[41], variable bus operating speeds [42], and transit signal priorities [36], [43].

For impacts assessment of EBL deployments, the primary objectives are to minimize total system cost [10], minimize networkwide total travel time [44]–[47], maximize consumer surplus and bus mode share [15], maximize network capacity utilization [48], minimize hourly variation of network total travel time with varying demand [49], and minimize network total travel time incorporating intersection delays [50]. Table 1 presents some notable studies on travelway design.

III. PROPOSED METHODOLOGY

This section describes a bi-level model as a mixed integer optimization formulation along with solution algorithms for the optimal travelway design. The lower-level model conducts traffic assignments to achieve individual traveler's O-D path travel time minimization for a given network

TABLE 1. Notable studies on different types of Travelway designs.

Category	Assumption	Cost component	Model	Decision variable	Objective function	Solution algorithm	Experiment
I. Studies on travelway designs with narrow lanes							
[10]	- Fixed travel demand - Fixed network geometry	- Link travel time	Bi-level	Upper level: Number of lanes added or subtracted from links Lower level: Traffic assignment	Upper level: Minimizing total cost of all vehicles Lower level: User equilibrium	Upper level: Particle swarm optimization Lower level: Variant convex combination	Network with 4 nodes and 5 links
[15]	- Fixed travel demand - Fixed network geometry	- Link travel cost - Bus dwelling cost - Bus waiting cost	Bi-level	Upper level: Allocation of exclusive bus lanes, orientation of one-way links, number of lanes allocated to individual intersection approaches, construction of new lanes Lower level: Mode split, traffic assignment	Upper level: Consumer surplus and bus demand share maximization Lower level: User equilibrium	Multi-objective hybrid genetic algorithm, particle swarm optimization algorithm, and harmony search algorithm	Abdulaal and LeBlanc network with 9 nodes, 12 links, and 2 bus lines; Nagurney network with 13 to 40 nodes, 19 to 66 links, and 3 to 5 bus lines; The Sioux Falls network with 14 to 24 nodes, 19 to 37 links, and 4 to 5 bus lines
[48]	- Fixed travel demand - Fixed network geometry	- Link travel time	Bi-level	Upper level: Orientation of one-way links, number of lanes allocated to individual intersection approaches, intersection signal timing plans Lower level: Traffic assignment	Upper level: Network capacity maximization Lower level: User equilibrium	Upper level: Genetic algorithm Lower level: Frank-Wolfe algorithm	Network with 40 links and 32 nodes
II. Studies on travelway designs with EBLs							
[15]	- Fixed travel demand - Fixed network geometry	- Link travel time - Bus dwelling time - Bus waiting time	Bi-level	Upper level: Allocation of exclusive bus lanes Lower level: Mode split, traffic/transit assignment	Upper level: Total travel time minimization Lower level: User equilibrium	Enumeration	Network with 6 nodes, 7 links, and 3 bus lines
[44]	- Fixed travel demand - Fixed network geometry	- Link travel time - Bus waiting time - Vehicle operating costs	Bi-level	Upper level: Allocation of exclusive bus lanes Lower level: Mode split, traffic/transit assignment	Upper level: Network total cost minimization Lower level: User equilibrium	Upper level: Genetic algorithm Lower level: Local algorithm embedded in VISUM	Grid network with 86 nodes, 306 links, and 10 bus lines
[45]	- Fixed travel demand - Fixed network geometry	- Link travel time - Bus waiting time - Vehicle operating costs - Exclusive bus lane deployment cost	Bi-level	Upper level: Allocation of exclusive bus lanes Lower level: Mode split, traffic/transit assignment	Upper level: Total network cost minimization Lower level: User equilibrium	Generalized benders decomposition	Network with 38 nodes, 49 links, and 9 bus lines
[31]	- Fixed travel demand - Fixed network geometry	- Link travel cost - Bus waiting cost - Added costs to bus passengers and motorists	Bi-level	Upper level: Allocation of exclusive bus lanes, frequency of bus line Lower level: Mode split, traffic/transit assignment	Upper level: Network total cost minimization Lower level: User equilibrium	Upper level: Genetic algorithm Lower level: Method of successive algorithm	Nguyen and Dupuis network with 13 nodes, 19 links, and 6 bus lines
[18]	- Fixed travel demand - Fixed network geometry	- O-D path travel time	Bi-level	Upper level: Allocation of and schedule block of exclusive bus lanes Lower level: Traffic assignment	Upper level: Average travel time minimization for non-bus and bus traffic	Upper level: NSGA-II Lower level: Genetic algorithm embedded in Paramics	Klang Valley region network with 16,726 nodes, 38,274 links, and 165 bus lines
[32]	- Fixed travel demand - Fixed network geometry	- Link travel time - Bus waiting cost - Bus operating costs - Environmental costs - Budget	Tri-level	Upper level: Allocation of exclusive bus lanes Middle level: Frequency of bus line Lower level: Traffic/ transit assignment	Upper level: Network total cost minimization Middle level: Total transit operator and user cost minimization Lower level: User equilibrium	Upper level: Genetic algorithm Middle and lower levels: Simulated annealing	Haidian district network in Beijing with 52 nodes, 86 links, and 9 bus lines
[33]	- Fixed travel demand - Uniform passenger arrival rate - Fixed network geometry	- Link travel time - Bus waiting time - Bus dwelling time	Bi-level	Upper level: Allocation of exclusive bus lanes, frequency of bus dispatching Lower level: Mode split, traffic assignment	Upper level: Average travel time minimization for all travelers, minimizing difference of passengers' comfort among all bus lines Lower level: User equilibrium	Upper level: Branch and bound, column generation Lower level: Method of successive averages	Network with 4 nodes, 5 links, and 2 bus lines; Dalian economic zone network in Dalian, China with 8 bus lines and 102 stops
II. Studies on travelway designs with EBLs							
[48]	- Fixed travel demand - Fixed network geometry	- Link travel time	Bi-level	Upper level: Orientation of one-way links, number of lanes allocated to individual intersection approaches, intersection signal timing plans Lower level: Traffic assignment	Upper level: Network capacity maximization Lower level: User equilibrium	Upper level: Genetic algorithm Lower level: Frank-Wolfe algorithm	Network with 40 links and 32 nodes
[35]	- Fixed travel demand - Fixed network geometry	- Link travel time - Bus operating costs - CO emissions	Bi-level	Upper level: Allocation of Exclusive bus lanes, frequency of bus line Lower level: Traffic/ transit assignment	Upper level: Minimizing total costs of system travel time, bus operations, and vehicle air emissions Lower level: User equilibrium	Upper level: NSGA-II Lower level: CONOPT solver in GAMS	Haidian district network in Beijing with 52 nodes, 86 links, and 9 bus lines

TABLE 1. ***(Continued.)*** **Notable studies on different types of Travelway designs.**

[49]	- Fixed travel demand - Fixed network geometry	- In-vehicle time - Walk time - Bus waiting time - Transfer penalty	Bi-level	Upper level: Allocation of exclusive bus lanes Lower level: Mode split, traffic/transit assignment	Upper level: Minimizing hourly mean and variation of travel time of all users Lower level: Mode split, traffic assignment	Upper level: Ant colony optimization Lower level: Solver embedded in PTV-VISUM 16	Network in Zanjan, Iran with 1,960 links, 797 nodes, and 36 bus lines
[50]	- Fixed travel demand - Fixed network geometry	- Link travel time - Intersection control delays	Bi-level	Upper level: Allocation of exclusive bus lanes, intersection signal timing plans Lower level: Traffic assignment	Upper level: Total travel time minimization for all passengers Lower level: User equilibrium	Upper level: Genetic algorithm Lower level: Logit stochastic traffic assignment solver in EMME 4.3.5	Network with 11 nodes, 20 links, and 3 bus lines; Network in Shanghai with 8 streets, 21 bus lines, and 102 bus stops

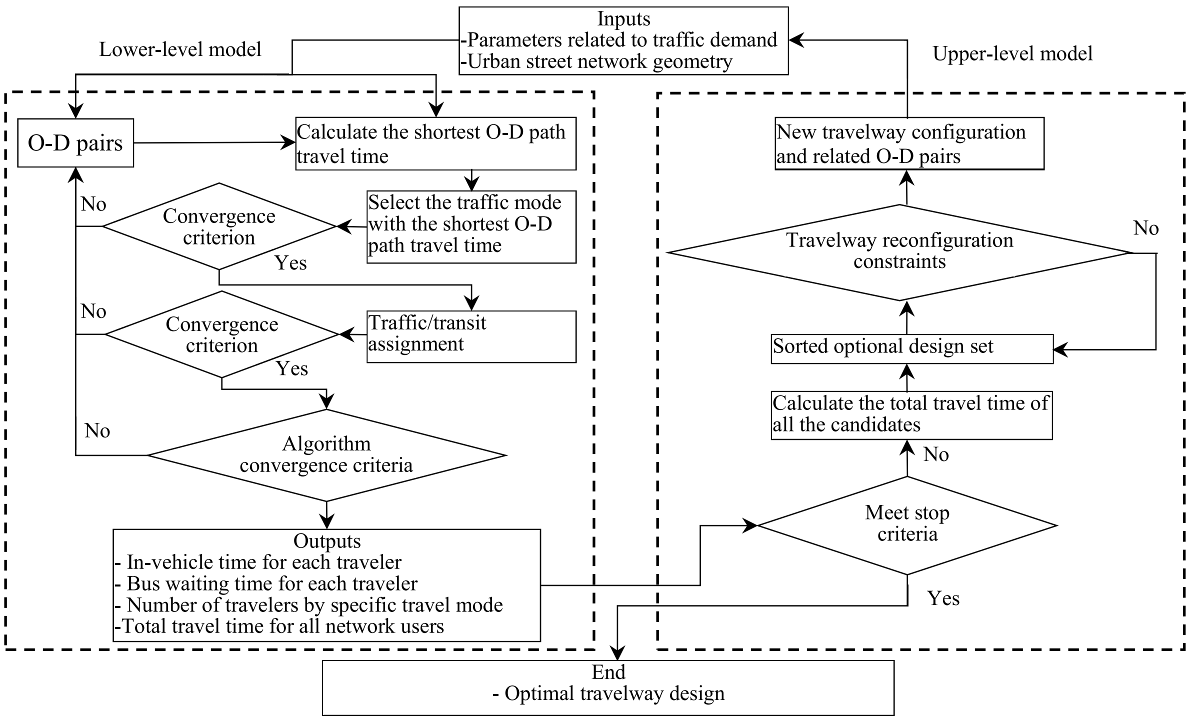

FIGURE 2. **The iterative computational process of the proposed bi-level model.**

travelway configuration. The outcomes of the lower-level model associated with alternative travelway configurations are used as inputs for the upper-level model to compute network total travel times and identify the travelway configuration leading to minimized network total travel time, which would subsequently be used as inputs for executing the lower-level model. The two models are iteratively executed in succession to arrive at the optimal travelway design once model convergence criteria are satisfied. Figure 2 illustrates the iterative computational process.

A. MODEL PARAMETERS AND NOTATIONS

Table 2 lists parameters and variables utilized in the proposed model with descriptions follow.

B. LOWER-LEVEL MODEL

The lower-level model assigns travel demand to the urban network with bus lines deployed to establish predictive traffic by auto and bus modes according to the user equilibrium principle. For each traveler, the shortest O-D travel time path is iteratively identified. When shortest O-D travel time paths of all travelers are determined, a bi-modal user equilibrium is reached where travel times of all feasible O-D paths for each traveler become equal and the traveler will not gain any benefit of travel time savings by unilaterally switching a chosen path [52]. The lower-level model is formulated as:

Objective:

$$\min \sum_{k\in K} \sum_{od\in OD} \sum_{m\in M} \sum_{p\in p^{od}_{mode}} \left(u_p^{k,od,m} - u^*_{k,od}\right) \cdot \delta_p^{k,od,m} \quad (1)$$

where, path travel time is calculated by

$$u_p^{k,od,m} = \sum\nolimits_{s\in S_R} t_s^{k,od,m} \cdot \delta_p^s + \sum\nolimits_{j\in S_{INT}} t_{j,d}^{k,od,m} \cdot \delta_p^{j,d} + P_1^{k,od,m}, \quad \forall m\in M,\ m\notin M_{BL},\ \forall p\in P^{od}_{mode},\ \forall od\in OD, \quad (2)$$

TABLE 2. List of parameters and variables.

a) Travel demand and supply parameters	
q	total travel demand expected to use the network
T	total travel time associated with all network travelers
OD	set of all O-D pairs
K	set of departure times for all O-D pairs during the study period
traveler (k, od, m)	traveler of O-D pair (o, d) departing at time interval k vehicle ID m
E_{HV}	auto equivalency factor for heavy vehicles
n_{HV}	bus-to-auto conversion coefficient based on number of riders per vehicle
$t_{alighting}$	average alighting time per passenger
$t_{boarding}$	average boarding time per passenger
$P^{k,od,m}_{mode=1}$	parking time of traveler (k, od, m) makes a trip by auto mode (mode =1) via auto ID m, with a default value of 5 minutes
S_R	set of all road segments in the network
S_R^{AT}	set of arterial road segments in the network, $S_R^{AT} \in S_R$
M_{BL}	set of bus lines in the network
S_R^{BL}	set of road segments utilized by bus lines in the network, $S_R^{BL} \in S_R$
M	set of bus lines and autos accommodating all network travelers
S_{INT}	set of intersections in the network
S_{ST}	set of bus stops set of the network
L	travel lane type, L= 1 for auto only lane, 2 for EBL, and 3 for auto/bus shared lane
P^{od}_{mode}	set of modal-specific feasible paths for O-D pair (o, d)
O^{max}_{mode}	the maximum capacity of travel mode, 1 for auto mode and 2 for bus mode
L_s	length of road segment s
W_s	total width of road segment s
$W_{min,l}$	lower bound of lane width for travel lane type l, $l \in L$
$W_{max,l}$	upper bound of lane width for travel lane type l, $l \in L$
CAP_0	base capacity of an auto travel lane, 1,200 pcphpl
$CAP_{s,l}$	capacity of road segment s for travel lane type l
$FFS_{s,l}$	free flow speed of road segment s for travel lane type l
α, β	parameters in the Bureau of Public Roads (BPR) function for travel time calculation, $\alpha = 0.15$, $\beta = 4.0$
b) Auxiliary variables	
$v^{k,od,m}_{s,\,mode}$	flow of travel mode on road segment s when traveler (k, od, m) uses road segment s
$t^{k,od,m}_{s}$	link travel time of traveler (k, od, m) passing through road segment s
$t^{k,od,m}_{j,d}$	signal control delay of traveler (k, od, m) passing through intersection j in direction d
$t^{k,od,m}_{b,w}$	waiting time of traveler (k, od, m) at bus stop b, $m \in M_{BL}$
$t^{k,od,m}_{b,d}$	dwelling time of traveler (k, od, m) at bus stop b, $m \in M_{BL}$
$NA^{k,od,m}_{b}$	number of alighting passengers at bus stop b when traveler (k, od, m) is at bus stop b, $m \in M_{BL}$
NB^{m}_{b}	number of boarding passengers at bus stop b when traveler (k, od, m) is at bus stop b, $m \in M_{BL}$
$O^{k,od,m}_{b}$	number of on-board passengers for the bus chosen by traveler (k, od, m) at bus stop b, $m \in M_{BL}$
$c^{k,od,m}_{j,d,g}$	immediate next green light start time at intersection j in direction d for traveler (k, od, m)
$c^{k,od,m}_{j,d,c}$	the arrival time when traveler (k, od, m) arrives at intersection j in direction d
$c^{k,od,m}_{b,a}$	immediate next bus arrival time at bus stop b for traveler (k, od, m), $m \in M_{BL}$
$c^{k,od,m}_{b,c}$	arrival time of traveler (k, od, m) at bus stop b, $m \in M_{BL}$
$f_{w,s,l}$	adjustment factor for lane width of road segment s for travel lane type l
$f_{HV,s,l}$	adjustment factor for heavy vehicles in traffic stream on road segment s for travel lane type l
$P_{HV,s,l}$	proportion of heavy vehicles in traffic stream on road segment s for travel lane type l
$u^{k,od,m}_{p}$	total travel time of travel path p chosen by traveler (k, od, m)
$u^{*}_{k,od}$	minimum total travel time of travelers with od pair departing at time interval k
$\delta^{k,od,m}_{p,u}$	$u^{k,od,m}_{p} = 1$, if traveler (k, od, m) boards at bus stop b; 0, otherwise
$\delta^{j,d}_{p}$	$\delta^{j,d}_{p} = 1$, if travel path p goes through intersection j from direction d; 0, otherwise
δ^{s}_{p}	$\delta^{s}_{p} = 1$, if travel path p utilizes road segment s; 0, otherwise
$\delta^{b,w}_{p}$	$\delta^{b,w}_{p} = 1$, if travel path p involves passenger boarding at bus stop b; 0, otherwise
δ^{b}_{p}	$\delta^{b}_{p} = 1$, if travel path p involves passenger dwelling at bus stop b; 0, otherwise
c) Decision variables	
$\delta^{k,od,m}_{p}$	binary variable $\delta^{k,od,m}_{p}$=1, if traveler (k, od, m) chooses travel path p; 0, otherwise
$W_{s,l}$	lane width of road segment s by travel lane type l
$N_{s,l}$	number of lanes of road segment s for travel lane type l
$N_{s',l}$	number of lanes of road segment s' in the downstream of road segment s for travel lane type l
$N_{\bar{s},l}$	number of lanes of the road segment in the opposite of road segment s for travel lane type l

$$u^{k,od,m}_{p} = \sum_{s\in S_R} t^{k,od,m}_{s} \cdot \delta^{s}_{p} + \sum_{j\in S_{INT}} t^{k,od,m}_{j,d} \cdot \delta^{j,d}_{p} + \sum_{b\in S_{ST}} \left(t^{k,od,m}_{b,w} \cdot \delta^{b,w}_{p} + t^{k,od,m}_{b,d} \cdot \delta^{b,d}_{p}\right), \quad \forall m \in M_{BL},\ \forall p \in P^{od}_{mode},\ \forall od \in OD, \tag{3}$$

$$t^{k,od,m}_{s} = \frac{L_s}{FFS_{s,1}} \times \left(1 + \alpha \cdot \left(\frac{v^{k,od,m}_{s,1} + (1 - N_{s,2}) \cdot n_{HV} \cdot v^{k,od,m}_{s,2}}{Cap_{s,1}}\right)^{\beta}\right), \quad for\ m \in M_{BL},\ m \notin M_{BL}, \tag{4}$$

$$t_s^{k,od,m} = \frac{L_s}{FFS_{s,2}} \times \left(1+\alpha\cdot\left(\frac{v_{s,2}^{k,od,m}+(1-N_{s,2})\cdot n_{HV}\cdot v_{s,1}^{k,od,m}}{Cap_{s,2}}\right)^{\beta}\right), \quad for\ m\in M_{BL}, \tag{5}$$

$$Cap_{s,l} = Cap_0\cdot N_{s,l}\cdot f_{w,s,l}\cdot f_{HV,s,l}, \tag{6}$$

$$f_{w,s,l} = 1+\frac{(w_{s,l}-3.6)}{9}, \tag{7}$$

$$f_{HV,s,l} = \frac{1}{1+P_{HV,s,l}(E_{HV}-1)}, \tag{8}$$

$$t_{j,d}^{k,od,m} = c_{j,d,g}^{k,od,m}-c_{j,d,c}^{k,od,m}, \tag{9}$$

$$t_{b,w}^{m} = c_{b,a}^{k,od,m}-c_{b,c}^{k,od,m}+t_{b,d}^{k,od,m}, \tag{10}$$

$$t_{b,d}^{k,od,m} = \max\left(t_{alighting}\cdot NA_b^{k,od,m}, t_{boarding}\cdot NB_b^{k,od,m}\right). \tag{11}$$

Subject to:

a) Traffic flow conservation constraints

$$\sum_{m\in M}\sum_{p\in P_{mode}^{od}}\delta_p^{k,od,m}=1,\quad \forall k\in K,\ \forall od\in OD, \tag{12}$$

$$\sum_{k\in K}\sum_{od\in OD}\sum_{m\in M}\sum_{p\in P_{mode}^{od}}\delta_p^{k,od,m}=q. \tag{13}$$

b) Path choice constraints

$$\sum_{b\in S_{ST}}\delta_{b,u}^{k,od,m}\le 2,\quad \forall k\in K,\ \forall od\in OD,\ \forall m\in M_{BL}, \tag{14}$$

$$O_b^{k,od,m}\cdot\delta_{b,u}^{k,od,m}\le O_2^{max},\quad \forall b\in S_{ST},\ \forall k\in K,\ \forall od\in OD,\ \forall m\in M_{BL}. \tag{15}$$

c) Mode split and traffic assignment constraints

$$\left(u_p^{k,od,m}-u_{k,od}^{*}\right)\cdot\delta_p^{k,od,m}=0,\ k\in K,\ p\in P_{mode}^{od},\ \forall m\in M,\ \forall od\in OD, \tag{16}$$

$$u_p^{k,od,m}-u_{k,od}^{*}\ge 0,\quad \forall m\in M,\ \forall od\in OD. \tag{17}$$

Equation (2) calculates the O-D path travel time for each auto traveler that is comprised of link travel time, intersection control delay, and auto parking time. Equation (3) computes the O-D path travel time for each bus rider that contains in-vehicle travel time including dwelling time at bus stops along the path and out-of-vehicle travel time in presence of bus stop waiting and transfers. Equations (4) and (5) estimate the link travel time using the function developed by the Bureau of Public Roads (BPR), which was the predecessor of the U.S. Federal Highway Administration (FHWA), for cases in absence and presence of EBLs. Equations (6)-(8) proposed by Highway Capacity Manual are employed to establish the link capacity and adjustment coefficients for auto lanes and EBLs [51]. Equation (9) quantifies intersection control delays. No delay occurs if the current time step is within the green interval of directional movements of the intersection. Equations (10) and (11) calculate bus waiting time and dwelling time at a bus stop. If the arrival time of a traveler is no later than the time step when a bus departs from current bus stop after picking up or dropping off passengers, then the traveler will board the bus. Otherwise, the traveler needs to wait for arrival of the next bus. The bus dwelling time is set as the longer duration of times between boarding and alighting at the bus stop. With the time profile of each travel path established, the bus waiting time for each traveler boarding at a bus stop could be accurately calculated.

Constraint (12) requires that only one travel mode is chosen for each O-D path. Constraint (13) necessitates traffic flow conservation. Constraints (14) limits no more than one bus transfer allowable along the O-D path. Constraint (15) renders no extra boarding is permitted for a fully loaded bus. Constraints (16) and (17) are applied to mode split and traffic assignment. The values of the two expressions will converge to zero when the objective function equals to zero to ensure non-negativity of the objective function value. In this way, the travel time of O-D travel path p chosen by *traveler* (k, od, m) where $\delta_p^{k,od,m}=1$ will be at the minimal, $u_p^{k,od,m}=u_{k,od}^{*}$, and the corresponding mode of travel will be the travel mode chosen by the traveler. This facilitates achieving the user equilibrium state for both auto and bus traffic assignments.

C. UPPER-LEVEL MODEL

Based on traffic details predicted by the lower-level model for alternative travelway configurations, the optimal travelway design leading to the lowest level of total travel time for all auto and bus travelers in the network could be determined by the following:

Objective:

$$min\ T=\sum_{k\in K}\sum_{od\in OD}\sum_{m\in M}\left(\sum_{s\in S_R}t_s^{k,od,m}+\sum_{j\in S_{INT}}t_{j,d}^{k,od,m}+\sum_{b\in S_{ST}}\left(t_{b,w}^{k,od,m}+t_{b,d}^{k,od,m}\right)+P_1^{k,od,m}\right) \tag{18}$$

Subject to:

a) Lane number constraints

$$\mathrm{W_s}=\mathrm{N_{s,1}}\cdot\mathrm{W_{s,1}}+\mathrm{N_{s,2}}\cdot\mathrm{W_{s,2}}+\mathrm{N_{s,3}}\cdot\mathrm{W_{s,3}}, \tag{19}$$

$$N_{s,1}\ge 1, \tag{20}$$

$$\begin{cases}N_{s,2}\cdot W_{s,2}+N_{s,3}\cdot W_{s,3}=1, & if\ s\in S_R^{BL}\\ N_{s,2}\cdot W_{s,2}+N_{s,3}\cdot W_{s,3}=0, & otherwise\end{cases} \tag{21}$$

b) Lanes width constraints

$$W_{min,1}\le W_{s,1}\le W_{max,1}, \tag{22}$$

$$W_{min,2} \leq W_{s,2} \leq W_{max,2}, \tag{23}$$
$$\mathrm{W}_{min,3} \leq \mathrm{W}_{s,3} \leq \mathrm{W}_{max,3}. \tag{24}$$

c) Lane number balancing constraints

$$0 \leq N_{s,1} + N_{s,2} + N_{s,3} - \left(N_{s',1} + N_{s',2} + N_{s',3}\right) \leq 1, \quad s, s' \in S_R^{AT}, \tag{25}$$
$$N_{s,l} = N_{\bar{s},l}, \quad \forall l \in L, s, \bar{s} \in S_R^{AT}, \tag{26}$$
$$N_{s,l} = N_{s',l}, \quad \forall s, s' \in S_R^{AT}, \quad \forall l \in L. \tag{27}$$

As shown in the objective function denoted by Expression (18), the total travel time of a *traveler (k, od, m)* departing at time interval k for O-D pair od via an auto or a bus with ID m consists of link travel time $\sum_{s \in S_R} t_s^{k,od,m}$, intersection control delay $\sum_{j \in S_{INT}} t_{j,d}^{k,od,m}$, and additional parking time $P_1^{k,od,m}$ for auto travel and bus stop waiting time $\sum_{b \in S_{ST}} t_{b,w}^m \cdot \delta_{b,u}^{k,od,m}$ and dwelling time $\sum_{b \in S_{ST}} t_{b,p}^{k,od,m}$ for bus travel, respectively. Equations (2)-(11) in the lower-level model could help compute individual travel time components.

The objective function of total travel time minimization for all network users is bounded by travel lane width, number, balancing, and continuity constraints. Constraint (19) ensures that the total width of all auto and bus lanes in one direction of a road segment equals to its directional cross-sectional width. Constraints (20) and (21) stipulate at least one auto travel lane and no more than one EBL be designated for a directional road segment. Constrains (22) and (23) define lower and upper bounds of an auto travel lane and an EBL, respectively. Constraint (24) requires that the lane width of an auto/bus shared travel lane should not be narrower than the minimum width allowed for a bus lane. Constraint (25) controls the difference between number of in-bound and out-bound lanes at an intersection within one travel lane. Constraint (26) requires that the same number of travel lanes be designed for the opposite directions of a two-way road segment. Constraint (27) ensures that the same number of travel lanes be designed along the same direction of consecutive segments to avoid abrupt lane drops that could potentially impose safety concerns.

IV. SOLUTION ALGORITHMS

The bi-level model is of a non-linear mix-integer optimization formulation, which is a (non-deterministically polynomial) NP-hard problem allowing for all NP problems reducible to it or having a given solution verified in polynomial time, but could not guarantee finding a truly optimal solution in polynomial time [53]. For this reason, heuristic algorithms are developed to derive the model solution.

A. ALGORITHM I

For finding a solution to the user equilibrium-based multimodal traffic assignment problem as per the lower-level model, a heuristic algorithm is introduced to solve variational inequality of Expression (1). In the iterative computation process, one or more shortest travel time O-D paths are sought for each traveler and are iteratively updated using the

Inputs	Input values of network travel demand parameters q, OD, P_{mode}^{od}, and K; road network geometry parameters S_{INT}, S_R, S_R^{AT}, L, W_s, L_s, $w_{s,l}$, N_s, and $N_{s,l}$; network operation parameters $FFS_{s,l}$, Cap_0 and $c_{j,d,g}^{k,od,m}$; travel mode parameters: M_{BL}, $P_1^{k,od,m}$, S_{ST}, O_{mode}^{max}, n_{HV}, $t_{alighting}$, and $t_{boarding}$; BPR function parameters α and β; $s \in S_R$, $l \in L$, $k \in K$, $od \in OD$, $m \in M$, $b \in S_{ST}$, and traffic mode of 1 for auto and 2 for bus; convergence precision ε_1; and maximum number of iterations N_1.
Step 0	Initialization Take the current travelway configuration as the initial network travelway design; for $od \in OD$, mode $=$ 1 for auto and 2 for bus, and $m \in M$, generate the feasible travel path set P_{mode}^{od}; for $m \in M_{BL}$ and $b \in S_{ST}$, load buses to bus lines according to bus dispatching schedules and calculate the bus arrival time at bus stop b; for $s \in S_R$, $j \in S_{INT}$, load the signal timing plan to intersection j and calculate traffic flow (only include buses at Step 0) on road segment s; for $\forall\, od \in OD$, $\forall m \in M$, and $\forall p \in P_{mode}^{od}$; set $n = 0$; and let $\delta_p^{k,od,m}(0) = 0$.
Step 1	Finding the shortest travel time O-D paths For $k \in K$, $od \in OD$, $m \in M$, and $p \in P_{mode}^{od}$, calculate $u_p^{k,od,m}(n)$ using Equations (2) and (3); For $k \in K$, $od \in OD$, $m \in M$, and $u_{k,od}^*(n) = \min\{u_p^{k,od,m}(n) \mid p \in p_{od}^m\}$, if $u_p^{k,od,m}(n) = u_{k,od}^*(n)$, $\delta_p^{k,od,m}(n) = 1$; otherwise, $\delta_p^{k,od,m}(n) = 0$. With the shortest travel paths for all travelers determined, the network total travel time $T(n)$ can be computed using Equation (18).
Step 2	Updating OD path travel times and bus arrival times Let $n = n + 1$, go to Step 1. For $k \in K$, $od \in OD$, $m \in M$, if $u_p^{k,od,m}(n) \neq u_p^{k,od,m}(n+1)$, $u_{k,od}^*(n)$ will be replaced by $u_{k,od}^*(n+1)$; otherwise, the current od will be removed from the OD and will no longer participate in the subsequent updating process. After traversing through all $od \in OD$ in the network, update the bus arrival time schedule for each bus stop $b \in S_{ST}$ and onboard passengers for buses $O_b^{k,od,m}$ according to all bus travel paths. Go to Step 3.
Step 3	Checking convergence If $\mathrm{n} \geq \mathrm{N}_1$ or $1 < \mathrm{n} < \mathrm{N}_1$ and $\sqrt{\sum_{k \in K} \sum_{od \in OD} \sum_{m \in M} \sum_{p \in P} \left(f_p^{k,od,m}(n+1) - f_p^{k,od,m}(n)\right)^2 / q} \leq \varepsilon_1$, stop; otherwise, go to Step 2.
Outputs	O-D path travel mode $\delta_p^{k,od,m}(n)$, traffic flow $v_{s,mode}^{k,od,m}(n)$, and travel time $u_{k,od}^*(n)$ for $k \in K$, $od \in OD$, $m \in M$, and $p \in P_{mode}^{od}$; link travel time $t_s^{k,od,m}(n)$, delay time $t_{j,d}^{k,od,m}(n)$, bus waiting time $t_{b,w}^{k,od,m}(n)$, and bus dwelling time $t_{b,d}^{k,od,m}(n)$ for $s \in S_R$, $m \in M$, $j \in S_{INT}$, $b \in S_{ST}$; bus arrival time $c_{b,a}^{k,od,m}(n)$ for $k \in K$, $od \in OD$, $m \in M$, $l \in L$, and $b \in S_{ST}$.

Dijkstra's algorithm. In consecutive iterations, if the shortest travel time paths for travelers associated with each O-D pair generated in the current iteration differ from those of the previous iteration, the shorter travel time O-D paths are updated and used as the new shortest time paths. The iterative calculations will terminate once the prespecified convergence precision level or the maximum number of iterations is reached. The main computational steps are highlighted below:

B. ALGORITHM II

For a transportation network with n road segments and each with m travelway configuration options, there will be m^n possible design combinations. This makes it highly impractical to identify the optimal design by enumerating all options [54]. Various constraints are imposed to lane width, number, and balancing within each road segment and between consecutive segments to significantly reduce possible design options that would remain practicality for real-world applications. Due to the discrete nature of upper-level model formulation, A tailored branch-and-bound algorithm is proposed to solve for network total travel time minimization. To ensure computational efficiency, the algorithm is designed to identify road segments as the right candidate in the process of creating the spanning tree based on such criteria as high traffic flow and constrained capacity. In this way, a merit index (MI) can be established for each road segment (without or with a bus line, without or with an EBL if with a bus line) according to its vehicle volume-to-capacity ratio level to sort out road segments with excessively high travel time as candidates to be prioritized for improvements and to prevent the re-configuration of road segments with low travel time. This will eventually lead to network total travel time minimization. The merit index is defined as follows:

$$MI_a = \left(\frac{v_a}{Cap_a}\right)_{a \in A} \tag{28}$$

where, MI_a is the merit index of candidate street segment a; v_a is the traffic flow on segment a; Cap_a is the capacity of segment a; and A represents the set of candidate segments. The following highlights key computational steps of the proposed algorithm:

Inputs	The outputs of Algorithm I on network geometry parameters, including $W_{min,l}$, $W_{max,l}$, $N_{s,l}$, $w_{s,l}$, for $l \in L$ and $s \in S_R$; convergence precision ε_2; and maximum number of iterations N_2.
Step 0	Initialization Set $n = 0$ and the original network travelway configuration as $X_s(0)$, $s \in S_R$.
Step 1	Computation, sorting, and creation of list of candidate segments according to merit indices Based on the traffic flows derived by executing the lower-level model, calculate merit indices of all segments using Equation (2), sort the list of segments by merit indices in descending order, and establish the list of candidate segments according to the threshold value of the merit index.
Step 2	Branch Let $n = n + 1$. for the list of candidate segments sorted by merit indices in descending order, the segment with the highest merit index will be chosen to branch first. Among all possible travelway configuration schemes, the scheme that satisfies the following criteria will be selected as the new travelway design scheme: i) if the selected segment a is without a bus line, it should satisfy $N_{s,l}(n) \geq N_{s,l}(n-1)$, which means only the schemes with more travel lanes will be considered to be feasible; ii) if the selected segment a serves a bus line, the following conditions should be satisfied:

$$\begin{cases} N_{s,2}(n) = 1 \text{ and } \left|N_{s,1}(n) + N_{s,3}(n) \right. \\ \left. -N_{s,1}(n-1) - N_{s,3}(n-1)\right| \leq 1, \\ \quad \text{if } N_{s,2}(n-1) = 0 \\ or\ N_{s,2}(n) = 0 \text{ and } \left|N_{s,1}(n) + N_{s,3}(n) \right. \\ \left. -N_{s,1}(n-1) - N_{s,3}(n-1)\right| \leq 1 \\ N_{s,2}(n) = 1 \text{ and } \left|N_{s,1}(n) + N_{s,3}(n) \right. \\ \left. -N_{s,1}(n-1) - N_{s,3}(n-1)\right| \leq 1, \\ \quad \text{if } N_{s,2}(n-1) = 1 \\ or\ N_{s,2}(n) = 0, \quad N_{s,3}(n) = 1, \text{ and } \left|N_{s,1}(n) \right. \\ \left. -N_{s,1}(n-1)\right| \leq 1 \end{cases}$$

Specifically, the first condition indicates that the n^{th} travelway configuration scheme should contain an EBL if no EBL is installed in the $(n-1)^{th}$ scheme, and the second condition shows that the n^{th} scheme should still keep an EBL if it exists in the $(n-1)^{th}$ scheme and the difference in auto lanes between the n^{th} and $(n-1)^{th}$ schemes should be controlled within one lane. Otherwise, auto/bus shared lanes are allocated in n^{th} scheme with EBLs cancelled.

For each candidate segment $a \in M_{IA}$, if one candidate cannot satisfy the above conditions, it will be skipped, and the next candidate will be tested. Once a new feasible travelway configuration is confirmed, go to Step 3.

V. EXPERIMENTAL SETUP

This section elaborates on a computational experiment conducted by applying the proposed bi-level model in conjunction with solution algorithms to derive the optimal network travelway design.

A. DATA PREPARATION

1) STUDY AREA, STREET NETWORK SETTINGS, AND TRAFFIC OPERATIONS

Figure 3 shows southwestern quadrant area of the central business district (CBD) of Xi'an, China with level terrain covering approximately 4.4-square-km selected as the study area for the computational experiment. The urban street network has been historically designed as a grid network,

Step 3 Bound
Given the new travelway configuration $X_s(n)$, the method of successive averages is employed to calculate the network total travel time $T(X_s(n))$. If the new travelway design includes EBLs and $\frac{T(X_s(n))-T(X_s(n-1))}{T(X_s(n-1))} < \varepsilon_2$, else if new travelway design excludes EBLs and $\frac{T(X_s(n))-T(X_s(n-1))}{T(X_s(n-1))} < 0$, the new travelway configuration $X_s(n)$ will be set as the current network travelway design and go to Step 4; Otherwise, discard $X_s(n)$ and go to Step 2.

Step 4 Checking convergence
If $n = N_2$ or $n < N_2$ and no more travelway design scheme is feasible, then stop and output $X_s(n)$; otherwise go Step 2.

Outputs The optimal travelway design for each segment s, including $w_{s,l}$, $N_{s,l}$, for $s \in S_R$, $m \in M$, $l \in L$.

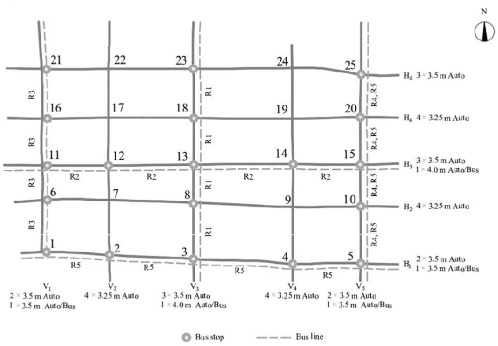

FIGURE 3. Illustration of the existing travelway design of the study area network.

which contains five north-south (vertical) and five east-west (horizontal) major arterial streets, leading to a total of 25 signalized intersections. The spacing of adjacent parallel streets is approximately 540 meters. The north-south streets from left to right are labelled as V_1, V_2, V_3, V_4, and V_5; and east-west streets from bottom to top are designated as H_1, H_2, H_3, H_4, and H_5. Currently, varying cross-sectional widths of 10.5, 13.0, and 14.5 meters per direction are designed for the above streets.

Apart from supporting auto travel, the street network accommodates five bus lines with three bus lines deployed along streets V_1, V_3, and V_5, one bus line along street H_3, and one bus line along street H_1 and street V_5. The auto equivalency factor of buses for vehicle volume conversion is 2.5. The speed limits are set as 50 km/h for auto only and dedicated bus lanes and 40 km/h for auto/bus shared lanes. The outmost travel lane of a segment providing bus services is designated for auto/bus shared use. Bus stops are in the near side of intersections. Buses are dispatched with a headway of 2 minutes.

2) TRAVEL DEMAND

Pertaining to the study area network, the daily travel for a typical working day could be grouped into 8:00-10:00 AM peak, 18:00-20:00 PM peak, and 7:00-8:00AM, 11:00AM-13:00PM and 17:00-18:00PM adjacent-to-peak periods, as well as off-peak period for the remaining daily hours. The demand intensities in AM/PM peak, adjacent-to-peak, and off-peak periods are 62,640, 43,200, and 33,120 person-trips per hour, respectively. The O-D locations of individual travelers utilizing the study area network by hour of the day especially those going through intersections of H_2, H_3, H_4, V_2, V_3, and V_4 streets have been scrutinized. These hourly person-trips largely correspond to 600 O-D pairs, indicating that one origin is approximately associated with 24 destination locations.

3) TRAVELWAY CONFIGURATION SCHEMES

The travel lane width of urban streets can be designed to vary in the range of 2.75-3.75 meters for auto only lanes and 3.5-4.0 meters for bus compatible lanes. For street segments without bus operations, tradeoffs need to be made between varying width and number of auto only lanes according to the total cross-sectional width to develop travelway configuration schemes. For street segments with bus services, it creates two cases denoted as scenario A without an EBL and scenario B with an EBL. For each street segment, different lane width and number combinations could be explored based on the total available width by reserving a minimum width of 3.5 meters for one auto/bus shared travel lane or an EBL. For consecutive street segments, lane continuity and balancing are maintained. For lane width combinations, the width of auto only lanes is widened from a minimum width of 3.00 meters by an increment of +0.025 meter in each scheme to a maximum of 3.75 meters. Concurrently, the width of EBL is reduced from a maximum width of 4.0 meters by a decrement of −0.05 meter or −0.075 meter to a minimum width of 3.5 meters. Table 3 summarizes travelway configuration schemes.

TABLE 3. Different Travelway configuration schemes.

Total	Design	Auto Only or Auto/Bus Shared Lane		Exclusive Bus Lane	
Width (m)	Scheme	No.	Width (W_{min}= 2.75 m, W_{max}= 3.75 m)	No.	Width (W_{min}= 3.5 m, W_{max}= 4.0 m)
10.5	1-11	2	3.25~3.5 (+0.025 per scheme)	1	4~3.5 (-0.05 per scheme)
	12	3	3.5	0	
13	1-7	3	3~3.15 (+0.025 per scheme)	1	4~3.55 (-0.075 per scheme)
	8	4	3.25	0	
14.5	1-7	3	3.5~3.65 (+0.025 per scheme)	1	4~3.55 (-0.075 per scheme)
	8	4	2.75	1	3.5
	9	4	3.625	0	
	10	4	2.9	0	
		1	3.5		

B. MODEL EXECUTION

The algorithms for solving the lower- and upper-level models are coded in Python 3.7 programming language and implemented using a desktop computer configurated with Intel(R) Core(TM) i7 CPU 3.70GHz and 16.0GB RAM. For executing the respective algorithms, 1,000 and 100 iterations are used as

TABLE 4. Optimal Travelway designs for the study area network under six scenarios.

Street	Bus Line	Travel Lane	Travelway Design Scenario													
			Existing		1. AM/PM peak				2. Adjacent- to-peak				3. Off-peak			
					A		B		A		B		A		B	
			No.	Width (m)	No.	Width	No.	Width	No.	Width	No.	Width	No.	Width	No.	Width
H_1	5	Auto only	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5
		Auto/bus shared	1	3.5	1	3.5			1	3.5			1	3.5		
		EBL					1	3.5			1	3.5			1	3.5
H_2		Auto only	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25
H_3	2	Auto only	3	3.5	4	2.75	4	2.75	4	2.75	4	2.75	4	2.75	4	2.75
		Auto/bus shared	1	4.0	1	3.5			1	3.5			1	3.5		
		EBL					1	3.5			1	3.5			1	3.5
H_4		Auto only	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25
H_5		Auto only	3	3.5	3	3.5	3	3.5	3	3.5	3	3.5	3	3.5	3	3.5
V_1	3	Auto only	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5
		Auto/bus shared	1	3.5	1	3.5			1	3.5			1	3.5		
		EBL					1	3.5			1	3.5			1	3.5
V_2		Auto only	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25
V_3	1	Auto only	3	3.5	4	2.75	4	2.75	4	2.75	4	2.75	4	2.75	4	2.75
		Auto/bus shared	1	4.0	1	3.5			1	3.5			1	3.5		
		EBL					1	3.5			1	3.5			1	3.5
V_4		Auto only	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25	4	3.25
V_5	4, 5	Auto only	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5	2	3.5
		Auto/bus shared	1	3.5	1	3.5			1	3.5			1	3.5		
		EBL					1	3.5			1	3.5			1	3.5

TABLE 5. Changes in Networkwide mode shares, travel time, and travel speed under six design scenarios.

Scenario			1. AM/PM Peak			2. Adjacent-to-Peak			3. Off-Peak		
			Existing	A	B	Existing	A	B	Existing	A	B
Modal share	Auto mode	%	69.9	69.93	66.04	68.64	68.75	63.85	65.16	65.2	60.94
		Change (%)		0.03	-3.9		0.11	-4.8		0.04	-4.2
Network travel time	All travelers	Person-hours	7,289.4	7,275.6	7,159.2	4,942.8	4,940.4	4,852.2	3,721.2	3,721.2	3,637.8
		Change (%)		-0.2	-1.8		-0.1	-1.8		0.00	-2.2
Network average travel speed	All travelers	km/h	44.19	44.33	48.50	45.29	45.34	49.49	45.10	45.11	49.70
		Change (%)		0.3	9.8		0.1	9.3		0.02	10.2
	Auto users	km/h	47.68	47.93	48.18	49.38	49.43	49.53	49.83	49.84	49.88
		Change (%)		0.5	1.1		0.1	0.3		0.03	0.1
	Bus riders	km/h	36.53	36.48	49.19	37.20	37.21	49.40	37.52	37.51	49.42
		Change (%)		-0.1	34.7		0.03	32.8		-0.04	31.7

the maximum. The convergence precisions are set as 0.001. The run times for generating model solutions based on hourly demand in AM/PM peak, adjacent-to-peak, and off-peak periods are 99.65 and 821.17 seconds, 52.25 and 476.59 seconds, and 27.19 and 231.49 seconds correspondingly.

VI. RESULTS

Optimal travelway designs are separately developed for AM/PM peak, adjacent-to-peak, and off-peak peak periods with different demand intensities. For each demand level, travelway design scenarios A and B are considered to differentiate travel lanes that support bus operations being designated for auto/bus shared use or bus exclusive use. This yields a total of six travelway design scenarios, including 1A (peak demand without an EBL), 1B (peak demand with an EBL), 2A (adjacent-to-peak demand without an EBL), 2B (adjacent-to-peak with an EBL), 3A (off-peak demand without an EBL), and 3B (off- peak demand with an EBL). Table 4 lists optimal travelway designs for the study area network. For all scenarios, changes of travelway configurations occur with streets H_3 and V_3 that serve bus lines 1 and 2. By coincidence, the optimal travelway designs for the two streets under the six scenarios are identical. One narrow travel lane of 3.5 meters is assigned as an auto/bus shared lane or an EBL. The remaining 3 travel lanes with a standard width of 3.5 meters in the existing design are converted to 4 narrow travel lanes of 2.75 meters for auto use only.

Table 5 shows changes of auto/bus modal shares, network total travel time, and average travel speed associated with optimal travelway designs. By allotting one travel lane for shared use by autos and buses or exclusive use by buses and increasing travel lanes for auto use only from three to four lanes, modal shifts would occur. For travelway designs without EBLs as per scenarios 1A, 2A, and 3A, modal shifts from bus riding to auto travel in different periods of the day by up to 0.2% are anticipated. Reductions in network total travel time by up to 0.4% are expected. Increases in average travel speeds are 0.02-0.3% for all travelers, 0.03-0.5% for auto travelers,

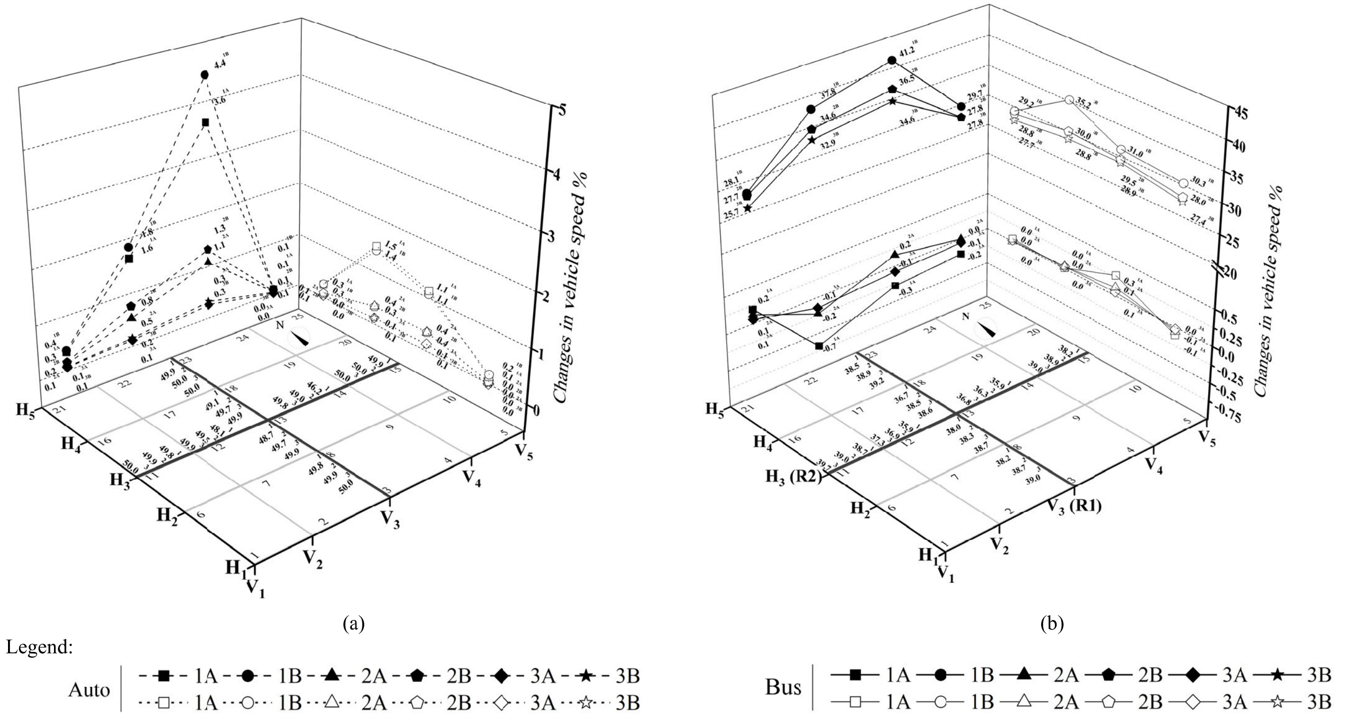

FIGURE 4. Changes in vehicle speeds for streets with narrow lanes and EBLs. (a) Auto. (b) Bus.

and −0.1% to 0.03% for bus riders. For travelway designs with EBLs according to scenarios 1B, 2B, and 3B, greater mobility impacts are created. Modal shifts from auto travel to bus riding are 3.9-4.8%. Reductions in network total travel time range 1.8-2.2%. Increases in average travel speeds are 9.3-10.2% for all travelers, 0.1-1.1% for auto travelers, and 31.7-34.7% for bus riders.

Figure 4 depicts impacts of travelway design optimization on vehicle speeds along streets H_3 and V_3 with narrow travel lanes adopted. For optimal travelway designs without EBLs based on scenarios 1A, 2A, and 3A, a higher number of narrow travel lanes is provided for auto use only that leads to reductions in auto volumes per lane. Meanwhile, the travel lane for auto/bus shared use is converted to a narrower travel lane. The combined effect has led to slightly higher auto running speeds on both streets, with higher speed increments occurring along different segments of street H_3 over street V_3 at 0.1-3.6%, 0.1-0.5%, and 0-0.3% for AM/PM peak, adjacent-to-peak, and off-peak periods correspondingly. Bus operating speeds on both streets fluctuate slightly. The related speed variations are larger along different segments of street H_3, which are −0.7% to 0.2%, −0.2% to 0.1%, and −0.1% to 0.1% for respective time periods.

Compared with the above travel lane configurations, optimal travelway designs with EBLs according to scenarios 1B, 2B, and 3B also contain a higher number of narrow travel lanes for auto travel, but the narrow lane for auto/bus shared use is transformed to an EBL. This renders auto travelers initially driving on the shared use narrow lane shifting to one

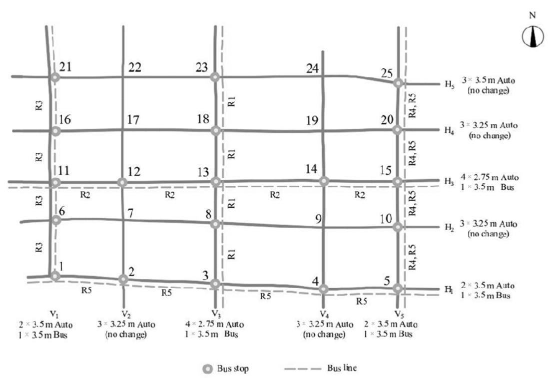

FIGURE 5. Optimal travelway design for the study area network.

of the narrow travel lanes for auto use only or even swapping to bus riding. The combined effect results in significant differences in changes of auto and bus speeds. For auto travelers, speed increases appear to be greater than those of scenarios 1A, 2A, and 3A, and are higher along different segments of street H_3 at 0.1-4.4%, 0.1-1.3%, and 0-0.3% for respective time periods. For bus riders, the use of EBLs for bus lines 1 and 2 along the two streets has significantly improved bus running speeds on all street segments. The extents of bus speed increases are 28.1-41.2%, 27.7-36.5%, and 25.7-34.6% for respective time periods. This seems to suggest that the optimal travelway design with EBLs that is identical for all three time periods be superior to the design without EBLs, which could be viewed as the optimal travelway design for the study area network as Figure 5.

VII. CONCLUSION AND FUTURE WORK

This study has introduced a bi-level model for optimal urban network travelway design. The lower-level model iteratively performs traffic assignments based on alternative street travel lane configurations. Details of the assigned traffic are used as inputs for the upper-level model to compute the networkwide total travel time aimed to be minimized. Successive executions of the lower- and upper-level models help identify the travelway configuration leading to minimized network total travel time, which is considered as the optimal travelway design.

A computational experiment is performed for optimal travelway design of a 4-square-km urban street network in Xi'an, China under six design scenarios in response to three travel demand intensities in AM/PM peak, adjacent-to-peak, and off-peak periods along with absence and presence of EBL considerations. Model execution results indicate that converting standard width travel lanes to a higher number of narrow lanes for auto use only in conjunction with auto/bus shared use could potentially increase the auto mode share and reduce network total travel time. For streets delineated by a higher number of narrow travel lanes, auto running speeds would increase, but the use of auto/bus shared narrow travel lanes could contribute to marginal decreases in bus operating speeds. If further converting the auto/bus shared narrow travel lanes to EBLs, it could increase the bus mode share and reduce network total travel time. Owing to removal of the auto/bus shared narrow travel lanes, the original auto travelers would be diverted to newly created narrow travel lanes for auto use only or be partially shifted to bus riding. For streets designated with a higher number of narrow travel lanes, a lesser extent of increases in auto running speeds takes place. Conversely, for streets with EBLs deployed, drastic increases in bus operating speeds happen along street segments supporting bus operations. The finding suggests that deploying EBLs in densely populated urban areas could be effective in improving people mobility, which is more so for networks with higher bus- or transit-ride shares.

The proposed bi-level model could be further enhanced. It could incorporate optimization of networkwide intersection signal timing plans, bus signal priorities, and bus dispatching frequencies to help produce more precise traffic predictions and further refine the optimal network travelway design.

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