Congestion-aware optimization of urban road space allocation for cars and bicycles

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Abstract

Allocating more road space to bicycles has been considered an effective way to enhance cycling modal share. However, this kind of transport policy often receives strong public criticism due to the concern of severe traffic congestion caused by the reduction of car road space. This work proposes a simulation-based optimization framework to determine the road space allocation scheme on urban road links for cars and bicycles considering network traffic performance. Possible lane configurations are first designed for various road width categories. Besides car traffic, non-lane-based bicycle traffic flow is also considered to avoid congestion on the bike lane network. The solution algorithm aims to maximize the average route-mean speeds experienced by road users in both traffic modes. A case study is conducted for a small-size network with heavy traffic demand. The results show that the optimal allocation schemes successfully mitigate the negative impact on bi-modal network traffic flow. The proposed framework is particularly crucial for a congested network with limited road space to foster a sustainable urban transport system.

Keywords

bicycle flow; mesoscopic traffic simulation; road space allocation; simulation-based optimization; urban road network

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Contents

List of Tables . . . 1

List of Figures . . . 1

1 Introduction . . . 2

2 Lane Configuration Design . . . 4

3 Mesoscopic Traffic Simulation . . . 5

4 Simulation-based Optimization Framework . . . 7

5 Case Study and Results . . . 8

6 Conclusions . . . 11

7 References . . . 12

List of Tables

1 Macroscopic traffic flow parameters . . . 7

List of Figures

1 Lane configurations of an 8-meter-wide road . . . 5
2 Queuing formation on bike lanes with different widths . . . 6
3 SO framework . . . 8
4 3x3 network grid . . . 9
5 Optimal road space allocation schemes . . . 10
6 Route-mean speed evolutions of the paths with the most significant speed drop pattern in every scenario . . . 11

1 Introduction

To decarbonize urban transport systems, many cities have been allocating more road space to public transit and active modes, such as walking or cycling. By providing safe and efficient infrastructure, the modal share of these non-motorized transport modes is expected to increase, providing a means of transition toward a sustainable road environment. However, policymakers face significant challenges when promoting such a transport policy because of its low public acceptance. The potential disturbances on car traffic and the speculated congestion effect after the road space reallocation is one of the major concerns even though studies aimed to show that this kind of policy can also benefit road users of those modes which space is taken away from (Gonzales *et al.*, 2010). To convince the general public and assist the decision-making process of such a radical transformation, a carefully-designed road space allocation scheme which ensures good level-of-services for all competing transport modes by utilizing the existing road space at its maximum is required.

The design of a dedicated bus lane (DBL) network has been the most commonly-discussed problem in this research direction. To handle travelers' mode and route choice behavior in traffic and transit assignment, there were studies adopting a bi-level programming approach, in which the upper-level determines the DBL locations, and the lower-level models the users' reactions to the new design, as formulated in Mesbah *et al.* (2011) and Yu *et al.* (2015). However, the link traffic performance in the traffic assignment method was described by a simplified function, which cannot accurately represent the affected traffic condition.

With the advancement of region-level traffic modeling and its supreme computation efficiency, many studies have applied network fundamental diagrams (NFDs) to describe the aggregated traffic dynamics in road space allocation problems. Simulated NFDs were first used in Gonzales *et al.* (2010) as an indicator to explore the effect of reserved road space for certain modes. In Zheng *et al.* (2017), three-dimensional NFDs, which takes the influence of bus accumulation into account, was used as the evaluation tool in the road space allocation algorithm to determine the fraction of space which should be distributed to buses. For a multi-region network, NFD-based traffic flow model was adopted by Zheng and Geroliminis (2013) to determine the optimal fraction of space allocated to a certain mode usage for every sub-region so that the passenger throughput is maximized. The transit network design problem proposed in Petit *et al.* (2021) also incorporated an NFD-based dynamic traffic assignment approach to optimize the route spacings and service frequency. Nevertheless, the impact of transit network design on car traffic dynamics was still based on macroscopic-level assumptions for a region in these studies. For network design or road space allocation problems with link-level decisions, this kind of approach does not suffice to capture the multi-modal interaction.

Considering the limitations mentioned above, simulation-based optimization (SO) is a suitable method to determine the road space allocation for multiple road links in a network. There were studies using macroscopic link-level dynamic traffic model to evaluate the network traffic performance. In Tsitsokas *et al.* (2021), an extended store-and-forward (eSaF) model was adopted to simulate the traffic evolution in the network after the DBL allocation. However, the eSaF model has the problem of overestimated available space at the upstream of the link. In addition, the route choice behavior after the DBL allocation was assumed to be unaffected. It is however believed to play an influential role for the resulting network traffic performance. On the other hand, the link-transmission model (LTM) was used in Bayrak and Guler (2023) to optimize the DBL location choice in the lower-level of the problem. Still, the study only conducted case studies for a virtual homogeneous grid network, in which LTM can be considered sufficient. The limitations of macroscopic traffic modeling, particularly when being applied to a network with limited road space in which the queue spillback and the resulting congestion propagation must be accurately reproduced, was never emphasized.

Comparatively, mesoscopic traffic model possesses the ability to consider the behavior of each individual road user. In light of the high computation requirement of a mesoscopic model and the large solution space of a traffic network design problem, a surrogate-assisted SO method was proposed in Li *et al.* (2022) to improve the optimization efficiency, while the surrogate model was trained by a machine learning model.

Unlike DBL allocation, little research endeavor can be found for the discussion of the competition of urban road space between cars and bicycles. There were studies proposing a heuristic algorithm to allocate dedicated bike lanes according to the existing road space and network topology (Ballo *et al.*, 2024), an optimization algorithm utilizing graph theory metrics for safety and comfort (Jurado *et al.*, 2024), an mathematical programming problem which quantifies the social welfare of bike lane network expansion through cost-benefit analysis (Paulsen and Rich, 2024), or a multi-objective optimization approach considering the accessibility of both car drivers and cyclists (Wiedemann *et al.*, 2025). However, the network traffic dynamics was never deeply investigated in this problem. As the simulated outcomes shown in Fulton *et al.* (2025), severe traffic breakdown may occur if there is a lack of consideration of the potential congestion effect, especially when the car modal split is rather high.

This paper proposes an SO framework to determine the lane configuration for cars and bicycles on road links in an urban network by minimizing the negative impact on traffic performance experienced by users of both modes. Before the optimization, the possible lane configurations are first designed for each road width category. The SO algorithm searches through the solution space according to the simulation outcomes of the previously-generated road space allocation scheme. It is expected that the optimal solution can effectively avoid severe network traffic congestion in comparison to a heuristic algorithm or an optimization approach for bike lane network design which only account for the accessibility aspect.

2 Lane Configuration Design

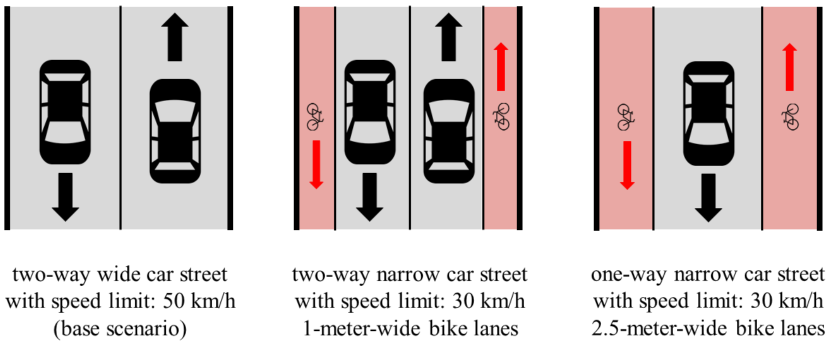
This section explains the design logic of the lane configuration on a road. In the base scenario with wide lanes, cars are able to drive with a relatively high free-flow speed. Once bike lanes are implemented in the network, the free-flow speed may drop due to the narrow lane width. This is similar to the safety effect in the situation of mixed traffic flow mentioned in Loder *et al.* (2021).

Based on the road width, the decisions to be made include the number of car lanes, directions of the car lanes, and width of the bike lanes. The consideration of car lane directions and bike lane widths creates additional dimensions in the decision-making, making it essentially different from a DBL allocation problem, which is a usually binary decision for each road.

It is worth noting that it is possible to create many one-way streets for car traffic following such a design logic. When all the car lanes on a road are in the same direction, the street becomes a one-way street. By doing so, the accessibility for car users is then negatively affected, but car traffic congestion may not exist. As we would like to greatly improve accessibility for cyclists, all road links in the network will be implemented with bike lanes in both directions, while their width can vary based on the traffic demand to avoid congestion.

Fig. 1 shows the possible lane configurations for an 8-meter-wide road link. Given that the minimum width of a car lane is 3 m, such a road can consist of either (1) two 1-meter-wide bike lanes and one car lane in both directions or (2) two 2.5-meter-wide bike lanes and a one-way car lane in either direction. The speed limit for cars changes when the car lane width reduces.

Figure 1: Lane configurations of an 8-meter-wide road



To ensure that the network is still easy for road users to navigate after the optimization, several road links may be bundled together into groups. It is required that road links within one bundle should all be either one-way streets in the same direction or bi-directional streets. This requirement act as a constraint in the solution algorithm. In practice, a bundle can consist of road links that share the same street name.

3 Mesoscopic Traffic Simulation

To capture the evolution of link-level traffic dynamics in the network, LIFT (Ni, 2024), an event-based formulation of the mesoscopic LTM for interrupted traffic flow in an urban road network, is used. It enables the tracking of individual road user microscopically while only relying on the property of macroscopic traffic flow to model the congestion dynamics. Compared to macroscopic models, LIFT can better prevent violating FIFO at intersections in congested conditions, which is particularly essential for an urban network with limited road space. Simulation output information, such as link density and route-mean speed over time, can be extracted for the evaluation of road space allocation schemes.

The non-lane-based characteristics of bicycle flow is considered in the simulation of traffic dynamics on the bike lane network. Unlike the lane-based setup in car traffic flow, there is a non-linear correlation between capacity and lane width for bicycle flow due to the difference in lateral space utilization efficiency, as demonstrated in Brunner *et al.* (2024). In addition, the jam density per meter width also varies between different lane widths because of the staggered queue configuration exhibited by cyclists before the stop line, which was first pointed out in Gavriilidou *et al.* (2019) and Wierbos *et al.* (2021). Hence, the unit vehicle equivalent length, which is used to determine the maximum number of vehicles the bike lane can accommodate, also differs.

The bicycle size and its diamond shape representation in Brunner *et al.* (2024) are used in this paper. Every cyclist occupies a 2-meter-long and 0.8-meter-wide diamond-shaped area. Fig. 2 illustrates cyclists' queuing formations on 1.0-, 1.5-, 2.0-, and 2.5-meter-wide bike lanes. It is worth mentioning that cyclists may also utilize the curbside lateral space to queue. However, it is also not expected that cyclists would maintain such a compact queuing formation throughout the entire bike lane. Therefore, we decide not to further increase the jam density to prevent an overestimation of traffic performance eventually.

Figure 2: Queuing formation on bike lanes with different widths

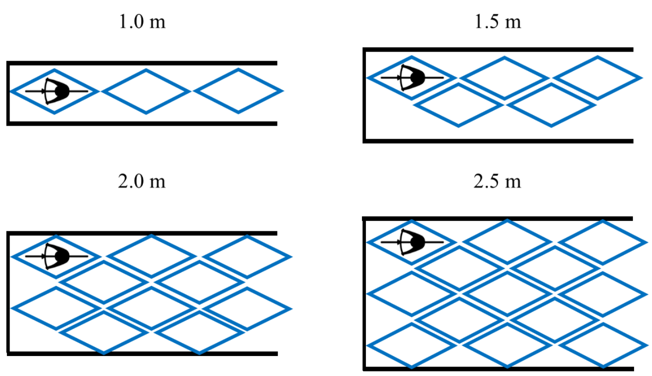


Table 1 summarizes all the traffic parameters used in LIFT for car flow and bicycle flow on different lane widths, including free-flow speed v^{f}, saturation flow per meter width q^{sat}, unit vehicle equivalent length l^{eq} (for jam density), and backward hole speed v^{hole}. Note that it is assumed that the parameters in each lane width category follow the relationship described with a triangular fundamental diagram. Whether the macroscopic variables of bicycle traffic flow also follows such a correlation is out of the discussion in this paper and should be investigated in future studies.

As indicated by the parameter values, a 1.5-meter-wide bike lane has the largest capacity per lane width because of its better lateral space utilization rate in free-flow conditions. On the other hand, in the formation of standing queue, a 2.0-meter-wide bike lane can accommodate a greater number of bicycles than a 1.5-meter-wide bike lane, as suggested by the unit equivalent length. This difference between free-flow and congested regimes stems from the consideration of safety region when cyclists are moving.

Table 1: Macroscopic traffic flow parameters

	car		**bike**			
	wide	**narrow**	**1.0 m**	**1.5 m**	**2.0 m**	**2.5 m**
$v^{\mathbf{f}}$ **[km/h]**	45	30	18.7			
$q^{\mathbf{sat}}$ **[veh/h]**	1800		2000	2150	1900	1750
$l^{\mathbf{eq}}$ **[m]**	7.5		2.00	1.33	0.57	0.46
$v^{\mathbf{hole}}$ **[km/h]**	19.29	24.55	5.14	5.63	2.46	2.27

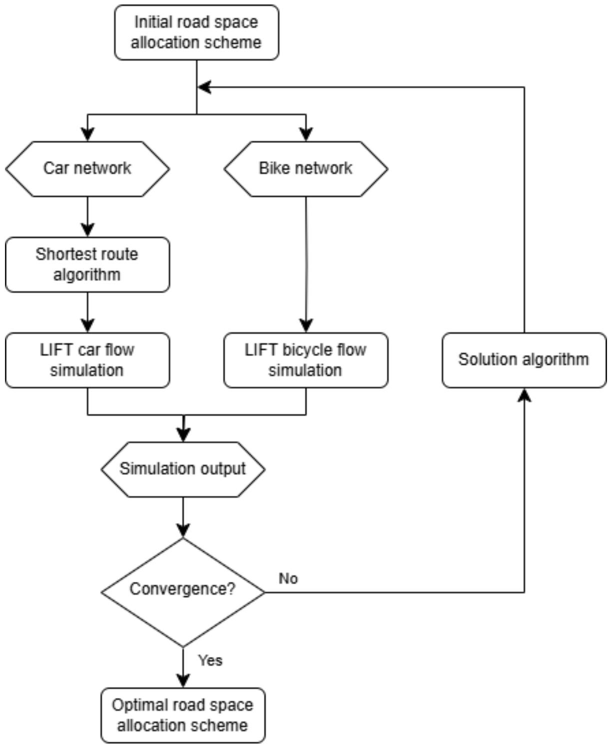
4 Simulation-based Optimization Framework

Fig. 3 shows the proposed SO framework. In the current setup, we first assume that travelers only use the shortest route between its origin-destination (OD) in the network. As the bi-modal road space allocation scheme can contain one-way car streets, routes which are originally connected may become dead ends in the newly-generated network. Therefore, Dijkstra algorithm is applied to generate all the shortest routes for cars before the mesoscopic traffic simulation in every iteration. Note that the routes for bicycles would not change since there are bike lanes for both directions on every road link. After evaluating the solution through simulation, the algorithm updates the road space allocation scheme for the next iteration.

The solution algorithm applied in this framework is omitted in this paper. Interested readers are encouraged to follow up on the authors' work in this research direction afterwards.

To evaluate every road space allocation solution, a weighted average route-mean speed, as written in Eq. (1), is calculated to serve as the fitness function. Hence, the optimization becomes a maximization problem aiming to avoid traffic congestion in the bi-modal road network by investigating the average route-mean speeds of each mode, $\overline{v^{\text{car}}}$ and $\overline{v^{\text{bike}}}$. The weights for each mode, ω_{car} and ω_{bike}, are determined so that they are proportionate to the corresponding free-flow speeds. Therefore, the values can be expressed by setting $\omega_{\text{car}} = 1$ and $\omega_{\text{bike}} = v^{\text{f}}_{\text{car}}/v^{\text{f}}_{\text{bike}}$. An additional weight factor for each mode, α_{car} and α_{bike}, can also be included according to the preference of the transport policy. In this work, we

Figure 3: SO framework



determine it based on the modal split of each mode. For instance, both α_{car} and α_{bike} can be set to 0.5 when half of the road users are using bicycles. To prioritize cycling, an even larger factor can be applied to avoid bicycle traffic congestion.

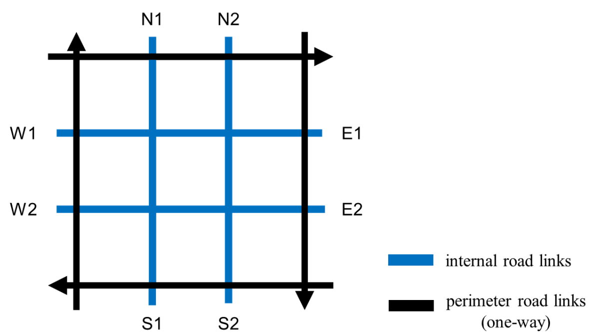
$$f = \alpha_{\text{car}} \cdot \omega_{\text{car}} \cdot \overline{v^{\text{car}}} + \alpha_{\text{bike}} \cdot \omega_{\text{bike}} \cdot \overline{v^{\text{bike}}} \tag{1}$$

5 Case Study and Results

A small-size 3x3 homogeneous network grid, as shown in Fig. 4, is used in the case study to test the proposed SO framework. Every road link is 100-meter-long. The signal timing plan at every intersection has a cycle length of 60 s and green length of 25 s.

The blue road links within the network have a width of 8 m, as described by the example

Figure 4: 3x3 network grid



in Section 2. In the base scenario, these links have one car lane for both directions. On the other hand, the black roads located on the network perimeter are single-lane one-way street, while the directions can be seen in the figure. Right-turn is allowed in the network, while left-turn is forbidden. The roads in the network already has limited road space, which makes it a proper option to test the proposed SO framework considering the difficulty of allocating bike lanes and in the meantime avoiding severe traffic breakdown.

The blue road links within the network are bundled into four corridors (N1-S1, N2-S2, E1-W1, E2-W2). Road links on the same corridor should have the same lane configuration. It is expected that cars would need to take a detour by using the perimeter roads to reach their destinations instead of entering network when any road link within the network becomes a one-way street.

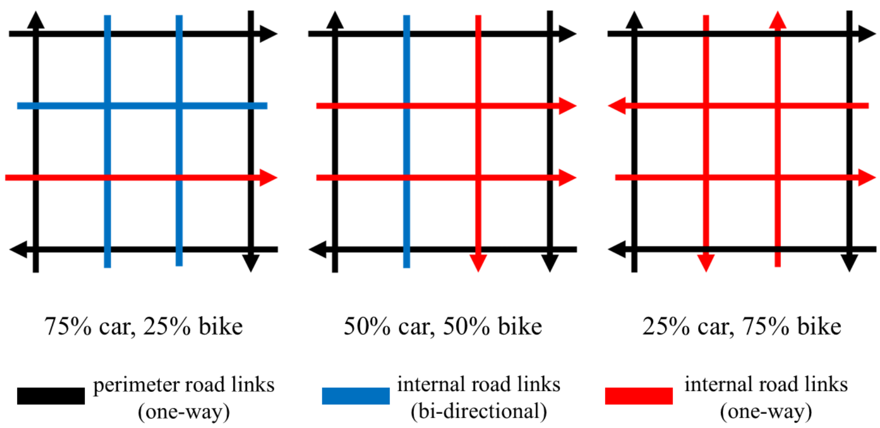
A three-hour simulation period containing sixteen OD routes entering from twelve different origin nodes with a varying inflow demand profile every 15-minute is designed. In the designed demand, routes in the east-bound direction has the largest amount of traffic demand, followed by those in the north- and west-bound directions, while the south-bound direction has the smallest amount. Such a setup makes it easy to verify the optimal road space allocation schemes and check if the one-way street designs align with the expectation.

An equivalent factor of 1.4 bicycles per car unit is applied in this cases study to calculate the bicycle traffic demand as a car usually contains more than one passenger (VSS, 2013). Three bi-modal split scenarios, each containing 25%, 50%, and 75% of bicycle users, are conducted. It is anticipated that the amount of road space allocated to bicycles would increase with the increment of its modal share.

Fig. 5 shows the optimal road space allocation schemes of the three modal split scenarios.

In the scenario with 75% of the road users using cars, only one corridor becomes one-way and is allocated with widened bike lanes to improve the bicycle traffic performance. When the modal shift toward cycling increases to 50%, as the impact on car traffic flow is reduced, three corridors are transformed into one-way streets for cars. Both corridors in the horizontal direction are in the east-bound direction because of the designed demand pattern, which implies that car traffic in the west-bound direction is all diverted to the perimeter road links. When the bicycle modal share further increases to 75%, all four corridors in the network are transformed. By maximizing the amount of road space that can be allocated to bicycles, its travel time in the network can be improved without sacrificing car traffic performance due to its low demand.

Figure 5: Optimal road space allocation schemes

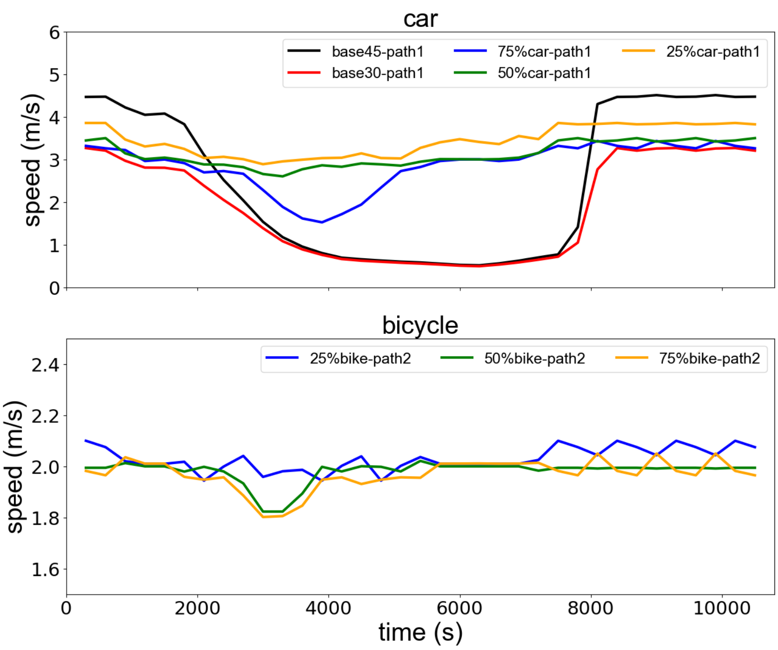


To understand the resulting congestion dynamics in the network, Fig. 6 plots the route-mean speed evolutions of the paths which have the most observable amplitude and duration of speed drop in each modal share scenario for both modes. The black curve in the first plot represents the outcome of the base network design shown in Fig. 4 with the original speed limit, while the red curve shows the outcome with the reduced speed limit. As shown in the figure, the car route-mean speed largely decreases from 4.5 m/s to below 1 m/s due to the heavy demand. After the car free-flow speed is reduced due to the allocation of bike lanes, the maximum route-mean speed that can be attained drops even though the minimum actually remains at the same level, showcasing that a lower speed limit does not necessarily degrade the urban traffic performance significantly.

With the new network designs, the durations of congestion become shorter, and the speed drop amplitudes are much smaller compared to the base scenario with reduced speed limit. This shows that the optimal road space allocation scheme can also provide route guidance for cars so that they are distributed more evenly throughout the network, leading to an even better car traffic performance than the situation in the base scenario. By comparing different scenarios, one can see that the speed drop amplitude becomes smaller as the car modal share decreases, showing the effect of modal shift on mitigating car traffic congestion phenomena.

On the other hand, the bicycle route-mean speed in the 25% modal share scenario shows a plateau. This means the bicycle demand is not large enough to cause any congestion effect. In scenarios with a larger bicycle modal share, a slight drop of speed can be found, but it does not last for a long time duration. Overall, there is no significant reduction of bicycle route-mean speed in the designed optimal bike lane networks, indicating that bicycle traffic congestion is successfully avoided.

Figure 6: Route-mean speed evolutions of the paths with the most significant speed drop pattern in every scenario



6 Conclusions

In this work, we propose an SO framework for the road space allocation between cars and bicycles considering the traffic performance of both modes in the network. The algorithm updates the road space allocation scheme by evaluating different solutions and the resulting network traffic dynamics with mesoscopic traffic simulation. Through the proposed SO framework, this paper seeks to proof that a congestion-informed road space allocation scheme outperforms other bi-modal network design logic by optimizing the traffic performance for both modes.

The case study results show that car traffic congestion can be mitigated in the optimal road space allocation schemes even with the decreased free-flow speed due to the implemented bike lanes and the reduced car road space. This demonstrates an improved utilization of the limited urban road space. By testing different modal splits, it is also found that the total amount of bike lane allocated can be increased if needed when the car modal share decreases.

To the best of the authors' knowledge, this is the first research attempt that takes into account traffic performance for bike lane allocation or bike network design problems. The consideration of non-lane-based bicycle flow characteristics is also one of the novelties in this work.

Future work will consider travelers' adaptive route choice behavior according to the dynamic changes of route travel times. This creates an extra layer of complexity for the solution algorithm to find the optimal road space allocation scheme because of the increased uncertain correlation between lane configurations and traffic performance. Furthermore, the case study will be extended to a medium-size urban road network in the real-world to showcase the applicability of the proposed SO framework.

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