Data-driven Bike Lane Layout Design

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Abstract

This project proposes designing bike lane layout by combining realistic bike trip data and mixed integer programming. The objective is to improve biking efficiency without imposing significantly negative impacts on automobiles. We apply the methodology to bike lane layout for Greenwich Village, and compare the new plan with the existing bike lanes. The results demonstrated that our methodology can significantly improve biking time and reduce the negative impacts on automobiles. However, the comparison of bike lane layout shows the optimized bike lane network has more horizontal lanes and less vertical lanes. It indicates that we might consider the external trips across the zone of interest.

1 Background

Bike is still one popular transportation mode, even in highly modernized areas. For example, it is reported that around 800000 New Yorkers ride a bike frequently and the daily bike trips have tripled in the recent 15 years. However, biking in urban roads may threaten cyclists' safety since they are exposed to motor vehicles. Meanwhile, bikes may slow down cars and buses [1].

Exclusive bike lanes might be a promising solution to the above problems. Well-planned bike lanes can not only cut accident risks [2], but also reduce traffic delays [3]. However, there are limited road infrastructure for exclusive bike lanes. Unreasonable bike lanes may appear less attractive for bikers and even worsen the traffic congestion [4]. Therefore, it is crucial to reasonably plan the location and connectivity of bike lanes.

Traditional bike lane planning is based on experience and surveys. Thanks to the accessible bike trip records, we can study this topic by combining optimization tools and realistic data. In this project, we use Citi Bike data to conduct a case study in Lower Manhattan. We expect that our new design will outperform the existing one which acts as the benchmark, and thus set an example of bike lane planning for other regions.

2 Problem statement

We consider the design of bike lane layout for Greenwich Village in Lower Manhattan. We intend to improve the biking efficiency but to alleviate the negative impacts on automobiles. The proposed methodology is based on real historical data from Citibike, which is one of the biggest bike operator in New York. Fig 1 shows the Citibike stations in Greenwich Village. We have access to the citibike dataset through the website https://s3.amazonaws.com/tripdata/index.html. The dataset includes the origin and destination of each trip. So we can obtain the demands between stations.

For simplicity, the following assumptions are made.

1. Citibike data can reveal the potential mobility pattern of bike trips in Greenwich Village;
2. Intersections are taken as network nodes and we set trip origins and destinations to the nearest intersections.
3. Biking efficiency is quantified by biking time, and biking speed in exclusive lanes is higher than that in mixed lanes.

4. The reduced capacity for automobiles is adopted to quantify the negative impacts of bike lanes, where reduced capacity is defined as lane-based capacity of urban roads since bike lanes take up the space for automobiles.

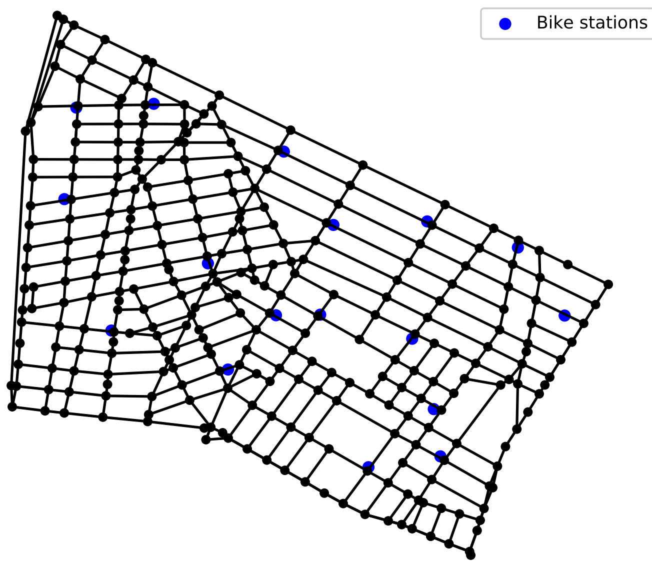


Figure 1: CitiBike stations in Greenwich Village

3 Methodology

We list the model notation in Tab 1, and the model formulation is given below. As seen in Eq (1), the objective function comprises three terms. The first and second term represents the total biking time in bike lanes and mixed lanes, respectively. And the third term denotes the capacity reduction for automobiles caused by bike lanes.

Constraint (2) denotes flow conservation at each node i for commodity k. Constraint (3) and (4) regulate that bike flows in exclusive lanes and mixed lanes depend on whether there is a bike lane in link (i, j). Constraint (5) can be recognized as the budget constraint on the total bike lane length. Constraint (6)–(8) tries to connect the downstream and upstream bike lanes and avoid isolated bike lanes. For instance, if we deploy a bike in link (i, j) as shown in Fig 2, these constraints require that the upstream links (ℓ, i) $(\ell \neq i)$ must have bike lanes denoted by x or artificial ones denoted by y. So do the downstream links. Herein the artificial bike lanes will not be deployed in practice, and their existence allows the bike lane network has end points. $Y = 0$ means that artificial links are not allowed, and then the bike lane network must have loops.

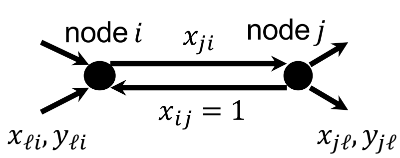


Figure 2: Illustration of connectivity

Table 1: Model notation

Set	
$\mathcal{G}(\mathcal{N}, \mathcal{A})$	Directed network with node set $\mathcal{N}$ and link set $\mathcal{A}$
$\mathcal{N}^-(i)$, $\mathcal{N}^+(i)$	Set of nodes upstream and downstream of node i
$\mathcal{O}_k$, $\mathcal{D}_k$, $\mathcal{T}_k$	Set of origin, destination and transshipment nodes of commodity k
$\mathcal{K}$	Set of commodity
Parameter	
t^e_{ij}	Biking time in bike lane in link (i, j)
t^m_{ij}	Biking time in mixed lanes in link (i, j)
c_{ij}	Reduced capacity of link (i, j)
l_{ij}	Length of link (i, j)
L	Total length of bike lanes
o^k_i, d^k_i	Supply and demand at orgin i of commodity k
γ	Weight of reduced capacity in the objective function
Y	Total artificial bike lanes
Decision variable	
e_{ij}	Bike flow of exclusive lanes in link (i, j)
m_{ij}	Bike flow of mixed lanes in link (i, j)
f^k_{ij}	Bike flow of commodity k in link (i, j)
x_{ij}	Whether link (i, j) has a bike lane
y_{ij}	Whether link (i, j) has an artificial bike lane

$$\min \sum_{(i,j)\in\mathcal{A}} (t^e_{ij} e_{ij} + t^m_{ij} m_{ij} + \gamma c_{ij} x_{ij}) \tag{1}$$

$$\text{s.t.} \sum_{j\in\mathcal{N}^+(i)} f^k_{ij} - \sum_{j\in\mathcal{N}^-(i)} f^k_{ji} = \begin{cases} o^k_i & i \in \mathcal{O}_k \\ -d^k_i & i \in \mathcal{D}_k \\ 0 & i \in \mathcal{T}_k \end{cases}, \forall k \in \mathcal{K} \tag{2}$$

$$e_{ij} \geq \sum_k f^k_{ij} - M(1 - x_{ij}), \forall (i, j) \in \mathcal{A} \tag{3}$$

$$m_{ij} \geq \sum_k f^k_{ij} - M x_{ij}, \forall (i, j) \in \mathcal{A} \tag{4}$$

$$\sum_{(i,j)\in\mathcal{A}} l_{ij} x_{ij} \leq L \tag{5}$$

$$x_{ij} \leq \sum_{\ell\in\mathcal{N}^+(j)\setminus\{i\}} (x_{j\ell} + y_{j\ell}), \forall (i, j) \in \mathcal{A} \tag{6}$$

$$x_{ij} \leq \sum_{\ell\in\mathcal{N}^-(i)\setminus\{j\}} (x_{\ell i} + y_{\ell i}), \forall (i, j) \in \mathcal{A} \tag{7}$$

$$\sum_{(i,j)\in\mathcal{A}} y_{ij} \leq Y \tag{8}$$

$$x_{ij}, y_{ij} \in \{0, 1\}, e_{ij}, m_{ij}, f^k_{ij} \in \mathbb{R}_{\geq 0}, \forall (i, j) \in \mathcal{A}, k \in \mathcal{K}$$

4 Evaluation

We consider two scenarios. In the first scenario, we assign the bike trips to the current bike lane layout which acts as the benchmark. The assignment is based on the shortest path. In the second scenario, we will optimize the bike lane layout given the current length of bike lanes. We compare these two scenarios in terms of total biking time and reduced capacity for automobiles. Finally, we investigate the impacts of the weight γ and the parameter Y.

4.1 Benchmark System

We first introduce the benchmark system. The existing bike lane layout is illustrated in Fig 3 and we represent the area with a network consisting of 295 nodes and 535 links as shown in Fig 4. The lane capacities for automobiles are listed in Tab 2. Besides, we assume free speed in bike lanes equals 15 km/h and biking speed mixed with vehicles equals to 10 km/h.

17 CitiBike stations are considered. The demands are visualized in Fig 5. There are 178 commodities with bike flows larger than zero.

Based on this setting, the total biking times is equal 177228 seconds and the reduced capacity equals to 70200 veh/h.

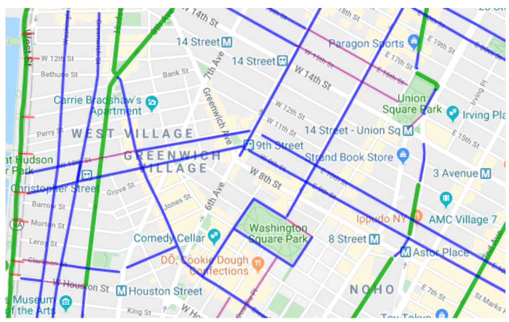


Figure 3: Existing bike lane layout

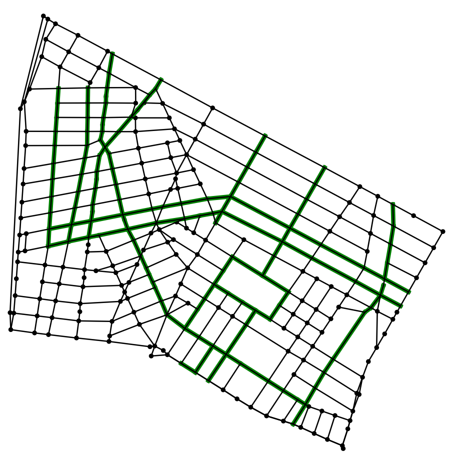


Figure 4: Network representation

Table 2: Parameter table

Parameter	Value	Parameter	Value
#Node	295	Mixed bike flow speed	10 km/h
#Link	535	Primary lane capacity	1000 veh/h
#Commodity	178	Secondary lane capacity	800 veh/h
Bike lane length	12 km	Tertiary lane capacity	600 veh/h
Free bike flow speed	15 km/h	Residential lane capacity	400 veh/h

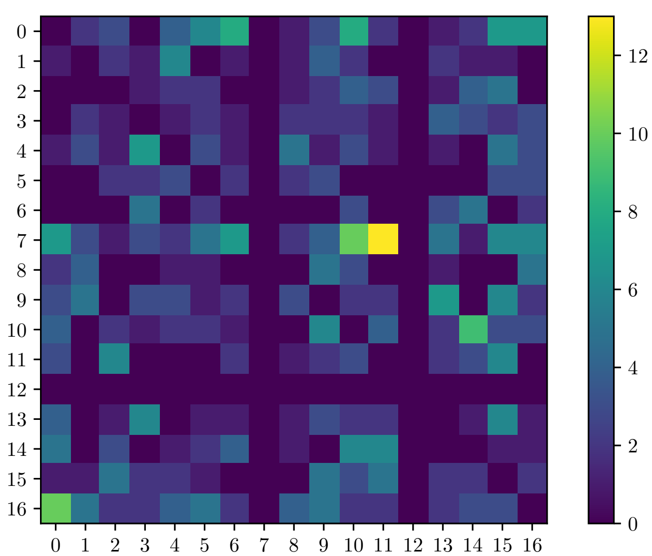


Figure 5: Citibike demand

4.2 Proposed System

We optimize the bike lane layout based the settings of $\gamma = 0.3$ and $Y = 0$, then we obtain the bike lane layout as shown in Fig 6 with the total biking time of 164751 seconds and the reduced capacity of 54000 veh/h. The results show that the total biking and the reduced capacity decrease by 7.3% and 23%, respectively.

Compared with the current one as shown in Fig 4, the optimized bike lane network has more horizontal lanes and less vertical lanes. The reason may lie in that we only consider the bike trips in the zones and neglect northbound or southbound trips across the zone.

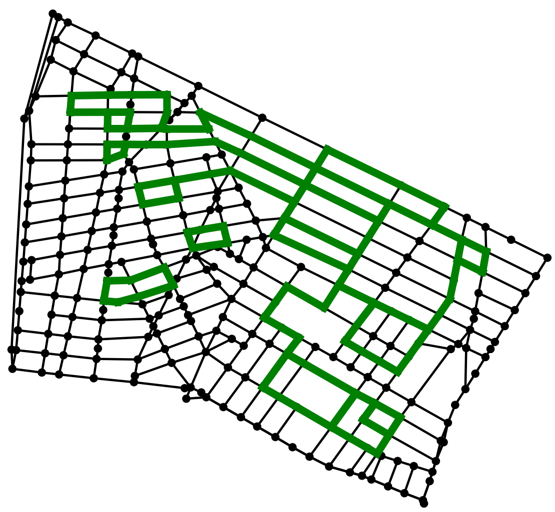


Figure 6: Proposed bike lane layout

4.3 Model Analysis

4.3.1 Impacts of weight γ

We test different γ between 0 and 1. The resulting total biking time and reduced capacity are presented in Fig 7. It is reasonable to find larger γ leads to lower reduced capacity and longer biking time. It can be found that the optimized bike network can achieve the similar total biking time but with fewer reduced capacity when γ equals to 0.5.

4.3.2 Impacts of parameter Y

We also evaluate the model performance given $Y = 0$, 5 and ∞. The obtained biking times are compared in Fig 8. It is not surprising to find that larger Y contributes to less biking time. However, we also note that larger Y tends to induce isolated bike lanes as shown in Fig 9b.

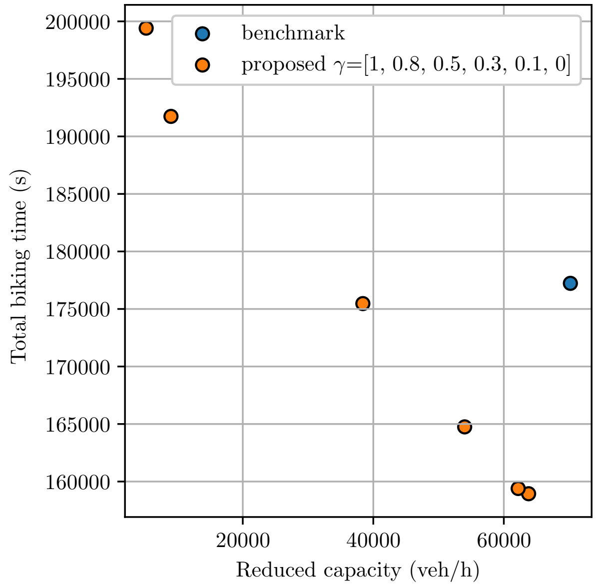


Figure 7: Analysis of weight γ

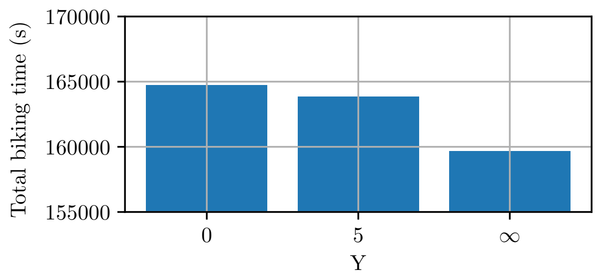
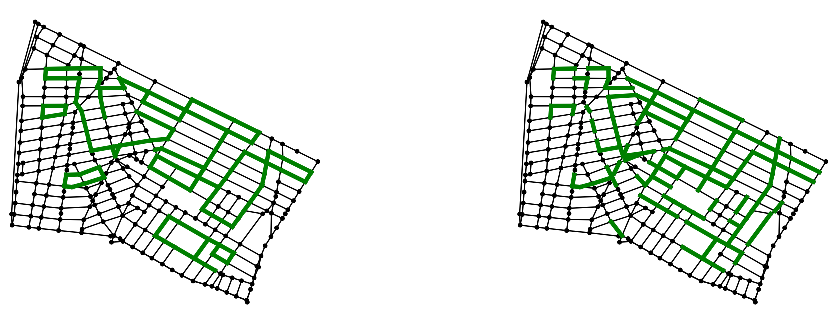


Figure 8: Analysis of Y



(a) $Y = 5$ (b) $Y = \infty$

Figure 9: Bike lane layout under different Y

5 Conclusion

This project proposes a mixed integer programming for designing bike lane layout. The proposed methodology attempts to improve biking efficiency without imposing significantly negative impacts on automobiles. We combine the model with the real CitiBike trip data to design bike lanes for Greenwich Village, and compare it with the existing bike lanes. The results reveal that our methodology can significantly improve biking time and reduce the negative impacts on automobiles. However, the comparison of bike lane layout shows the optimized bike lane network has more horizontal lanes and less vertical lanes. It indicates that we might consider the external trips across the zone of interest.

References

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