Three-dimensional Macroscopic Fundamental Diagrams for Dedicated Bicycle and Car Traffic in an Actuated Signal Control Network

Ying-Chuan Ni

Michail Makridis

Anastasios Kouvelas

STRC conference paper 2023 **April 9, 2023**

STRC | 23rd Swiss Transport Research Conference
Monte Verità / Ascona, May 10-12, 2023

Three-dimensional Macroscopic Fundamental Diagrams for Dedicated Bicycle and Car Traffic in an Actuated Signal Control Network

Ying-Chuan Ni
IVT
ETH Zurich
ying-chuan.ni@ivt.baug.ethz.ch

Michail Makridis
IVT
ETH Zurich
michail.makridis@ivt.baug.ethz.ch

Anastasios Kouvelas
IVT
ETH Zurich
kouvelas@ethz.ch

April 9, 2023

Abstract

To promote the usage of active transport modes, urban areas are reallocating more road space for bicycles nowadays. With the expansion of dedicated cycling infrastructure in future cities, the bicycle traffic demand is expected to grow significantly. However, this also implies the reduced capacity for car traffic. Therefore, road traffic needs to be managed by monitoring the congestion dynamics of bicycles and cars at the same time. In this study, we consider a busy bi-modal road traffic network with car lanes and dedicated bike lanes. Actuated signals are implemented on both types of infrastructure so that the signal control strategy is responsive to bi-modal demand at intersections. Due to the conflict between the two modes, larger demand from one mode causes longer waiting time on another. Three-dimensional macroscopic fundamental diagrams (3D-MFD) can be used to model the traffic performance of such a bi-modal network. A simulation approach is adopted to compute the traffic states in the 3D-MFDs. The proposed modeling framework may also be applied to various actuated control setups according to the practical interest or extended to investigate the effect of other traffic-dependent signal control strategies for cars and bicycles.

Keywords

Bicycle traffic, Macroscopic fundamental diagram, Three-dimensional macroscopic fundamental diagram, Multi-modal traffic, Dedicated bike lane, Microscopic traffic simulation, Actuated signal control

Suggested Citation

Ni, Y. C., Makridis, M., Kouvelas, A. (2023). Three-dimensional Macroscopic Fundamental Diagrams for Dedicated Bicycle and Car Traffic in an Actuated Signal Control Network. 23rd Swiss Transport Research Conference (STRC 2023)

Contents

List of Tables

List of Figures

1 Introduction

Cycling is considered an important active transport mode for sustainable urban development. Cities around the world have been seeking to expand the relevant infrastructure for bicycles to facilitate their usage by the general public. However, given the limited urban road space, reallocating more space to bicycle traffic may lead to serious car traffic congestion. Thus, it is a huge challenge to transform an existing car-centric urban network into a bicycle-friendly environment. In addition, because of the potentially growing cycling demand in a bicycle-centric network, cyclists may also face congestion even on dedicated bike lanes, not to mention the impact caused by the interaction between bicycles and cars. Therefore, a tool which can model the traffic performance of these two modes at the same time is essential.

The concept of 3D-MFD was first developed to investigate the relationship between car accumulation, bus accumulation, and the traffic production of a network where roads are shared by cars and buses (Geroliminis et al., 2014; Zheng et al., 2013). It was pointed out that 3D-MFD outperforms those methods using passenger car unit to represent the influence of bus operation considering its ability to describe the various effects of bi-modal interaction at different congestion levels. From the simulation results in the paper, it was found that the relationship shows low scatter and can be approximated into a functional form by curve-fitting. Ortigosa et al. (2015) then used the framework and a microsimulation tool to investigate the network traffic performance with different levels of public transit operation regarding the share of dedicated lanes and the existence of signal priority. Loder et al. (2017) estimated the 3D-MFD using empirical data. The existence of such a bi-modal relationship at the network-scale was verified. A linear model describing the relationship between car speed, car accumulation, and public transport vehicle accumulation which can be estimated through regression based on empirical data was also proposed. Loder et al. (2019) aimed to derive a functional form for the 3D-MFD of an urban network through generating theoretical boundary planes and smoothing its shape with empirical data. Later on, Paipuri and Leclercq (2020) started to apply 3D-MFD to model the traffic dynamics in a bi-modal urban network.

3D-MFD has also been adopted by many different studies regarding multi-modal network traffic management strategies, such as road space reallocation among different modes (Zheng et al., 2017), mode-specific perimeter control (Ampountolas et al., 2017), public transit network design (Dakic, Leclercq, et al., 2021), and modular bus dispatching optimization (Dakic, Yang, et al., 2021).

Up until now, most of the 3D-MFD applications focused on the interaction between public transit and cars. Few studies have discussed the macroscopic relationship between bicycles and cars in the network. Huang et al. (2021) used empirical data to investigate the impact of bicycle traffic on car MFD. However, the production of bicycles was not of interest in the study. Loder et al. (2021) first proposed an approach to construct multi-modal MFDs for a tri-modal urban transport system. By doing so, the performance of each individual mode can be derived, which is helpful for relevant management strategies. Huang et al. (2022) also used 3D-MFD to model car-bicycle traffic. However, the bicycle production was only derived by estimating the parameters of assumed linear models based on empirical data and microsimulation. There was no in-depth discussion on analytical bicycle MFD. In short, bicycle MFD and its application have not received much attention in the research field.

This study considers an urban network consisting of multiple one-way streets with car lanes and dedicated bike lanes. Actuated signals are implemented at every intersection to regulate the traffic demand of each mode from every approach. The 3D-MFD framework is applied to describe the traffic performance of such a bi-modal urban network.

2 Method

This section first introduces the network layout, signal control scheme, microsimulation parameter settings, and simulation scenarios. The second part explains the method adopted to derive the 3D-MFDs.

2.1 Network and Simulation Setup

The virtual network grid consists of six horizontal and six vertical one-way streets, as shown in Figure 1 The block length is 250 m. There are a car lane and a 2 meter wide dedicated bike lane on each street. Figure 2 shows the intersection configuration and the signal stages. For all approaches, straight and turning directions are grouped together due to the single lane space limitation. The fifth stage is assigned to pedestrians to allow crossing in every direction. Induction loop detectors are placed on each approach to detect and response to the presence of traffic demand. The distances between detectors and stop lines correspond to the specified actuated traffic control logic.

Figure 1: Network grid

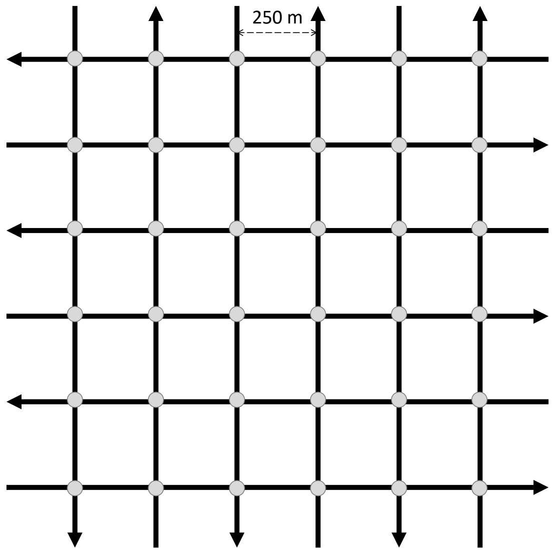
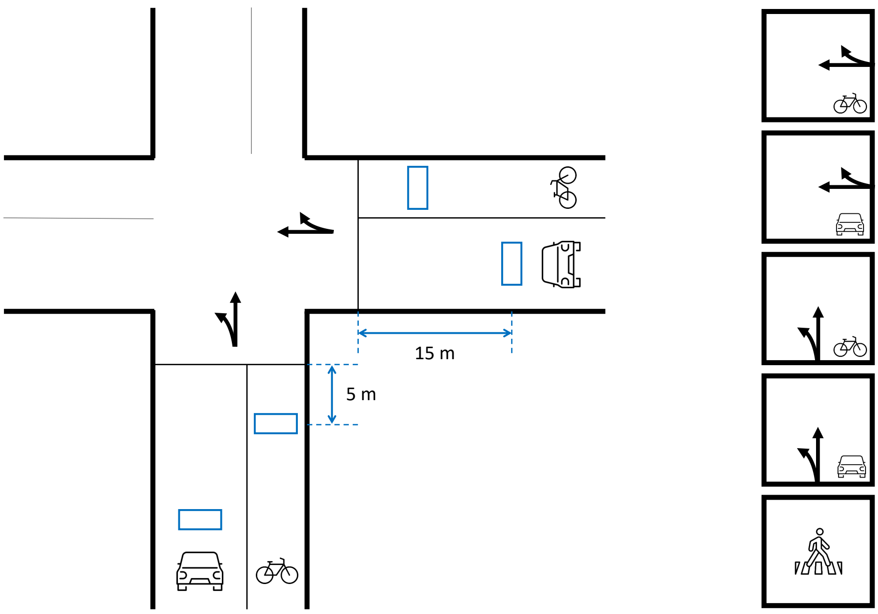


Figure 2: Intersection layout (left) and signal stages (right)



The actuated signal control logic is explained as follows:

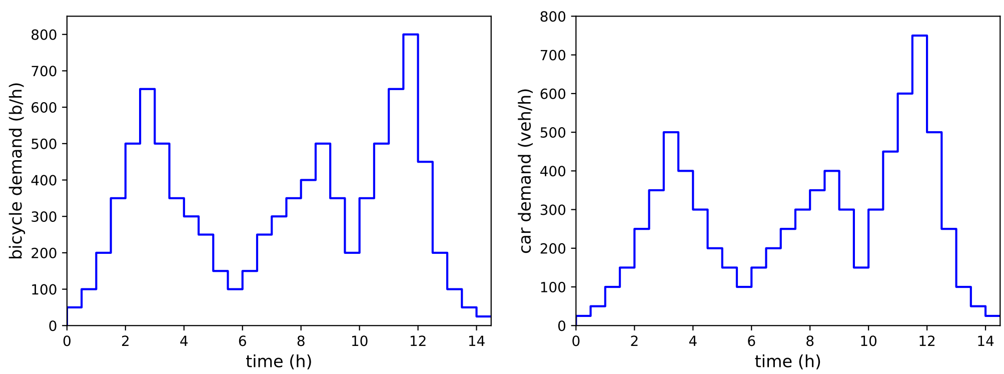
- Minimum green length = 5 s
- Critical time headway = 2 s
- Maximum green length = 20 s

The typical point detection logic is adopted. The minimum green time is sufficiently long for vehicles queuing between the stop line and the detector to be discharged. The extension green time ends when the detected headway is longer than the critical headway so that the detected vehicle has sufficient time to pass the stop line. The same logic is applied to both bicycle and car traffic. It is worth noting that different control strategies, e,g, different maximum green lengths, can be implemented for the two modes according to the interest of the practitioner.

A microsimulation approach is adopted to simulate and compute the traffic states. PTV Vissim, a commercial microscopic traffic simulation tool, is selected considering its relatively profound bicycle simulation function (PTV Group, 2023). All the model parameters for bicycle simulation follows the results in Kaths et al. (2021).

Scenarios with various bi-modal demand are generated to explore all the traffic states in various bicycle-car accumulation situations. In each simulation run, either the bicycle demand or car demand would be fixed. This also allows us to investigate the bicycle production in response to different average car demands, and vice versa. Figure 3 shows the demand profiles of bicycle and car traffic used in the simulation runs. The intersection capacity for bicycels and cars based on the signal control logic is pre-computed to make sure the varying demand profiles can produce almost all possible traffic states.

Figure 3: Demand profiles of bicycles (left) and cars (right)



2.2 MFD Derivation

3D-MFD is a suitable framework for describing the relationship between the bi-modal traffic accumulation and production in a network. To derive the MFDs for both bicycle traffic and car traffic, the simulation output is analyzed following the extended Edie's definition for network traffic, as discussed by Saberi et al. (2014). The network flow and network density can be calculated by:

$$q = \frac{TDT(\omega)}{L(\omega) \cdot \Delta t}, \tag{1}$$

and

$$k = \frac{TTS(\omega)}{L(\omega) \cdot \Delta t}, \tag{2}$$

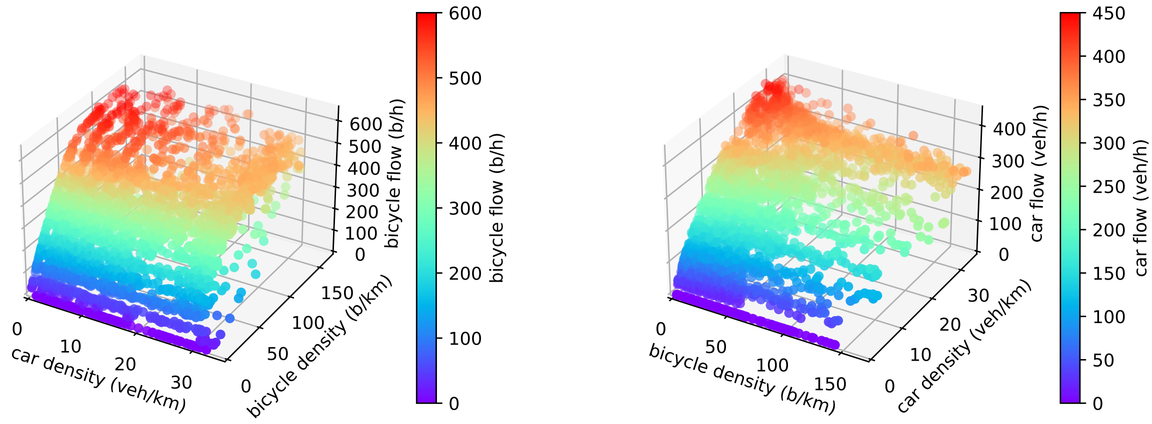
where ω represents the entire network, TDT is the total distance traveled, TTS is the total time spent, L is the total length of the network, and Δt is the length of each aggregation time interval. $L(\omega) \cdot \Delta t$ equals the area of the time-space region. In this study, TDT and TTS can be directly computed via the built-in function in Vissim, while $L(\omega) \cdot \Delta t = \frac{1}{12}(\mathrm{h}) \cdot 15(\mathrm{km})$.

The incoming and outgoing links connected with the inflow and outflow nodes are excluded from the analysis. The first ten minutes of the simulation are also removed as it is considered the warm-up period for the traffic demand to enter the network. The aggregation time interval is 5 minutes. In total, 172 traffic states are generated from each simulation run.

3 Results

The 3D-MFDs obtained from the simulation output is presented in Figure 4. As shown in the plots, the largest bicycle production occurs at the region with medium bicycle density and small car density. The same goes for the car production. Note that there is no decreasing production resulted from gridlock in the network since it is difficult to reproduce such a condition in the simulation of a network with a homogeneous topology and proper signal timing design.

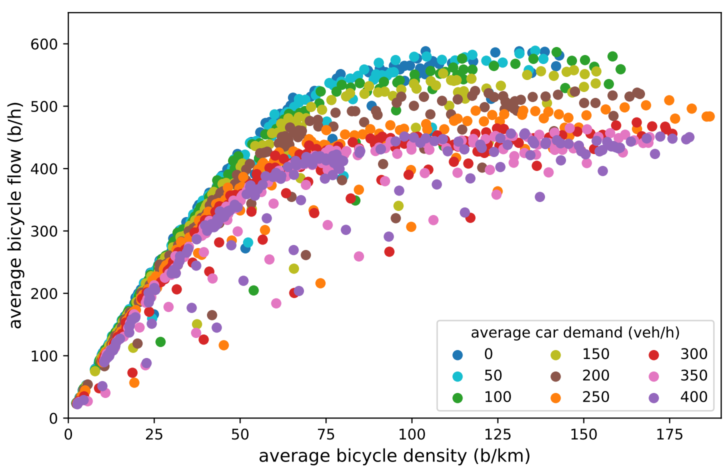
Figure 4: 3D-MFDs of bicycles (left) and cars (right)



Figures 5 and 6 plot the bicycle and car MFDs generated under different car demands in 2D. Figures 5 clearly shows the decreasing bicycle traffic capacity due to the increasing car demand. Although the actuated signals increase the green time for bicycles when there are more bicycles in the network, the capacity is still reduced due to the longer resulting cycle length.

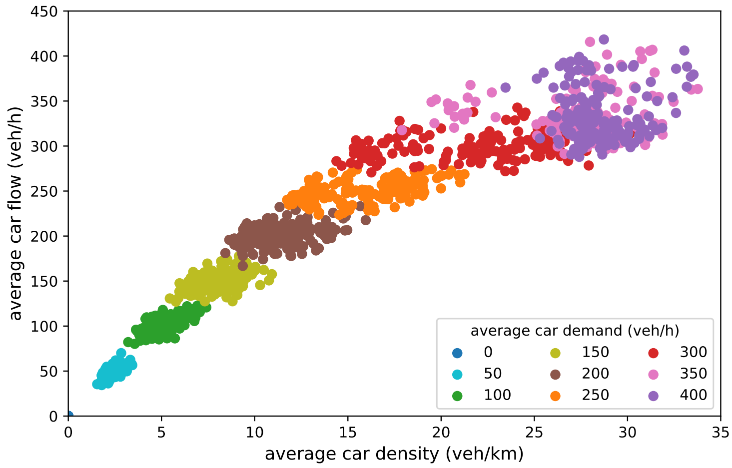
It can also be found in Figure 5 that the capacity reduction is insignificant when average car demand is less than 50 veh/h, which is because of the minimum green time for the car approaches. It also becomes less significant when the average car demand exceeds 300 veh/h, implying that the maximum green time for the car traffic is reached so that the signal timing plans stay the same.

Figure 5: Bicycle MFDs in simulation runs with different average car demands



On the other hand, Figure 6 shows the car production in different car demand scenarios. In each scenario, one can observe the scatter of data points, which is due to the varying bicycle accumulation in the simulation run. The maximum car flow in the network is reached when the average car demand exceeds 350 veh/h.

Figure 6: Car MFDs in simulation runs with different average car demands



4 Conclusions

This study proposes a modeling framework for the bi-modal bicycle-car traffic in a network with actuated signals using 3D-MFDs which consider both car and bicycle productions. A microsimulation approach is adopted to generate the traffic states and derive the MFDs. The resulting 3D-MFDs show the competition between bicycle production and car production. The effect becomes less significant when the two modes both reach their accumulation limits.

Future work will focus on the analytical derivation of the 3D-MFDs. Although using an analytical method to derive the MFDs of such a network with changing signal timing and cycle length is still difficult given the current research development, it is feasible to apply an approximation approach with physical meaning to create functional forms for the 3D-MFDs (Ambühl et al., 2020; Loder et al., 2019). By doing so, we can easily create the 3D-MFDs for different network layouts, signal control logic settings, and degrees of interaction between the two modes.

Again, this paper aims to shed light on the potential application of the proposed 3D-MFD framework. It can be employed to model the bi-modal traffic dynamics within an urban network with a lot of bicycle infrastructure. The MFDs allow the retrieval of the performance of each mode individually. Hence, it can be applied to macroscopically simulate the effect of dedicated bike lane allocation plans and traffic management strategies, such as pricing, signal control logic, routing, and perimeter control, with differential treatment on bicycles and cars.

5 References

Ambühl, L., Loder, A., Bliemer, M. C., Menendez, M., & Axhausen, K. W. (2020). A functional form with a physical meaning for the macroscopic fundamental diagram. *Transportation Research Part B: Methodological*, *137*, 119–132. https://doi.org/10.1016/j.trb.2018.10.013

Ampountolas, K., Zheng, N., & Geroliminis, N. (2017). Macroscopic modelling and robust control of bi-modal multi-region urban road networks. *Transportation Research Part B: Methodological*, *104*, 616–637. https://doi.org/10.1016/j.trb.2017.05.007

Dakic, I., Leclercq, L., & Menendez, M. (2021). On the optimization of the bus network design: An analytical approach based on the three-dimensional macroscopic fundamental diagram. *Transportation Research Part B: Methodological*, *149*, 393–417. https://doi.org/10.1016/j.trb.2021.04.012

Dakic, I., Yang, K., Menendez, M., & Chow, J. Y. (2021). On the design of an optimal flexible bus dispatching system with modular bus units: Using the three-dimensional macroscopic fundamental diagram. *Transportation Research Part B: Methodological*, *148*, 38–59. https://doi.org/10.1016/j.trb.2021.04.005

Geroliminis, N., Zheng, N., & Ampountolas, K. (2014). A three-dimensional macroscopic fundamental diagram for mixed bi-modal urban networks. *Transportation Research Part C: Emerging Technologies*, *42*, 168–181. https://doi.org/10.1016/j.trc.2014.03.004

Huang, Y., Sun, D., Li, A., & Axhausen, K. W. (2021). Impact of bicycle traffic on the macroscopic fundamental diagram: some empirical findings in Shanghai. *Transportmetrica A: Transport Science*, *17*(4), 1122–1149. https://doi.org/10.1080/23249935.2020.1832157

Huang, Y., Sun, D., & Zhang, S. (2022). Three-dimensional macroscopic fundamental diagram for car and bicycle heterogeneous traffic. *Transportmetrica B: Transport Dynamics*, *10*(1), 312–339. https://doi.org/10.1080/21680566.2021.1994050

Kaths, H., Keler, A., & Bogenberger, K. (2021). Calibrating the Wiedemann 99 Car-Following Model for Bicycle Traffic. *Sustainability*, *13*(6), 3487. https://doi.org/10.3390/su13063487

Loder, A., Ambühl, L., Menendez, M., & Axhausen, K. W. (2017). Empirics of multi-modal traffic networks – Using the 3D macroscopic fundamental diagram. *Transportation Research Part C: Emerging Technologies*, *82*, 88–101. https://doi.org/10.1016/j.trc.2017.06.009

Loder, A., Bressan, L., Wierbos, M. J., Becker, H., Emmonds, A., Obee, M., Knoop, V. L., Menendez, M., & Axhausen, K. W. (2021). How Many Cars in the City Are Too Many? Towards Finding the Optimal Modal Split for a Multi-Modal Urban Road Network. *Frontiers in Future Transportation*, *2*. https://doi.org/10.3389/ffutr.2021.665006

Loder, A., Dakic, I., Bressan, L., Ambühl, L., Bliemer, M. C., Menendez, M., & Axhausen, K. W. (2019). Capturing network properties with a functional form for the multi-modal macroscopic fundamental diagram. *Transportation Research Part B: Methodological*, *129*, 1–19. https://doi.org/10.1016/j.trb.2019.09.004

Ortigosa, J., Zheng, N., Menendez, M., & Geroliminis, N. (2015). Analysis of the 3D-vMFDs of the Urban Networks of Zurich and San Francisco. *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 113–118. https://doi.org/10.1109/ITSC.2015.27

Paipuri, M., & Leclercq, L. (2020). Bi-modal macroscopic traffic dynamics in a single region. *Transportation Research Part B: Methodological*, *133*, 257–290. https://doi.org/10.1016/j.trb.2020.01.007

PTV Group. (2023). PTV Vissim. Available at https://www.myptv.com/en/mobility-software/ptv-vissim. (Accessed 20 February 2023).

Saberi, M., Mahmassani, H. S., Hou, T., & Zockaie, A. (2014). Estimating Network Fundamental Diagram Using Three-Dimensional Vehicle Trajectories. *Transportation Research Record: Journal of the Transportation Research Board*, *2422*(1), 12–20. https://doi.org/10.3141/2422-02

Zheng, N., Aboudolas, K., & Geroliminis, N. (2013). Investigation of a city-scale three-dimensional Macroscopic Fundamental Diagram for bi-modal urban traffic. *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, 1029–1034. https://doi.org/10.1109/ITSC.2013.6728367

Zheng, N., Dantsuji, T., Wang, P., & Geroliminis, N. (2017). Macroscopic Approach for Optimizing Road Space Allocation of Bus Lanes in Multimodal Urban Networks Through Simulation Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, *2651*(1), 42–51. https://doi.org/10.3141/2651-05