Empirical and modelling contributions of the BikeZ-ETH project towards the understanding of mass cycling traffic dynamics

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Short summary

The rise in urban cycling is a promising avenue for improving both sustainability and public health in future cities. The BikeZ-ETH project seeks to deepen the understanding of cyclists' behaviour overall and, more specifically, to provide quantitative tools to evaluate, from a traffic engineering standpoint, how large-scale and massive cycling influences urban transport systems. Despite existing research, current knowledge on macroscopic bicycle flow dynamics and microscopic cycling behaviour is still lacking, signalling the need for high-resolution empirical trajectory data. To bridge this gap, BikeZ-ETH has assembled a dataset from naturalistic and controlled experiments conducted at several locations in Zurich (Switzerland) using drone-based observations. Additionally, a microscopic bicycle model built on SUMO is being actively developed to better simulate cycling by incorporating all its key characteristics, as well as interactions with other road users.

Keywords: Bicycle flow, Cycling behaviour, Fundamental diagram, Microscopic traffic simulation, Trajectory Data

1 Introduction

The promotion of active transport modes, including cycling, has become a key element of urban mobility strategies worldwide. This trend is largely driven by sustainability objectives such as the United Nations Sustainable Development Goals (UN SDGs), congestion reduction policies, and public health concerns (Pucher & Buehler, 2017). Public authorities at national and local levels are increasingly investing in cycling infrastructure and reallocating road space to encourage a shift away from private motorised vehicles (Lanvin et al., 2025). The BikeZ-ETH project follows on the footsteps of the E-Bike City project which has demonstrated that the massive integration of bicycles into urban transport networks can substantially alleviate congestion, improve the efficiency of road space usage, and offer a flexible substitute for car travel (Ballo et al., 2023; Fulton et al., 2025). In addition, cycling is also linked to considerable health and socio-economical benefits (Deenihan & Caulfield, 2014).

A major obstacle to the accurate study of bicycle traffic flow is the scarcity of high resolution trajectory data of cyclists. Indeed, the heterogeneity of strategies, complex overtaking manoeuvres, or queueing of cyclists can only be studied with realistic and accurate datasets, which are not aggregated. Previous datasets have important limitations such as small sample size, complex interactions between modes without isolation of bicycles or limitation to single file dynamics among other pitfalls (Andresen et al., 2014; Jiang et al., 2017; Robicquet et al., 2016). Gavriilidou et al. (2019) conducted an indoor ring-road cycling experiment and collected video footage from cameras for the analysis microscopic and macroscopic cycling traffic flow characteristics. Wierbos et al. (2019) and Wierbos et al. (2021) also designed small-scale cycling flow experiment to explore the effect of lane widths on capacity and the impact of queue formations on queue discharge rate. However, the data in these studies were not made openly-available. Kutsch et al. (2025) recently analysed the cyclists' trajectories on a bicycle lane in the TUMDOT-MUC dataset, which was collected via drones. Still, data in various scenarios and more extensive analysis are required to gain in-depth understanding of bicycle traffic congestion phenomena.

To fill this gap, BikeZ-ETH has generated a large cycling trajectory dataset encompassing diversified traffic situations in Zurich (Switzerland) by conducting drone-based experiment. This dataset goes beyond bicycle observations by also capturing the interaction of bicycles with other modes.

In terms of traffic flow modelling, research has up to recently been largely focused on motorised traffic. In this context, cycling was often considered a mode of transport of secondary importance, usually modelled similarly to cars by omitting some of its crucial aspects such as non-lane-based movements, for example Zhou et al. (2015). This is the reason why the BikeZ-ETH project is actively developing an efficient microscopic simulation API written in Python and based on SUMO (Lopez et al., 2018), which is capable of reproducing the unique bicycle traffic flow properties (Twaddle et al., 2014; Brunner et al., 2024). It does so by incorporating a decision-based framework derived from naturalistic observations from the dataset previously mentioned, non-lane based movements and realistic queuing behaviour, among other key characteristics.

This paper aims to introduce the experiment campaigns for cycling trajectory data collection in the BikeZ-ETH research project and present the methods and preliminary research outcomes regarding bicycle fundamental diagrams and microscopic cycling behaviour simulation.

2 Data Collection

High-resolution (3840×2160 pixels at a frame rate of 25 fps) trajectories were collected using stationary drones flying approximately 20 meters above ground. Both naturalistic and controlled experiments were captured. Naturalistic observations have the advantage of reducing any biases or changes in the behaviour of cyclists, which can possibly occur in controlled experiments. These observations were carried out in various locations (mixed traffic un-/signalized intersections, straight segments with different widths of bicycle lanes, roads with bicycles only, ...) during the morning and evening peaks to ensure that sufficient bicycle flows are captured. Particular care was taken to ensure that bicycles are clearly visible and not hidden by any overhead obstacles, thus the tracking of their trajectory can be done without any interruption. Figure 1 shows a screenshot from the drone video recordings.

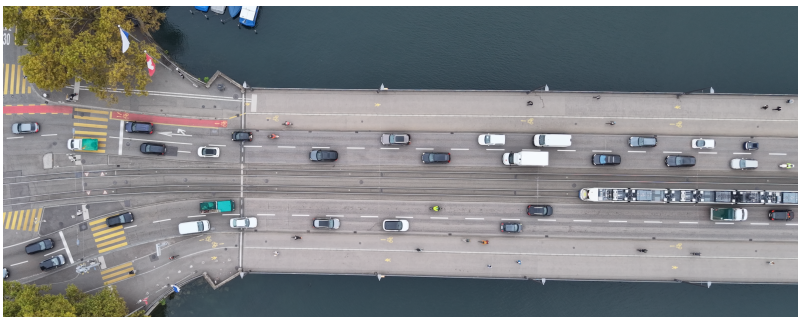


Figure 1: Screenshot from the video recordings at location 6 of the BikeZ-ETH drone-based observation campaign

The controlled experiments on the other hand, enabled to generate larger flows than usually observed in Zurich, while also allowing to create specific situations of interest such as merging or crossing of intersecting flows. The experiment was carried out on Baslerstrasse (locations 12 and 13), an open road, to ensure that realistic interactions with other modes of transport can still be observed. A distinction between human-powered and e-bikes was done by using coloured jackets visible from the drones, so that both types of bicycles can be distinguished. The number of participants in the controlled experiment amounted to 58, which was sufficient to create the desired mass cycling traffic flows and, in particular, to observe enough overtakes and long queues.

The observed locations in Zurich are depicted in Table 1 and Figure 2. Locations 1, 12 and 13 correspond to the controlled experiment locations. Every location contains 80 - 160 minutes of video recordings. The collected drone observations, in the form of stationary top-down videos, were subsequently processed by Mobylisis Sàrl (*MobiLysis*, 2026) using their in-house computer vision tool to identify the absolute positions of the cyclists. Figure 3 shows the trajectories observed in

a 20-minute period at location 2.

Table 1: List of experiment locations in Zurich

No.	Location	No.	Location
1	Albert-Einstein-Str. roundabout	2	Gessnerbrücke - Kasernenstr.
3	Gessnerbrücke - Gessnerallee	4	Zollstr. - Langstr.
5	Zollstr. - Klingenstr.	6	Quaibrücke
7	Bullingerplatz	8	Duttweilerbrücke
9	Bullingerstr. - Herdenstr.	10	Birmensdorferstr. - Gutstr.
11	Birmensdorferstr. - Schweighofstr.	12	Baslerstr. - Freihofstr.
13	Baslerstr. - Flurstr.		

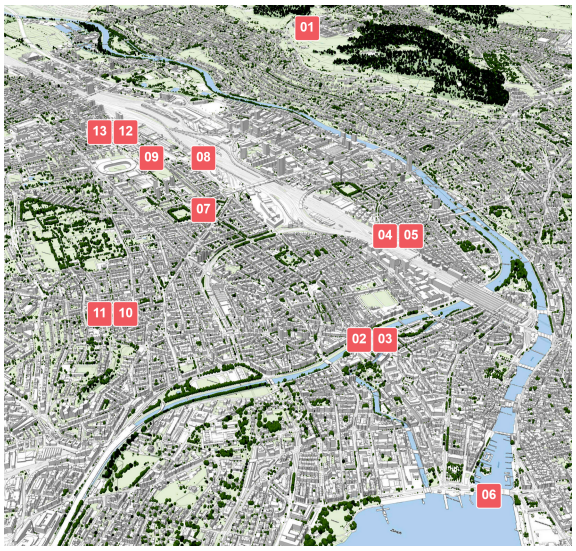


Figure 2: Locations of the drone-based BikeZ-ETH measurement campaign in Zurich, Switzerland.

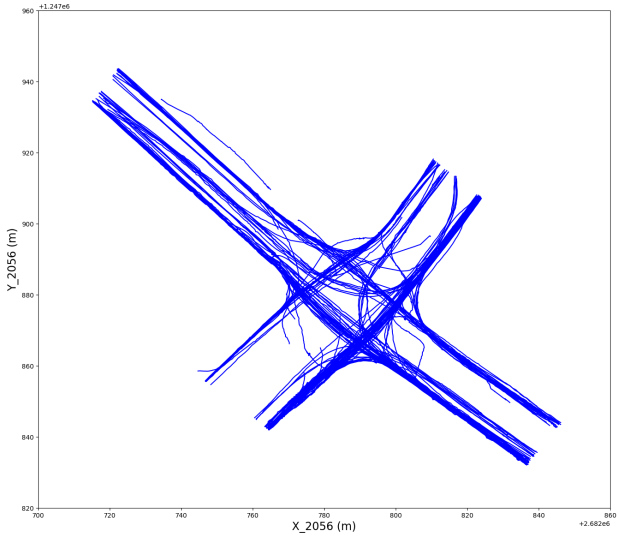


Figure 3: Collected trajectories in 20-minute period at location 2.

Finally, the absolute coordinates of the trajectories were transformed into lane based coordinates, to ease the analysis of the traffic flow characteristics. The method used for performing this transformation of coordinates is an adaptation of the method described in Zayandehroodi et al. (2026) to enable the processing of bicycle trajectories. The data and replicated animations will be made available and can be accessed via this website: `https://www.bikez.ethz.ch/`.

3 Bicycle Fundamental Diagrams

The trajectory dataset is currently used among other applications, to compute the bicycle fundamental diagram (BFD) (El-Baklish et al., 2026). Using a variation of the platoon fundamental diagram (PFD) methodology (Makridis et al., 2025), the first complete fundamental diagram is retrieved for bicycles, including the congested branch, which has not been done in previous studies (Guo et al., 2021; Liang et al., 2018). The PFD method essentially obtains traffic pseudo states from Leader-Follower pairs, which enables to use non-stationary data to compute the Fundamental diagram. This differs from the classical computation of the fundamental diagram, which requires traffic data at equilibrium. As in the case of bicycle flows, stationary conditions are very challenging or often impossible to observe, this method enables one to retrieve sufficient data to infer the shape of the BFD. Figure 4 shows BFDs analysed using data at one location in the dataset. This demonstrates how the BikeZ-ETH dataset is used to generate the BFDs for different widths of the bicycle lane by fitting the FD function proposed by Wu (2002), following the method proposed in Ni et al. (2024). The results improved understanding of the influence of the bicycle lane width on the free-flow speed, capacity, jam density of bicycle flow, which is crucial for urban planners to assess which parts of the infrastructure benefit the most from increased bicycle road space allocation.

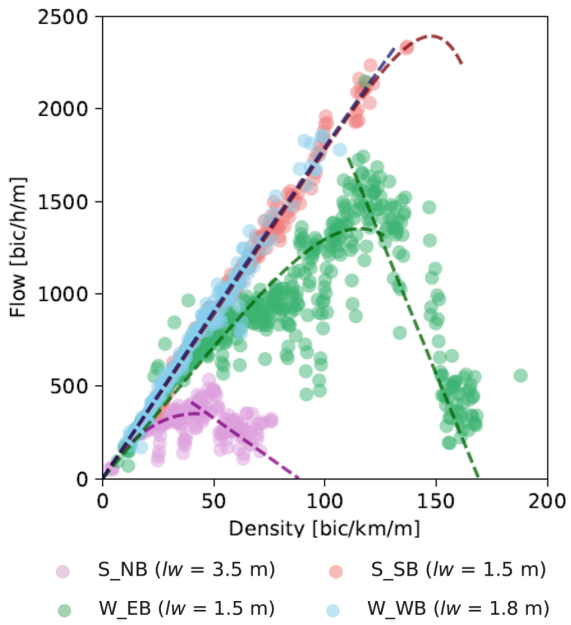


Figure 4: BFD shapes for different bicycle lane widths lw using the BikeZ-ETH drone based dataset. (Taken from El-Baklish et al. (2026))

Ongoing work is analysing the trajectory data at other locations to compute BFDs. More insights on the lane width effect and multi-modal interactions can be drawn afterward.

4 Microscopic Bicycle Flow Simulation

The BikeZ-ETH microscopic model is integrated into SUMO and uses a Python interface, TraCI, to interact with the simulation. Compared to *CyclistsModel* that computes cyclists' absolute position at every simulation step (Kaths, 2023), this model maintains more SUMO setup by incorporating the non-lane-based movement logic with the built-in sub-lane environment in SUMO, thereby improving its flexibility in the context of large road network simulations.

The model can be summarised by four key characteristics (Ni et al., 2026). First, cyclists' physical boundaries are represented using a hexagonal shape, as shown in Figure 5. This shape is used in the gap calculation between cyclists to enable staggered formations as observed empirically, which is not possible using a rectangular shape as used for the modelling of cars for example. Second, the high jam density and queue discharge rates observed empirically are reproduced by using a special lateral gap finding mechanism, which enables the simulated cyclists to find, using lateral movements, the farthest downstream gap when queuing. Third, for any lateral movement, a non-lane based collision avoidance mechanism is used. During this process, the ego-cyclist looks ahead and behind it, up to specified maximum distances. The shape of the ego-cyclist is modelled using a triangular shape, which scales according to speed, called the safety region. This safety region has a minimal size at rest, which grows with increasing velocity to model the corresponding required increase in safety margin. This procedure ensures that collisions are prevented by avoiding manoeuvres that encroach on surrounding cyclists. Finally, a mental-layer and physical-layer determine the operational behaviour of the cyclists. The mental layer identifies the surrounding bicycles and classifies them according to their speed and situation on the road. According to the assessment of the situation, the ego-cyclist will decide its course of action, which could be for instance to stop, queue, follow, or overtake. The desired lateral movement is also computed at this stage. Subsequently, the physical-layer decides the longitudinal acceleration that is appropriate based on the chosen action, surrounding bicycles, and desired lateral movement computed previously. Different models are used depending on the action chosen: if the ego-cyclist stops or queues, the deceleration is computed using the distance to the stop line or the immediate leader. If neither of these two actions is chosen, the Intelligent Driver model is used (Treiber et al., 2000). In particular, if the ego-cyclist is in uninterrupted flow, it will look at all the leaders within the look-ahead distance and choose the leader with the most restrictive acceleration.

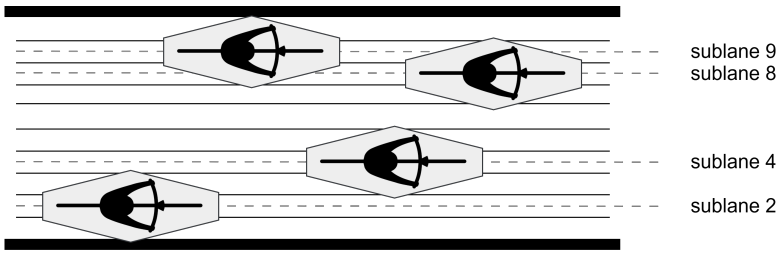


Figure 5: Integration of the hexagonal bicycle representation and the sub-lane model in SUMO

The BikeZ-ETH dataset is also being actively used to improve the BikeZ-ETH microscopic bicycle model, as mentioned above. One such example is shown in Figure 6, which shows the identification of bicycles (red shapes) during queuing at an intersection. These data are crucial to improve the model by enabling verification of behavioural aspects of cyclists, as well as the measurement of typical lateral and longitudinal gaps between cyclists for different types of traffic situation. These measurements are also crucial to help calibrate/validate the IDM model, refine the safety region parameters, or measure the level of heterogeneity among cyclists.

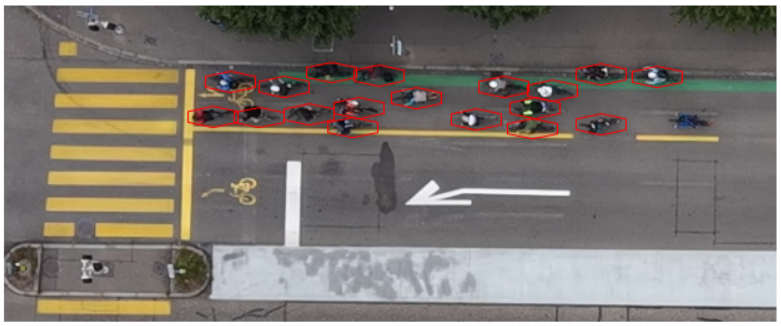


Figure 6: Bicycles identification during queuing taken from the BikeZ-ETH dataset. (Taken from Ni et al. (2026))

Figure 7 shows how the microscopic model improves the current SUMO queuing model (left picture), qualitatively reproducing the staggered formation seen in Figure 6 (Ni et al., 2026). The staggered formation is achieved using hexagonal shapes for cyclists instead of the typical rectangular shapes used in SUMO, which is not appropriate for bicycles, as explained in the previous section. A realistic queuing is crucial for the accuracy of the simulation, as it also affects the subsequent discharge phase for example.

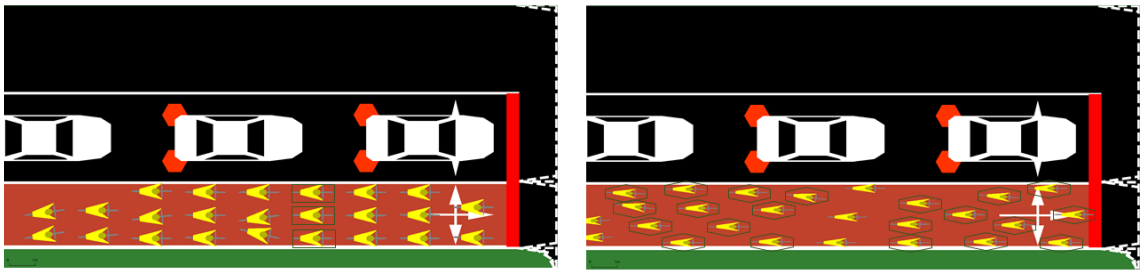


Figure 7: Left: Vanilla SUMO queuing of bicycles. Right: Improved queuing of bicycles using the BikeZ-ETH microscopic model. (Ni et al. (2026))

5 Conclusions

The BikeZ-ETH project will contribute to improving the current understanding of the dynamics of bicycle traffic flow. To do so, an open source trajectory dataset of controlled experiments and naturalistic traffic situations containing large number of cyclists will be published. In addition, an open source microscopic bicycle simulation API based on SUMO is developed to improve the cycling modelling using the specific characteristics of this mode of transportation.

In addition to the analysis of BFDs, we also plan to investigate microscopic cycling behaviour in different states, such as free-flow, following, overtaking, and queueing, using the collected trajectories. Accordingly, further work on the microscopic model includes in particular the careful calibration of it's parameters using the BikeZ-ETH dataset, consideration of collective behaviours, and the interaction with cars. The contributions of BikeZ-ETH will enable accurate simulation and planning of future cities with large share of bicycle usage, which is a crucial requirement to improve the sustainability of cities throughout the world. By enabling the simulation of different scenarios (varying modal share or road allocation for example), BikeZ-ETH can help traffic engineers and city planners to achieve better informed decisions based on quantitative results.

The emphasis of BikeZ-ETH on openly accessible data and models will also further improve the reproducibility of research in the field of multi-modal transportation by providing useful benchmarks for researchers.

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