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## Large-Scale Bicycle Flow Experiment: Setup and Implementation

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### Abstract

Cycling research at the operational behavioral level is limited, mainly because of the lack of empirical data. To overcome this data shortage, we performed a controlled, large-scale cycling experiment in the Netherlands. In this paper we describe the methodology for setting up and implementing such an experiment, from the motivation of its design using a conceptual model describing cyclist behavior to adjustments that were required during the experiment. The main contribution of this paper is, therefore, to be used as a guide in future experimental data collections. Moreover, we present the characteristics of the participants and their bicycles, and provide a qualitative description of phenomena observed during the experiment. Finally, we elaborate on the potential that the collected dataset holds for future research into understanding and modeling operational cycling behavior.

Cycling as a main mode of transportation has in recent years been promoted by many governments worldwide because of its health and environmental benefits. The focus is mostly on finding ways to attract more people to the bicycle, while at the same time it is important to ensure a safe and comfortable infrastructure that can handle high cyclist volumes. This requires understanding of bicycle traffic characteristics, as well as insights into behavior of cyclists while cycling on the road and making decisions to interact with other traffic participants and with the infrastructure. Research in this field is, however, limited and that is to a large extent because of the lack of empirical data.

To overcome this shortage of data, we performed a controlled, large-scale cycling experiment. This paper describes the methodology for setting up and implementing such an experiment. These steps may be used as a guide in future experimental data collections and as a reference for future analyses using the data. We describe the collected dataset and elaborate on its potential uses. The contribution of this paper is, therefore, threefold: (i) delineating the process to set up a large-scale cycling experiment; (ii) describing the performance of the experiment; and (iii) presenting a large database of cyclist trajectories.

This paper is structured as follows. In the first section we provide a background of existing literature on operational cycling behavior and identify the research gaps. Based on these, we then formulate our research objectives

and discuss the findings of a stated preference survey that we conducted as a first step to meet the objectives. Next, we describe the development of the data collection plan, and discuss its implementation. Finally, the dataset is presented, followed by an outlook of future research.

### Background on Operational Cycling Behavior

This section provides an overview of existing research on operational cycling behavior on an individual and on an aggregated level and identifies research gaps in each level.

#### Individual Cycling Behavior

Operational cycling behavior on an individual level can be represented by decisions regarding the use of the provided infrastructure while cycling and the interaction with other traffic participants.

In unconstrained situations, interaction decisions depend on the individual's choice for speed and positioning on the cycle path. A number of studies have looked

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into desired speed and acceleration profiles in free-flow conditions (1, 2), on different road surface types and gradients (3), with normal bicycles as opposed to electric ones (4), and at wide or narrow cycle lanes (5). These personal preferences might be constrained at high bicycle traffic volumes and when multiple directions intersect, an effect which is yet to be investigated. The interaction decisions in such situations, their coverage in literature, and the corresponding knowledge gaps are the following:

- Steering to avoid colliding with other cyclists: Steering maneuvers of bi-directional cyclists on collision course have been studied by Yuan et al. (6), but the interaction with other directions is yet unknown.
- Overtaking cyclists: Research on cyclists moving in the same direction has looked into following behavior (7), but overtaking decisions have not yet been investigated.
- Yielding to other cyclists: To the best of our knowledge, there has been no research on yielding decisions at unsignalized crossings where priority rules apply, but are not enforced.
- Accepting a gap in a conflicting stream: The gap acceptance of cyclists against right-turning vehicular traffic has been studied (8). This, however, might differ significantly when cyclists interact with other cyclists and may also be influenced by whether the intention is to cross or merge.
- Stopping at a red traffic light: Researchers have analyzed red-light running of cyclists at specific intersections across the world and identified influencing attributes that explain this behavior, such as gender, age, amount of conflicting motorized traffic, crossing distance, and cycling with company. An overview of these studies can be found in Richardson and Caulfield (9).
- Positioning when joining a queue: The formation of multiple channels in queues has been observed at one signalized intersection, stressing the need for a bigger sample (10). The queue formation process in other situations, such as upstream of an open bridge or on a reduction of the cycle path width, has not yet been studied.

### Aggregated Cycling Behavior

The aggregated behavior of traffic participants is typically captured by the so-called fundamental diagram, which is the relation between average speed, density, and flow. Several studies have investigated this relationship for cyclist flows and identified characteristics that are similar to vehicular traffic and pedestrian flow (11, 12).

Other studies focused on understanding bicycle traffic flow and collected empirical data through:

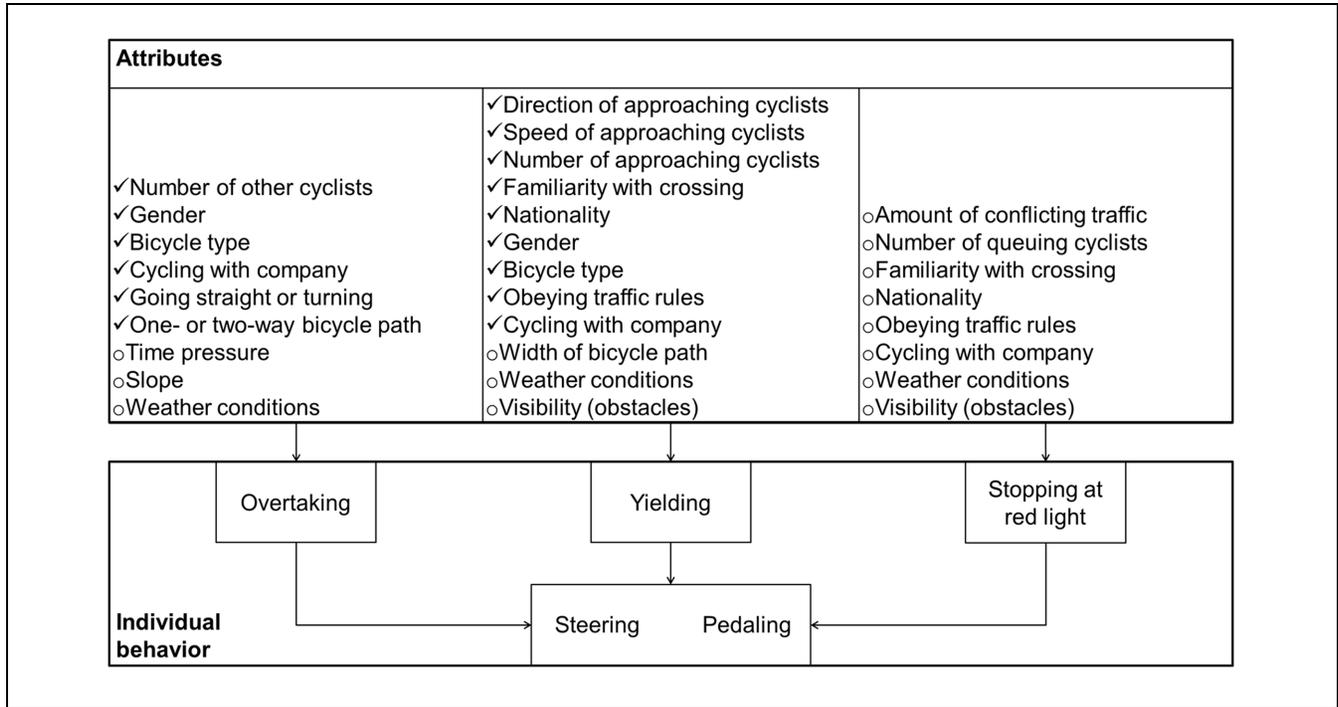
- Single-file controlled experiments: These have been conducted outdoors on circular tracks (7, 13–16). In this setting, bicycle flow in low- and high-density situations can be observed, resulting in empirical data covering the full density range of the fundamental diagram. This provided insights into the dynamics of bicycle flow and identified flow characteristics such as stop-and-go waves. However, overtaking was not allowed in these experiments, which is often observed in real-life situations.
- Observing cycling behavior in daily traffic: Studies have estimated capacity of bicycle paths and resulted in a wide range of values (17–20). This might be explained by the differences in infrastructure or bicycle type composition. The influence of electric bicycles has been studied (20–22), but could not be controlled because of the nature of the empirical data. By controlling the infiltration rate of electrical bicycles, its impact to the overall flow characteristics can be identified more clearly. Furthermore, most empirical data is collected in conditions with low cyclist volumes and lacks observations in the congested regime of the fundamental diagram.

In short, the literature so far provides limited insight into the bicycle flow dynamics for high-demand situations when overtaking is allowed and the effect of different attributes, such as the infiltration rate of electric bicycles, on the shape of the fundamental diagram, has not yet been studied.

### Research Objectives

Based on the given literature overview, it can be concluded that the research effort to observe and understand cycling behavior is limited. The most essential gap seems to be studying high cyclist volumes, as well as bicycle-to-bicycle interactions at designated cycling infrastructure. With respect to individual behavior, overtaking and yielding have been studied the least. At an aggregated level, overtaking is also important, as it is expected that it can explain the flow differences in the congested regime. Its effect on the shape of the fundamental diagram has not yet been studied, nor has the penetration of electric bicycles.

To address these gaps, we focus on bicycle traffic in the absence of other transport modes. Our objective is to collect a novel dataset that captures high cyclist volumes and where overtaking and yielding interactions take

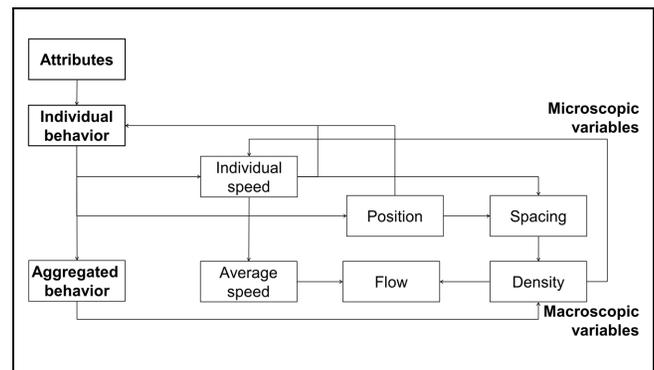


**Figure 1.** List of influential attributes per decision according to our survey results. The check marks indicate the attributes that can be studied with the dataset collected in our experiment.

place. The aim of this dataset will therefore be to retrieve the characteristics of the fundamental diagram when overtaking is allowed and also to study the effect of bicycle type, and in particular electric bicycles, to the overall flow dynamics. Moreover, the dataset will be used to investigate the attributes that best explain the decisions to overtake and yield.

### Survey on Influencing Attributes

To investigate the attributes that can explain overtaking and yielding decisions, we conducted an online stated preference survey in the Netherlands in summer 2017. The respondents were asked to name the attributes that influence their decision-making in three situations: (i) overtaking or staying behind a single or a small group of cyclists; (ii) going ahead or stopping at a crossing to allow cyclists with priority to merge or cross; and (iii) stopping or continuing at a red traffic signal. The latter was included to check whether the attributes found from observations match the stated ones and as such justify the predictive value of the survey. The specificities of each situation were outlined, and always involved cycling during daytime on road infrastructure designated for cyclists and separated from other traffic. Per situation, a list of attributes was provided to the respondents based on behavioral hypotheses regarding the most influential attributes. Each list contained ten attributes displayed in random order, and three empty fields to enter other



**Figure 2.** Conceptual model of operational cycling behavior. Attributes are linked to individual behavior, as already shown in detail in Figure 1. Collectively they lead to aggregated behavior. These behaviors can be observed via microscopic and macroscopic variables.

attributes. A selection of three to ten attributes was requested per situation. Apart from that, general information about the respondents was collected, such as gender and nationality.

By analyzing the 444 responses, using principal component analysis to reduce dimensionality, the most influential attributes per decision could be obtained. In Figure 1 the prevalent attributes for each decision are linked to the corresponding decision (the check marks indicate the attributes that can be studied with our dataset). These decisions are part of the individual behavior,

together with steering and pedaling decisions. The schematic fits into the conceptual model of Figure 2 which describes cycling behavior at the operational level. According to it, attributes influence the behavior of individuals, who collectively give rise to aggregated behaviors. These behaviors can be observed via microscopic and macroscopic variables, whose relations are visualized in the conceptual model.

The validity of the survey findings is demonstrated by the attributes found significant for the decision to stop at a traffic light as they match those found in literature. However, more data are needed to quantify the effect of the attributes on overtaking and yielding decisions. A data collection plan is thus necessary.

### Development of Data Collection Plan

The research steps to set up the data collection plan are described. First, the data needs and requirements are identified, followed by the motivation of the choice for the data collection approach and equipment. A controlled experiment is selected and its setup is presented, covering the design of the scenarios and the cycling track, the estimation of participants needed, and the duration required for each scenario.

#### Data Needs and Requirements

As previously mentioned, one of our aims is to retrieve the characteristics of the fundamental diagram when overtaking is allowed and the fleet consists of different bicycle type compositions, as well as to investigate the overtaking and yielding decisions of individuals and to identify the attributes that best explain them. The data type necessary to study individual cycling behavior is trajectories, i.e., cyclist positions in time and a two-dimensional space. Trajectories are the most detailed type of traffic data, which can be aggregated in time or space to study macroscopic variables needed for the construction of the fundamental diagram. By examining trajectories, the use of the cycle-path width and the speed adjustments can be studied relative to the position and speed of other cyclists and the environment (width, curve). The accuracy that is required for the trajectories lies within 10 cm which sets requirements for the data collection equipment. Additionally, it is crucial to be able to track and distinguish each individual, also linking the observations to personal characteristics.

Another requirement is set by the need to capture the fundamental diagram. Therefore, it is necessary to observe low as well as high densities, which can be achieved by controlling the infrastructure setting and bicycle inflow rates. Studying the effect of different bicycle types means that the composition of the fleet

should also be controlled. Moreover, controllability is necessary to ensure that the desired cyclist interactions (overtaking and priority negotiation) take place and that the effect of the influencing attributes of Figure 1 can be investigated.

#### Data Collection Approach and Equipment

Three data collection approaches can be used to retrieve trajectory data:

- Observing real-life situations: Even though this approach can capture uninfluenced and unbiased behavior, the degree of controllability is very low and does not meet the prescribed requirements.
- Doing an experiment in virtual reality: Existing bicycle simulators are of unknown validity and behavioral realism. They also do not allow for multiple individuals to cycle simultaneously and interact with each other.
- Doing a controlled experiment in a physical environment: A controlled experiment allows for a high degree of controllability and thus satisfies the requirements.

In a controlled experiment, the number of cyclists using the infrastructure, the routes they take, as well as the design of the infrastructure itself can be controlled. By carefully instructing the participants, specific elements of their behavior, like their choice of speed, can be steered when necessary. Even the external conditions, such as light and wind, may be controlled.

However, the approach has some disadvantages that should be mitigated as far as possible through the experimental design. One of the main disadvantages is the occurrence of the so-called “learning-effect.” This means that participants change their behavior over time as their familiarity with the experimental setting increases and they get tired. This can be minimized by varying the layout and tasks that the participants are asked to perform during the day and by shortening their cycling duration.

Another potential drawback relates to data validity and representativeness. It may be argued that the behavior is not realistic because of the fact that participants know they are being observed. We counter this argument based on the fact that the behavior is observed several times and as they need to interact with other cyclists, their consciousness shifts to the riding task and any differences observed in behavior are attributed to intra-personal variability. Moreover, this is intuitive behavior, and the observation equipment will hardly be visible.

Regarding the data collection equipment, as the trajectories need to have high accuracy, overhead video cameras are selected. By placing them above the cyclists, the

cameras track their movements with as little occlusion as possible, and continuously in time. To be able to automate the extraction of trajectories from the video images, a red cap is assigned to each participant. This is because red is the color easiest to recognize under a wide range of lighting conditions (23). Last but not least, since it is crucial to be able to link the observed trajectory to a specific individual, the caps are assigned a unique identification code.

### Scenario Design

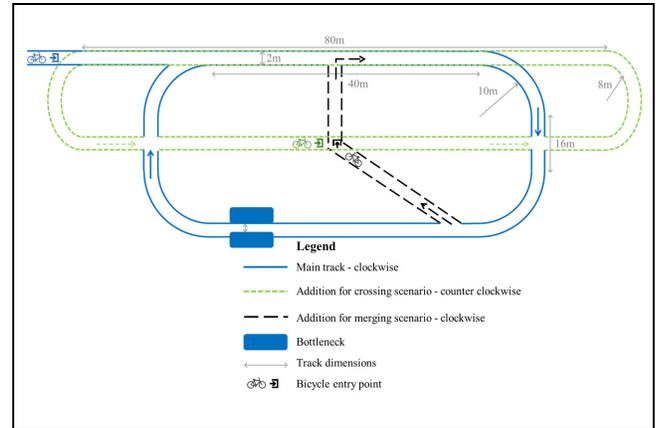
On a microscopic level, the aim is to investigate the effect of the attributes of Figure 1 on overtaking and yielding decisions. In the scenario design we can control for two of them, namely the bicycle type and the directionality of the cycle path. Regarding bicycle type, separate runs are scheduled, each with a different fleet composition and the scenarios are referred to as “Overtaking.” More specifically, there is a run for regular bicycles only, runs that combine regular bicycles with one special type, and a run with all types. In these scenarios there is a one-way flow on the cycle path. For the fleet with all types, the behavior is compared with a run that allows for bi-directional flow.

With respect to yielding decisions, the direction of approaching cyclists is an attribute. Its effect can be investigated by separately studying crossing and merging streams. Therefore, two scenarios are designed, namely “Crossing” and “Merging.” As bicycle type is an attribute, runs are performed with a mixed cycling fleet as well as with regular bicycles only.

On a macroscopic level, scenarios are needed to observe low as well as high densities to construct the fundamental diagram. We implement this by narrowing the cycle path, which obstructs the cyclist flow and leads to queue formation upstream of the narrow section when the demand exceeds its capacity. By varying the width of the narrow path (“bottleneck”), various congested patterns occur, determining both density and speed upstream of the bottleneck. We call it “Active bottleneck” scenario. It consists of different runs, each having another bottleneck width or a different cycling fleet composition, to observe the effect of bicycle types on the fundamental diagram. Specifically, the effect of electric bicycles is investigated by comparing three penetration rates: 0%, 10%, and 20%. These values represent typical values of electric bicycles in urban traffic situations in the Netherlands.

### Track Design

The layout of the track needs to be carefully designed because it largely determines the behavior that can be

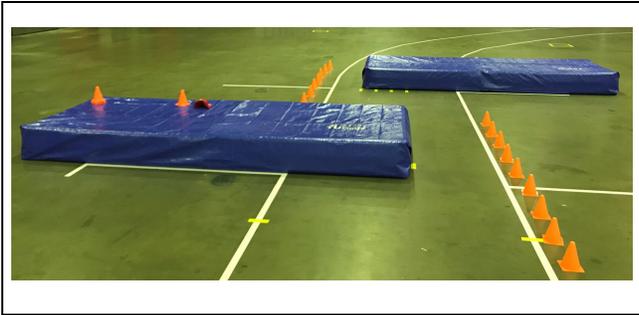


**Figure 3.** Track layout showing the elements activated for different scenarios.

observed in the experiment. First of all, cyclists should maintain a speed as close as possible to their normal cycling speed and behave as they would in reality. For this reason, a continuous track is selected, where participants make laps instead of short stretches that would require frequent acceleration from, and deceleration towards, standstill. A rounded rectangle shape is preferred over a circular one, because: (i) the cyclists will not be constantly steering in a curve; (ii) there is a straight stretch for overtaking maneuvers; and (iii) there is the possibility to study the effect of the attribute “going straight or turning” for overtaking decisions.

In relation to dimensions, the length of the straight stretch is set at 40 m, which is an adequate length for cyclists to overtake in (6). The width of the track is chosen to be 2 m. This width ensures that there is enough space for cyclists to overtake and it is also possible to sketch situations with a bi-directional flow (24). The radius of the curve should allow cyclists to maintain a comfortable speed without the inside pedal hitting the surface if they lean. For a riding speed of 20 km/h, the minimum radius is 7 m (3).

To ensure that the desired interactions take place, different track elements have been integrated into a single track layout, see Figure 3. The blue continuous line is the main track, used in all scenarios, where cyclists enter at the top left corner and cycle clockwise. The choice for this cycling direction is based on the norm to cycle on the right-hand side in the Netherlands and as such the inside curve will be taken by the slower cyclists. The inside curve radius is set at 10 m, with a quarter of a circle placed on each side and connected with a long straight stretch of 40 m and a short one of 16 m. The long stretch on the top side gives room for overtaking, while the bottleneck is placed at the bottom side in the Active bottleneck scenario. The short stretch accommodates crossing conditions at a straight stretch rather than within a curve.



**Figure 4.** Construction of meander bottleneck using two mattresses.

Another element is activated to observe crossing behavior (green dotted line in Figure 3) where cyclists are riding counter clockwise. With this configuration, there is a bi-directional flow on the top part where the two routes overlap enabling the investigation of the effect of “one- or two-way cycle path” on the overtaking behavior, and also creating two crossing points which increases the amount of observations. An extension of 10 m of straight stretch is added at the crossing points and the curve radius is set at 8 m, such that the crossing takes place in the middle of the blue track.

A third element is added (black dashed line in Figure 3) for the Merging scenario, which is connected to the main track in two locations; one is the off-ramp where cyclists can exit the main track and the other one is the merging point where cyclists join the main flow again. It is worth noting that no markings indicating priority are added on the track to prevent that they influence the behavior.

With respect to controlling the flow, a bottleneck is introduced at the bottom side of the track. It consists of two inflatable mattresses placed next to each other on the track to create a narrow stretch 4 m long. The height of the bottleneck is 33 cm which blocks pedaling over it but does not hinder steering, creating the impression of an elevated curb rather than that of a wall which could be unsafe to drive through. The bottleneck is moved inwards to decrease the width of the track in that section. This way the cyclists are obstructed, leading to queue formation when the cyclist demand exceeds the capacity of the bottleneck. It is placed downstream in the straight stretch (seen from the cycling direction) ensuring that the queue will grow along the straight stretch, and the observations are uninfluenced by the curve. By varying the bottleneck width, various congested patterns occur upstream of the bottleneck.

The bottleneck is set to four different widths, namely 75, 100, 125, and 150 cm. These numbers are based on a preliminary bicycle flow experiment that we performed, where the main path width was also 2 m and the path was narrowed to a width of 150 to 50 cm using steps of

25 cm. The 50-cm width was found to be too narrow for safety reasons. To observe high densities, the flow through the bottleneck should then be reduced in a different manner. The shape of the bottleneck is changed from a small straight stretch to one that cyclists have to meander through, referred to as the “Meander.” The two mattresses are placed behind each other with 2-m space in between and in such a way that they leave a path of 75 cm to the side of the track (Figure 4).

### Number of Participants

The next step is determining the number of participants. We base this primarily on the aim to capture the relation between density, speed, and flow. Assuming a diamond queue formation of 2-1-2-1, the jam density is 0.7 cyclists per  $m^2$ , which leads to 28 cyclists for a queue length of 20 m, which is enough to observe the behavior for the high-density and low-speed situation.

To maintain a 20-m-long queue, there need to be as many cyclists joining the tail of the queue as leaving the queue through the bottleneck. The number of cyclists that need to circulate the track depends on the outflow rate of the bottleneck, as well as on the average cycling speed of the circulating cyclists. To estimate the maximum number of participants, the scenario with the highest queue outflow rate should be considered. Based on our preliminary experiment, the outflow rate of the bottleneck of 150-cm width is 1.82 cyclists per second. Based on an average cycling speed of 19 km/h (17), 55 additional cyclists are needed. Consequently, a total number of 83 participants is required in the experiment.

### Scenario Duration and Scheduling

The estimation of the duration needed for each scenario is based on the requirement to have enough observations to draw statistically significant findings. In the Overtaking scenario this is translated into giving each cyclist the chance to make at least ten decisions whether to overtake or not (i.e., cycle through the top straight stretch). When the bottleneck is inactive, it takes about 30 s to complete a lap, which leads to a required duration of 5 min.

With respect to the Merging and Crossing scenarios, the indicator to base the observation calculations on is the attribute “number of approaching cyclists.” To investigate its effect on the decisions being made, different group sizes, i.e., number of cyclists approaching the negotiation point from each side, need to be observed. As large numbers are appreciated, the bottleneck that would constrain the outflow is removed. The time needed to collect sufficient observations of different group sizes is calculated using a simple microsimulation. It assumes a constant cycling speed and simulates dots moving

around the track. Once a dot is detected close to the negotiation point, the number of dots present on each approaching stream is counted, taking into account a physical length of about 2 m. If both approaches have a positive number, it is counted as an interaction of a group size coming from the right against a group size coming from the left. After running for a longer duration, the number of encounters of the occurring group combinations at the merging and crossing points is calculated. The result is that the Merging scenario requires 40 min and achieves interactions with a maximum group size of six against five cyclists, and every combination in between. Since the Crossing scenario has two observation points on the track, it requires half the time (20 min) for these observations.

In the Active bottleneck scenario, a 5-min duration is chosen. This duration enables the estimation of flow, density, and speed in continuous and homogeneous conditions in the queue, without lengthening the total duration of the experiment. Also, it accommodates capacity estimation using different aggregation times, which decreases the influence of individual behavior. Since participants are able to pass the bottleneck multiple times, approximately 5–10 times depending on the bottleneck width, the individual behavior averages out, which benefits the capacity estimation.

In relation to scheduling, the day of the experiment is divided into two sessions, one with special bicycle types and one without, so that we can observe the behavior of regular bicycles only and compare it with the behavior when special bicycle types are present. In the latter, the runs with these special types are dominant, checking the overtaking behavior and the fundamental diagram for different penetration rates. Only two bottleneck widths (75 and 125 cm) are kept to limit the total running time. In the session without special bicycles, there is time to test all the widths and to focus on the Merging and Crossing scenarios. Because of the fact that the latter require long observation times, we split the duration into batches of smaller runs of 10 min each.

It is estimated that it takes 2 min for all cyclists to enter the track in a one-by-one pattern, and therefore the Overtaking and Active bottleneck scenario runs are scheduled to last 7 min. Since three fleet compositions (no special types, electric and regular bicycles, all types) are in both scenarios, their corresponding runs are scheduled in continuation, i.e., without any break. First the Overtaking scenario takes place and then the bottleneck is activated, which is estimated to take 1 min. The activation is performed by introducing a moving bottleneck on the track, i.e., two persons cycling slowly and next to each other, such that they cannot be overtaken and forming a queue behind them. This way, all cyclists are led as one group up to the bottleneck, activating it.

Summing up all these times leads to a net cycling time of 90 min for each session. To prevent exhausting the participants, breaks of 15 min are scheduled every three runs and in between runs there is a small pause of 5 min to initialize the next one. Apart from exhaustion, the learning effect and boredom need to be prevented. We solve this by alternating the scenarios in the schedule and by keeping the runs at about 10 min each. The planned order of scenario runs and their properties are summarized in Table 1.

## Implementation of Experimental Design

Having set the requirements and the experiment design, the implementation follows and is divided into the selection of the location, the recruitment of participants, and the setup of the measuring and tracking equipment.

### Location Selection

The selection of the place where the experiment can be executed is based on several criteria. The most important criterion is that it has enough space to fit the track. The floor area required for the designed track is 100 m x 40 m. Moreover, the location should strictly prevent the presence of other modes. These conditions, along with the fact that a specific track with this shape and curves will be hard to find, point towards the construction of the track at a location rather than the use of existing infrastructure. Another benefit of creating the track is that it can be made obstacle-free to ensure good visibility. Even though the visibility because of obstacles has been found to be an attribute in the yielding decision, it is left out of scope to avoid accidents during the experiment.

Another criterion relates to the controllability of external conditions such as weather and light. These can only be controlled when the experiment takes place indoors. The weather conditions influence cycling behavior, but investigating their effect would require repeating the experiment under different circumstances, which is hard to predict and anticipate, as well as costly and difficult to plan with a sufficient number of participants. Therefore, we need to keep the circumstances constant during the whole experiment.

The indoor environment raises two needs. Firstly, the ceiling to be at least 10-m high to accommodate tracking equipment and prevent the feeling of cycling in a closed space. Secondly, the surface type should resemble real-world cycling conditions, be safe, and, therefore, be neither slippery nor adhesive.

Last but not least, the location should be easy to find and access, preferably near a crowded and inhabited area. This increases the chances of recruiting enough participants who will show up on time.

Given these criteria, we selected a large exhibition hall in the Ahoy Convention Center, Rotterdam (The

**Table 1.** Schedule of Scenario Runs during the Day of the Experiment

Scenario	Bicycle fleet composition				Bottleneck width (cm)	Run duration (min)	Time to next run (min)	Session
	Regular	Electric	Racing	Cargo				
Overtaking	60%	20%	10%	10%	125	7	1	Morning
Active bottleneck	60%	20%	10%	10%	125	5	5	Morning
Overtaking	86%	–	14%	–	–	7	5	Morning
Active bottleneck	75%	25%	–	–	75	7	15	Morning
Overtaking	75%	25%	–	–	125	7	1	Morning
Active bottleneck	75%	25%	–	–	125	5	5	Morning
Merging	60%	20%	10%	10%	–	10	5	Morning
Active bottleneck	86%	14%	–	–	75	7	15	Morning
Crossing	60%	20%	10%	10%	–	10	5	Morning
Active bottleneck	60%	20%	10%	10%	75	7	5	Morning
Active bottleneck	86%	14%	–	–	125	7	15	Morning
Merging	60%	20%	10%	10%	–	10	5	Morning
Overtaking	86%	–	–	14%	–	7	–	Morning
Overtaking	100%	–	–	–	125	7	1	Afternoon
Active bottleneck	100%	–	–	–	125	5	5	Afternoon
Active bottleneck	100%	–	–	–	100	7	5	Afternoon
Merging	100%	–	–	–	–	10	15	Afternoon
Active bottleneck	100%	–	–	–	75	7	5	Afternoon
Crossing	100%	–	–	–	–	10	5	Afternoon
Active bottleneck	100%	–	–	–	150	7	15	Afternoon
Active bottleneck	100%	–	–	–	Meander	7	5	Afternoon
Merging	100%	–	–	–	–	10	5	Afternoon
Active bottleneck	100%	–	–	–	Meander	7	15	Afternoon
Crossing	100%	–	–	–	–	10	5	Afternoon
Merging	100%	–	–	–	–	10	–	Afternoon

Netherlands). The size of the rented hall is 142 m x 70 m x 12 m, which satisfies all the dimension requirements and the floor surface is cement, thus similar to cycling on road surface. Furthermore, it is well accessible by bicycle, connected by public transport and has a car park.

### Participant Recruitment

The next step in the implementation is the recruitment of participants. Since it is desired to study the effect of gender and nationality of cycling behavior, anyone is welcome to join. The only restriction is set with respect to age because of ethical reasons; to being at least 16 years old. A maximum age threshold is not set, but participants are asked to be physically able to cycle for around 90 min including breaks. As reward for the time they spent in the experiment, participants are given a small monetary compensation.

To increase the behavioral realism, participants are asked to bring their own bicycle. Upon registration, participants are asked for the bicycle type they intend to bring, as well as for other bicycle types they own. Special focus is placed in the recruitment phase on three special bicycle types (racing, electric, and cargo).

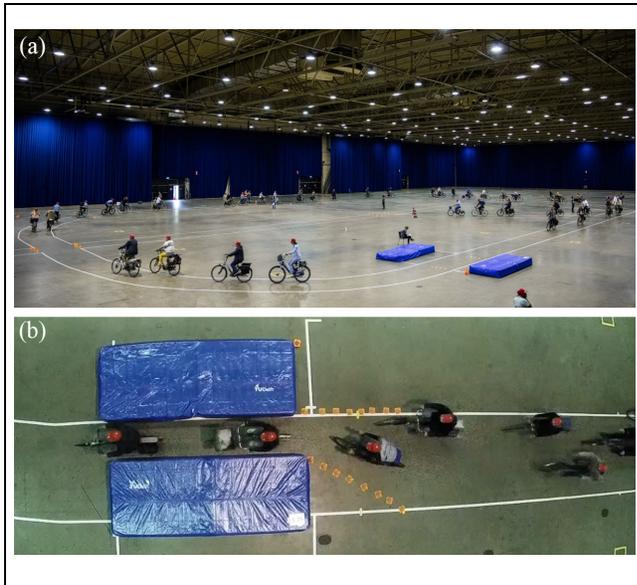
Registration is performed through an online form, where availability in time of day (morning/afternoon session) and bicycles is declared. For those that meet the

requirements, a confirmation is sent which includes the request to avoid red clothing which obstructs the tracking of the red caps in the camera images. Several platforms are used for the recruitment, such as posts in social media, universities, and schools in Rotterdam and advertisements in local newspapers.

### Measuring and Tracking Equipment

As previously mentioned, cameras are placed above the track to record the cyclist movements throughout the day. Because of the lighting conditions of the hall, which were low and variable, high-quality cameras had to be used. Two snapshots of the experiment are shown in Figure 5. Figure 5a is a side view (from an overview camera, not to be used for tracking) during a Merging scenario. The cameras are placed at the ceiling next to the lights to improve the image quality and are 10 m above the ground. To cover the complete straight stretches, three cameras are required on each side with an overlapping area to ensure a continuous trajectory. Two more cameras are placed above the crossing points to observe the cyclist interactions there.

A top view at the location of the bottleneck can be seen in Figure 5b. From this view the trajectories can be extracted by tracking the red cap of each cyclist. As shown in the image, each cap has a pattern of white



**Figure 5.** Camera snapshots: (a) side view of the merging scenario; (b) top view of the active bottleneck scenario.

boxes (like a bar code) on the flap which is unique and linked to the participant characteristics. An additional dot is marked in the middle, to identify looking and cycling direction.

Last but not least, we set up a corner to measure three main bicycle dimensions, i.e., full bicycle length, length from the front wheel to the handlebar, and width of the handlebar. This enables studying the effect of different bicycle sizes on the behavior in addition to the bicycle types.

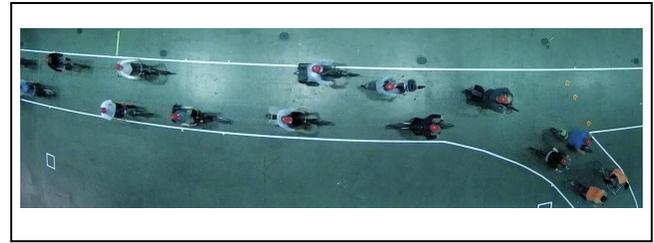
## Experiment Execution and High-Level Description of Data

The experiment took place on 25 April 2018 with 178 participants evenly spread over the morning and afternoon sessions. This section presents the collected dataset, starting with adjustments of the plan that were needed during the day and continuing with the statistics of the participant characteristics and a qualitative description of the data.

### Plan Adjustments

During the first run in the morning session, it became clear that there were too many cyclists on the track. The queue configuration of 2-1-2-1 that was expected upstream the bottleneck was not observed. Instead, participants anticipated the bottleneck and started braking already at the curve. This resulted into a lower density than anticipated and an overall low speed (congested conditions).

The solution was to create two groups, each with half of the participants, and alternate the group on the track. This way, the long breaks could be skipped as the participants could rest when the other group was cycling. Thanks



**Figure 6.** Queue formation behind a moving bottleneck.

to this change, it was possible to not only follow the plan, but have time for some additional scenario runs.

Since the narrowing at the bottleneck was anticipated and a dense queue was not naturally arising, we activated it using the moving bottleneck (i.e., the two persons in orange vests in Figure 6).

In the Merging scenario, we initialized with a group starting from inside but the participants self-organized during the runs and dynamically shifted among the two routes. We decided not to obscure this process since it enhances observation of heterogeneity and could even lead to a model on route choice.

### Participant Characteristics

The descriptive statistics of the participants and their bicycles are summarized in Table 2 by session. It can be seen that more males participated in the experiment with a higher share in the afternoon session. The majority of the sample is Dutch and there is a wide range of ages.

With respect to the bicycles, the morning session contained special bicycle types with a high share of electric (35%) and a considerable share of 9% of racing bicycles. Unfortunately, no participants with cargo bicycles could be recruited. In the afternoon, almost all participants had regular bicycles. On average, the bicycle dimensions seem consistent between the two sessions.

### Qualitative Data Description

In total, six hours of videos have been collected which capture the cyclist movements throughout the day. Since there was time left, we tried one more situation. We had one run where we slowly filled up the track with everyone in to study the occurring wide moving jams. The planned scenarios were executed and additional to our expectations, the following phenomena were observed:

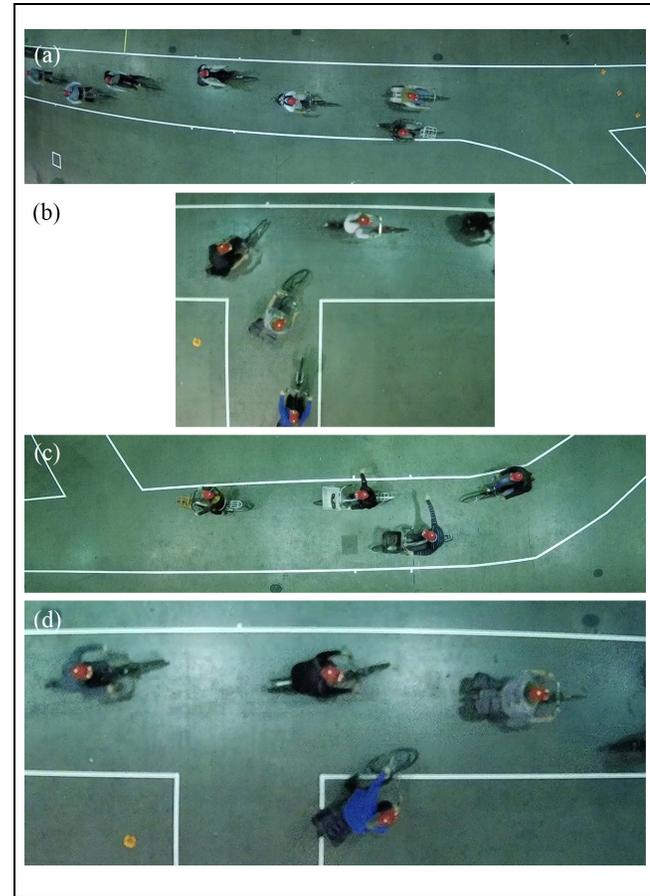
- Participants were braking already upstream the curve which led to lower than expected density.
- Many cyclists were overtaking in curves rather than the top straight stretch.
- Pairs were formed on the track, which blocked overtaking maneuvers (Figure 7a).

**Table 2.** Descriptive Statistics of Participants and Their Bicycles by Session

Characteristic	Morning session	Afternoon session
Females	34	30
Males	54	60
Dutch	78	84
Other European	8	2
Non-European	2	4
Minimum age	19	17
Average age	52	51
Maximum age	80	89
Standard deviation of age	19	19
Average height (cm)	174	177
Standard deviation of height	10	10
Average weight (kg)	79	77
Standard deviation of weight	15	13
Electric bicycles	31	3
Racing bicycles	8	0
Average bicycle length (cm)	180	180
Standard deviation of bicycle length	6	5
Average handlebar width (cm)	59	59
Standard deviation of handlebar width	6	4

- A variety of yielding decisions was observed regardless of group sizes. Sometimes steering to create space was preferred to stopping (Figure 7b).
- During the Merging scenario runs, participants alternated between the two routes, leading to a dynamic share and different group sizes interacting at the merge.
- Some of the merging-route cyclists used their arms to indicate they would take the off-ramp and others taking that route would copy (Figure 7c).
- The right angle at the merging point was not always feasible to follow, so some cyclists went slightly off the track to merge (Figure 7d).

These observations show that anticipation plays a key role while cycling. In this obstacle-free environment where the curve and bottleneck were in sight, cyclists adjusted their speed in preparation for them. Moreover, speed differences could be better expressed in curves where the cautious cyclists would brake and the rest used this opportunity to overtake. Personal characteristics seem to be dominant with respect to yielding decisions and less so the number of approaching cyclists. Participants respected the rule to cycle inside the cycle path, unless it would have led them to unsafe situations. Last but not least, self-organization has been found for cyclists in the form of distributing over different routes and copying the behavior of others. These qualitative findings will be the starting point for future research,



**Figure 7.** Examples of observed phenomena: (a) pair of cyclists obstructing the flow; (b) cyclist in black makes space for merging cyclists instead of yielding; (c) route indication using arms; (d) straying off the path to merge.

additional to what was already intended with the collected dataset.

### Future Research with Collected Dataset

In this paper, we described the setup of a large-scale, controlled cycling experiment and qualitatively presented the collected dataset. The next research step is to process the video data and automatically extract trajectories out of the images, stitch trajectories between consecutive cameras, and link to a participant number. This rich dataset will be used to investigate behavior of different bicycle types and personal characteristics, and derive theoretical models that represent the decisions individual cyclists make while cycling and interacting with other cyclists, as well as models that describe the operationalization of these decisions. The dataset will also be used to calibrate and validate these models. Apart from studying individual behavior, we will study macroscopic bicycle traffic characteristics and construct the fundamental diagram for cycling. Such models can be used in future

research to assess the quality of different bicycle infrastructure designs under several demand conditions.

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### Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: AG, MJW, WD; data collection: AG, MJW, WD; analysis and interpretation of results: AG; draft manuscript preparation: AG; study supervision: WD, YY, VLK, SPH. All authors reviewed the results and approved the final version of the manuscript.

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