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Riding the Green Wave –
How Countdown Timers at Bicycle Traffic Lights Impact on Cycling Behavior

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The "Leezenflow" system is an open-source green wave assistant designed specifically for cyclists and is installed 110 meters in front of a traffic light in Münster, Germany. The system indicates the remaining time of the current traffic light phase through an expiring bar, colored either green or red. This is intended to help cyclists adjust their speed in order to cross the traffic lights when green, and consequently optimize cycling flow. We conduct a natural field experiment in real traffic to analyze the impact of the Leezenflow system on cycling flow and safety, and find that it impacts statistically significantly on cycling flow. Due to the Leezenflow system, the number of cyclists that have to stop at the red lights decreases by 6.6 %. Accordingly, the share of cyclists that pass the green lights increases. The data also indicate positive effects on traffic safety. The results of the natural field experiment confirm and put into perspective the feedback of an accompanying online survey. The majority of surveyed users reports that the Leezenflow system does improve the cycling flow. The influence on traffic safety is predominantly seen as positive or neutral by the survey participants. The Leezenflow system can thus help city planners to promote cycling, thereby enabling more sustainable mobility.

Keywords: Bicycle traffic flow, traffic safety, open-source green wave assistant, countdown timer, natural field experiment, survey. JEL: R49, C93

I. Introduction

Cycling is a highly sustainable mode of transport. Thus, the promotion of cycling is essential for city planners aiming at more environmentally friendly mobility. According to Pucher and Buehler (2008), promoting safe and convenient cycling starts with the design of intersections and the corresponding traffic lights. Being able to safely cross intersections without having to stop, enhances cycling quality and can result in increased bicycle ridership within cities.

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Against this backdrop, the city of Münster, Germany, installed the so-called "Leezenflow" system ("Leeze" is a regional term for a bicycle) at one selected intersection in order to increase the *flow* of crossing cyclists. The basic idea behind the open source Leezenflow system originated from a programming competition called "Münsterhack". The system was then developed by local programmers and other stakeholders, under the supervision of the city of Münster. The Leezenflow system is a green wave assistant designed specifically for cyclists. In our study, we investigate its impact on cycling flow and safety by conducting an online survey and a natural field experiment in real traffic. We start by providing information on the functionality of the Leezenflow system (I.A), the current state of research on bicycle traffic countdown timers (I.B), and how our study contributes to the literature by generating important insights for both researchers and traffic planners (I.C).

A. The Leezenflow system

The Leezenflow system was installed in Münster on the Promenade on May 17, 2021 approximately 110 meters in front of the bicycle traffic light at the intersection Promenade / Hörstertor.[1] Hörstertor is a regular street for motorized traffic and cyclists, with sidewalks for pedestrians on both sides. The Promenade is a bikeway running in a ring around the center of Münster, thereby distributing bicycle traffic and connecting different parts of the city. It is the most frequented bikeway in the city of Münster. A nearby automated bicycle counting station counted about 5,274 cyclists per day (an average of 220 cyclists per hour) in 2021, thereby considering only cyclists who ride in the direction of the Leezenflow-System and the intersection Promenade / Hörstertor. The peak traffic times are during the week in the morning (6 to 9 a.m.) and in the late afternoon (4 to 7 p.m.).

The basic idea of the Leezenflow system is to inform cyclists about the remaining time of the current traffic light phase, i.e. when the traffic light switches from red to green or from green to red. Thus, the Leezenflow system basically serves as a countdown timer for the traffic light to which it is connected. With this real time information, cyclists are able to adjust their cycling speed more accurately, and subsequently, might be able to cross the intersection without stopping. In contrast to other countdown timers, however, the Leezenflow system is designed specifically for cyclists and is not placed directly next to the traffic light itself, but approximately 110 meters in front of the traffic light in order to give cyclists sufficient time to optimize their cycling (see Figure 1).

The Leezenflow system features a colored LED-panel displaying how long the traffic light will remain green or red. The design of this countdown timer is shown in Figure 2. When the traffic light has just turned green, the LED-panel of the Leezenflow system displays a full green bar. From then on, a moving bicycle is displayed underneath the green bar and the green bar expires from the bottom to the top. It vanishes when the green traffic light phase ends. Consequently, Figure 2a indicates a situation in which the traffic light has just turned green and the green traffic light phase will remain for some time, whereas Figure 2b

[1] GPS coordinates of the intersection: 51.96549, 7.63363. GPS coordinates of the Leezenflow system: 51.96445, 7.63404.

[2] When the photo was taken, it was ensured that no cyclists or other people were visible in the picture, in order to comply with data protection and privacy. In addition, this allows the structural features, i.e. the demarcation of the bicycle and pedestrian paths of the Promenade to be clearly depicted.

Figure 1. : Location of the Leezenflow system[2]

indicates a situation in which the green traffic light phase is about to end and the traffic light will soon switch to red. When the latter occurs, the LED-panel of the Leezenflow system accordingly displays a full red bar (see Figure 2c). From then on, a standing bicycle is displayed below it and the red bar similarly disappears from the bottom to the top (see Figure 2d).

(a) Full green (b) Expiring green (c) Full red (d) Expiring red

Figure 2. : Design of the Leezenflow system

The information displayed on the Leezenflow system corresponds to the traffic light to which it is connected. On average, the green light phase is about 48 seconds, and the red light phase about 42 seconds. This traffic light, however, is coordinated with other traffic lights and reacts to actual road traffic, resulting in varying durations of the traffic light phases. Therefore, the Leezenflow system does not display the remaining number of seconds until the traffic light changes. For example, if the traffic light phase were 5 seconds longer than normal, a numerical countdown timer might display a switch from 10 remaining seconds to 15 remaining seconds. This would be more confusing than a constant bar in the LED-panel.

Furthermore, both the construction manual, as well as the programming code of the Leezenflow system are provided free of charge as open source files.[3] Hence, municipal governments and traffic planners can build their own Leezenflow systems and install them in their cities at relatively low cost.[4]

B. Research on the effects of bicycle countdown timers

The idea underlying the Leezenflow system is that its installation should have a positive impact on cycling flow. Furthermore, the Leezenflow system can have an impact on overall traffic safety at the intersection. The related literature on the impact of countdown timers on bicycle traffic is still relatively scarce. Wiersma (2006) finds that countdown timers in Amsterdam result in a 7 % reduction in red light violations, and after increasing the visibility of the countdown timers, red light violations are reduced by a further 10 %. In Munich, the installation of traffic light countdown timers for cyclists at three intersections led to mixed results, implying that both increases and decreases of red light violations can be observed. Kaths et al. (2019) therefore state that the effect of a green phase countdown timer on cycling behavior depends on various factors, for example on structural conditions at the intersection. In Shanghai, Dong et al. (2011) observe that the speed of non-motorized traffic increases at intersections with green phase countdown timers or with a flashing traffic light that signals the end of the green phase. Nygårdhs (2021) investigates the impact of a green light countdown timer on the cycling behavior of 26 participants in Groningen, Netherlands. The participants of the study cycle in real traffic, but are wearing eye-tracking equipment. The results show that the cyclists react to the green phase countdown timer, for example, by adjusting their speed to reduce the number of stops. The countdown timer does not affect the attention that cyclists pay to important traffic objects, but an increase in red light violations can be observed.

A central difference between the aforementioned traffic light countdown timers and Münster's Leezenflow system is that the former are installed directly next to the traffic lights and not, as in Münster, about 110 meters in front of the actual traffic light. There is, however, a simulator study by Ruf and Kaths (2021), which examines the effects of a traffic light countdown timer installed 60 meters in front of the traffic light. The authors find that countdown timers for cyclists can reduce

[3] The source code and documentation of the Leezenflow system is available at: https://www.bcyber.de/leezenflow or https://smartcity.ms/leezenflow/.

[4] The total costs for an additional Leezenflow system are estimated at approximately 10,500-19,800 €. Of this, 500-800 € would be for material costs, 2,000-3,000 € for personnel costs for manufacturing the system, and 8,000-16,000 € for personnel and material costs for reprogramming the corresponding traffic light system (incl. roadside units). In comparison, the construction of a new traffic signal system at a major intersection would cost at least 140,000 € for the minimum version.

red light violations and stops at the traffic signal. In the context of their simulator study, it does not matter whether the countdown timer is installed directly next to the traffic signal or 60 meters in front of it.

In summary, the abovementioned studies on the impact of traffic light countdown timers on red light violations of cyclists appear to provide mixed results. Additionally, the impact of countdown timers on bicycle traffic flow have so far only been treated superficially in the literature. The impact on traffic safety has not yet been considered explicitly.

C. Contributions to the literature

The installation of the Leezenflow system in Münster provides an interesting and useful opportunity to learn more about the impact of traffic light countdown timers on cycling flow and safety. To the best of our knowledge, we are the first to study the real-world impact of a traffic light countdown timer for cyclists that is not positioned next to the actual traffic light, but approximately 110 meters in front of it, thus giving cyclists more time to adjust their cycling behavior.

Our results show that the Leezenflow system indeed has a statistically significant impact on bicycle traffic. All in all, we monitored 41,845 cyclists who crossed the affected intersection. When the Leezenflow system was not installed or was turned off, 30.1 % of the cyclists stopped at the red traffic light. We find that the Leezenflow system decreases this share by 2.0 percentage points. In terms of the effectiveness of the Leezenflow system, this means that the number of cyclists who have to wait at the red light decreases by 6.6 %. Accordingly, the Leezenflow system increases the share of cyclists who can cross the green traffic light without stopping by 2.4 percentage points. The share of red light violations is slightly reduced, but this reduction is not statistically significant in all regression models. Nevertheless, the analysis of the traffic data clearly confirms that the Leezenflow system increases cycling flow. With respect to traffic safety, we observe one crash (without personal injury) when the Leezenflow system was turned off, and no crashes when the Leezenflow system was turned on. Moreover, the observed frequency of near-crashes is lower when the Leezenflow system is turned on. Due to the small number of crashes and near-crashes, however, the observed reduction in crashes and near-crashes cannot be explicitly classified as a causal consequence of the Leezenflow system.

The results of the natural field experiment confirm and put into perspective the feedback from the accompanying online survey. The majority of the surveyed users agree that the Leezenflow system improves their cycling flow. Its influence on traffic safety is predominantly seen as positive or neutral, but also negative by some survey participants. In general, however, most users see an increase in cycling quality and some even report cycling more frequently due to the Leezenflow system.

The remainder of this article is structured as follows. Section II presents the user feedback that was collected through an online survey. In Section III, the impact of the Leezenflow system on actual cycling flow and traffic safety at the intersection is analyzed through a natural field experiment. Section IV discusses the results and concludes.

II. Survey

A. Implementation and participation

In order to gain insight into how people evaluate the Leezenflow system and perceive its impact on cycling flow and traffic safety, we conducted an online survey. We chose an online format to prevent disrupting the cycling flow – which would run counter to the intention of the Leezenflow system – and also to reduce personal contacts due to the Covid-19 pandemic. The survey was started at the time of installation of the Leezenflow system on May 17, 2021 and was closed on June 14, 2021. Participation was financially incentivized by raffling 30 shopping vouchers as well as 10 bicycle bags.

In total, we collected 534 valid questionnaires. Table 6 in Appendix V.A shows the socio-demographic characteristics of the 534 participants. The proportion of male and female participants is relatively balanced, and the participants are generally younger than 30 years (45.9 %), only 4.8 % are 60 or older. Accordingly, participants are predominantly pupils and students or employees. Thus, it is likely that cyclists regularly passing the Leezenflow system are represented quite well in our sample.

B. Results

The participants' answers are mainly based on their own experience with the Leezenflow system. At the time of survey participation, 485 of the 534 participants report having passed the Leezenflow system at least once. In the following, these participants are called "users". Most users (46.4 %) report passing the Leezenflow system several times a week, 19.2 % at least once a day and 34.4 % once a week at most.

The frequency of use depends on the purpose of cycling (see Table 7 in Appendix V.A). As expected, users who pass the Leezenflow system for occupational reasons state a higher frequency of use. Overall, fewer users report passing the Leezenflow system only for occupational (17.7 %) than only for leisure reasons (42.5 %). 39.8 % of the users report passing the Leezenflow system for both reasons.

Most users do not understand the information displayed on the Leezenflow system the first time they pass it. Figure 3 indicates that after passing the Leezenflow system only once, user rating of the system understandability is roughly uniformly distributed on a 5-point-Likert scale from "very good" to "very bad". After passing the Leezenflow system several times, most users (71.5 %) rate the understandability as "good" or "very good", while 17.7 % rate it as "bad" or "very bad". Learning effects regarding the understandability of the Leezenflow system can therefore be assumed. Furthermore, such learning effects are explicitly confirmed by users who had passed the Leezenflow system more than once at the time of survey participation. Almost half of these users observe learning effects with the second use, 31.1 % after multiple uses, whereas 19.6 % observe no learning effects at the time of survey participation.

Figure 4 shows whether the reported learning effects regarding the understandability of the Leezenflow system are reflected in optimized cycling behavior. First, users were asked whether the Leezenflow system has an impact on their own cycling behavior at all. This is confirmed by 72 % of the 485 users (n = 349),

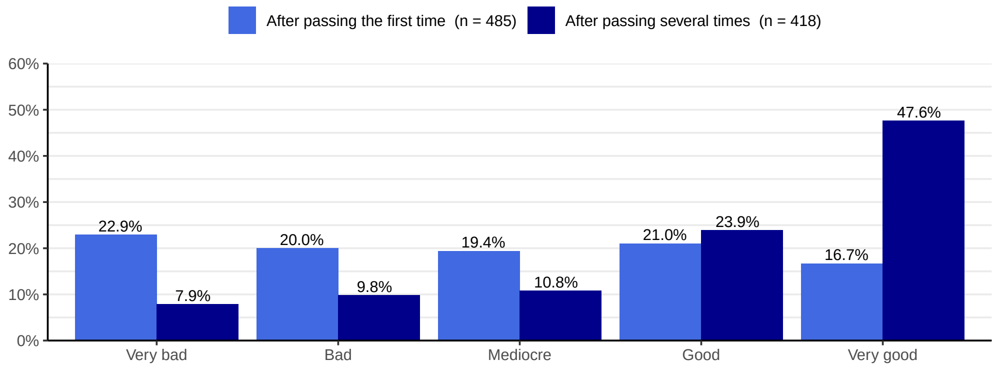

Figure 3. : Understandability

whereas 28 % see no impact.[5] The majority of the former then state that the frequency of abrupt braking, stopping/getting off and the time spent standing at traffic lights is reduced, and that their cycling flow is increased. However, the impact of the Leezenflow system on cycling speed does not seem clear. This basically corresponds to the idea and aim of the Leezenflow system, as individual speed reactions depend on the respective states of the display.

Below, all users were asked whether they feel that the Leezenflow system helps them to reach the destination more smoothly. 63.1 % of the users say yes, 25.6 % say no, 11.3 % do not know. Among those users who do see an impact on their own cycling behavior (n = 349), a vast majority of 84.2 % perceives a positive impact of the Leezenflow system on their cycling flow (see Figure 5). Conversely, 67.6 % of those users who do not see an impact of the Leezenflow system on their own cycling behavior (n = 136) do not perceive a positive impact of the Leezenflow system on their cycling flow. Some of these 136 users, however, perceive a positive impact on their cycling flow (8.8 %), potentially because they are subconsciously "pulled along" by others.

With regard to traffic safety, the majority of users state that the focus on traffic increases or remains constant with the Leezenflow system. Nevertheless, there is a small share stating that the focus on traffic decreases with the Leezenflow system (see Figure 4).[6] A similar picture emerges when all participants are asked directly whether they see a positive, negative or zero impact on traffic safety. 6.7 % of the participants see a negative impact on traffic safety. They report that the Leezenflow system is distracting and motivates excessively fast cycling. However, the vast majority of participants observe a positive or no impact of the Leezenflow system on traffic safety (58.4 % and 25.5 %, respectively). The former participants report that the Leezenflow system enables more predictable and focused cycling, an increased cycling flow and less red light violations (see Table 8 in Appendix V.A).

[5] The 28 % of users who see no impact on their cycling behavior were not asked the following, more detailed questions on how the Leezenflow systems influences their cycling behavior. They are therefore labelled as "not asked" in Figure 4.

[6] If certain aspects of the cycling behavior are stated to be negatively affected by the Leezenflow system, this is more often the case for the focus on traffic than for the other areas of interest, i.e. abrupt braking, stopping/getting off the bike, standing at the traffic light and cycling flow.

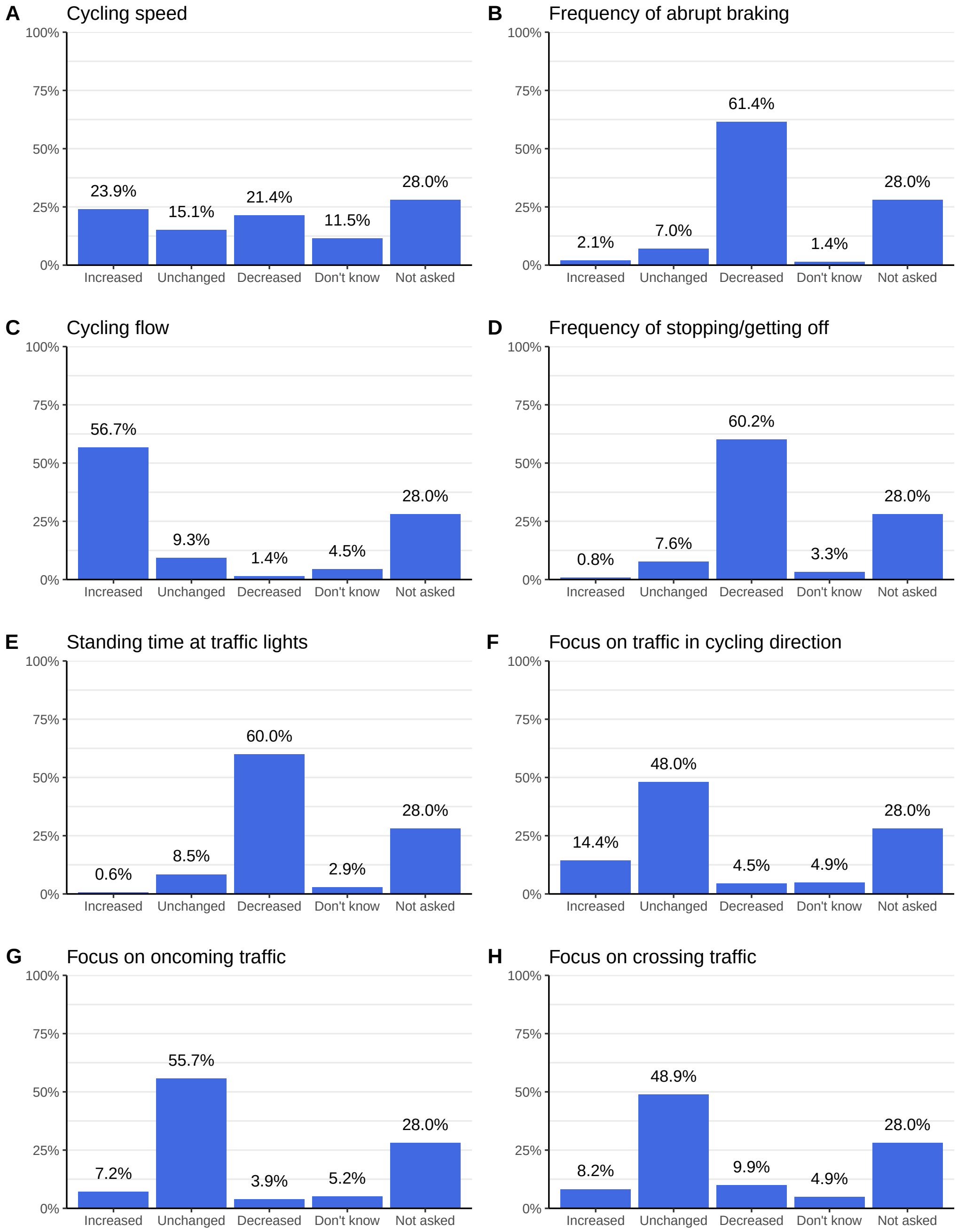

Figure 4. : Impact on cycling behavior (n = 485)

Finally, 75.9 % of the users perceive an increase in cycling quality due to the installation of the Leezenflow system, 11.3 % even report having increased their cycling frequency. It remains unclear whether this is induced or shifted traffic. Although participants still make some suggestions for improvement, mainly in the direction of optimizing the information displayed,[7] 77 % report being in favor

[7] Some participants suggest rather displaying the respective number of seconds until the traffic light

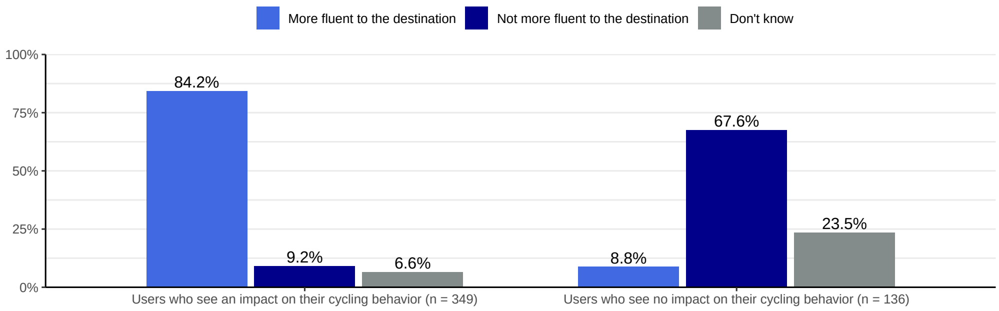

Figure 5. : Influence on cycling flow (n = 485)

of additional Leezenflow systems in Münster, especially at all intersections on the Promenade, on other bicycle ring roads, or on cycling axes from the suburbs to the city center.

III. Traffic analysis

A. Methodology

Design of the natural field experiment

The majority of surveyed users states that due to the Leezenflow system, they stop less often at the red lights and notice an improved cycling flow. Additionally, the influence on traffic safety is predominantly seen as positive or neutral, but also negative by some survey participants. In order to evaluate the actual impact of the Leezenflow system on cycling flow and traffic safety, we conducted a natural field experiment. For this purpose, we monitored the traffic at the intersection Promenade / Hörstertor at various times of day during April 12, 2021 and July 1, 2021, as well as between October 25, 2021 and November 12, 2021. The monitoring times within these 15 weeks were chosen in such a way that they allow for a high degree of representativeness of the overall traffic at this intersection, thus encompassing both peak and off-peak hours.

For identifying the impact of the Leezenflow system on bicycle traffic at the intersection Promenade / Hörstertor, we then exploit exogenous variation in the availability of information on the remaining time of the current traffic light phase. This information availability entails two different states. (1) Cyclists receive no information on when the current traffic light phase will end. This is the case when the Leezenflow system was not yet installed or turned off. (2) Cyclists receive information on when the current traffic light phase will end. This is the case when the Leezenflow system was already installed and turned on.

The outlined variation in the availability of information can be considered as exogenous for two reasons. First, the time of installation of the Leezenflow system was determined by the city of Münster. This decision was mainly based on the technical progress of the prototype and resulted in an installation on May 17, 2021. Therefore, cyclists could not actively influence the time of installation of

changes, some would like to see clear recommendations for action, others just want a clearer explanation on how the Leezenflow system works.

the Leezenflow system and, consequently, had no influence on the point in time at which they would receive information on the remaining time of the current traffic light phase. In the following analysis, the five weeks before and the four weeks after the installation of the Leezenflow system will be referred to as the *Before-After* comparison. This comparison allows for an analysis of very immediate effects of the Leezenflow system.

Second, we generated additional variation in the availability of information by intentionally turning off the Leezenflow system at various times during two three-week periods. The first three-week period started four weeks after the installation of the Leezenflow system, i.e. from June 14, 2021 to July 1, 2021, thus allowing an analysis of whether there are short-term learning effects for cyclists. The second three-week period started roughly five months after the installation of the Leezenflow system, i.e. from October 25, 2021 to November 12, 2021, thus capturing potential long-term learning effects. For each of these two three-week periods, pairs of observations were collected on two consecutive days and at the same times[8]. Each pair then consists of observations with the Leezenflow system turned off, and corresponding observations on the next day with the Leezenflow system turned on. This ensures a high degree of comparability and mitigates bias due to seasonal effects. In the following analysis, these three-week periods will be referred to as *With-Without 1* comparison and *With-Without 2* comparison. A timeline showing the variation in information availability is outlined in Figure 6.

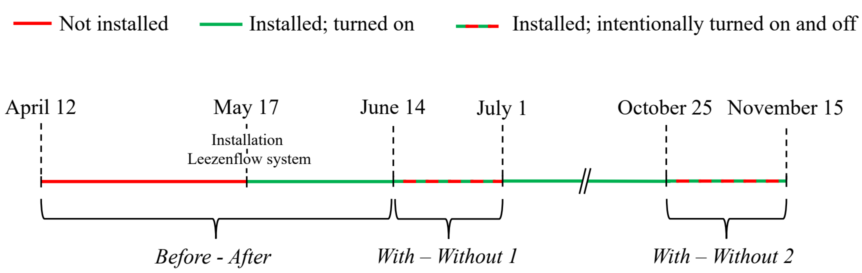

Figure 6. : Timeline of the natural field experiment

It is worth noting that the public was not informed that the Leezenflow system was intentionally turned off as part of a natural field experiment. Moreover, the times when the Leezenflow system was turned off were not communicated to the public and were randomly chosen over different weekdays and times of day. Thus, cyclists could only know if information on the remaining time of the current traffic light phase was available when actually passing the Leezenflow system.

[8] On November 11, 2021 the Leezenflow system should have been turned on, but was turned off due to technical problems. Therefore, the observations from November 10, 2021 were matched with observations from November 12, 2021. Thus, we have one pair of observations with two consecutive days in between.

Data collection and methods of analysis

The data on cycling behavior were collected by comprehensively instructed personnel, because using cameras for traffic monitoring was not feasible due to privacy concerns, and opaque treetops would have prevented filming from a sufficiently steep angle. When monitoring the bicycle traffic at the intersection Promenade / Hörstertor, each cyclist was assigned to one of 12 different traffic situations. These 12 situations correspond to the detailed classification, displayed in Table 1. Situation S5 would then, for example, capture cyclists who cross the traffic light during the first 5 seconds of the green phase, at normal speed.[9]

Table 1—: Traffic situations

No.	Standard classification	Detailed classification
S1	Stopping when red	after full braking
S2		first 5 seconds
S3		after 5 seconds at normal speed
S4		after 5 seconds at slow speed
S5	Cycling when green	first 5 seconds at normal speed
S6		first 5 seconds at slow speed
S7		without first and last 5 seconds
S8		last 5 seconds at normal speed
S9		last 5 seconds at quick speed
S10	Cycling when red	first 3 seconds
S11		after 3 seconds
S12		right turn

For the sake of clarity, however, we only analyze the detailed classification as part of the sensitivity analysis in Section III.B. In general, we analyze the standard classification that consists of only three different traffic situations: stopping when red, cycling when green, and cycling when red. As indicated in Table 1, the standard classification can easily be derived from the 12 traffic situations of the detailed classification.

Our sample thus includes 4,254 full traffic light phases (each consisting of one green and one red traffic light phase). 13 of these full traffic light phases could not be used in our analysis, because the monitoring personnel were distracted by other people (e.g. being asked questions about the Leezenflow system or the monitoring itself). During the remaining full traffic light phases, 41,845 cyclists were monitored. 10,653 cyclists were monitored before the installation of the Leezenflow system. After the installation, 18,386 and 12,806 cyclists were monitored when the Leezenflow system was turned on and turned off, respectively.

To analyze our sample data, we use two different methods. First, we follow Ruf and Kaths (2021) and use Chi-square tests of independence in order to test

[9] The monitoring personnel was provided with videos for each of the 12 traffic situations. Additionally, we conducted joint test monitoring sessions in order to ensure the quality and consistency of the data. Nevertheless, the regression for the detailed classification is estimated with personnel fixed effects to control for potentially subjective perceptions of timing and speed.

whether the cyclists' distribution across the traffic situations is independent of the Leezenflow system. Second, we use a multinomial logit model (MNL model) in order to estimate the impact of the Leezenflow system on individual cycling behavior. This method is also used by Twaddle and Busch (2019) or Ambo et al. (2021) in the context of traffic analysis. The MNL model also allows controlling for potential subjective bias of the monitoring personnel, such as the assessment of cycling speeds, by using personnel fixed effects. For better interpretability, we always present the marginal effects of the MNL model.

B. *Cycling flow analysis*

Main results

Analysis of overall data

To obtain an overview of the impact of the Leezenflow system on cycling flow, we first consider all $n = 41,845$ cyclists of our sample. For this analysis, each cyclist is assigned to one of the three traffic situations of the standard classification, i.e. stopping when red, cycling when green, and cycling when red. If the Leezenflow system was not yet been installed or is turned off, 30.1 % of the observed cyclists are stopping when red and 63.7 % of the observed cyclists are cycling when green (see Figure 7). If the Leezenflow system is installed and turned on, the share of the cyclists stopping at red is about 2.0 percentage points lower, and the share of cyclists riding when green is 2.4 percentage points higher. The share of those cycling when red declines by 0.4 percentage points.

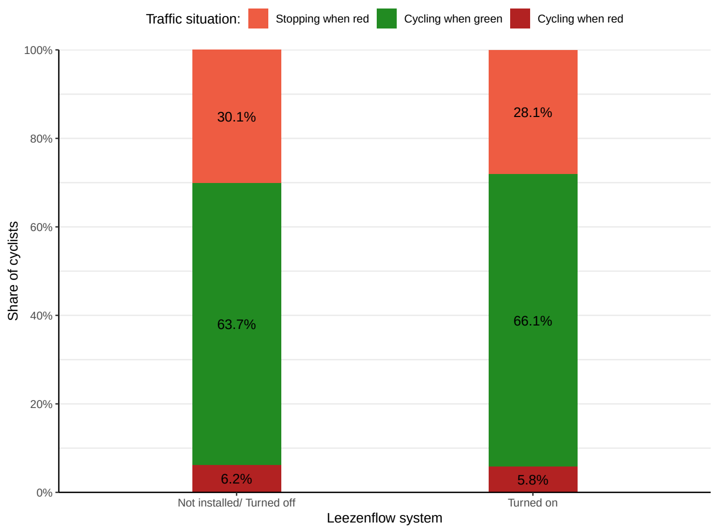

Figure 7. : Overview of traffic situations ($n = 41,845$)

The Chi-square test confirms a statistically significant impact of the Leezenflow system on cyclist distribution ($\chi^2(df = 2; n = 41,845) = 26.287; p = 0.0000$). In addition, we use an MNL model to estimate the impact of the Leezenflow system on individual cycling behavior. The results of the MNL model with all observations are shown in Column (1) of Table 2. The Leezenflow system reduces the share of cyclists stopping at red by 2.0 percentage points. On the other hand, the share of cyclists riding when green increases by 2.4 percentage points. Both coefficients are statistically significant at the 1 %-level. The change in the share of cyclists illegally crossing a red traffic light is slightly negative and statistically significant at the 10 %-level. Thus, our overall analysis confirms that cyclists indeed use the Leezenflow system as intended. Now, the 30.1 % of cyclists who had to stop at the red traffic lights are reduced by 2.0 percentage points, resulting in an effectiveness of the Leezenflow system of $2.0/30.1 = 6.6\,\%$.

Table 2—: Marginal effects of the Leezenflow system on traffic situations

	All observations (1)	Before-After (2)	With-Without 1 (3)	With-Without 2 (4)
Stopping when red	−0.020***	−0.013*	−0.026***	−0.020**
	(0.004)	(0.007)	(0.008)	(0.008)
Cycling when green	0.024***	0.020***	0.026***	0.021**
	(0.005)	(0.008)	(0.009)	(0.008)
Cycling when red	−0.004*	−0.007*	0.001	−0.001
	(0.002)	(0.004)	(0.004)	(0.004)
Observations	41,845	16,903	11,948	12,994
LR χ^2	26.32	7.99	9.94	6.87
Prob > χ^2	0.0000	0.0184	0.0069	0.0322

Significance levels: ***: 0.01, **: 0.05, *: 0.1. Standard errors in parenthesis.
Shown here are the marginal effects of the respective MNL models. The original regression coefficients as well as odds ratios are available upon request.

Analyses of different time periods

In order to analyze whether learning effects are realized, we separate the data into the three different time periods as outlined in Section III.A, i.e. *Before-After*, *With-Without 1* and *With-Without 2*. First, we can confirm a statistically significant impact of the Leezenflow system on cyclist distribution at the traffic light by conducting separate Chi-square tests for each of the three periods.

With the *Before-After* comparison, we analyze whether the installation of the Leezenflow system has an immediate and direct effect on cycling behavior. The results of the corresponding MNL model are presented in Column (2) of Table 2 and basically confirm the results of the overall analysis with all data. After the installation of the Leezenflow system, the share of cyclists stopping at red decreases by 1.3 percentage points, while the share of cyclists riding when green increases by 2.0 percentage points. Again, the small reduction in red light violations is statistically significant at the 10 %-level.

Using the *With-Without 1* comparison and the *With-Without 2* comparison, we analyze whether there are short-term and/or long-term learning effects for cyclists. The results are shown in Columns (3) and (4) of Table 2. The number of cyclists stopping at a red light decreases significantly for both comparisons. While this share declines by 2.6 and 2.0 percentage points, the share of cyclists riding when green increases by 2.6 and 2.1 percentage points, respectively. However, we do not observe a significant impact of the Leezenflow system on red light violations.

The reduction in the share of cyclists stopping when red is stronger than for the *Before-After* comparison, thereby suggesting that learning effects might be present. It is interesting that the effect magnitudes appear to be larger roughly *one* month after the installation, compared to *five* month after the installation. Thus, we find no clear evidence that long-term learning effects might be present. Nevertheless, the results confirm a positive and causal impact of the Leezenflow system on cycling flow.

Weekdays vs. weekend

Third, we split the overall dataset by day of the week to differentiate between different traffic types. During the week, there tends to be more utilitarian traffic (e.g. commuting to work or school), while there is logically more leisure traffic on weekends. We thus investigate whether the impact of the Leezenflow system differs between these two types of traffic. Table 3 presents the results of the MNL models for both subsets. During the week, cyclists clearly benefit from the Leezenflow system. For weekends, however, the coefficients are not statistically significant. Potential reasons for this difference could be that utilitarian cyclists have a higher desire to save travel time than leisure cyclists. Moreover, utilitarian cyclists pass the Leezenflow system more frequently and have thus more opportunities to learn to adjust and optimize their cycling behavior according to the displayed information on the remaining time of the current traffic light phase.

Table 3—: Marginal effects of the Leezenflow system on traffic situations (weekdays vs. weekend)

	Weekday (5)	Weekend (6)
Stopping when red	−0.019***	−0.021
	(0.005)	(0.017)
Cycling when green	0.024***	0.012
	(0.005)	(0.018)
Cycling when red	−0.005*	0.009
	(0.002)	(0.009)
Observations	37,977	3,868
LR χ^2	23.353	2.12
Prob > χ^2	0.0000	0.3462

Significance levels: ***: 0.01, **: 0.05, *: 0.1. Standard errors in parenthesis.
Shown here are the marginal effects of the respective MNL models. The original regression coefficients as well as odds ratios are available upon request.

Detailed insights into cycling behavior

In addition to the previously discussed main results of the standard classification, the collected data also allow for a more detailed analysis of cycling flow. We analyze the specific points in time within the traffic light phases at which each cyclist stops at or crosses the traffic lights, as well as the cyclist's speed when approaching the intersection. This is reflected in the detailed classification (see Table 1).[10] Again, the Chi-square test shows a significant impact of the Leezenflow system on cyclist distribution across traffic situations ($\chi^2(df = 11; n = 37,054) = 73.925; p = 0.0000$).

The results of the MNL model can be found in Column (7) of Table 4. Here, we use personnel fixed effects to control for differences in individual perceptions of cycling speeds, as well as times within the traffic light phases at which the cyclists stop at or cross the traffic lights.

We can observe that the share of cyclists stopping when red after 5 seconds at normal speed decreases by 1.9 percentage points, whereas the share of cyclists at normal speed in the first 5 seconds of the green phase increases by 1.6 percentage points. This suggests that the Leezenflow system induces a shift towards a better cycling flow, as fewer cyclists have to stop at a red traffic light.

In addition, there is a 1.0 percentage point increase in the share of cyclists crossing the intersection in the middle of the green phase. This could, for example, be due to fewer cyclists crossing the intersection in the last 5 seconds of the green phase at normal speed (-0.4 percentage points), as well as fewer cyclists in the first 3 seconds of the red phase (-0.2 percentage points). Again, the Leezenflow systems appears to influence cyclists as intended.

C. *Traffic safety analysis*

In order to complete the bicycle traffic analysis at the intersection Promenade / Hörstertor, the crashes and near-crashes that were observed in the monitoring periods are examined below. These statistics are shown in Table 5.

Of all 41,845 observed cyclists, only one cyclist was involved in a collision with an oncoming cyclist after crossing the traffic light (without personal injury). This crash occurred when the Leezenflow system was turned off. Other than that, no crashes were observed.

When the Leezenflow system was turned off, 11 cyclists were involved in a traffic situation that was classified as a near-crash (0.047 % of passing cyclists). When the Leezenflow system was turned on, only 4 cyclists were involved in traffic situations that could be classified as near-crash (0.022 %).

These findings, however, should be interpreted with caution. This is mainly due to the very small number of traffic situations that could be classified as crashes or as near-crashes. Accordingly, small changes in the absolute numbers, caused by, for example, slightly changed observation periods, could strongly influence the direction of the results. Moreover, the classification of a traffic situation as a near-crash may vary slightly between monitoring personnel, despite prior briefing. Hence, the observed decrease in near-crashes should not be interpreted as a causal consequence of the Leezenflow system.

[10] For the detailed classifications, only observations from April 28, 2021 onwards are taken into account (37,054 cyclists). Only from this point in time onwards, was a distinction made between the first 5 seconds and the subsequent seconds within the red traffic light phases, in order to enable a more detailed evaluation. This does not affect the standard classification, so that all observations can always be used.

Table 4—: Marginal effects of the Leezenflow system on traffic situations (detailed classification)

	Detailed classification (7)
Stopping when red, after full braking	0.000
	(0.000)
Stopping when red, first 5 seconds	0.000
	(0.002)
Stopping when red, after 5 seconds at normal speed	−0.019***
	(0.004)
Stopping when red, after 5 seconds at slow speed	0.001
	(0.004)
Cycling when green, first 5 seconds at normal speed	0.016***
	(0.003)
Cycling when green, first 5 seconds at slow speed	−0.000
	(0.002)
Cycling when green, without first and last 5 seconds	0.010*
	(0.006)
Cycling when green, last 5 seconds at normal speed	−0.004*
	(0.002)
Cycling when green, last 5 seconds at quick speed	0.001
	(0.001)
Cycling when red, first 3 seconds	−0.002*
	(0.001)
Cycling when red, after 3 seconds	−0.001
	(0.001)
Cycling when red, right turn	−0.002
	(0.002)
Personnel fixed effects	Yes
Observations	37,054
LR χ^2	2434.21
Prob > χ^2	0.0000

Significance levels: ***: 0.01, **: 0.05, *: 0.1. Standard errors in parenthesis.
Shown here are the marginal effects of the respective MNL models. The original regression coefficients as well as odds ratios are available upon request.

IV. Concluding remarks

To summarize, from the natural field experiment, we find that the Leezenflow system indeed has a statistically significant impact on cycling flow. Due to the Leezenflow system, the share of cyclists passing the green lights increases by 2.4 percentage points, whereas the share of cyclists stopping when red decreases by 2.0 percentage points. In terms of the effectiveness of the Leezenflow system, this means that the number of cyclists who have to wait at the red lights decreases by 6.6 %. The share of red light violations is slightly reduced, but not statistically significantly in all regression models. In addition, the collected data

Table 5—: Crashes and near-crashes

	Leezenflow system off or not yet installed		Leezenflow system on	
	Absolute	Percent	Absolute	Percent
Crashes	1	0.004 %	0	0.000 %
Near-crashes	11	0.047 %	4	0.022 %
before traffic light with oncoming traffic	1	0.004 %	1	0.005 %
before traffic light with traffic in direction of flow	2	0.009 %	1	0.005 %
after traffic light with oncoming traffic	4	0.017 %	1	0.005 %
after traffic light with traffic in direction of flow	0	0.000 %	1	0.005 %
with pedestrians	4	0.017 %	0	0.000 %
with cars	0	0.000 %	0	0.000 %

at least indicate positive effects on traffic safety. The results of the natural field experiment confirm and put into perspective the feedback from the accompanying online survey. The majority of the surveyed users agree that the Leezenflow system improves their cycling flow. The influence on traffic safety is predominantly seen as positive or neutral, but also negative by some survey participants. In general, however, most users perceive an increase in cycling quality and some even report cycling more frequently due to the Leezenflow system. Finally, the majority is in favor of more Leezenflow systems in Münster.

With regard to the observed impact of the Leezenflow system on cycling flow, it can be argued that its magnitude is rather modest. One reason for this may lie in the characteristics of the traffic lights at the intersection Promenade / Hörstertor, which are coordinated with other traffic lights and react to actual street traffic. Consequently, the duration of the traffic light phases varies, with the green light phase lasting about 48 seconds on average, and the red light phase about 42 seconds. Since the green light phase for cyclists is already relatively long, many cyclists are likely to cross the intersection without stopping anyway. Therefore, they might not feel any need to optimize cycling behavior. At other intersections, however, green light phases are often much shorter, leading to more cyclists having to stop at red traffic lights. At such intersections, the need to optimize cycling behavior might be more pronounced, which could lead to more cyclists actually using the Leezenflow system and thereby, to a larger impact of the Leezenflow system on cycling flow.

Based on the durations of the green and red light phases outlined above, it can be expected that 48/90=53.3 % of all cyclists are able to cross the intersection without stopping. However, even without the Leezenflow system, this share is substantially higher in reality (63.7 %). This could be due to the fact that cyclists can already see the traffic lights from a distance of ca. 250 meters at the analyzed intersection. Therefore, frequent cyclists, i.e. those who know the approximate duration of the traffic light phases, are able to adjust their speed based on their own approximation of the duration of the traffic light phases. Consequently, such cyclists could have already optimized their cycling behavior, thereby mitigating the impact of the Leezenflow system at this intersection. At other intersections with traffic lights that are not visible from afar, the impact of the Leezenflow system on cycling flow could thus be larger.

Against this backdrop, we also evaluated how many cyclists look directly at the display of the Leezenflow system. We found that this is done by 45 %, and that these cyclists adjust their speed more frequently than cyclists that do not look directly at the Leezenflow system. These observations, however, were made in immediate proximity of the Leezenflow system. As the Leezenflow system can already be seen from a larger distance, we could not capture whether or not cyclists adjusted their speed well in advance of the Leezenflow system.

Consequently, a comparative analysis of the Leezenflow's impact on cycling flow at intersections with different characteristics could provide valuable additional insights. In this context, professional eye-tracking equipment could help to more accurately analyze the relationship between cycling speed adjustment and looking directly at the display of the Leezenflow system.

In general, the impact of the Leezenflow system on cycling flow could be further increased, if the system were more readily comprehensible for users. As the user feedback from the online survey shows, about 18 % still rate the understandability of the Leezenflow system after several passes as poor or very poor. Thus, if a city plans to install a green wave assistant like the Leezenflow system, this should be accompanied by detailed and well communicated explanations on how it works and on how to use it, as explicitly requested by some survey participants. Learning effects occur (more easily) this way, leading to more cyclists being able to pass the intersection without stopping.

In addition to studying the Leezenflow's impact on cycling flow at intersections with different characteristics, future research should focus further on its impact on traffic safety. Due to the low absolute number of observed crashes as well as near-crashes, we cannot confirm causality between the Leezenflow system and the observed reduction in crashes and near-crashes. Nevertheless, some survey participants state that the Leezenflow system is distracting and even motivates excessively fast cycling. Therefore, additional data on traffic safety is needed to evaluate whether the observed increase in traffic safety persists and applies to other settings.

For the intersection Promenade / Hörstertor in Münster, we could observe positive changes in traffic safety and found a positive impact on cycling flow. Based on this, the installation of Leezenflow systems could also be attractive for other cities. Especially against the backdrop that the Leezenflow system is open source and therefore can be installed at relatively low cost, it offers an interesting opportunity for increasing cycling quality within cities. The Leezenflow system can thereby increase bicycle ridership and contribute to more environmentally friendly mobility.

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V. Appendix

A. Survey

Table 6—: Socio-demographic characteristics of the participants (n = 534)

Sex	
Female	42.5 %
Male	55.1 %
Other	0.0 %
Not specified	2.4 %
Age	
$\leq$ 17	1.1 %
18-29	44.8 %
30-39	24.9 %
40-49	10.9 %
50-59	12.4 %
60-69	4.1 %
$\geq$ 69	0.7 %
Not specified	1.1 %
Job	
Unemployed	1.1 %
Pupils or students	25.1 %
Self-employed	4.7 %
Trainee	3.2 %
Employee	48.5 %
Director	1.7 %
Officials	8.8 %
Retiree or pensioner	2.6 %
Other	3.7 %
Not specified	0.6 %

Table 7—: User behavior (n = 485)

	Less than once a week	Once a week	Several times a week	Daily	Several times a day
Occupational	3.5 %	9.3 %	44.2 %	30.2 %	12.8 %
Leisure	26.2 %	36.9 %	35.0 %	1.9 %	0.0 %
Both	3.1 %	10.4 %	59.6 %	15.5 %	11.4 %

The table shows the reported frequency of passing the Leezenflow system by purpose of cycling.
Regardless of the cycling purpose, the reported frequency of passing is as follows: 13.0 % less than once a week, 21.4 % once a week, 46.4 % several times a week, 12.4 % daily, 6.8 % several times a day.
Regardless of the frequency of passing, the reported purpose of cycling is as follows: 17.7 % occupational, 42.5 % leisure, 39.8 % both.

Table 8—: Impact on traffic safety

Impact on traffic safety (n = 170)	Absolute (multiple answers possible)	Percent
Positive impact or more predictable / more steady cycling, increased cycling flow	88	40.4 %
No impact on traffic safety	35	16.1 %
Negative impact or less predictable / more steady cycling, decreased cycling flow	22	10.1 %
Fewer red light violations	20	9.2 %
Distracted by system / focusing solely on traffic light	14	6.4 %
Less focus on traffic	13	6.0 %
Higher focus on traffic	11	5.0 %
Avoidance of grouping / congestion (at traffic light)	10	4.6 %
Increased attention / better overview	5	2.3 %
	218	100 %

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