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Improving urban bicycle infrastructure-an exploratory study based on the effects from the COVID-19 Lockdown

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ABSTRACT

Introduction: During the COVID-19 lockdown significant improvements in urban air quality were detected due to the absence of motorized vehicles. It is crucial to perpetuate such improvements to maintain and improve public health simultaneously. Therefore, this exploratory study approached bicycle infrastructure in the case of Munich (Germany) to find out which specific bicycle lanes meet the demands of its users, how such infrastructure looks like, and which characteristics are potentially important.
Methods: To identify patterns of bicycle infrastructure in Munich exploratory data is collected over the timespan of three consecutive weeks in August by a bicycle rider at different times of the day. We measure position, time, velocity, pulse, level of sound, temperature and humidity. In the next step, we qualitatively identified different segments and applied a cluster analysis to quantitatively describe those segments regarding the measured factors. The data allows us to identify which bicycle lanes have a particular set of measurements, indicating a favorable construction for bike riders.
Results: In the exploratory dataset, five relevant segment clusters are identified: *viscous, slow, inconsistent, accelerating,* and *best-performance*. The segments that are identified as *best-performance* enable bicycle riders to travel efficiently and safely at amenable distances in urban areas. They are characterized by their width, little to no interaction with motorized traffic as well as pedestrians, and effective traffic light control.
Discussion: We propose two levels of discussion: (1) revolves around what kind of bicycles lanes from the case study can help to increase bicycle usage in urban areas, while simultaneously improving public health and mitigating climate change challenges and (2) discussing the possibilities, limitations and necessary improvements of this kind of exploratory methodology.

1. Introduction

The COVID-19 pandemic has fundamentally changed how movement and interaction take place in urban areas. As social distancing is the new norm in public spaces all over the world (De Vos, 2020) people change their transport behavior with immediate effect. Despite the rise of new formats of interaction and remote working, transport is and will remain a fundamental aspect of daily life (Brooks et al., 2020; Laverty et al., 2020). Nonetheless, new challenges are imposed on the way people move around cities, encouraging new and innovative solutions for major challenges such as urban health and climate change adaptation.

Many studies have shown that a strong immune system is an indicator for a mild course of infection (Taghizadeh-Hesary & Akbari, 2020). At the same time, Gupta et al. (2020) observe a positive correlation between air pollution and the lethality of a COVID-19 infection. Against the background of the global decrease in the use of public transport (De Vos, 2020; Tirachini & Cats, 2020) cities need to face the challenge of maintaining public health by adapting their urban transport infrastructure towards the needs of people. One main factor is infrastructural adaptation enabling individual traffic while reducing emissions at the same time. The lockdown during the first wave of the COVID-19 pandemic has shown that positive environmental effects are immediately visible when reducing motorized traffic (Kerimray et al., 2020).

One aspect of addressing this challenge is strengthening individual bicycle traffic in urban areas. Before the emergence of COVID-19 around the world, the level of physical commuting activity declined in many countries (Fraser & Lock, 2011). During the global lockdown, active transport (such as cycling) has increased as people can travel while keeping social distancing upright (Brooks et al., 2020). Teixeira and Lopes (2020) have shown that people started switching from the subway to bike-sharing possibilities in the case of New York

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City, but also other major cities have witnessed similar developments. De Vos (2020) frames cycling as a way to maintain public health while Hammami et al. (2020) highlight the importance of sufficient physical activity, especially during lockdown situations. An increase in bicycle traffic is, therefore, a possibility to face two challenges at the same time – mild courses of infection for COVID-19 patients and adaptation for climate change in urban areas – as this mode of transport does not only reduce emissions, improve air quality, and has environmental as well as public health benefits (Cole-Hunter et al., 2015), but cycling is also a vital part in building up a strong immune system to fight infectious diseases (Aman & Masood, 2020).

The situation caused by the pandemic needs to be framed as a public health opportunity (Brooks et al., 2020). It requires long-overdue infrastructural change, as infrastructure is a leading factor that influences individual decisions for cycling as a preferred mode of transport (Boss et al., 2018). As bicycles constitute an important part of a community's transportation system, the increasing pressure of individual transport (Dewulf et al., 2015) is an obstacle for cyclists, due to increased interaction with motorized traffic and associated safety concerns (Bagloee et al., 2016). Bao et al. (2017) argue that bicycle traffic has the potential to reduce the challenges imposed by too much motorized individual traffic. King and Krizek (2020) argue that changes in street design can rapidly increase access by individual modes of transport (Barros et al., 2020), but as financial means for such changes are usually limited they need a thorough evaluation to have the expected effect (Boss et al., 2018).

The global lockdown provided a test scenario with little individual motorized traffic in urban areas. Therefore, the aim of this exploratory study is the following: *How are bike lanes perceived from a bicycle rider's perspective and what do they need to look like so that increasing individual traffic (triggered by the COVID-19 pandemic) will shift towards cycling?* As cycling infrastructure should be based on the users' needs and not spatial constraints, such as existing road networks or limitations by buildings (Guerreiro et al., 2018) a rider-related approach is chosen. This may help to identify potential bike lanes that meet those demands and do not hinder the usage of bicycles as a sustainable mode of transport in urban areas. The exploratory case study was conducted in the city of Munich (Germany). Future COVID-19 policies will have a strong effect on the development of public spaces (Honey-Rosés et al., 2020) and the global lockdowns are an opportunity to change the previous state of traffic infrastructure (Laverty et al., 2020).

This paper is structured as follows: First, the lockdown is framed against (a) the background of 'Geographies of Health' with a special focus on air pollution development as well as the accompanying barriers to cycling at the same time and (b) the connection of bicycle infrastructure and bicycle usage. We document the exploratory methods used to identify types of bicycle lanes that enable cyclists to perform best and enjoy the ride at the same time and explain how their clustering was carried out. The case study investigates an exploratory dataset, that shows the analysis for a selected route in Munich. Based on this case study we discuss (1) aspects that revolve around what kind of bicycles lanes can help to increase bicycle usage in urban areas, while simultaneously improving public health and mitigating climate change challenges and (2) the possibilities, limitations, and necessary improvements of this kind of exploratory methodology.

2. Theoretical background & previous research

For this study, concepts originating from 'Geographies of Health' provide valuable insights into the analysis and choice of factors to identify how bike lanes need to be designed to enable the shift from motorized individual traffic towards human-scale individual carbon-neutral bicycle traffic. Health is not only about the absence of sickness in a person, but also the social and cultural construct of health, wellness, identity within the environment, and spatial experience (Giesbrecht et al., 2014). As societies will probably continue to face public health issues after the COVID-19 pandemic, knowledge about how cities can address those challenges needs to be deepened. Cities that encourage active transport can address such challenges more efficiently and profoundly (Giles-Corti et al., 2016).

Public transport systems are potential sources of infection, as social distancing cannot be upheld at all times. Long-lasting effects such as mistrust against public transport, as pointed out by Conway et al. (2020) can therefore be directly incorporated into the future planning of urban transport systems and be enriched by knowledge about other communicable or non-communicable diseases, e.g. cardiovascular diseases (CVD) (Giles-Corti et al., 2016). Many studies have shown a strong correlation between bicycle usage and health indices (e.g. Bagloee et al., 2016). Furie and Desai (2012) state that insufficient physical activity may result in CVD as well as obesity, diabetes, and blood-pressure-related health problems. Therefore, cycling is among the modes of transport that add to the daily amount of recommended physical activity (Panik et al., 2019). Celis-Morales et al. (2017) describe in their case study that 90% of active commuters meet the minimum of recommended daily physical activity which is a factor for a lower risk of CVD mortality. Additionally, even on a psychological level bicycle transport has positive effects: According to Avila-Palencia et al. (2017)) people who cycle to work experience positive effects for their self-esteem coupled with a positive environmental impact and significantly feel less stress. Those positive effects are among the motivations of people to use bicycles instead of other modes of transport – consciousness, pro-health, and the cyclist lifestyle (Biernat et al., 2018).

To incorporate those positive public health effects into individual daily schedules, Cole-Hunter et al. (2015) highlight the importance of urban environments to facilitate such changes. A proof of the positive development of less motorized traffic in cities was not the rise of bicycle traffic but the global lockdown situation that forced many people to work at home instead of daily commuting to work. Liu et al. (2020) have shown that during the lockdown and the following reduction in human activities there was a decrease of 8,8% in global CO_2 emissions (less individual motorized transport cannot account for this as a whole, but passenger transport accounts for 45,1% of all CO_2 emissions caused by transport (Ritchie, 2020)). In the 1940s up to 85% of trips in European cities were taken by bike, however, the development of cheap oil favored motorized individual transport (Larsen, 2017), although the distances are amenable to cycling: Rissel et al. (2013) state that for the case of Sydney 25% of distances traveled by car are below 2 kms and even half are less than 5 kms.

Many cities have experienced significant improvements in air quality during the lockdown. In Wuhan (China) the lockdown had a substantial effect on the ozone and nitrogen oxide (NO_x) concentration. As NO_x decreased by 53,3% the concentration of ozone increased by 116,6% (Lian et al., 2020). Kerimray et al. (2020) measured similar values for Almaty (Kazakhstan, −35% NO_x concentration). Forster et al. (2020) estimate that the global NO_x concentration decreased by approximately 30%. For the city of Munich, where the empirical study took place, similar observations were made, regarding the NO_x concentration in the city.

Fig. 1 shows the differences in the NO_x concentration in Munich for three different periods (2019, 2020 1st quarter, 2020 2nd quarter). The strongest difference is noticeable between the first and second quarters of 2020 when the lockdown was imposed, and traffic was significantly reduced. This figure backs up the findings of Laverty et al. (2020) investigating NO_x measures in urban areas and shows that transportation has direct and indirect impacts on public health. This is not only based on the decrease of NO_x but also less carbon dioxide and noise, resulting in higher air quality and a better urban atmosphere (Zambrano-Monserrate et al., 2020). Nonetheless, such developments might not be permanent: Chang et al. (2020) have shown for the case of Taiwan that post-lockdown the NO_x concentration rose between 5 and 12%, due to the shift from public transport to individual motorized transport – as a way to enable safe transport in pandemic times.

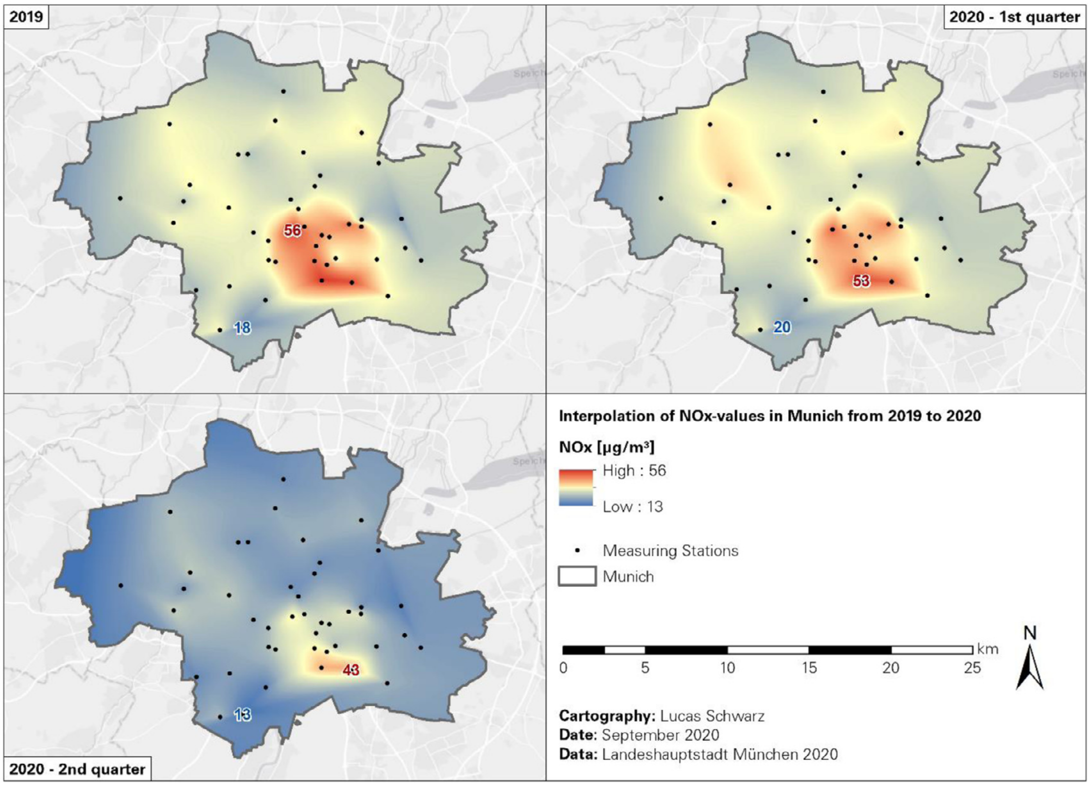

Fig. 1. Interpolation of NOx -values in Munich from 2019 to 2020 (1st and 2nd quarter), data derived from München (2020).

Conway et al. (2020) state, based on a US survey, that some behavioral changes initiated by the lockdown will persist, especially when it comes to cycling and walking more often. Although this study was carried out with highly educated US citizens only, the authors conclude that it is unlikely to fully return to pre-pandemic transportation habits. Especially health is a reason to frequently travel by bicycle but it is still outweighed by factors revolving around physical effort and the lack of a safe cycling network (Félix et al., 2019).

Although cycling already is the default choice of transport for many cyclists in urban areas (Kuhnimhof et al., 2010) there seems to be a connection between the individual choice to cycle and the built environment. Piras et al. (2021) provide an empirical example stating that there is a positive correlation between perceived cycling benefits, perceived comfort, and perceived importance of bicycle infrastructure and the propensity to cycle. In addition, they identified a connection between socio-demographic factors (e.g. age, gender), structures in urban areas, and bicycle usage and therefore conclude to focus on the built environment and behavioral and perceptional factors equally (Piras et al., 2021). Lanzendorf and Busch-Geertsema (2014) conclude that cycling is intertwined with infrastructural improvements. Buehler and Pucher (2021) reviewed the difference between urban traffic in the US as well as European countries but reach the same verdict: They explain differences in cycling and walking fatalities in Europe by better infrastructure and lower urban speeding limits.

Of course, infrastructural change has been intensely analyzed by scholars. Blitz et al. (2020) demonstrate by drawing from a case study in the German Rhine-Main Metropolitan Region that infrastructural improvements of bicycle streets have positive impacts, especially for frequent bicycle users. Nonetheless, they emphasize including individual urban travel behavior in future studies. Ghekiere et al. (2014) focused on cycling safety for children and conducted qualitative interviews about cycling infrastructure. They identified wide and even cycle tracks, a good overview of traffic, and traffic density as key factors for perceived safety. Although they reached those results by interviewing children, their findings seem to apply to a broader range of cyclists. For the German city of Münster, Schröder (2021) suggests that significant improvements of the built environment result in more safety, comfort, and shorter travel times. She demonstrates this by drawing from empirical evidence from improved bicycle streets. Further studies focused on barriers to using bicycles in urban infrastructure (e.g. traffic and too few bike lanes) (e.g. Dill & McNeil, 2016).

Although infrastructural improvement seems to be omnipresent in most studies, Assunçao-Denis and Tomalty (2019) name factors that cannot be influenced by infrastructural planning, such as cultural, demographic, or economic settings. Despite the importance, they emphasize the effect of local measures by expanding bicycle infrastructure. In a statistical study, Haustein et al. (2020) describe the model of perceived ease derived from cycling safety and security, autonomy, and priority in planning. This model explains 65% of the variance of the individual cycling perception (Haustein et al., 2020). Other authors analyze behavior and perception from different angles: Aletta et al. (2018) describe how the sound level is a factor to the cycling comfort but highly dependent on personal perception. van Cauwenberg et al. (2012) assign the personal perception of safety to gender differences and Pooley et al. (2011) draw attention to the individual perception of safety. In this context, Schwedes, Wachholz, & Friel (2021) support this thesis and state that safety cannot be understood as a number but needs to be analyzed from a qualitative point of view.

Abdai and Hurwitz (2018) analyzed the perceived level of comfort during a bicycle ride when overtaking truck loading zones as a factor to increase or decrease the share of cyclists. They analyzed ambient traffic (volume and truck traffic) as well as pavement markings and traffic signs as factors that influence the comfort during a ride, thus affecting future decisions to choose the bicycle as an adequate mode of transport. Other studies, such as Cho et al. (2009) argue similarly.

While Pooley et al. (2011) show that cyclists are especially concerned about risks that stem from interaction with motorized traffic), Dill and McNeil (2016) characterize four types of cyclists as not all cy-

Table 1
Comparison of Modal Split (Munich and Germany) in percent, data derived from BMDV (2019).

Modal Split	Pedestrians	Cyclists	Motorized Individual (Drivers)	Motorized Individual (Passengers)	Public Transport Users
Munich	24	18	24	10	24
Germany	22	11	43	14	10

clists have the same perception of safety, risk, or comfort. Nonetheless, not only the perception of cyclists is important but also of motorized vehicle users. Huemer and Strauß (2021) present an empirical experiment showing that car drivers feel more confident to overtake cyclists when those travel in lanes segregated by a marking.

As the presented studies have shown the analysis of behavioral and perceptional rider-related data (e.g. level of sound or level of comfort) in connection with bicycle infrastructure (e.g. type of bicycle lane) is necessary to expand bicycle infrastructure as a medium to combat health and environment-related crises. In the following section, we, therefore, present our exploratory approach for this case study.

3. Methods & case study

The case study is carried out in Munich, Germany's third-biggest city and home to one of the country's biggest car manufacturers. Cycling is a popular trend in the city, leading to an increase of cyclists in the modal split: While only 10% of inner-city travelers used bicycles in 2002, the share increased to 18% in 2017 (BMDV 2019). As Table 1 shows, the share of cyclists of all traffic participants in Munich is higher than the German average, while there is also comparatively less motorized individual traffic.

Drawing from literature and studies about behavioral, perceptional, and individual perspectives while cycling in urban areas, we use bicycle-rider-related data as a way to obtain data on how riders experience a route by bicycle and as a possibility to focus on multiple factors that influence a ride at the same time. This honors the critique formulated by Ryu et al. (2015). We include different aspects that depend on the rider, such as velocity or pulse as well as environmental data (temperature, humidity, and level of sound (as an indicator of nearby-motorized traffic and the traffic situation)). This data is held against the background of the status of the bicycle lanes, and segments are identified depending on their design (type of bike lane, interaction with traffic, structural condition) and qualitative evaluation of the rider's comfort after each ride (perceived safety, perceived quality of bike lanes, perceived comfort of infrastructure, perceived flow of the ride, perceived interferences with other traffic participants). To enable a comparison between different segments the data is spatially obtained: Most of the data is obtained using free apps on an Android smartphone fixed to the handlebar of the bicycle. The route is agreed upon beforehand and one bicycle rider carries out test routes. Table 2 gives an overview of the measurement devices and which apps are used to measure.

The bicycle trips are carried out on weekdays between 8 and 9 am during the morning commute and between 4 and 6 pm during the evening commute. All trips follow the agreed-upon route and all traffic rules are strictly obeyed. The chosen route consists of a cross-section of Munich from the West to the South-East and represents a commutable distance that is amenable to average bicycle users (6–10 km). Additionally, the route contains different kinds of bicycle lanes: segregated and shared lanes as well as no bicycle lanes; lanes that range from interaction with motorized traffic (in motion or parked) or pedestrians to no interactions; and bicycle lanes that have a high quality down to lanes that are consistently inter- or disrupted by sidewalks or other structural features. As the route is mostly flat (except for one short uphill segment, 300 m distance, elevation gain 14 m) the influence of altitude can be neglected.

To receive information on the identified segments a cluster analysis is carried out. Data was collected for defined time intervals (10 s) which concluded in 5.424 data points along the route, including all information mentioned in Table 2. A hierarchical cluster analysis is carried out as beforehand no structures were existent in the dataset (Janssen & Laatz, 2017). We select the squared Euclidean distance as a proximity measure and the Ward method as a merging algorithm to keep the variance within a group to a minimum (Backhaus et al., 2016; Bortz & Schuster, 2010). It is possible to simplify the multiple and complex relations between the single data points to detect spatial relations. To calculate the different clusters, we utilize personal (velocity, pulse) and environmental factors (level of sound). The environmental factors humidity and temperature are excluded from the analysis as they do not add to the differentiation of the clusters. As the case study is carried out in August, temperature and humidity do not significantly differ during the single rides. The decision for the exact number of clusters is made, using the elbow criteria as well as the dendrogram. The attribution of a feature to a cluster is made using standardized residuals. Additionally, we run a discriminant analysis to categorize waypoints that are lacking information due to measurement errors (Backhaus et al., 2016). In the last step, the spatial data is enriched by the information gained from the cluster analysis, and implications for bike lanes are derived.

4. Results

The cluster analysis sheds light on which type of bicycle lanes enables cyclists to perform best, move the most efficiently and safely between two destinations, and enjoy the ride at the same time. Those are the most important factors to decide for or against the usage of bicycles as a mode of transport (Bagloee et al., 2016; Félix et al., 2019). The following section presents the five identified clusters: *viscous, slow, inconsistent, accelerating,* and *best-performance*.

Table 3 shows the five different clusters along the personal and environmental factors used for the cluster analysis. The number in brackets indicates the standardized residuals. When the standardized residual is >2,0 it is interpretable and the higher it is, the stronger the attribute is linked to the corresponding cluster (Backhaus et al., 2016).

Fig. 2 represents the spatial distribution of the clustered segments, including the position of traffic lights along the routes. Three of the identified clusters represent data points that are characterized by non-optimal comfort of bicycle usage: *viscous, slow,* and *inconsistent*. The cluster *viscous* is characterized by a (very) slow velocity (<10 km/h to 10–15 km/h) and a (very) high pulse at the same time (115–130 to >130 bpm). The level of sound is ranging from quiet (75–80 dB) to normal (80–85 dB). The assigned bicycle lanes are usually intensely used by motorized traffic, such as cars or buses, and there is always plenty of interaction between all traffic participants. As the level of sound is quite low, motorized traffic is most of the time not in full motion but congested. Usually, bicycle riders can overtake but always have to be alerted to not cause any damage to cars (in motion or stopping) as well as not have any damage caused to themselves. *Viscous* segments usually have little to no coverage of bicycle lanes.

Another segment that is distinguished by a high level of interaction with other traffic participants is the *slow* segment. Bicycle riders cannot accelerate to a comfortable fast velocity as the segment is often disrupted by motorized vehicles or construction sites (although this is mostly a temporal phenomenon). Although the traffic lights are usually controlled to be in a series there are long waiting times to be expected as soon as a series is missed, resulting in a slow overall velocity. Based on all the forced stops the pulse is within a normal range (100–115 bpm).

Table 2
Overview of data measurement.

Factor	Sensor	Software/ App	Position	Type	Average	Minimum	Maximum
Spatial position	Smartphone	OSMTracker for Android™	Handlebar	Spatial	N/A	N/A	N/A
Trip time	Smartphone	see above	Handlebar	Time	20 min	16 min	35 min
Temperature	Psychrometer	–	Handlebar	Environmental	24,4 °C	15,1 °C	34,4 °C
Humidity	Psychrometer	–	Handlebar	Environmental	64%	28,5%	100%
Sound	Smartphone	Physics Toolbox Sensor Suite	Handlebar	Environmental	92,6 dB	69,8 dB	98,6 dB
Velocity	–	Derived from the spatial position	–	Personal	17,9 km/h	4,5 km/h	58,81 km/h
Pulse	Fitbit Charge 2™ fitness watch	Fitbit	Rider's wrist	Personal	114,6 bpm	71 bpm	160 bpm

Table 3
Results of the cluster analysis.

Factors/clusters		viscous	slow	inconsistent	accelerating	best-performance
Personal	*Velocity*	Very slow *(15,2)* Slow *(18,7)*	Very slow *(33,5)*	Slow *(2,3)* Very fast *(2)*	Fast *(2,4)* Very fast *(7)*	Normal *(7,4)* Fast *(10,5)* Very fast *(8)*
	Pulse	High *(12,8)* Very high *(7,2)*	Normal *(13,4)*	Very low *(12,9)* Low *(38,8)*	Very high *(38,7)*	Normal *(5,4)* High *(5,4)*
Environ.	*Sound*	Quiet *(4,1)* Normal *(2,8)*		Very loud *(2,1)*	Very loud *(2,6)*	

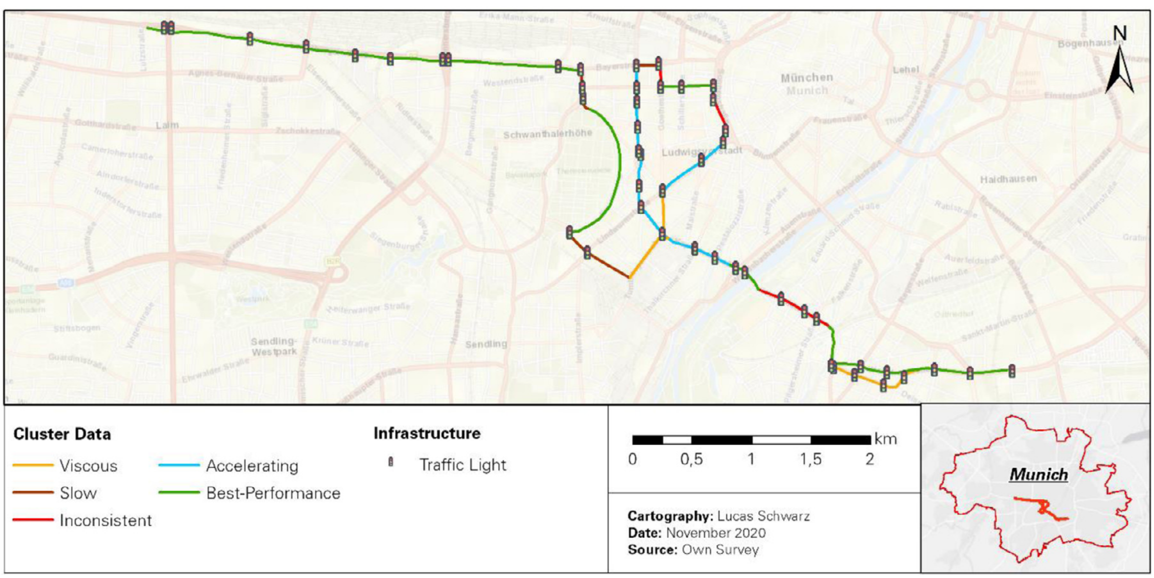

Fig. 2. Spatial distribution of clustered segments of the test dataset related to selected bike ride parameters.

The last cluster that is assignable to the non-optimal bicycle ride performance segments is *inconsistent*: The velocity ranges from slow (<10 km/h) up to very fast (>25 km/h) – this suggests a very uneven and non-consistent riding dynamic. Despite the fast velocity, the pulse is usually in a (very) low range. It is significant that the level of sound is very loud (>90 dB), which indicates that surrounding traffic is omnipresent, either accelerating or in full motion. Such segments tend to feature strong interactions with other traffic participants, e.g. motorized vehicles or pedestrians. The quality of bicycle lanes varies strongly from segregated lanes to narrow lanes that are embedded between shops and parked vehicles. The intensity of interaction varies accordingly by the time of the day.

The first cluster that is assigned to a more optimal riding and performance experience is *accelerating*. Segments that are marked *accelerating* can be traveled fast or very fast, resulting in a high pulse (>130 bpm). The level of sound is very loud which indicates traffic in motion in the vicinity of the segment. The traffic light is usually controlled to be synchronized but another factor responsible for disruptions and braking maneuvers are pedestrians and motorized vehicles. The main difference between *accelerating* and *inconsistent* is therefore the possibility of higher velocity on *accelerating* segments.

The optimal bicycle riding performance is possible on segments labeled as *best-performance*. The velocity ranges from normal (15–20 km/h) and fast (20–25 km/h) to very fast (>25 km/h). Accordingly, pulse ranges between 100 and 115 bpm (normal) up to 115–130 bpm (high). *Best-performance* segments offer the highest quality of bicycle lanes: wide, evenly paved lanes with little to no interaction with accompanying traffic. Along such lanes, some segments are even segregated through the construction of barriers, giving bicycle riders protection, and hindering interaction that would result in dangerous breaking maneuvers or physical injury. Besides, traffic lights are often in favor of bicycle riders, giving them the smoothest and most efficient bicycle riding experience of all identified cluster segments. Taking the research question into the account, what kind of bicycle lanes are needed to prevent the shift of individualization in urban transport towards motorized vehicles, lanes that fit the *best-performance* description are most likely to make people decide in favor of bicycles instead of cars. Those are the factors that result in positive associations with bicycle paths, as described

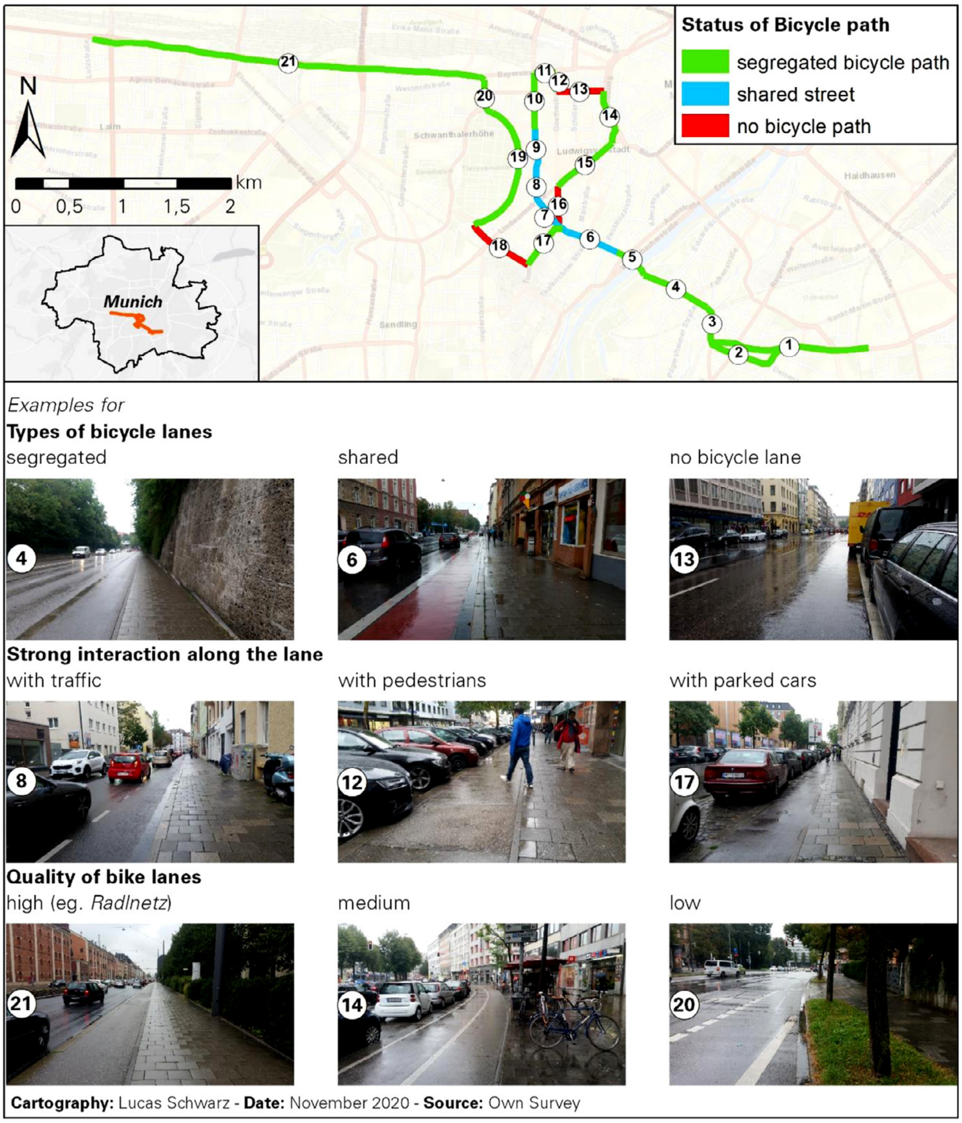

Fig. 3. Overview of bicycle paths on the test route related to pictures at selected sites – the numbers in the pictures correspond to the segments in the map above.

by Fraser and Lock (2011). Such segments are mostly found outside of densely used city centers towards residential areas where space is less contested (Fig. 2).

Fig. 3 compares the quality and the differences between the different bicycle lanes that occur along the route. The numbers in the pictures correspond to the segments on the map. Picture 21 is an example of the *best-performance* segment. There is no interaction with the traffic on the left side of the bicycle lane and no parking, shops, or any other source of possible interaction with pedestrians on the right side of the bicycle lane. Additionally, the bicycle lane is constructed differently than the pedestrian lane, adding up to the clear border, enhancing the safe usage for both cyclists on the left side and pedestrians on the right side. *Accelerating* segments are best represented by picture 8. The bicycle lane is quite narrow and motorized vehicles are often crossing into the bicycle lane as there is only an overlookable marking between the car and bicycle lane on this shared street. The non-optimal performance segment *inconsistent* is shown in picture 14. Parking is possible on the left side of the bicycle lane and shops are found on the right side. Additionally, there is the possibility to park and lock bicycles on the right side which is another possibility that bicycle riders will need to abruptly stop their bicycle. *Slow* segments are presented in picture 13, despite the difference that such segments are characterized by very dense traffic (mostly made up by motorized vehicles). Picture 17 represents an example of the *viscous* segment. The bicycle lane is quite narrow and there is a constant interference of the bicycle ride by opening car doors and people walking on the bicycle lane as the pedestrian lane is narrow. Additionally, people crossing the road are not easily spotted between cars, so bicycle riders on this *viscous* segment need to ride more carefully than on open bicycle lanes to avoid physical injury.

As the empirical survey was carried out in August the environmental weather conditions did not vary fundamentally. There was a slight difference in the daytime of the commute as the temperature was usually lower in the morning than in the evening, but no significant correlation was detected. For this study, it can be concluded that the influence of the environmental factors weather and humidity can be neglected for the summer months. This supports several studies' findings' (Bagloee et al., 2016; Félix et al., 2019): The main reasons to decide for or against bicycles as a suitable mode of transport is determined by the quality of bicycle lanes and the resulting implications for safety and comfort.

5. Discussion

We engage in two discussions: (1) What kind of bicycle lanes can help to increase bicycle usage in urban areas as means to improve public health in times of crisis and mitigating to climate change challenges? (2)

What are the possibilities, limitations, and necessary improvements of this kind of exploratory methodology?

5.1. Improved bicycle lanes as means to combat environmental challenges in urban areas

As the COVID-19 pandemic has shown, the prevention of crises is a cheaper solution than a cure. This applies to the climate crisis as well (Manzanedo & Manning, 2020). At the moment there are two scenarios for transportation in urban areas possible: business as usual or significant change to decrease the number of motorized vehicles in cities by either increasing the attractiveness of working from home (Hensher, 2020) or increasing the attractiveness of bicycles as a preferred mode of transport.

This exploratory study shows that only a share of all segments in an urban area meet the demands that cyclists have for *best-performance* segments. This supports the findings of Bagloee et al. (2016) as well as Parkin and Koorey (2012): The authors suggest that bicycle infrastructure cannot be simply added to an existing road network that is primarily used by motorized traffic but has to be promoted by separate networks. Although Cole-Hunter et al. (2015) suggest that bicycle lanes that are embedded in urban green areas are increasingly frequented, our findings cannot reproduce this correlation. This needs further differentiation as Aletta et al. (2018) focused on the relationship between the comfort of a bicycle ride and green areas contrasted by the perception of sound. In our case especially the separation as mentioned by Bagloee et al. (2016) and Schröder (2021) has a positive effect on the rider's perception of comfort and performance on the segment (see the comparison in Fig. 3). This also supports the findings by Ghekiere et al. (2014) although they focused on children's comfort while cycling.

The *best-performance* segment is characterized by an efficient mode of traveling by bicycle. This finding is in accordance with Dewulf et al. (2015) arguing that lost time is a major factor for dissatisfaction in commuters as well as Wild and Woodward (2019) stating that bicycle traffic can diminish transport-related uncertainties, such as congestions.

While the implementation of bicycle infrastructure that fits the characterization of *best-performance* segments seems necessary, there are barriers: Although the positive effects for urban health and climate change mitigation are obvious, urban developments have to be taken into account: Larsen (2017) argues that urban sprawl poses a threat to bicycle commuting as distances will not be amenable to most bicycle riders anymore, thus resulting in higher use of motorized vehicles and additional implications for the environment that cannot be subsidized by constructional improvements buy only by a strong link between public transport and bicycle usage. While this study only covered amenable distances between 5 and 10 km, further evidence from longer distances is necessary to generate reliable insights. This is especially necessary, as the course of COVID-19 infections remains unpredictable and the increase in individual motorized traffic continues to pressure urban transportation systems.

To promote cycling as one of the few carbon-neutral forms of urban transport (Fraser & Lock, 2011) while simultaneously increasing physical activity for public urban health (Perez et al., 2015; Zambrano-Monserrate et al., 2020), the cluster analysis shows, that infrastructure enabling such positive changes is already partly available in urban areas but needs further spread. It is essential to improve bicycle infrastructure in the sense of *best-performance* segments as they contain the highest perceived feeling of safety, which is necessary for the choice of transportation (Ghekiere et al., 2014; Marshall & Ferenchak, 2019).

5.2. Possibilities, limitations, and necessary adaptations of this exploratory methodology

We present a new approach for analyzing bicycle lanes in an urban area. Especially, the usage of bicycle-rider-centric data bears the potential of new insights for future analysis of bicycle networks. In addition, the qualitative identification of segments with similar perceptions of safety, comfort, interaction, and quality of bike lanes offers insights that are detached from purely quantitative approaches and therefore focus on the personal perception of bicycle riders.

To further consolidate the findings of this exploratory study a few improvements are necessary: As only one bicycle rider carried out the measurement rides and gave qualitative insights that led to the identification of segments, the perspectives of additional riders are necessary. Therefore, it is important to create a sample that covers a large share of the population, e.g. from younger to older people, all genders, as well as regular and irregular bicycle riders. Especially the latter is important to include the different types of cyclists as shown by Dill and McNeil (2016). By enhancing the sample of riders, personal effects can be bypassed, resulting in a more neutral and nuanced analysis.

Another point for improvement is the length of the study. Although this study was carried out in August, probably the busiest month for cyclists in German cities due to favorable weather conditions, cycling infrastructure will need to be sufficient all year long during all kinds of weather conditions (especially during colder seasons or rainy conditions). New analyses can focus on the effect of weather conditions on different kinds of bicycle lanes. For this sample, the weather conditions did not differ sufficiently.

While this study contains the most direct factors that influence a bicycle ride, an addition of qualitative urban data might generate interesting insights: For example, the proximity to urban green spaces (Aletta et al., 2018; Cole-Hunter et al., 2015), congestions (e.g. data from GoogleMaps), airflow within the city or shadow and direct sunlight situations can add to complex but more in-depth findings to the comfort and performance of bicycle riders.

As a novelty, this study used qualitative data to identify segments based on the perception of the bicycle rider. Although this is a new approach, it should be used directly within the cluster analysis, so that such effects can be directly compared to the average velocity and infrastructural occurrence on site. Finally, a comparison of different cities will be interesting. In Germany, Berlin can be an insightful example, as during the COVID-19 lockdown a lot of new pop-up bicycle lanes have been instated (Kraus & Koch, 2020, 2021).

6. Conclusion

This exploratory study raises several questions: *How are bike lanes perceived from a bicycle rider's perspective? How do they need to look like, that the rise in individual traffic (triggered by the COVID-19 pandemic) will shift towards cycling?* By using a bicycle-rider-centric approach, we can identify bicycle lane segments that fulfill riders' wishes for safety and efficient travel between two destinations in urban areas as well as a distinction between desirable and non-desirable bicycle infrastructure. The clusters *viscous, slow, inconsistent, accelerating,* and *best-performance* are identified and spatially applied to the empirical example of Munich. Following the study's result, we agree with Parkin and Koorey (2012) that cycling has to be treated as a distinct mode of transport instead of a side-product that can be added to existing road networks. Following Harms et al. (2014) we confirm that there is a need for a differentiated approach to analyze cycling infrastructure adequately. We conclude that the improvement of bicycle infrastructure bears the potential to tackle environmental or health-related challenges in urban areas, such as climate change or the spread of infectious diseases like COVID-19.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during the study are available at GitHub via the following link: https://github.com/schwal95/floatingbikedata

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