Applied Spatial Analysis and Policy (2023) 16:209–228
https://doi.org/10.1007/s12061-022-09476-w

Spatiotemporal Patterns of Cyclist Collisions in Germany: Variations in Frequency, Severity of Injury, and Type of Collision in 2019

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Received: 28 December 2020 / Accepted: 18 July 2022 / Published online: 12 August 2022

Abstract
Cycling has gained increasing interest in Germany in recent years due to its manifold environmental, societal, and economic benefits. However, the number of cyclist collisions resulting in injury or death remains high and little is known about regional variations in frequency, severity of injury, and type of collision. This study investigates spatial and temporal patterns and characteristics of cyclist collisions across Germany in 2019. Using a detailed cyclist collision dataset for most German federal states, we identified statistically significant regional differences in frequency, severity of injury, and type of collision. To facilitate this and future cyclist collision surveillance studies in Germany, we developed and published a custom R package to download and combine the collision data with geographical data. Our analysis reveals that densely populated regions exhibit higher collision rates and a higher share of collisions involving turns, but lower severity of injuries and a lower share of collisions whilst driving in a straight line, a higher collision frequency during the work week compared to weekends, and a higher collision frequency peak during morning rush hour. We also observed a markedly high share of fatal bicycle-truck collisions in densely populated regions. In contrast, rural regions show lower collision rates, but a higher share of severe collisions, a higher share of collisions whilst driving in a straight line, as well as higher collision frequencies during weekends and summer months. Our findings underscore the complex and multifaceted geographical variations in collisions involving cyclists. The results of this study suggest that a one-size-fits-all approach to collision prevention infrastructure and policy may be insufficient for addressing variations in risk, and that future efforts to improve cyclist safety should be tailored to the local geographical context.

Keywords Cyclists · Collision · Spatiotemporal analysis · Germany · Bicycle accidents

Extended author information available on the last page of the article

Introduction

Cycling is widely considered an environmentally, societally, and economically sustainable transport mode (Woodcock et al., 2007; Reynolds et al., 2009; Buehler et al., 2017). The direct and indirect health and social benefits of cycling include reductions in physiological health risk (Chapman, 2007; de Hartog Jeroen et al., 2010; Oja et al., 2011; Reynolds et al., 2009; Woodcock et al., 2007), noise and air pollution (Woodcock et al., 2007; de Hartog Jeroen et al., 2010), space and energy consumption (Woodcock et al., 2007; Chapman, 2007), infrastructure costs (Vandenbulcke-Plasschaert, 2011), and social inequities due to improved accessibility for low-income groups (Woodcock et al., 2007). However, it is only in recent years that cycling as a practical mode of transport has gained significant attention in science and policy in large cities in the USA and Europe (Pucher & Buehler, 2017), including Germany (Lanzendorf & Busch-Geertsema, 2014).

Despite the known benefits, there exist numerous geographical barriers that deter people from cycling, for example, distances between points of interest, slopes, a lack of cycling infrastructure, and weather/climatic conditions (Vandenbulcke-Plasschaert, 2011). However, previous studies indicate that the most prominent barrier is traffic safety (Reynolds et al., 2009; Heinen et al., 2010; Winters et al., 2010; Fishman et al., 2012), as cycling is one of the most vulnerable modes of transportation (Evgenikos et al., 2016). The high risk is mostly attributed to sharing the road with motorized vehicles, moving at a slower speed, no licencing requirements, and lower adherence to the rules of the road (Shinar et al., 2018). Estimates from Europe and North America suggest that cyclists are at least seven times more likely to be injured than automobile occupants, per trip or per kilometre travelled (Elvik, 2009; Reynolds et al., 2009). One also must keep in mind that a significant underreporting of cycling collisions can be expected (Elvik & Mysen, 1999; Shinar et al., 2018). Earlier studies have shown that perceived improvements in bicycle safety attracts more people to cycling (Noland, 1995). Moreover, an increase in cycling is known to lead to a *safety in numbers* effect which means that the more cyclists are on the road the lower the individual risk of a collision[1] (Jacobsen, 2003; Elvik, 2009).

Germany is often perceived to be a global leader in non-motorized transport policy (Buehler & Pucher, 2009; Buehler et al., 2017). However, the share of cycling is only slowly increasing (Nobis 2018) and cycling collisions have remained constantly on a high level (Statistisches Bundesamt 2020). Since 2010, reductions in automobile (-24.6%) and pedestrian (-12.4%) deaths were reported, but the number of pedal cyclists killed in a collision exceeds the number of reported deaths in 2010 by 16.8% (Fig. 1; Statistisches Bundesamt 2020). It should be noted that pedelecs have been counted as bicycles since 2018.

Recent studies and the official data indicate that cyclists have not benefited from the last decade of traffic safety improvements to the same degree that other road

[1] The literature about traffic-related injuries frequently uses the word "accident". It has been argued that the term "accident" implies that the event in question has happened by chance, and thus is unpredictable and unpreventable (Neira & Bosque, 2004). Following Reynolds et al., (2009) the term "collision" is preferred herein to "accident".

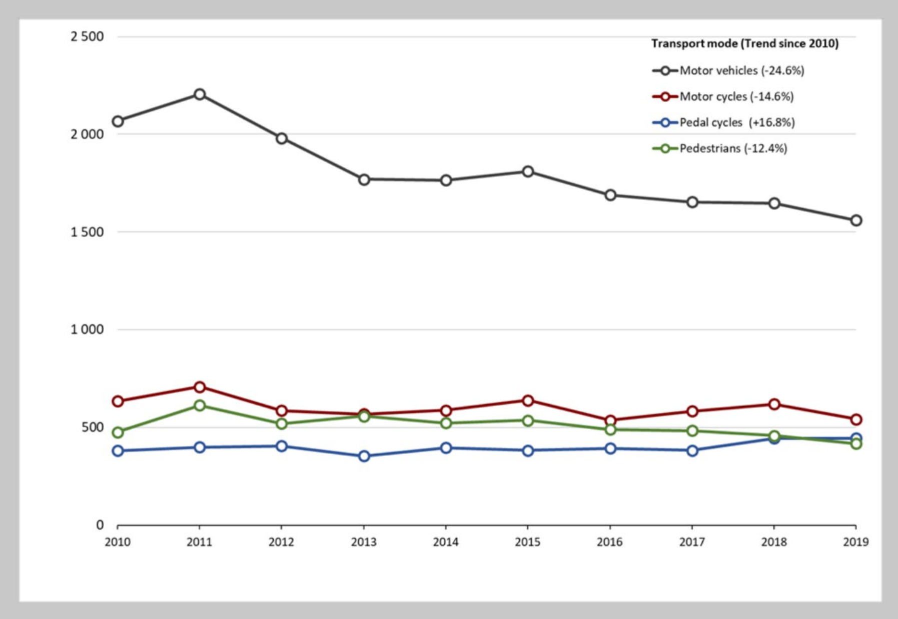

Fig. 1 Development of total number of annual road deaths by type of road user since 2010. (Source: Statistisches Bundesamt 2020, visualization and calculations by authors)

users have in Germany (Schreck, 2017). This underscores a need for more research and better-informed traffic safety policy focussing on reducing cyclist collisions and mortality in Germany. Collisions are not distributed randomly over space and time and thus exhibit specific spatiotemporal trends or patterns, the investigation of which may contribute to a better understanding of the spatial determinants of such collision events (Vandenbulcke-Plasschaert, 2011). Research in England and Belgium has shown that analysing regional differences is an important factor for explaining spatial variations in cyclist collisions (Vandenbulcke-Plasschaert, 2011; Lovelace et al., 2016). The Mobility in Germany study (MiD) in 2017 has highlighted strong variations in bicycle use across different regions in Germany (Nobis 2018) but to our knowledge, no study for Germany exists, that looks at regional variations of bicycle collisions. So far in the reports or studies we found for Germany, collisions were aggregated to administrative areas or broadly divided into urban and rural regions (Schreck, 2017; Statistisches Bundesamt 2020b). We believe that spatial distributions of bicycle collisions have not yet been sufficiently addressed in the case of Germany, especially since bicycle collision data exist on very high spatial resolution in the Unfallatlas by the Federal Statistical Office (Statistisches Bundesamt 2020a).

By aggregating bicycle collision data by the regional classes used in the MiD, this study explores and examines the spatio-temporal patterns of cyclists' collisions in Germany, focussing on frequencies, severity of injuries, and type and time of collision. To the knowledge of the authors this is the first study to explore reported bicycle collisions in Germany within this geographical framework. With this study, we have developed and provide an R package that allows the geographical framework to be used with the annually updated collision database (*Unfallatlas*) by the Federal statistical office in future studies.

Materials and methods

Data

For this study we choose the country of Germany because it is an excellent case for a regionally heterogeneous cycling environment with little knowledge on existing regional differences of cycling collisions. Which is even more astonishing since detailed data on cycling collisions is available and policy agendas highlight the importance of cycling. Germany is subdivided in federal states with large regional differences in size of population and land use, ranging from densely built city states, such as Berlin or Hamburg, to low-densely populated rural regions such as the area of Brandenburg.

To analyse cycling collisions, cyclist collision data for the calendar year 2019 were acquired from the *Unfallatlas* developed by Federal Statistical Office (Statistisches Bundesamt 2020), comprising all police-reported collisions resulting in personal injury across Germany (N=268,370), excluding the state of Mecklenburg-Vorpommern. The collision data contain the geographic coordinates of the collision, the official municipality code, date and time of the collision, severity, collision category and type[2], light conditions, parties involved, and the street surface condition. Since the acquisition of the collision data varies between federal states, the reported collisions undergo a plausibility check by the Federal Statistical Office before they are published. This involves an automated comparison of reported data to cadastral datasets to check the distance of the collision incident to a section of road. The road designation (e.g., "federal road B54"), and the road type (motorway, federal road, state road, etc.) can be confirmed and the geocoded collision location can be mapped to the corresponding road section. According to the Federal Statistical Office over 90% of reported collisions are successfully assigned to a point location (Statistisches Bundesamt 2020).

From each collision event we used information about the severity, collision type, and date (month, day of the week, and hour of day) from the Federal Statistical Office (2020). Collision severity is classified as slightly injured, seriously injured and fatal. The Federal Statistical Office (Statistisches Bundesamt 2021) classifies collisions with fatal outcome as those, where at least one person involved deaths within 30 days as a result of the collision. Seriously injured are those, who were admitted directly to hospital for in-patient treatment (at least 24 h) and slightly injured are all other injured persons. The type of collision describes the conflict situation that led to the collision, i.e., the phase of the traffic event in which a misbehaviour or other cause made the further course of events uncontrollable. The type of collision is classified into seven groups:

[2] Type of collision describes the conflict situation leading to the collision i.e., the phase of the traffic event in which a misbehaviour or other cause made the further course of events uncontrollable.

- *Driving collision*: The collision was caused by the loss of control of the vehicle (due to inappropriate speed or incorrect assessment of the course of the road, road conditions, etc.) whilst not conducting a manoeuvre such as parking or turning, and only includes incidents that were not due to any contribution from other road users but may have resulted in a collision with other road users due to uncontrolled vehicle movements. The data do not indicate fault.
- *Collision when turning off*: The collision was caused by a conflict between a person turning off and a road user (including pedestrians) coming in the same or the opposite direction at crossroads, junctions, access roads to properties or car parks. Anyone who follows a road with right of way is not a person turning off.
- *Collision when turning into/crossing*: The collision was caused by a conflict between a person who is obliged to wait and who is turning or intersecting and a vehicle with right of way at intersections, junctions or exits of properties and car parks. In other words, "collision when turning off" describes a person turning along a non-intersection road segment and being impacted by a road user coming in the same or the opposite direction, while "collision when turning into/crossing" explicitly refers to conflicts at crossroads, junctions, access roads to properties, or car parks, where one participant is obliged to wait and the other has right of way.
- *Collision while pedestrian crossing*: The collision was caused by a conflict between a vehicle (in our study always a bicycle) and a pedestrian on the roadway, provided that the latter was not moving along, and that the vehicle did not make a turn. This also applies if the pedestrian was not hit. A collision with a pedestrian moving along on the roadway is of type *collision while moving along.*
- *Collision with stationary vehicle*: A collision caused by a conflict between a vehicle in moving traffic and a vehicle parking/stopping or making manoeuvres related to parking/stopping. Collisions involving vehicles that are only waiting due to traffic conditions are not included. This category also includes cyclists who are struck with the open door of a stationary motor vehicle.
- *Collision while moving along*: The collision was caused by a conflict between road users moving in the same or opposite direction unless this conflict corresponds to another type of collision.
- *Other collision*: This includes all collisions which cannot be assigned to any other type of collision. Examples: Turning, reversing, parking among each other, obstacle or animal on the road, sudden vehicle damage (brake failure, tyre damage or similar).

To analyse the regional variations of the collision data in Germany we use the *Regional Statistical Spatial Typology for Mobility and Transport Research* (RegioStaR) that has been developed by the Federal Ministry of Transport and Digital Infrastructure (BMVI) with the support of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). The typology differentiates 17 spatial types according to their settlement structure (Table 1). The spatial types are assigned to all municipalities (Gemeinden) in Germany which can be downloaded in a reference file (accessible on the website of BMVI) that contains a municipality code, yearly number of population, and the area of each municipality.

Table 1 Hierarchical structure of the regional typology classifications in this study. (adapted from: Federal Ministry of Transport and Digital Infrastructure 2020, p.2)

Regional typology classification	Hierarchical structure							
regional statistical regional type *RegioStaR 2*	1	urban region			2	rural region		
differentiated regional statistical regional type *RegioStaR 4*	11	metropolitan urban region	12	regio-politan urban region	21	rural region close to an urban region	22	pe-riph-eral rural region
regional statistical spatial type *RegioStaR 17*	111 112 113 114 115	metropolis large city medium-sized city urban area small-town area, village area	121 123 124 125	regiopo-lis medi-um-sized city urban area small-town area, village area	211 213 214 215	central city medium-sized city urban area small-town area, vil-lage area	221 223 224 225	cen-tral city medi-um-sized city urban area small-town area, vil-lage area
combined regional statistical spatial type *RegioStar 7*	71 72 73 74	metropolis (111) regiopolis and large city (112, 121) medium-sized city, urban area (113, 114, 123, 124) small-town area, village area (115, 125)			75 76 77	central city (211, 221) medium city, urban area (213, 214, 223, 224) small-town area, village area (215, 225)		

In this study the Combined Regional Statistical Spatial Type (RegioStaR 7) is used as the geographical framework to explore the spatial variation of collisions with cyclist participation3 to correspond with the mobility survey (see Nobis 2018). As the regional classes *Medium-sized City* and *Small-town Area* are represented twice in *RegioStaR 7*, once in the upper category *urban* and once in the upper category *rural* (see Table 1), they are marked in the figures with either *u* (urban) or *r* (rural)

Methods

To analyse collision incidents by their region, we combined the municipality code given in collision incident data with reference file of RegiostaR, where every municipality in Germany is assigned to their corresponding regional types. As a result, every collision incidence from the *Unfallatlas* contains information in which regional type it occurred (Fig. 2).

Descriptive spatial and aspatial quantitative analysis was conducted to examine the frequency, severity, collision type, and temporal patterns by month, day of the week, and hour of day. We analysed the differences in collision frequencies across region types by calculating the number of collisions with cyclist participation per 10,000 residents (population data from 2018). Statistical significance of categorical differences between rates were assessed using Chi-square, relative rates and their 95% confidence intervals (CI) were computed using the standard log-transform method. For multiple comparisons we conducted sets of likelihood ratio tests using the Sidak

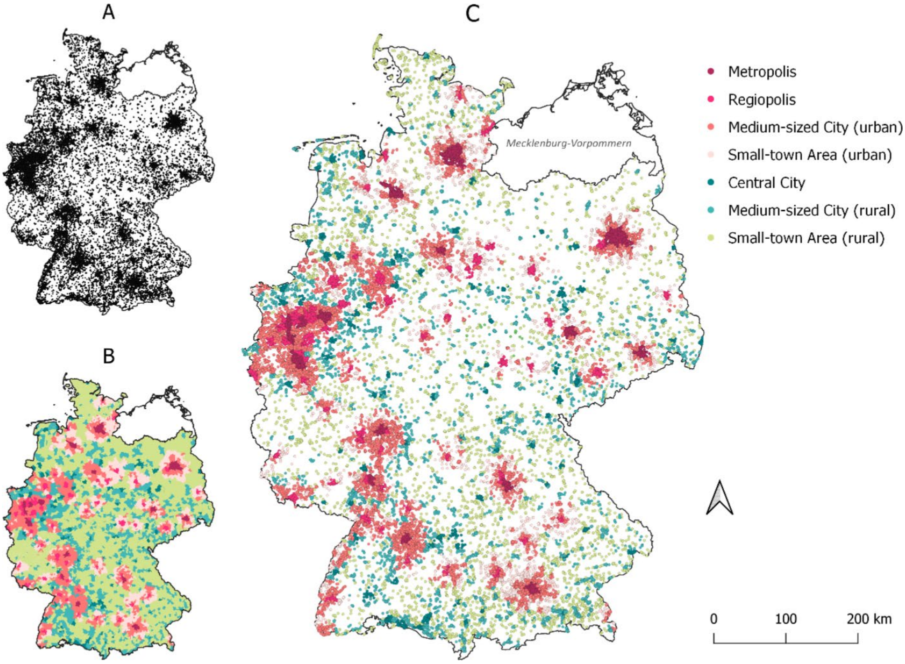

Fig. 2 Collisions in Germany in 2019 by regional type. A: All reported collisions with cyclist participation in 2019 mapped by their x-y coordinates from the Unfallatlas. B: Municipalities in Germany classified to the Regional typology (see legend C). C: Cyclist collisions classified to their corresponding regional typology class (2019)

adjustment and Bonferroni correction. The correlation between population density and collisions was assessed using ordinary least squares regression. All inferential statistical procedures were conducted using the WinPepi (v.11) software.

Following earlier studies that identified different cycling collision patterns at different temporal dimensions (Li et al., 2007; Fan et al., 2018) we compared the regional types and frequencies by three temporal variables, calculating the shares by month, day of week, and time of day. The descriptive analysis results were then compared against those of the MiD survey and other related literature to advance discussion on possible explanatory relationships between regional typology and other factors which may explain the observed patterns and characteristics of cyclist collisions.

All steps of the workflow were undertaken and documented in R. The data import process and the adding of location information are written as functions which are part of our R package *collisionDE*, which was developed in this study to support future analysis regarding the collision dataset. This package and all supporting documentation can be found at (https://github.com/lutzhutz).

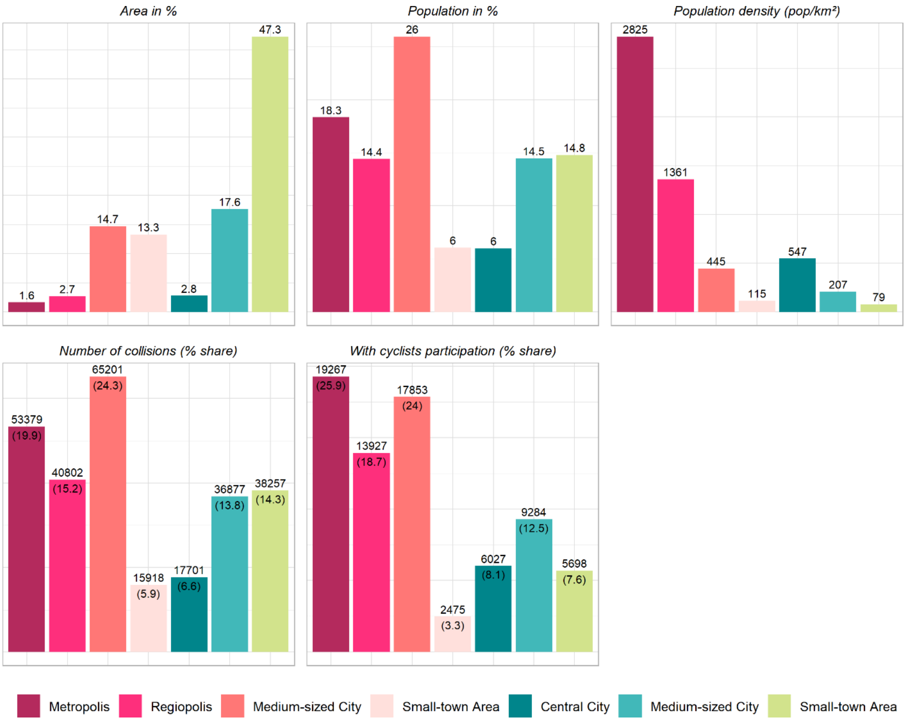

Fig. 3 Characteristics and collisions in regional types

Results & discussion

Characteristics and patterns of cyclist collisions across regional spatial types

Frequency of collisions

From a total of 268,370 reported collision events in 2019, 74,549 (27.8%) collision incidents had at least one cyclist involved. Of these, 74,531 incidences could be successfully assigned to the seven regional classes. While Small-town Area covers nearly half of the area, only 14.3% of the collisions and even only 7.6% of the collisions with cyclist participation are located there (Fig. 3). Population density is only 79 cap/km² in the Small-town Area. In contrast, Metropolis show the highest population density with 2,825 cap/km² covering only 1.6% of the area but accounting for 19.9% of the collisions and even 25.9% of collisions with cyclist participation. Interestingly, the number of collisions in total is highest in Medium-sized Cities (24.3%) and so is the population (26%), however, the number of cyclist collisions is lower (24%) compared to Metropolis (25.9%).

Our results show that the rate of collisions with cyclist participation (per 10,000 residents) is positively correlated with population density ($R^2=0.62$, $p<0.01$). The rate of collisions with cyclist participation were highest in Metropolis areas with 14.2 collisions per 10,000 residents and lowest at 4.8 collisions per 10,000 residents in rural Small-town Areas. All per-capita cyclist collision rates exhibited significant differences by regional type (Chi-square $p \leq 0.012$).

A high rate of collisions with cyclist participation per 10,000 residents does not necessarily say that the individual risk of being involved in a collision incident as a cyclist is greater in densely populated areas than in sparse populated areas. Outcomes from the MiD suggest that the bicycle use is higher in densely populated spatial types (24–27%) than in spatial types with low population density (17–21%) (Nobis 2018, p. 47), which has mainly been a development of the last recent years (Nobis 2019). This has also been shown by Lanzendorf & Busch-Geertsema (2014), who analysed the cycling boom in large German cities (Lanzendorf & Busch-Geertsema, 2014). Therefore, it can be expected that with increasing population density the relative share of cyclists on the road is higher as well, increasing the likelihood of collision with cyclist participation (Jacobsen, 2003). In addition, areas with higher population densities also experience more traffic in general, as they are usually located in or near employment centres, thus experiencing not only local traffic but also regional traffic entering from other areas (Ewing & Dumbaugh, 2009) and thereby increasing the likelihood of traffic conflicts.

Even though such findings suggest that the high rate of collisions with cyclist participation in densely populated regions is rather related to an increased bicycle use and traffic volume in general than a higher relative risk for cyclists, they still stress the importance of providing a safe environment for cyclists in those areas. Improvements in safety measures for cyclists can therefore be expected to affect a larger group of people immediately.

Collision severity

Analysing the collisions with cyclist participation by their severity reveals that collisions tend to be more severe in rural, sparsely populated areas than in densely populated urban regions. In Metropolis areas, the share of all collisions with slight injuries was more than two times higher (27.4%) than the share of reported collisions with fatal outcome (11.5%). Remarkable differences were observed in rural Small-town Areas, where the share of reported fatal collisions (18.6%) was nearly three times higher than the share of collisions with slight injury (6.5%). Compared to the reported incidents in urban Metropolis regions, the relative risk (RR) of fatality increased along the aforementioned gradient: the RR for Regiopolis to Metropolis was 1.28 (95% CI: 1.05, 1.57), while the RR for Medium Cities was 3.24 (2.76, 3.81) and for Small Cities was 12.49 (10.48, 14.88). For reported incidents in rural regional types, a similar pattern was observed: RR for Medium Cities to Central Cities was 2.46 (2.01, 3.01) and for Small-town Areas the RR was 7.17 (5.91, 8.69).

The findings in collision severity across the regions changes the impression given by the results of collision rates. While the rate of collisions with cyclists involved suggests that less populated, rural areas are not as much affected by high collision rates as densely populated areas, the share of collision severity categories indicates, that the collisions reported in rural areas had in fact a much higher likelihood of serious injury or fatal outcome. This tendency has also been confirmed in other studies (Carter & Council, 2007; Alyson West, 2017). One reason may be the differences

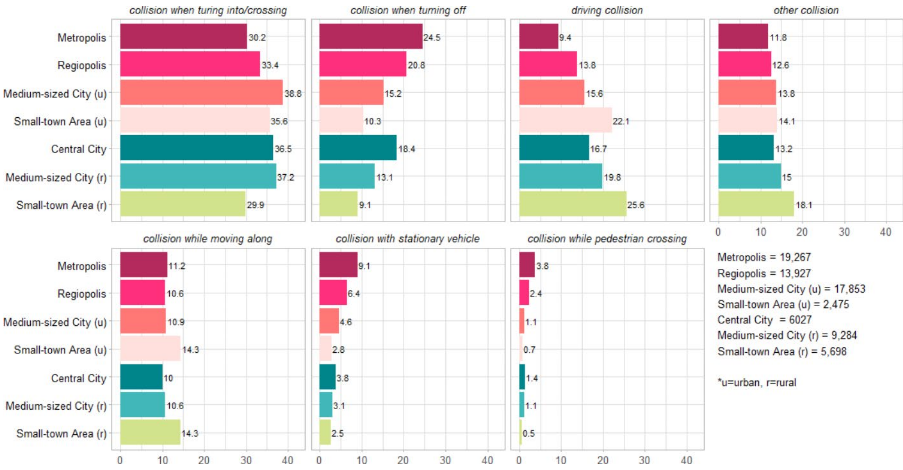

Fig. 4 Shares of collisions with cyclist participation by collision type and region

in street morphologies between urban and rural areas. Rural areas tend to have less complex street networks with fewer intersections and longer street segments. Thus, the assumption is that collisions are more likely to happen at higher speeds, which increases the risk of more severe collision outcomes. Several studies of motor vehicle collisions have found a positive association between street segment length and casualty counts (Abdel-Aty & Radwan, 2000; Anastasopoulos & Mannering, 2009; Sarkar et al., 2018). In addition, Ewing and Dumbaugh point out, that the stop-and-go, high-volume traffic environments of dense urban areas appear to be safer due to a lower driving speed, which in turn reduces the probability of a fatality should a collision occur (Ewing & Dumbaugh, 2009).

Collision type

Results show that the greatest regional differences in types of collisions could be observed in "conflicts while turning off" as well as "driving collisions" (Fig. 4). Shares of "collisions when turning off" suggested that such types of collisions were much more likely to happen in densely populated areas than in regions with lower population density (e.g., Metropolis regions 24.5%, rural Small-town Area 9.1%) while collisions when driving tended to be distributed vice-versa (e.g., Metropolis regions 9.4%, rural Small-town Area 25.6%). Most collisions happened when turning into/crossing with similar shares for all regions. When statistically modelled, significant differences in the odds ratios for regional types were observed for most pairwise comparisons, indicating that regional type exhibits a significant association with the odds of collision for all seven collision types.

The most evident regional differences in conflicts while turning off and driving collisions may also be related to differences in street morphology as well as in traffic movements. As pointed out before, densely populated areas tend to have more complex street morphologies resulting in more multiple way intersections and shorter street link lengths. Densely populated areas are also characterized by a higher share

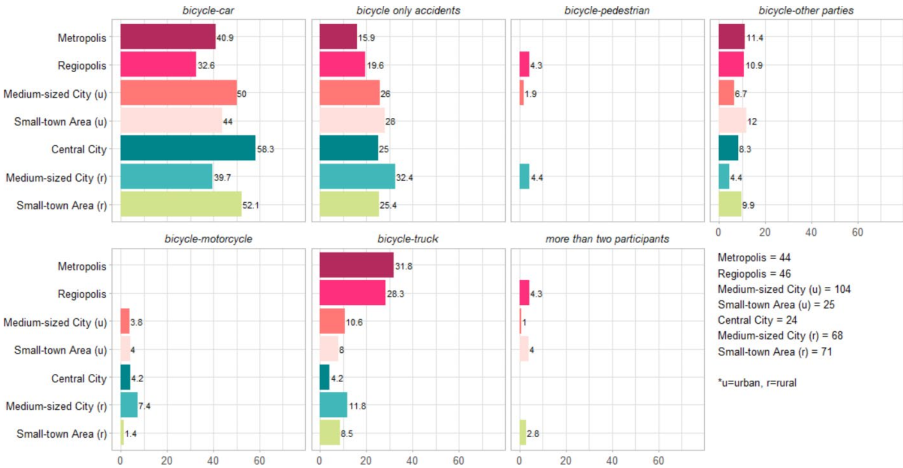

Fig. 5 Shares of collisions between cyclists and other parties with fatal outcome by regional type

of mixed use areas (Ewing & Dumbaugh, 2009). Such mixed form and complexity require traffic participants in these areas to do much more turning manoeuvres, increasing the likelihood of conflicting situations while turning off. On the other hand, longer road link lengths and fewer intersections increases the likelihood of collisions during driving. In a similar study, Carter & Council (2007) also identified that a major difference between urban and rural collisions: rural collisions did often occur at midblock segments while the urban collision types often occurred at intersections. Such findings suggest that differences in collision types are influenced by regional differences in street morphologies and land use. More in-depth insights however would require data about driver behaviour and more detailed analysis of the built environment. A promising indicator could be measurements of street network complexity (see for example Boeing 2018).

Collisions between cyclists and other parties with fatal outcome

Results of collisions between cyclists and other parties with fatal outcome showed that in Metropolis and Regiopolis areas, bicycle-truck collisions have a markedly high share in “collisions with fatal outcome” (31.8% and 28.3%) (Fig. 5). Most of the collisions with fatal outcome are, however, bicycle-car collisions.

The risk potential of the different conflict situation shown in Fig. 6 becomes most evident when considering the rate for all collision severity categories (Fig. 7). At least 80% of all reported collisions were either bicycle-car or bicycle only collisions. Among those collisions that have a fatal outcome, the share of bicycle-truck collisions increased greatly, especially in Metropolis (from 1.6 to 31.8%) and Regiopolis (from 1.2 to 28.3%) areas. The odds of fatality were also observed to vary significantly by regional type. Compared to an urban Metropolis, the odds ratio of fatality in a reported collision involving a car was 3.38 ($p<0.001$) times higher in an urban Medium City, 6.16 ($p<0.001$) times higher in an urban Small-town Area, and 9.97 ($p<0.001$) times higher in a rural Small-town Area. Similar significant differences

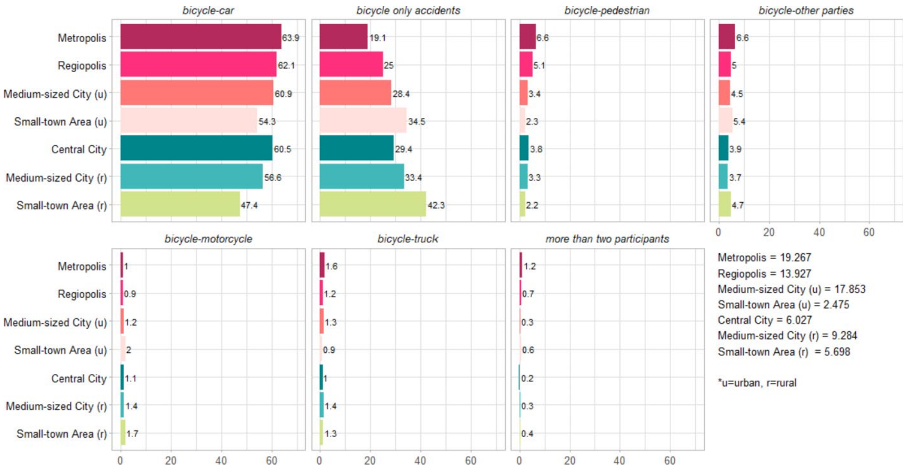

Fig. 6 Shares of collisions between cyclists and other parties by regional type (all categories)

were observed for incidents involving a pedestrian, those involving a truck, and those involving a motorcycle. This result may indicate that the effect of regional type is a stronger predictor of fatality than the type of parties involved.

One major problem in collisions between heavy trucks and cyclists is due to the cyclist moving in an area behind/adjacent to the vehicle where he/she cannot be seen (Schreck, 2017; Michel, 2019). Recent trends in bicycle use and freight transport increase the probability of cyclist-truck encounter. The number of cyclists is increasing in cities across the world (Pucher & Buehler, 2017) while recent developments in land use and urban planning, economic development, and consumer behaviour are driving an increase in the number of trucks in these spaces (Davies & White, 2015; Pokorny & Pitera, 2019). In Germany, too, road freight transport has more than doubled since 1991 and is still constantly growing (Umweltbundesamt, 2020). Considering these developments and results shown in Fig. 6, an urgent need for taking measures regarding bicycle-truck conflicts (especially in Metropolis and Regiopolis areas) can be identified. For example, the EU Parliament and member states have agreed to make driver assistance systems in new cars mandatory by 2024. Particular attention is paid to systems for reducing blind spots in trucks and buses, the so-called turn-off assistants (Tagesschau 26 March 2019). A more detailed analysis of each collision event could provide further knowledge about how these conflicts arise.

Temporal distribution

In the temporal distribution of collision frequency, regional differences were mostly observed between Small-town Areas and the other regions (Fig. 7). The monthly distribution showed a higher collision frequency in all regions during the warmer months (May-September). During these months, collision frequency in Small-town Areas was usually among the highest and lower during the rest of the months. Among the weekdays, greatest differences in collision frequency occurred between weekends and during the week. The share of collisions in Small-town Areas was about 3%

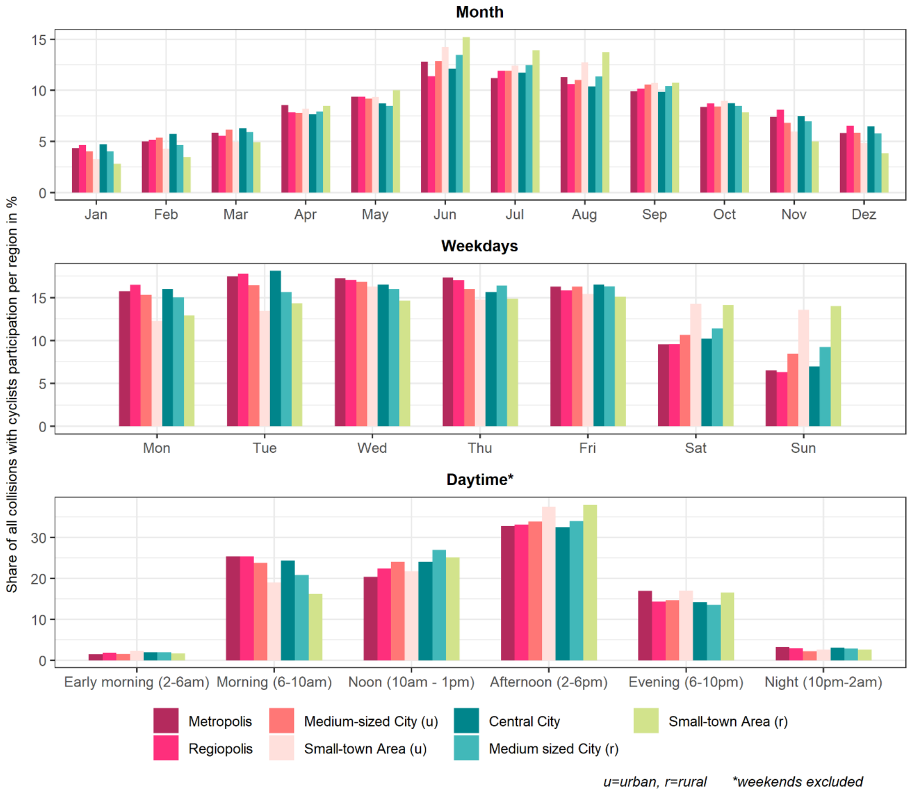

Fig. 7 *Share of all collisions with cyclist participation by regional type. The shares are calculated by month, weekday and daytime, where weekends were excluded. Please note different scaling of the y-*axis *in panel 3*

higher on Saturdays and 5–10% higher on Sundays. In the daytime distribution, collision frequencies in densely populated areas were higher than in regions with lower population density in the morning and lower around noon. The highest frequency shares in all regional types occurred during afternoon (30–35%) with slightly higher shares in Small-town Areas. As travel behaviour is expected to be significantly different during weekends, Saturdays and Sundays were excluded from the daytime distribution.

In the monthly distribution, the share of collision with cyclist participation show a typical seasonality with higher shares of collisions in summer and lower shares in winter. The seasonal distribution is most likely closely linked to seasonal bicycle use. Results from MiD indicate that bicycle traffic in Germany is up to twice as high in the summer month than in the winter months (Nobis 2019). One interpretation that could be made is that there is a substantial amount of bicycle tourists which significantly increases the bicycle traffic volume during the summer season and mostly in sparsely populated areas. According to the ADFC (Allgemeiner Deutscher Fahrrad-Club) bicycle travel analysis report, “experiencing nature” and “exploring unfamiliar regions” have been the two most popular reasons for Germans to go on a cycling trip

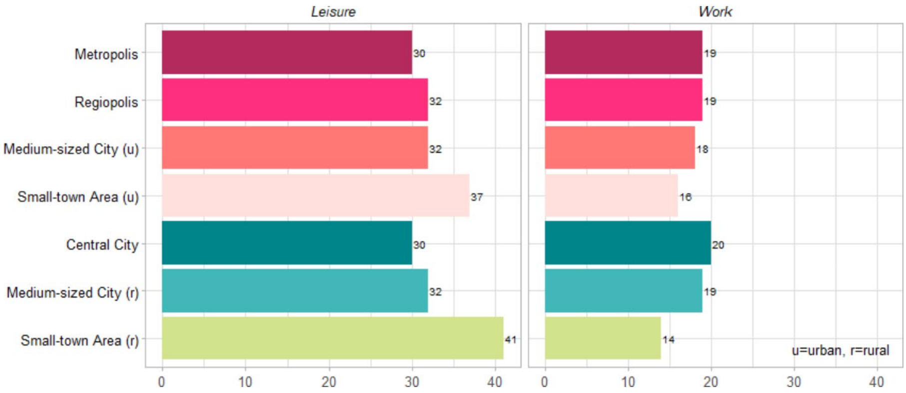

Fig. 8 Shares of trip purposes "Leisure" and "Work" for all trips with bicycle across regional types. The shares are from seven possible answers for the trip purpose of a person using a bicycle for a trip form which two of them were "leisure" and "work". 100% refers to all trips reported in a regional typology class. In total 101,992 trips were recorded (Data source: Nobis (2018))

in 2018 (ADFC 2019). The same survey also found that the most popular months for cycling trips have been from about the mid of April to the end of September (ADFC 2019). This may explain the higher seasonality in the monthly distribution of Small-town Areas For the distribution of weekdays Carter & Council (2007) made similar observations in their study of urban and rural collisions: "Crashes in all datasets were spread fairly evenly throughout days of the week, with the exception of weekends, which had an overrepresentation of rural crashes" (Carter & Council, 2007, p.9). Another assumption is that differences in collision distribution on weekdays may be related to different trip purposes. Results from MiD on trip purpose show that residents of Small-town Areas tend to use the bicycle more often for leisure activities and less often for commuting to work (Fig. 8). As most of work-related activities occur from Mondays to Fridays, trip purpose is likely to influence bicycle traffic volume and consequently the collision frequency distribution among the weekdays. Trip purpose is also likely to influence the collision distribution during different daytimes across regional spatial types. With an increasing share of people using the bicycle to commute to work the rush hour peak in the morning from 6–10:00 increases as well, whereas during noon and afternoon there is a slightly higher share of collision incidents in regions that tended to have high trip purpose shares on leisure activities.

Limitations of this study

The findings presented in this study reveal new insights into characteristics of spatial variations of collisions with cyclist participation across the seven regional types. Several limitations are, however, necessary to consider. The results are not representative for the entire country, as data for one federal state (Mecklenburg-Vorpommern) were not included in the original dataset. Secondly, the reporting process of the collision data leads to a significant underreporting of collisions. In a meta-analysis of the level of underreporting of 19 countries, Elvik & Mysen (1999) concluded, that while there is a great variability among countries, of all the collision types, consistently the least reported are bicycle collisions (Elvik & Mysen, 1999). In a survey from more than 7.000 bicyclists from 30 different countries, Shinar et al., (2018) showed that across all countries, an average of only 10% of all collisions were reported to the police. Germany, who had the highest rate of all countries, still only had a rate of 35% reported collisions (Shinar et al., 2018).

Severity of the collision is also clearly related to the likelihood of reporting the collision to the police: collisions with higher severity are more likely to be reported than collisions with lower severity (Schepers et al., 2015; Shinar et al., 2018). As a consequence, the probability of being seriously injured in a cycling collision incident is overestimated, whereas the probability of being slightly injured is underestimated (Ye & Lord, 2011). Underreporting may also vary regionally and and may depend on the degree of urbanization (Amoros et al., 2006) which could have an effect on the distributions in this study as well. According to the Federal Statistical Office, well over 90% of the collisions reported from the police are assigned to a road section in the *Unfallatlas* (Statistisches Bundesamt 2020). However, it remains unclear what the exact number of the collision events that were not considered are and if they are potentially clustered around a certain place.

While this study focuses on regional differences of collisions only, additional factors that might explain differences could not be included because of missing data on exposure variable (e.g. the total distance or time spent cycling), demographic variables (e.g. age, gender etc.), data on bicycle infrastructure (e.g. bicycle paths) and on driver behaviour (e.g. who caused the collision).

Even though several reasons have been presented in favour of using the regional typology classification, the obtained results are conditional upon the definition of the areas for which these data are spatially aggregated, here: regional types (see: Modifiable Area Unit Problem, Openshaw 1984). More knowledge about the influence of the used geographical framework could be gathered by comparing the outcomes to different spatial aggregations (e.g. two classes: rural or urban) or developing independent classes based on geostatistical measures (e.g. spatial cluster analysis). The analysis exclusively performed on the macro level of Germany comes at the cost of the micro level perspective of collision events. While various trends on the level of regional types could be identified, the local, individual conditions of the collision incidents and spatial concentrations and clusters of collision hotspots (Lakes, 2017) could be assessed in a next step.

Conclusions

*The purpose of this study was to analyse patterns of cyclist injury across Germany by incident characteristics including urbanicity/rurality of incident location (regional type), temporal characteristics (time of day, day of week, and time of year), injury severity, types of vehicles involved, and collision type (e.g., collision whilst turning left). Using data from 2019, which exclude the federal state of Mecklenburg-Vorpommern, our results demonstrate variations in the patterns and characteristics of collisions with cyclist participation across regional types. We observed that regional typology features like land-use context, mobility behaviours, and vehicle operating conditions can vary between regional types and may be significant factors in collision outcomes. These findigs lend evidence to the hypothesis that regional typology plays an important role in injury risk and severity.

Over a quarter of all reported vehicular collisions in 2019 involved a cyclist (N = 74,549). The odds of a bicycle-truck collision was up to ten times higher in a metropolis than in small cities, while the risk of fatality was 12.5 times higher in small cities than in a metropolis. These findings underscore the importance of constructing and upgrading cycling infrastructure. In light of the large observed difference in mortality risk, infrastructure upgrades may be more effective in less densely populated regions. Prior studies indicate that measures targeting finer-scale features of the built environment may be effective, such as road/bikeway design and the relative position of signage, in addition to bike lanes and other cycling-specific infrastructure (Schuurman et al., 2020). While measures to increase cycling safety should be as comprehensive as possible, those that are adapted to the specific challenges of different regional typologies may prove to be more effective. For example, in Metropolis and Regiopolis areas, it may be more beneficial to target specific infrastructure upgrades for reducing the risk of collision between cyclists and trucks, while in small-town areas the focus could be more on avoiding situations where motorized traffic comes near cyclists at high speeds without adequate barriers.

Funding Humboldt-Universität zu Berlin; Friedrich-Alexander-Universität Erlangen-Nürnberg.

Open Access funding enabled and organized by Projekt DEAL.

Data Availability Data and material available at: https://github.com/lutzhutz.

Code Availability Code available at https://github.com/lutzhutz.

Conflicts of interest/Competing interests None.

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