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Groundwork for adolescent bikeability assessment in Germany: An open GIS and regularised regression approach across cities, towns and rural areas

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ABSTRACT

Adolescents need safe infrastructure, accessible places and comfort to cycle for transport. However, the bikeability literature focuses almost exclusively on adult cycling in large cities. The aims of the study are to operationalise bikeability characteristics adapted to adolescents in the German context using open GIS data and assess the relation between bikeability characteristics within different cycling distances and cycling to school in adolescents living in cities, towns and rural areas.

Cycling infrastructure and access to different destinations relevant to adolescents were operationalised using open GIS data. German-wide cycling-to-school data of 1,133 adolescents aged 11–17 years (50.0 % girls) from the Motorik-Modul Study were linked to the bikeability measures. A logistic ridge regression identified relevant bikeability characteristics in cities, towns and rural areas within five different cycling radii between 4–20 min.

Adolescents living in cities had higher odds of cycling if there were more residential streets with a slow speed limit within a 16-minute cycling radius from home and better access to outdoor sports facilities, shops and food outlets within 4–16 min of cycling. In towns, cycling was positively associated with both slow residential streets and separated cycling infrastructure, as well as access to schools, shops and food outlets, outdoor sports facilities, and a larger residential population within similar travel ranges.

Cycling may be facilitated by different infrastructure and accessibility characteristics in cities and towns. Future bikeability research should target vulnerable groups and people living in less densely populated areas. This work lays the groundwork for an adolescent bikeability index for Germany.

1. Introduction

Insufficient physical activity among adolescents is a major health concern. In response, the World Health Organisation has set the goal of a 15 % relative reduction in the prevalence of physical inactivity in adolescents and adults by 2030 (Guthold et al., 2020).

Active travel, particularly cycling, is a low-threshold activity that can be integrated into everyday life to increase physical activity (Martin et al., 2016; Prince et al., 2022). Cycling to school is associated with several health benefits including higher cardiovascular fitness (Larouche et al., 2014; Lubans et al., 2011) and reduced psychosomatic symptoms (Kleszczewska et al., 2020). In addition, cycling may not only improve individual but also planetary health by reducing CO_2 emissions, air and noise pollution when used instead of motorised transport (Abu-Omar et al., 2023). Despite this, many short trips are still made using passive transport modes, and it is estimated that up to 44 % of these could be replaced by cycling based on a study on mostly urban-living adolescents living in Victoria, Australia (Loh et al., 2022). Among adolescents and their parents, the most common barriers for cycling are access to places to cycle to, long distances and traffic safety aspects (Aranda-Balboa et al., 2021; Klos et al., 2023b). The latter are especially important as adolescents are still inexperienced in managing traffic and begin to

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travel independently (Mitra, 2013). In addition, adolescents tend to display a greater inclination toward risk-taking in traffic, which is shaped by less parental supervision, heightened sensitivity to peer approval, and a general rise in exploratory and reward-seeking behaviours (Feenstra et al., 2010) which underscores the need for safe cycling infrastructure that minimise exposure to motor traffic. Further, adolescence is a key developmental period for establishing lifelong health behaviours including physical activity and active travel habits (Kaseva et al., 2023; van Sluijs et al., 2021).

The term bikeability, meaning "an assessment of an entire bikeway network for perceived comfort and convenience and access to important destinations" (Lowry et al., 2012, p. 41) was established in recent years to identify neighbourhoods that are conducive to cycling and those that require improvements. Several reviews addressed the growing number of bikeability indices, most of them comprised of indicators of cycling infrastructure, traffic safety, land use, accessibility, and hilliness measured via geographic information systems (GIS) (Castanon and Ribeiro, 2021; Kellstedt et al., 2021; Muhs and Clifton, 2016; Valenzuela et al., 2022). However, they are almost exclusively developed for adults living in single large cities such as Vancouver, Barcelona or Munich (Codina et al., 2022; Hardinghaus et al., 2021; Kamel et al., 2020). Although bikeability measures were developed for primary school children in Stockholm (Paulusová and Sharmeen, 2025), an adolescent population has not been addressed yet. Further, there is a lack of bikeability assessments outside of large cities, e.g. in towns or rural areas, despite their potential for cycling promotion (Kircher et al., 2022).

Cycling should be inclusive of all age groups and across cities, towns and rural areas, as emphasised by the Global Action Plan on Physical Activity (World Health Organization, 2018) and the European Declaration on Cycling (European Commission, 2024). Rather than developing a comprehensive bikeability index, this study takes a foundational approach by identifying and operationalising key GIS-based measures focusing on cycling infrastructure, accessibility, and topography that are tailored to adolescent cycling. These measures are then evaluated in relation to cycling to school across varying cycling radii. This study provides the groundwork for developing a bikeability index for adolescents applicable to different urbanisation levels in Germany.

Therefore, the aims of the study are to (1) operationalise bikeability characteristics adapted to adolescents in the German context using open GIS data and (2) assess the relation between bikeability characteristics within different cycling distances and cycling to school in adolescents living in cities, towns and rural areas.

2. Methods

In this section, the selected GIS indicators and their operationalisation is documented. It follows a brief description of the Motorik-Modul (MoMo) Study, its data used for the analysis and the statistical approach.

2.1. GIS-indicators

The indicators selected for this study are based on the three categories most commonly represented in bikeability indices: cycling infrastructure and traffic safety, connectivity and urbanisation, and the surrounding environment (Castanon and Ribeiro, 2021; Paulusová and Sharmeen, 2024; Valenzuela et al., 2022). Within each category, indicators were identified following the suggestions of Paulusová and Sharmeen's (2024), review on school bikeability, adapted to the German context, and operationalised using open GIS data with nationwide coverage. Unless indicated otherwise, references refer to findings from studies with adolescents within the age range of 11–17 years or attending secondary school.

2.1.1. Cycling infrastructure and safety

Children and adolescents require safer cycling infrastructure than adults. Paulusová and Sharmeen (2024) highlight that both the presence and the type of cycling infrastructure, as well as traffic volume and speed, are decisive for adolescents' bikeability. For example, in a UK study, 88 % of adults preferred cycling in a painted cycle lane, but only 42 % would allow their 12-year-old to do so (Aldred, 2015). In contrast, physically separated cycle paths or shared cycle-foot paths disconnected from motor traffic were perceived as safe options for children by most adults. Similarly, a stated preference survey among 9,554 adolescents living in urban, rural, and insular areas in Greece and Cyprus indicated that the presence of physically separated cycle paths compared to cycle lanes would lead to substantially more adolescent cyclists based on their mode choice model (Kamargianni, 2015).

In addition to separated cycling infrastructure, residential streets with a low traffic volume and speed are also perceived as safe to cycle by Belgian adolescents (Benoit et al., 2022). Supporting this, Verhoeven et al. (2018b) compared the shortest and actual cycling routes taken by adolescents in Flanders and found that many chose detours to avoid arterial roads and instead cycle on streets with a 30 km/h speed limit, indicating a clear preference for calmer traffic conditions. Although empirical data on adolescents' cycling preferences are limited for Germany, findings from comparable European contexts are likely to be transferable. Moreover, concerns about crime are not related to active travel among adolescents in Germany (Klos et al., 2024) and thus crime-related safety indicators were excluded from this analysis.

Three types of street infrastructure were operationalised using OpenStreetMap (OSM) data (see Tab. 1): Main streets with a physically separated cycle path, total designated cycling infrastructure including paths disconnected from car traffic, and residential streets with a speed limit of 30 km/h or less. Further cycling infrastructure indicators stated by Paulusová and Sharmeen (2024) such as the width and quality of the cycle path, signage or signalling, were not included due to limitations in OSM data coverage and mapping consistency.

2.1.2. Connectivity and urbanisation

Connectivity plays a dual role in cycling environments. On one hand, a highly connected street network offers cyclists greater route flexibility and accessibility. On the other hand, it increases the number of intersections, which may require cyclists to slow down, stop at traffic lights, or navigate potential conflicts with other road users (Paulusová and Sharmeen, 2024). To account for connectivity, time penalties for intersections were applied when defining the feasible cycling radius.

Closely related to connectivity is accessibility to different destinations that are context- and age-dependent. In Germany, approximately 36 % of adolescents' trips are school-related, 40 % are for leisure activities (e.g. visiting friends or sports facilities), and 15 % are for shopping or errands (Nobis and Kuhnimhof, 2018). Between 30 % and 50 % of these trips are regularly made by bicycle (Marzi et al., 2023), highlighting the importance of these destinations and their potential for cycling in adolescents.

Therefore, five different destinations were included as accessibility measures: schools, sports facilities, parks, shops and food outlets, and friends and relatives. Schools, shops and food outlets were operationalised as counts. Sports facilities were limited to outdoor sports facilities, as indoor sports facilities are tagged inconsistently in OSM and could therefore not be used. For parks and outdoor sports facilities, area size rather than count was used to reflect capacity differences (e.g. a football pitch can be used by more people at the same time than a tennis pitch). Population count at a 100 x 100 m resolution from the German Census was used as a proxy for proximity to friends and relatives.

Cycling behaviour differs significantly between urbanisation levels. For example, only 12 % of children and adolescents aged 4-17 years commute by bike in rural areas compared to 30 % in medium-sized towns in Germany (Reimers et al., 2021). In addition, previous research indicates that associations between environmental characteristics and cycling vary across urbanisation levels. For example, access to shops and having a neighbourhood that is pleasant for walking and cycling is positively associated with cycling in rural areas and small

Table 1
GIS-measures used to operationalise bikeability characteristics.

Construct	Operationalisation	Data source and date	OSM keys & values
Overall designated cycling infrastructure	Any cycling infrastructure that is physically separated or disconnected from car traffic	OSM, 01/11/2023	highway = cycleway highway = path, footway & bicycle = yes, designated highway = trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link & cycleway = track
Main streets safe for cycling	Main streets that have a physically separated cycleway	OSM, 01/11/2023	highway = trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link & (bicycle = yes, designated or cycleway = track, separated)
Residential streets safe for cycling	Residential streets with a speed limit ≤ 30 km/h and living or bicycle streets	OSM, 01/11/2023	highway = residential, unclassified & (maxspeed ≤ 30 or bicycle_road = yes) highway = living_street
Schools	(Centroid) location/Number of schools	OSM, 01/11/2023	amenity = schools
Shopping facilities	(Centroid) location/Number of shopping and food facilities	OSM, 01/11/2023	shop = convenience, kiosk, general, department_store, mall, supermarket, bakery, food amenity = café, fast_food, ice_cream
Parks	(Centroid) location and area (m^2) of parks	OSM, 01/11/2023	leisure = park
Sports facilities	(Centroid) location and area (m^2) of outdoor sports facilities	OSM, 01/11/2023	leisure = pitch
Home of friends and relatives	(Centroid) location and number of residents in 100 m x 100 m tiles	German Census, 09/05/2011	–
Hilliness	Bare-earth heights at 8–10 m vertical accuracy at 1:100000 scale	EuroDEM, 04/2008	–
Urbanisation	Classification of the home municipality based on the degree of urbanization (city, town, rural area)	Eurostat, 31/12/2022	–

Note: OSM: Open Street Map; EuroDEM: European Digital Elevation Model.

towns whereas in medium-sized towns, the presence of cycling paths and fewer cars relate positively to cycling in Germany (Klos et al., 2024). Similarly, population density has been shown to be positively associated with cycling to school; however, this relationship may attenuate or even invert in very dense areas, potentially due to higher traffic volumes and increased accident risk (Paulusová and Sharmeen, 2024; Zhang and Hu, 2024). These findings suggest that bikeability measures may operate through different mechanisms across urbanisation contexts, such that associations are best estimated within, rather than pooled across, urbanisation levels.

The degree of urbanisation from Eurostat (2021) was used. It first classifies 1 km^2 grid cells based on population density and contiguity into, urban centres (>50000 inhabitants and ≥1500 inhabitants/km^2), urban clusters (>5000 inhabitants and ≥300 inhabitants/km^2), and rural grid cells (everything else). Municipalities are then categorised into cities (≥50 % of population lives in urban centres), towns (<50 % of population lives in an urban centre and ≥50 % of population lives in urban clusters) and rural areas (≥50 % of population lives in rural grid cells).

2.1.3. Surrounding environment

Most important indicators of the surrounding environment relate to slopes or hilliness and natural elements (Paulusová and Sharmeen, 2024). Cycling in hilly terrain is less comfortable (Ghekiere et al., 2014) and it requires more effort and time (Tscharaktschiew and Müller, 2021). To account for this, slopes were integrated into the routing algorithm by applying time penalties, thereby reducing the effective cycling distance within a given time frame. Elevation data was sourced from the European Digital Elevation Model (EuroDEM) using the bare-earth heights excluding vegetation and buildings at 8–10 m vertical resolution. In addition to topography, natural elements such as parks contribute to the cycling experience. Parks serve a dual function: they are both destinations for leisure and pleasant environments to cycle through. For the purpose of this analysis, parks were primarily considered as an accessibility measure.

2.2. Motorik-Modul Study

The MoMo Study is a nationwide study that assesses physical fitness, physical activity, health, and their determinants in a representative sample of children and adolescents aged 4–17 years in Germany (Woll et al., 2021). It consists of four cross-sectional cohorts spanning from 2003 to 2022 and a longitudinal sample that was followed up at each measurement point after the baseline (2003–2006). Originally, MoMo was an in-depth study module of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS) (Kurth et al., 2008). Its third measurement wave applied the same sampling procedure: 167 sample points were systematically drawn, stratified by degree of urbanisation and geographic distribution. At each point, a pre-specified number of children and adolescents were selected via addresses obtained from local population registries. This analysis used data from Wave 3 (2018–2022), including age, sex, cycling behaviour, socioeconomic status (SES), and geocoded home addresses of adolescents aged 11–17 years. We restricted our analysis to adolescents, as children's school travel differs substantially in terms of cycling prevalence, parental accompaniment, and legal restrictions on cycling infrastructure use, which makes results not directly comparable. On-site assessments were interrupted due to the COVID lockdowns. Therefore, only data collected before the governmental restrictions in March 2020 were used in this analysis. Up until this point, data collection at 128 of 167 sample points was completed.

Participation was voluntary, with written consent obtained from participants (aged ≥16 years) or their legal guardians (if participants were aged <16 years). The study was conducted according to the Declaration of Helsinki, and ethics approval was granted by the Karlsruhe Institute of Technology.

2.2.1. Cycling to school

Cycling to school was assessed via a single question on the most frequently used travel mode to and from (pre-)school choosing from the options "by foot", "by bike", "by bus/train", "by car", "by motorbike", or "others". Responses were dichotomised into "by bike" and "not by bike".

2.2.2. Home address

The address data of the participants were provided by the registration office and geocoded using data from the Federal Agency for Cartography and Geodesy. Exact residential addresses were obtained from the participants and geocoded to building centroids, which served as the starting points for the routing algorithm.

2.2.3. Covariates

In Germany, several individual and contextual factors influence adolescent cycling. Boys, younger adolescents, and those with a high socioeconomic status (SES), are more likely to cycle to school (Marzi et al., 2023; Reimers et al., 2021, 2013; Schönbach et al., 2020). Therefore, these variables were included in the analysis as covariates. Age and sex were assessed via questionnaire. SES was assessed via a health interview, asking for parental education, occupation, and household income. Each dimension was scored from 1 to 7 and the highest parental scores were summed (range: 3–21) and categorised into low (lowest quintile), medium (middle three quintiles), and high (highest quintile) SES (Lampert et al., 2018). Cycling rates also vary significantly between municipalities (Klos et al., 2024) and those were also included as a covariate.

2.3. Cycling radius and time-based routing

As only the home location is known, the bikeability characteristics cannot be provided on a trip but rather on a neighbourhood level. Previous studies used buffers, i.e. zones around a point at a specified distance, either based on the Euclidean distance or the distance through a street network, that range from 100 m up to 5 km around home to approximate the most relevant area in which environment characteristics can be linked to active travel data (Smith et al., 2021). In general, there is a trade-off between small buffers, that may miss some areas that are important for the travel behaviour that lie outside the buffer and large buffers, that include all relevant characteristics and destinations but also contain large areas that are irrelevant and therefore weaken the relationships. There is no consensus which is the optimal buffer size to use for a neighbourhood reachable by bike for adolescents. In Germany, adolescents on average cycle 4 km to school and 2 km to shops, leisure activities and friends or relatives (Marzi et al., 2023). Therefore, a cycling distance up to 5 km seem adequate as environment characteristics within that rather large range were related to cycling in Australian school children (Carver et al., 2015). To find out which cycling distances are most relevant and to understand the implications of different buffer sizes, five different cycling ranges are calculated for this analysis. Instead of distance-based calculations, a time-based routing algorithm is used to apply time penalties for intersections and hilliness (Conveyal, 2024; Tobler, 1993) for a more realistic cycling radius estimation.

All GIS data was processed in R version 4.3.0 using the package “sf” (Pebesma, 2018; Pebesma and Bivand, 2023). Street network data from OSM was accessed via download.Geofabrik.de. OSM data to calculate the accessibility were accessed using the “osmextract” package (Gilardi and Lovelace, 2025). The open-source Rapid Realistic Routing on Real-world and Reimaged networks (R^5) was used to assess accessibility and street infrastructure within a bikeable distance of participants’ homes. The *accessibility* function from the “r5r” package (Pereira et al., 2021) calculated accessibility (i.e. to schools, shops and food outlets, parks, outdoor sports pitches, population tiles) within 4, 8, 12, 16, and 20 min cycling radii at an average cycling speed of 15 km/h. To calculate the accessibility to each population tile, centroids were snapped to the closest street prior to analysis, as the exact locations of those points are arbitrary. Time penalties were applied for intersections and hilliness for a more realistic distance-time estimation (Conveyal, 2024; Tobler, 1993). The same settings were used to calculate isochrones and therefore the areas that can be reached within the set time and the length of each street infrastructure type (i.e. total designated cycling infrastructure including paths disconnected from car traffic, main streets with a physically separated cycle path, and residential streets with a speed limit of 30 km/h or less) within those areas. Finally, the cumulative measures were transformed to incremental measures by subtracting the next smaller buffer’s measure from the larger one (i.e. 0–4 min, >4–8 min, >8–12 min, >12–16 min, and >16–20 min). This approach avoids buffer overlap, reduces multicollinearity, and improves interpretability.

2.4. Statistical analysis

All analyses were done in R version 4.3.0. To identify relevant GIS measures related to cycling to school across different buffer sizes, we used regularisation in combination with logistic regression. Regularised logistic regression is particularly useful for feature selection in datasets with a large number of predictors and high multicollinearity (Zou and Hastie, 2005). We chose regularised logistic regression rather than non-parametric machine learning approaches such as random forests, because our primary aim was not prediction accuracy but the identification and quantification of associations. Regularised logistic regression provides interpretable effect estimates in the form of odds ratios, while simultaneously addressing multicollinearity and enabling feature selection.

According to Friedman et al. (2010, p. 8), the logistic elastic net regression can be expressed as:

$$\max_{(\beta_0,\beta)\in R^{p+1}}\left[\frac{1}{N}\sum\nolimits_{i=1}^{N}\{I(g_i=1)\log p(x_i)+I(g_i=2)\log(1-p(x_i))\}-\lambda P_\alpha(\beta)\right]$$

where the first part represents the log-likelihood function for binary classification with $g_i\in\{1,2\}$ and the second part is the elastic net penalty where the shrinking parameter λ determines the strength of regularisation applied to $\beta_1,\cdots,\beta_p$ but not to the intercept β_0. The elastic net mixing parameter $\alpha\in[0,1]$ determines the balance between ridge (L2) and lasso (L1) regularisation:

$$P_\alpha(\beta)=(1-\alpha)\frac{1}{2}\|\beta\|_{l_2}^2+\alpha\|\beta\|_{l_1}$$

For example, in case of the ridge regression ($\alpha=0$), the penalty simplifies to:

$$P_0(\beta)=\frac{1}{2}\|\beta\|_{l_2}^2$$

The ridge penalty shrinks coefficients towards zero by penalizing their squared magnitudes but retains all variables.

The optimal configuration of the hyperparameters α and λ was determined through a 10-fold cross validation with an automatically chosen range of λ using the packages “glmnet” (Friedman et al., 2010; Tay et al., 2023) and “glmnetUtils” (Ooi, 2017). Twenty-one different α-values were provided ranging from 0 to 1 in 0.05 increments, therefore including ridge ($\alpha=0$), elastic net ($\alpha=0.05$–0.95), and lasso regressions ($\alpha=1$). For each model with a fixed α-value, the optimal λ was selected based on cross-validation performance. Subsequently, the models corresponding to each α-value and its optimal λ were compared based on their mean squared error (MSE), and the model with the lowest MSE was chosen as the best-performing configuration. The one-standard-error rule was applied to model selection; specifically, the model with λ one standard error above the minimum was used to report the coefficients. This approach yields a more parsimonious model and helps reduce the risk of overfitting, particularly given the relatively small sample size (James et al., 2021, p. 237).

The outcome variable was a binary indicator of whether an adolescent reported cycling to school (yes/no). Explanatory variables included GIS-based bikeability measures – cycling infrastructure (total cycleways, separated cycleways along main streets, and residential streets with ≤30 km/h speed limits) and access to destinations (schools, outdoor sports pitches, parks, shops and food outlets, and population) –

calculated within incremental cycling radii of 4, 8, 12, 16, and 20 min.

Urbanisation was treated as an analytical context rather than as an effect modifier to identify context-specific associations between bikeability measures and cycling to school within cities, towns, and rural areas. Bikeability measures were standardised within each urbanisation level and specified as urbanisation-specific predictors, allowing associations to be estimated and interpreted separately for each context. A nested contrasts parameterisation (Schad et al., 2020) was used in the model, in which predictor effects are defined within, but not compared across, urbanisation levels. This approach aligns with the research aim, avoids assumptions of cross-context comparability of standardised predictors, and reduces model complexity and the risk of overfitting, particularly given the smaller rural sample.

Covariates comprised age, sex, SES, and municipality, with the latter included as a fixed effect to account for clustering. Sex, SES, and municipality were centred to reflect deviations from the overall mean rather than a reference group as not to distort the differences from the reference group due to the regularisation. The R code for the statistical model and its outputs can be found in Suppl. 1.

Estimates are reported as odds ratios (OR). Typically, *p*-values or confidence intervals cannot be provided for the individual coefficients in models using regularisation unless working with very large data sets and meeting specific assumptions (Zhao et al., 2021). The estimated odds ratios of the standardised bikeability measures as a descriptive variable importance metric, with their magnitude used to explore relative associations rather than to draw inferential conclusions.

3. Results

Geocoded address data were available for 1,253 adolescents. Of these, 77 participants had missing data in the cycling to school variable and an additional 43 had missing SES data. These cases were excluded, resulting in a final sample of 1,133 adolescents, with an equal gender distribution (50.0 % girls).

As shown in Table 2, 27 % of the sample lived in cities, 53 % in towns, and 20 % in rural areas. SES was highest among adolescents residing in cities. The prevalence of cycling to school varied by urbanisation level, with the highest rate observed in towns (36.6 %) and the lowest in rural areas (3.4 %).

The ridge regression model with $\alpha = 0$ and $\lambda = 0.1047$ yielded the lowest mean squared error (MSE = 0.9227), indicating the best model fit (see Fig. 1). After applying the one-standard-error rule, coefficients of the model one standard error from the minimal λ, $\lambda_{1se} = 0.3508$, are reported.

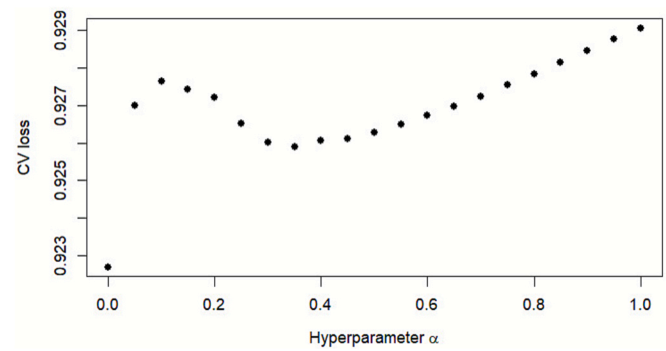

Fig. 1. Comparison of model fit based on the Mean Squared Error (MSE) for models with varying α-values.

Fig. 2 presents the coefficients for the bikeability characteristics. Among the covariates, age showed a negative association with cycling to school (OR = 0.96). Boys were more likely to cycle than girls (OR = 1.06 vs. OR = 0.95). SES was positively associated with cycling, with odds ratios increasing from low (OR = 0.87) to medium (OR = 1.00) and high (OR = 1.15) SES groups. Cycling rates were highest in towns (OR = 1.26), followed by cities (OR = 1.05), and lowest in rural areas (OR = 0.69). A complete table of the results can be found in Suppl. 2.

Regarding the bikeability characteristics, a greater presence of safe residential streets within 8–12 and 16–20 min of the home was positively associated with cycling to school in cities. Additionally, access to outdoor sports pitches within 4–16 min and to shops and food outlets within 8–16 min was linked to higher cycling rates. In towns, the total length of separated cycleways and the availability of safe residential streets within 4–12 min were positively associated with cycling. The number of schools within a 4-minute radius was negatively associated with cycling, whereas schools within a 4–12-minute radius showed a positive association. Access to outdoor sports pitches within 8–16 min, shops and food outlets within 8–12 min, and higher population density within 4–16 min were also positively related to cycling to school. In rural areas, separated cycling infrastructure along main streets within 4–12 min was positively associated with cycling, as was access to schools within 8–12 min, outdoor sports pitches within 4–8 min, parks within 0–12 min, and population density within 8–12 min of cycling distance. However, given the low number of cyclists in rural areas (n = 11), the results in rural areas should be interpreted with caution.

Table 2
Description of the sample.

	Cities (n = 293)	Towns (n = 573)	Rural areas (n = 267)	Overall (n = 1,131)
Sex				
Boys	147 (50.2 %)	291 (50.8 %)	129 (48.3 %)	567 (50.0 %)
Girls	146 (49.8 %)	282 (49.2 %)	138 (51.7 %)	566 (50.0 %)
Age (years)				
Mean (SD)	14.3 (2.03)	14.3 (2.01)	14.2 (1.90)	14.3 (1.99)
Socioeconomic status				
Low	43 (14.7 %)	129 (22.5 %)	69 (25.8 %)	241 (21.3 %)
Medium	165 (56.3 %)	333 (58.1 %)	166 (62.2 %)	664 (58.6 %)
High	85 (29.0 %)	111 (19.4 %)	32 (12.0 %)	228 (20.1 %)
Cycling to school				
No	212 (72.4 %)	367 (64.0 %)	256 (95.9 %)	835 (73.7 %)
Yes	81 (27.6 %)	206 (36.0 %)	11 (4.1 %)	298 (26.3 %)

4. Discussion

This study aimed to operationalise bikeability characteristics relevant to adolescents in Germany using open GIS data and to examine their associations with cycling to school across different urbanisation levels in Germany. Three types of street infrastructure and five accessibility measures were derived, and hilliness was integrated directly into the routing algorithm. Using regularised logistic regression, distinct patterns were found linking bikeability characteristics to cycling to school within different cycling radii in cities, towns, and rural areas.

In both cities and towns, the presence of safe residential streets was positively associated with cycling to school. Additionally, separated cycling infrastructure was particularly important in towns. Accessibility to key destinations such as sports facilities, shops, and schools within a 4–16-minute cycling radius was linked to higher cycling rates. These findings align with previous research that links environment characteristics to cycling behaviour and also show that the strength of these associations varies by urbanisation level in Germany and the Netherlands (Gao et al., 2018; Klos et al., 2024). For instance, in cities, several accessibility indicators, such as proximity to schools, parks, and

Cycling radius (incremental)	Cycleways total	Cycleways along main streets	Safe residential streets	Schools	Outdoor sports pitches	Parks	Shops and food outlets	Population
Cities								
0-4 min	0.99	1.01	1.02	1.02	0.97	0.97	1.02	0.97
>4-8 min	0.99	0.98	1.03	0.99	1.06	0.97	1.00	0.97
>8-12 min	1.01	1.01	1.09	1.02	1.05	0.96	1.05	0.98
>12-16 min	0.99	0.99	1.01	1.00	1.09	0.94	1.06	1.00
>16-20 min	1.05	1.01	1.06	0.96	0.96	0.98	0.99	0.98
Towns								
0-4 min	1.06	1.01	1.00	0.90	1.03	0.97	1.01	0.97
>4-8 min	1.05	1.02	1.05	1.03	1.00	1.01	1.02	1.06
>8-12 min	1.06	1.01	1.06	1.06	1.05	1.02	1.10	1.08
>12-16 min	1.06	1.01	1.02	1.03	1.08	1.03	1.01	1.04
>16-20 min	1.08	1.02	0.98	1.00	0.98	0.99	0.98	0.96
Rural areas								
0-4 min	0.99	1.00	1.02	0.98	0.99	1.06	1.01	1.02
>4-8 min	1.01	1.07	0.99	1.02	1.06	1.05	1.01	1.00
>8-12 min	1.03	1.04	1.00	1.05	1.00	1.10	1.00	1.05
>12-16 min	1.00	0.99	0.98	0.98	1.00	1.02	1.00	0.99
>16-20 min	0.99	0.98	0.98	0.99	0.99	1.02	1.00	0.99

Fig. 2. Coefficients of the ridge regression for cycling to school (yes/no): bikeability characteristics across incremental buffers in cities, towns and rural areas. Note: Displayed are odds ratios based on the standardised bikeability characteristics of the ridge regression (including age, sex, socioeconomic status and municipality as covariates). Cell colours are based on the odds ratio values (>1–green, 1–white, <1–red); higher opacity indicates larger effect sizes.

population, showed less favourable associations with cycling compared to towns. One possible explanation is a saturation effect, where in highly urbanised areas, accessibility may already be sufficient for adolescents to reach desired destinations, so further increases offer little additional benefit. In addition, when considering population within cycling distance, a threshold effect may occur (Zhang and Hu, 2024). Beyond a certain point, higher population density could lead to increased traffic volumes, which in turn may negatively impact perceived and actual traffic safety. Supporting this interpretation, a study on adolescents in Germany found that perceived access to shops and bus stops was positively associated with cycling in rural areas and small towns, but not in more urban settings. Conversely, the presence of cars was negatively associated with cycling in medium-sized towns and cities only (Klos et al., 2024). Notably, access to parks was negatively associated with cycling in cities, a pattern also observed in an Israeli study (Moran et al., 2013). Rather than being a popular destination for adolescents, parks may act as barriers by increasing trip length or obstructing direct routes, which can discourage cycling (Gao et al., 2018) or people may prefer to walk when parks are nearby.

One of the main challenge in linking GIS and survey data is the modifiable areal unit problem (MAUP), stating that analyses may provide different results depending on the spatial scale used (Wong, 2009). To address this, time-based routing buffers were used that account for intersection delays and hilliness, providing a more realistic estimate of travel distance than traditional network buffers. The use of multiple buffer sizes also allowed us to identify the most influential areas (Mitra and Buliung, 2012; Smith et al., 2021). The sequential buffers used in this study provide valuable new insights: Most accessibility measures, such as outdoor sports pitches, are associated with cycling within a 4–16-minute radius. This range aligns with average cycling distances among adolescents in Germany: around 2 km for leisure and shopping trips and up to 4 km for school journeys (Marzi et al., 2023). Relevant destinations may lie within 16 min of the adolescents' home, aligning with the 15-minute city concept, stating that most daily necessities and services should be easily reachable by foot, bike or urban transport within 15 min to promote healthy and sustainable living (Khavarian-Garmsir et al., 2023).

Interestingly, access to e.g. schools in very close proximity (<4 min) was negatively associated with cycling, particularly in towns. This supports previous findings that adolescents are more likely to walk short distances (<1 km), while cycling becomes more common for longer trips (van Dyck et al., 2010). Future research should consider accessibility within a cycling radius as a core component of bikeability, especially to capture destinations beyond typical walking distances.

Consistent with the literature, residential streets with speed limits of 30 km/h or less that are typically associated with lower traffic volumes were positively associated with cycling in both towns and cities, a finding that was also reported in Belgian adolescents (Benoit et al., 2022; Vanparijs et al., 2020). This preference is not only found among adolescents but also for other vulnerable groups such as parents with their children, adults with a low SES, and older cyclists (Beirens et al., 2024; Hardinghaus and Weschke, 2022). "Interested but concerned" cyclists that require safe infrastructure to feel comfortable are often found in those vulnerable groups (Dill and McNeil, 2013; Pearson et al., 2024). Cycling promotion for adolescents, i.e. by enforcing a low speed limit in residential streets, could therefore also greatly benefit other vulnerable groups and enable the potential for new and more frequent cyclists among those interested but concerned.

Our findings also highlight the influence of individual and socio-structural factors. Boys and adolescents with higher SES living in cities were more likely to cycle to school. In Germany, bike availability is unlikely to explain these differences (Marzi et al., 2023). However, little is known about whether environmental requirements, such as traffic safety or accessibility, differ by gender or SES. The "cycling boom" in Germany has been largely concentrated in urban, high-SES populations (Hudde, 2022). This raises concerns about growing social inequalities in access to safe cycling environments. Deprived neighbourhoods may have a higher cycling injury risk due to poorer infrastructure as was shown by Vidal Tortosa et al. (2021) using the English National travel Survey, and adolescents from lower SES backgrounds in Germany are more likely to maintain or adopt passive commuting habits into adulthood (Klos et al., 2023a). These disparities warrant further investigation in future bikeability research.

Finally, the strong association between separated cycleways and cycling in towns, even beyond 16 min, may reflect differences in infrastructure quality between towns rather than within them. It is also important to consider data quality as OSM coverage differs between regions (Ferster et al., 2020) and is generally more complete in cities than in less populated areas (Bres et al., 2023), which may influence the observed associations. Cycling infrastructure may also be better mapped in areas with more active cyclists, potentially introducing bias.

4.1. Policy implications

This study underscores the importance of low-speed residential streets, as their presence was positively associated with cycling. Introducing a 30 km/h speed limit in urban and town settings not only encourages active travel, but also reduces crashes, injuries, and fatalities, lowers air and noise pollution and fuel consumption, and can enhance traffic flow and street liveability (Yannis and Michelaraki, 2025). The recent nationwide implementation of a 20 mph default limit in Wales in 2023 illustrates that such large-scale policy changes are both feasible and politically achievable (Currie, 2024). On arterial roads with high traffic volumes, physically separated cycling facilities remain essential to ensure comfort and safety, features that adolescents in particular value highly (Verhoeven et al., 2018a). Although safe infrastructure is universally important, adolescents' travel patterns centre on destinations that are age-specific, most notably secondary schools, but also sports facilities and shops. This means that planning decisions should prioritise placing these key destinations within bikeable distance. Locating new schools in residential areas that can be reached safely by bicycle, or encouraging enrolment in the closest school where feasible, can substantially increase active commutes for adolescents (Mandic et al., 2023). Further, ensuring safe, direct, and well-connected cycling networks that minimise hazardous crossings and unnecessary detours is critical to avoid gaps in the network and to support consistent cycling uptake (Buehler and Dill, 2016).

4.2. Strengths and limitations

The present study focuses on context-specific associations between built environment characteristics and adolescent cycling rather than on the construction of a composite bikeability index or direct comparability across cities. German-wide data from over 100 municipalities were used, providing a diverse picture of bikeability across cities, towns, and rural areas. Nevertheless, the sample size and the number of municipalities does not allow for fully representative conclusions at the national level. While the municipalities were selected to be representative of the German population in terms of urbanicity and state, it must be acknowledged that only about two third of municipalities were tested due to COVID-lockdowns. Accordingly, results should be interpreted as context-specific associations rather than population-level estimates of cycling behaviour among German adolescents.

Although the sample is geographically diverse, the number of adolescent cyclists, particularly in rural areas, is limited, restricting statistical power for confirmatory analyses. Consequently, the present analyses should be interpreted as exploratory and hypothesis-generating rather than as definitive evidence of context-specific effects. Further, the use of regularised logistic regression implies that associations between correlated bikeability characteristics are jointly shrunk. While this approach improves model stability in the presence of multicollinearity, it also limits the interpretability of individual predictors as independent or causal contributors. Feature-importance measures derived from the fitted models therefore reflect relative associations rather than stable rankings of predictor relevance. Taken together, these limitations suggest that the present study is best understood as a structured exploration of potentially relevant bikeability characteristics and spatial scales for adolescents, providing a methodological and empirical basis for future studies with larger samples and longitudinal or confirmatory designs. New data from the ongoing MoMo 2.0-Study (Woll et al., 2025) may be used to test the model performance in the future and help to validate these results in an independent sample of similar composition. Alternative approaches, such as random forest models, could have been considered for feature selection; however, they do not handle multicollinearity as effectively as regularised regression models and lack interpretable coefficients essential for the exploratory approach of this study.

Time-based routing and incremental cycling buffers were used to get detailed insights into the cycling environment of adolescents and to appropriately address the MAUP, introducing a new analytical approach. The use of incremental buffers resulted in a large number of highly correlated predictors, which led to the regularised regression approach.

Choosing an open data approach enables future research to validate the model using independent datasets or replicate the approach in other European countries. Nevertheless, data availability and data quality may differ between regions and countries, e.g. when it comes to cycling infrastructure, which may result in different findings (Bres et al., 2023; Ferster et al., 2020). Additionally, the relatively coarse vertical resolution of the elevation data may have led to an over- or underestimation of hilliness in the routing algorithm.

5. Conclusion

This study identified key bikeability characteristics for adolescents in Germany. By using open GIS data, these characteristics were linked to cycling-to-school data across cities, towns and rural areas. Separated cycleways and safe residential streets emerged as critical infrastructure components, with their relevance varying by urbanisation level. Accessibility to destinations within a 4–16-minute cycling radius was positively associated with cycling, suggesting that most cycling trips occur beyond typical walking distances but within a manageable cycling range.

The findings highlight the need for context-sensitive strategies to promote cycling in cities, towns, and rural areas. Providing safe and accessible infrastructure not only supports adolescent cyclists but also benefits other vulnerable groups, such as older adults and parents with children. This aligns with the vision of "cycling for everyone" as outlined in the European Declaration on Cycling (European Commission, 2024). Importantly, the results also point to socioeconomic disparities in cycling behaviour, with adolescents from higher SES backgrounds more likely to cycle to school. This underscores the need to address equity in cycling infrastructure and ensure that safe, accessible environments are available in all neighbourhoods, particularly those that are socioeconomically disadvantaged.

Future research should continue to refine bikeability measures for adolescents and other vulnerable populations using open GIS data, with a particular focus on less densely populated areas. Expanding the scope beyond school commutes to include, e.g. leisure and shopping trips will also provide a more comprehensive understanding of adolescent cycling behaviour.

CRediT authorship contribution statement

Leon Klos: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Claudia Lazarides:** Writing – review & editing, Methodology. **Rebecca Pedrick-Case:** Writing – review & editing, Methodology. **Richard Fry:** Writing – review & editing, Methodology. **Hagen Wäsche:** Writing – review & editing, Supervision. **Claudia Niessner:** Writing – review & editing, Supervision. **Alexander Woll:** Writing – review & editing, Supervision.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2026.101875.

Data availability

The authors do not have permission to share data.

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