TSR TRAFFIC SAFETY RESEARCH
AN INTERDISCIPLINARY JOURNAL

Research article

Determinants of cyclists' willingness to comply with mixed traffic provision and to ride on the carriageway rather than the pavement

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Received: 14 February 2024; Accepted: 13 August 2024; Published: 14 September 2024; Updated: 17 September 2024 (minor corrections in figures)

Abstract: Stakeholders in many municipalities worldwide are committed to promoting cycling and improving cycling provision. Scarcity of space is a major issue in most of these cities, particularly for main streets with significant movement and place functions. Multiple demands exist on these streets, including moving pedestrians, cyclists, motorised vehicles, parking, people waiting at public transport stops, or staying in the street for place activities. Mixing cyclists and motorised vehicles in the same space in the carriageway might be the only possible solution for cycling provision in these contexts, which is applied in many German cities. The aim of this study is to evaluate the acceptance of cycling in mixed traffic, which we measure as the proportion of cyclists riding on the carriageway versus on the pavement. The empirical work in this study is based on video observations at 273 study sites with a total length of 124 km located in 13 cities in Germany. 260 of these study sites have no marking for cyclists, and 13 have bicycle pictograms. A total of 34 874 cyclists are recorded at these study sites. A logistic regression model is used to quantify the effect of exposure and infrastructure characteristics on the proportion of cyclists on the carriageway. Volumes of motorised vehicles, lane widths > 3.00 m and city type show a significant negative effect on the acceptance of cycling on the carriageway. Cyclist volumes, bicycle pictograms, and a speed limit < 50 km/h significantly increase the likelihood of cycling on the carriageway. The model is then applied to develop evidence-based recommendations on appropriate conditions for mixed traffic provision for cyclists, ensuring pre-defined levels of acceptability. Cycling in mixed traffic without bicycle pictograms should only be recommended with traffic volumes of a maximum of 400 vehicles per hour and a speed limit of < 50 km/h to achieve a proportion of cyclists on the carriageway of 90%. The marking of bicycle pictograms increases acceptance.

Keywords: binary logistic regression, cycling provision, shared lane markings, speed limit

1 Introduction

Stakeholders in many municipalities worldwide are committed to promoting cycling and improving cycling provision. Scarcity of space is a major issue in most of these cities, especially for main streets with multiple demands, including the movement of pedestrians, cyclists and motorised vehicles as well as activities that take place on the pavement (also called sidewalk) such as communicating, eating, shopping, sitting in the sun or waiting at public transport stops. Requiring cyclists to share the carriageway with motorised vehicles might be the only possible solution for cycling provision in these contexts, which is applied in many German cities. Mixed traffic solutions for cycling in this study mean either no cycling markings at all or bicycle pictograms consisting of a bicycle and one or more arrows (also known as sharrows; Ruf et al. (2023)). In some references, marked advisory lanes are also considered as mixed traffic solution (Hantschel, 2022). Advisory lanes are cycle lanes demarcated by a broken white line that allows motorists to drive on the cycle lane if necessary, e.g., when two motorised vehicles encounter. However, advisory cycle lanes are not included in this study.

From the cyclists' perspective, mixed traffic is the second best solution for the majority of cyclists who prefer to be separated from motorised traffic. This preference has been consistently found in previous studies investigating perceived safety and comfort, mental stress, physiological markers such as galvanic skin response, and route choice, as stated in survey responses and revealed in field observations and naturalistic driving studies, among others (Chataway et al., 2014; Hu et al., 2023; Huber, 2022; Rossetti et al., 2019; Zhang et al., 2024). For the city of Berlin, FixMyCity (2020) finds in their online survey that only 11% of the surveyed cyclists perceive cycling in mixed traffic with a speed limit of 50 kilometres per hour and on-street parking to be safe or rather safe, this proportion increases to 28% with a speed limit of 30 kilometres per hour and no parking. Avoidance strategies are identified in the literature including the use of alternative routes with cycle facilities (Chataway et al., 2014; O'Connor & Brown, 2010) and the decision not to cycle at all (Chataway et al., 2014; Pearson et al., 2022).

Despite these concerns and the reluctance of cyclists to cycle in mixed traffic, they still use these facilities, mainly due to a lack of alternatives. Although it is illegal for cyclists to ride on the pavement in such streets, they might move onto the pavement to be better separated from motorised traffic and thus to increase their perceived level of safety. Very few studies could be identified that have observed cyclists' in such situations. Compliance levels, measured as the proportion of cyclists using the carriageway or cycle facility, were observed in the studies conducting on-site observations (Figure 1), including different types of cycle provision and street sections with two and four lanes. All four studies from the USA (Birk et al., 2004; Hunter et al., 2010; Mills et al., 2010; Pein et al., 1999) examine the effects of bicycle pictograms, which is also the focus of Koppers et al. (2021) from Germany and Vasilev et al. (2017) from Norway. Studies on the other facility types (except pictograms) are based in Germany (Alrutz et al., 2009, 2015; Kaulen et al., 2014; Ohm et al., 2015; Richter et al., 2019; Schüller et al., 2023) and Switzerland (Dietiker et al., 2012). The high variability in the proportion of cyclists using the carriageway with mixed traffic, advisory cycle lanes and bicycle pictograms shows that these facilities can achieve high compliance levels. At the same time, some studies show very low proportions, suggesting problems with perceived safety and/or comfort. The compliance level is significantly higher and variances are lower for the two dedicated cycle facilities, cycle lanes and cycle tracks. The mean values are lowest for mixed traffic and bicycle pictograms. Even marking an advisory cycle lane already leads to a significant increase of cyclists on the carriageway, which is even higher for cycle lanes and cycle tracks.

The wide range of compliance levels for mixed traffic provisions in Figure 1 indicates the existence of systematic determinants, which are mainly analysed using descriptive statistics. Factors related to lower compliance levels include high volumes of motorised vehicles (Ohm et al., 2015; Schüller et al., 2023; Zweibrücken et al., 1999), high shares of heavy goods vehicles, a speed limit of 50 kilometres per hour compared to lower values, the active use of the buildings adjacent to the street which might be a proxy for high pedestrian volumes (Schüller et al., 2023), the existence of on-street parking (Zweibrücken et al., 1999), and frequent school traffic (Zweibrücken et al., 1999). Higher compliance levels are found for study sites with higher cyclist volumes (Schüller et al., 2023).

Bicycle pictograms (sharrows) on the carriageway are used in several countries to increase the acceptance of cycling in mixed traffic and improve motorists'

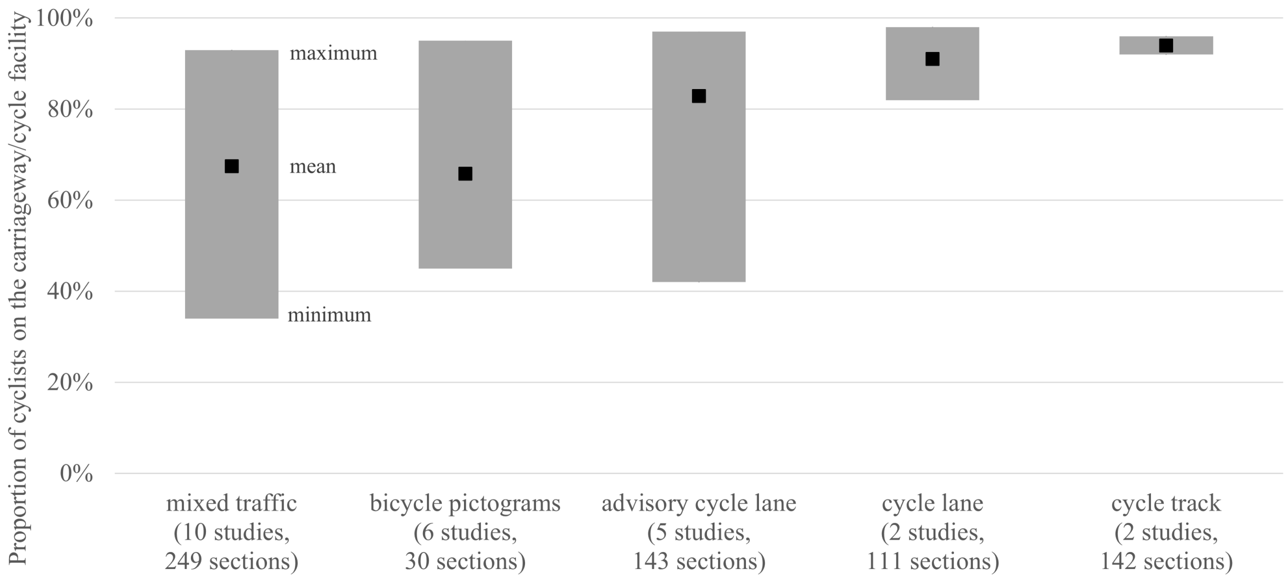

Figure 1 Overview of the results of previous studies on the proportion of cyclists complying with cycle provision (Alrutz et al., 2009, 2015; Birk et al., 2004; Dietiker et al., 2012; Hunter et al., 2010; Kaulen et al., 2014; Koppers et al., 2021; Mills et al., 2010; Ohm et al., 2015; Pein et al., 1999; Richter et al., 2019; Schüller et al., 2023; Vasilev et al., 2017)

awareness of cyclists on the carriageway. Examples of countries using sharrows include the USA and Canada (MTO, 2021; AASHTO, 2012), although they have only been evaluated in the USA to date. Sharrows are also used in some cities in Germany, but are not regulated by law. Using German street sections as an example, Koppers et al. (2021) show that the proportion of cyclists on the carriageway without bicycle pictograms is on average around 50%, and with pictograms around 60%. Birk et al. (2004), Pein et al. (1999), and Hunter et al. (2010) also find an increase in the proportion of cyclists on the carriageway with the marking of pictograms, whereas Mills et al. (2010) and Vasilev et al. (2017) find no effect.

These studies provide important insights into the willingness of cyclists to comply with mixed traffic cycle provision, but there are still open research questions. The analyses in previous studies are mainly based on descriptive statistics and do not disentangle the complex interrelationships between the various relevant factors. Schüller et al. (2023) is the only exception that applies a linear regression model providing first indications of these interrelationships. In addition, the number of cases in the existing studies is often small, which might be one main reason for the exclusive use of descriptive statistics. Exposure data are limited, particularly for cycling.

These research gaps are of high relevance because we need to understand cyclists' on-street behaviour in order to design mixed-traffic streets that are perceived as safe and attractive, and therefore actually used by cyclists as intended. This means that cyclists ride on the carriageway and do not move onto the pavement to avoid being mixed with motorised traffic. Pedestrians benefit from such compliance because cyclist volumes on the pavement and related conflicts are likely to be reduced. Cyclists may also profit by being able to cycle at higher speeds on the carriageway.

This study combines the video data collected at 273 study sites in 13 German cities by Koppers et al. (2021), Ohm et al. (2015), and Schüller et al. (2023) into a unique dataset that allows the identified research gaps to be addressed. The following three research questions are formulated for this study: (1) What are the proportions of cyclists using the carriageway versus the pavement at specific types of street sections with mixed traffic in German cities? (2) What are the determinants of the probability for cycling on the carriageway in terms of exposure and design characteristics? (3) Which recommendations can be derived from this analysis for designing mixed traffic provisions for cyclists to achieve high levels of compliance?

To answer these research questions, detailed data on design characteristics, surrounding land use and volumes of motorised vehicles, cyclists and pedestrians are collected for each street section and combined with data on cyclists' general on-street behaviour and, in particular, their observed choices of whether to cycle on the carriageway or the pavement. In the following, we first describe the German legal framework and introduce criteria for mixed traffic provision from international guidelines in section 2. Section 3 introduces data and methods for this study, followed by the presentation of the results in section 4, which includes descriptive and model-based analyses. Results are discussed in section 5 as the basis for drawing conclusions and for developing recommendations for the future design of mixed traffic provisions for cyclists in section 6.

2 German legal framework and international guidelines

Mixed traffic in Germany means that no separate cycle facilities are provided on the street. Pavements are for pedestrians only and are not open to cyclists. Cyclists must cycle on the carriageway and share the space with motorised vehicles; cycling on the pavement is prohibited and is against the German Road Traffic Regulations. The only exception to this rule is made for children. According to section 2 (5) of the German Road Traffic Regulations (Leue & Bouska, 2018), children up to the age of eight must cycle on the pavement; they may use the pavement up to the age of ten. Children up to the age of eight may be accompanied on the pavement by a person of any age.

The guidelines for cycle facilities in Germany (FGSV, 2010) recommend mixed traffic provision with a speed limit of 50 kilometres per hour up to a volume of 400 motorised vehicles per hour and with a speed limit of 30 kilometres per hour up to a volume of 800 motorised vehicles per hour. Table 1 provides an overview of the criteria for mixed traffic provision for cyclists in urban areas according to international guidelines. The table shows that other countries, such as the Netherlands, are stricter than Germany and only recommend the mixing of cyclists and motorised vehicles on residential streets with low volumes (< 500 motorised vehicles per hour) and speeds (30 or 40 kilometres per hour) of motorised traffic. Only a few countries are identified that recommend mixed traffic provision at a speed limit of 50 kilometres per hour. These countries use lower thresholds for the volume of motorised traffic. Austria is the only exception where mixed traffic solutions are recommended up to 10 000 motorised vehicles per hour. The high thresholds for mixing cyclists and motorised vehicles in Germany raise questions about possible negative impacts on cyclists' safety and comfort but also provide an opportunity to examine cyclists' compliance with mixed traffic provision, as is done in this study.

3 Data and methods

3.1 Study sites and design features

The empirical work in this study is based on video observations at 273 study sites located at 138 street sections in 13 German cities with a total length of 124 kilometres. All street sections have 2-lane carriageways with one lane per direction. A study site is defined as one side of a street section, including the pavement and the part of the carriageway that is used to travel in the same direction. 260 of these study sites have no markings at all for cyclists, and 13 have bicycle pictograms. All street sections are main streets, part of the cycle network and have a carriageway width between 5.00 and 8.50 metres. The infrastructure and exposure data are taken from previous studies by Schüller et al. (2023), Ohm et al. (2015) and Koppers et al. (2021). The data are merged, checked for plausibility and combined with additional data where necessary.

The dataset is based on street sections, which are first processed and then divided into study sites in the respective travel directions. Street sections were defined differently in the three studies providing the data, so they need to be harmonised as a first step of data processing. The criteria for defining a street section in this study are chosen based on the following considerations and applied to all data:

- Each street section must be homogeneous in terms of infrastructure design (e.g. number of lanes, type of cycle facilities, parking provision) and operation (e.g. speed limit).
- Street sections are cut off at major intersections where the examined street section crosses another major street. Possible changes in traffic volumes are the main reason for this criterion. Street sections are not cut off at minor intersections, where residential streets cross, because no significant changes in traffic volumes are expected. Minor intersections are considered as a characteristic of a street section (measured as the density of minor intersections) and

Table 1 International overview of criteria for mixed traffic provision for cyclists in terms of speed and volume of motorised traffic on urban streets (Hantschel, 2022)

Country	Source	Mixed traffic recommended with $AADT_{mot}$ [veh/24h] and speed limit [km/h]			Bicycle pictograms
		30	40	50	
Denmark	Andersen et al. (2012)		≤ 2 500		not mentioned
Germany	FGSV (2010)	≤ 8 000		≤ 4 000	not mentioned
France	Cerema (2020)	≤ 5 000*			not mentioned
Great Britain	DfT (2020)	≤ 2 500			not mentioned
Ireland	NTA (2023)	≤ 4 000			not mentioned
the Netherlands	CROW (2016)	≤ 5 000*			not mentioned
Norway	NPRA (2013)			≤ 4 000	not mentioned
Austria	FSV (2014)	≤ 15 000		≤ 10 000	not mentioned
Switzerland	VSS (2017)	≤ 8 000			not mentioned
Australia	Austroads (2017)	≤ 6 000		≤ 3 000	not mentioned
Canada	MTO (2021)		≤ 3 000		recommended
USA	NACTO (2014)**			≤ 3 000	recommended

*Additional criteria for cyclist volume < 2 500 cyc/24h
**No criteria mentioned in AASHTO (2012)

not as cut-off points.

Homogeneity of infrastructure design and operation for each street section, as the first of the two criteria introduced above, is detailed based on Hantschel (2022) with the following characteristics that should not vary within a street section:

- type of cycle facility (mixed traffic without any marking, bicycle pictograms)
- presence of parking (on one side, on both sides, no parking)
- lane and pavement width
- speed limit (50 kilometres per hour, < 50 kilometres per hour)
- tram tracks (present, not present)
- raised median (present, not present)

With the street sections being spatially delineated, the final dataset of the study sites can be compiled. Based on the spatial delineation, the guidelines' requirements and the literature, the characteristics listed in Table 2 are collected and analysed as possible explanatory variables for the decision of cyclists to use the carriageway or the pavement at each study site. The variable 'city type' is included as a proxy for city size and city characteristics in terms of spatial structures, transport supply and residents' travel behaviour (Gerike et al., 2020). This variable is defined based on the theory of central places which is the basis for spatial planning in Germany. Different levels of equipment with public facilities and services (e.g. for education and health care) are assigned to each municipality depending on their status in the hierarchy of central places (Gerike et al., 2011).

3.2 Exposure

The volumes of bicycles, motorised vehicles and pedestrians were counted from video recordings at one cross section per study site. The traffic volumes for the three user groups are assumed to be constant over the whole length of a study site due to their spatial definition, as introduced above. The traffic volumes are available as total average hourly volumes for all study sites. Bicycle volumes are measured separately for cyclists riding on the carriageway and the pavement.

All counts were carried out between 2012 and 2019 on weekdays (excluding local holidays) and from April to October. 80% of the counts were carried out in 2017. The counts were carried out over a period of three hours. The time of day varied, with 88% of the counts taking place between 3 pm and 6 pm. Other counting times were 8–11 am, 9–12 am, 10 am–1 pm, 1–4 pm and 2–4 pm.

Table 2 Definition of variables describing the individual study site

Variable	Level of measurement	Unit/ Value
Bicycle pictograms	categorical	[no | yes]
Lane width	categorical	[< 3.00 m | 3.00 to 3.50 m | > 3.50 m]
Pavement width	continuous	[m]
Presence of car parking	categorical	[no | yes]
Type of car parking	categorical	[no parking | parallel | angle | perpendicular | mixed]
Location of car parking	categorical	[no parking | carriageway | carriageway marked | parking bay | pavement | mixed]
Car parking proportion of the total length	continuous	[%]
Speed limit	categorical	[50 km/h | < 50 km/h]
Median	categorical	[no | marked | raised]
Tram tracks	categorical	[no | yes]
Buildings with shops: proportion of the total length	continuous	[%]
Density of minor intersections with traffic lights	continuous	[intersection/km]
Density of minor intersections without traffic lights	continuous	[intersection/km]
Density of centre islands (crossing facilities)	continuous	[crossing facility/km]
Density of signalised pedestrian crossings	continuous	[crossing facility/km]
Density of crosswalks	continuous	[crossing facility/km]
City type (Central place theory)*	categorical	[upper-level centres| mid-level centres]

*Based on the theory of central places, selected municipalities in Germany are assigned with categories from lower to upper-level centres in spatial planning, which corresponds to different levels of equipment with facilities of public services. Two groups of centrality are distinguished in this study: upper-level centres: highest level of centrality, provision of all types of specialised services; mid-level centres: second level of centrality, provision of specialised services to complement upper-level centres and to provide for municipalities with lower or no level of centrality in their catchment area (Gerike et al., 2011).

Children and adults accompanying children were not included in the evaluation, as German law requires them to cycle on the pavement until the age of eight and allows it until the age of ten.

3.3 Statistical analysis

Schüller et al. (2023) measure cyclists' compliance with mixed traffic provision as the proportion of cyclists on the carriageway. They model compliance levels with linear multiple regression, assuming that deviations are normally distributed. Binary regression is a possible alternative to linear regression in this case, as the decision to cycle on the carriageway versus the pavement is binary. It is further supported by the fact that cycling on the carriageway is a legal requirement in Germany for mixed traffic provision, as is the case for all sites in this study. The distribution of frequencies should approach a proportion of cyclists using the carriageway of one when the majority of cyclists behave in accordance with the traffic rules. Therefore, a binary logistic model is chosen for this study to explain the probability of cyclists riding on the carriageway. It is shown in its basic form in Equation (1):

$$\log\frac{\pi_i}{1-\pi_i} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \tag{1}$$

with

π_i: probability of occurrence P (cyclist rides on the carriageway);

x_k: explanatory variables to be multiplied by the regression coefficients β_k.

The explanatory variables used to develop the binary regression model describe the exposure (volumes of pedestrians, cyclists, motorised vehicles) and infrastructure characteristics (as presented in Table 2) at each study site; they are identical for each cyclist at a study site. When covariate vectors (i.e., rows of the design matrix) are identical, for example when multiple observations are made under the same conditions (cyclists making decisions about where to cycle at a study site), the data can be grouped. This means that the design matrix only contains rows with unique covariate vectors. For modelling the probability π_i, the same binary regression models can be used as in case of individual data (Fahrmeir et al., 2013). We follow this approach and group all cyclists at each study site, which reduces the number of cases from 34 874 cyclists to 273 study sites. The dependent variable is defined as the ratio of the number of events (number of cyclists on the carriageway) to the number of observations (total number of cyclists) at the study site rather than a yes/no decision by an individual cyclist, as would be the case with ungrouped data. Each of the 273 study sites is treated as one group because they all differ in the volume of the different user groups. To address the disparity in the number of observations (total number of cyclists) across study sites and to ensure that groups with larger observation counts exert a proportional influence on the model, the total number of cyclists across all study sites is normalised to a standard value of 100.

Correlations between study site characteristics related to infrastructure, operation and exposure are analysed using bivariate Spearman coefficients before modelling. Characteristics correlated by a factor of 0.5 or more are not to be considered together in one model. In these cases, both variables were tested for significance in the model. If both variables were significant, the one with the greatest explanatory power was included in the model.

4 Results

4.1 Descriptive analysis

34 874 cyclists (29 802 cyclists on the carriageway and 5 072 cyclists on the pavement) are recorded at the 273 study sites. The average proportion of cyclists using the carriageway across all study sites is 80%. Table 3 and Table 4 provide an overview of key descriptive characteristics of cyclists' compliance levels with the mixed traffic provision at the 273 study sites for each explanatory variable. It gives a first insight into the effects of the different variables on the proportion of cyclists using the carriageway, but correlations between the variables must be considered. Compliance levels are higher at study sites with bicycle pictograms than at sites without markings. We observe higher compliance levels at study sites with a narrow lane width (< 3.00 metres) than at sites with wider lane widths and at study sites without marked or raised medians. Lower speed limits (40 or 30 kilometres per hour) show a higher proportion of cyclists on the carriageway than at a speed limit of 50 kilometres per hour. A non-infrastructure-related effect is the higher compliance level in upper-level centres compared to mid-level centres. The higher proportion of cyclists using the carriageway in mixed traffic with parking compared to no parking seems to be a general effect across the three considered variables; no clear pattern can be identified for the different types of parking. There are also no differences in the presence of tram tracks.

Exposure data on the volume of all user groups range from low to very high on the study sites. When comparing the motorised traffic volumes with the recommendations for cycling in mixed traffic in Germany (see section 2), it can be seen that the maximum motorist volume is 959 vehicles per hour, which is higher than the recommendation of a maximum of 800 motorised vehicles per hour for a speed limit of 30 kilometres per hour (FGSV, 2010).

The correlation matrix in Appendix A shows the relationships between the independent variables. Only correlations that are significant at a significance level of 5% are included in the table. Strong correlations (> 0.5) are highlighted in pink and briefly described here: the pedestrian and cyclist volumes show a positive correlation (at study sites with more cyclists, we also observe more pedestrians). The volume of pedestrians is also correlated with the density of shops in a study site. In addition, there are strong correlations between all variables describing parking characteristics.

4.2 Model

Table 5 shows the results of the model describing the probability of cyclists using the carriageway. The main effects on the probability of cyclists using the carriageway (interpretation of odds ratios (OR = $\exp(\beta_k \cdot \mathrm{x}_k)$)) can be described as follows: The higher the cyclist volume, the higher is the probability of cyclists using the carriageway. For example, the chances of cyclists using the carriageway is three times higher with a volume of 200 cyclists per hour compared to 100 cyclists per hour. An increase in motorist volume has an opposite but weaker effect: the higher the volume of motorised vehicles, the lower the probability of cycling on the carriageway (e.g. the chances decrease by a factor of 0.8 for a volume of 500 motorised vehicles per hour compared to 400 motorised vehicles per hour). It can be seen that the cyclist volume has a greater influence than the volume of

Table 3 Section characteristics and proportion of cyclists on the carriageway

Proportion of cyclists on the carriageway	Value	Study sites	Min	Q15	Mean	Q85	Max
Total	-	273	0.06	0.64	0.80	0.95	1.00
Bicycle pictograms	no	260	0.06	0.64	0.80	0.95	1.00
	yes	13	0.65	0.84	0.89	0.96	0.99
Lane width	< 3.00 m	11	0.78	0.81	0.90	0.99	1.00
	3.00 to 3.50 m	170	0.06	0.63	0.79	0.96	1.00
	> 3.50 m	92	0.13	0.65	0.81	0.95	1.00
Presence of parking	no	72	0.13	0.51	0.77	0.96	1.00
	yes	201	0.06	0.66	0.81	0.95	1.00
Type of parking	no parking	72	0.13	0.51	0.77	0.96	1.00
	parallel	186	0.06	0.66	0.81	0.95	1.00
	angle/ perpendicular/ mixed	15	0.18	0.67	0.79	0.92	0.97
Location of parking	no parking	72	0.13	0.51	0.77	0.96	1.00
	carriageway	90	0.49	0.73	0.84	0.95	1.00
	carriageway marked	13	0.06	0.45	0.69	0.96	0.99
	parking bay	32	0.48	0.63	0.77	0.92	0.97
	pavement	51	0.18	0.66	0.80	0.93	1.00
	mixed	15	0.72	0.74	0.86	0.96	1.00
Speed limit	50 km/h	201	0.06	0.62	0.78	0.94	1.00
	40 km/h	8	0.80	0.84	0.91	0.96	0.96
	30 km/h	64	0.42	0.76	0.86	0.97	1.00
Median	no	121	0.13	0.72	0.83	0.95	1.00
	marked	150	0.06	0.56	0.78	0.95	1.00
	raised	2	0.74	0.75	0.79	0.82	0.83
Tram tracks	no	237	0.06	0.64	0.80	0.96	1.00
	yes	36	0.48	0.72	0.81	0.92	1.00
City type (central place theory)	upper-level centres	251	0.13	0.65	0.81	0.96	1.00
	mid-level centres	22	0.06	0.55	0.71	0.92	1.00

Table 4 Exposure

Exposure	Unit	Min	Q15	Mean	Q85	Max
Cyclist volumes in the direction of travel	cyclists/h	2	8	43	77	403
Pedestrian volumes on the adjacent pavement	pedestrians/h	0	12	64	113	659
Volume of motorised vehicles in the direction of travel	vehicles/h	11	172	322	472	959
Proportion of heavy vehicles	%	0	1	3	5	23

motorised vehicles. The presence of bicycle pictograms increases the chance of cyclists using the carriageway by a factor of 1.8 compared to mixed traffic situations without markings. In terms of lane width, medium and wide profiles show similar effects, but the presence of narrow profiles compared to the other two profiles increases the chance of cycling on the carriageway by a factor of about two (inverse of the OR). Both effects should be interpreted with caution because the number of study sites with bicycle pictograms (13) and with a lane width < 3 metres (11) is small (Table 3). Speed limits < 50 kilometres per hour (40 or 30 kilometres per hour) increase the chance of cycling on the carriageway by a factor of 1.6. Compared to upper-level centres, the chance of cycling on the carriageway decreases by a factor of 0.6 in mid-level centres. With a McF-R^2 of

Table 5 Results of the logistic regression model with grouped data for the probability of cyclists on the carriageway

Variable	Unit/features	Regression coefficient β[1]		SE	OR	p[2]
Constant term	-	2.557	****	0.268	12.901	****
Cyclist volume in direction of travel	cyclists/h	0.011	****	0.002	1.011	****
Volume of motorised vehicles in direction of travel	vehicles/h	-0.003	****	0.000	0.997	****
Bicycle pictograms	none	Ref.			Ref.	0.055
	yes	0.581	*	0.287	1.787	
Lane width	< 3.00 m	Ref.			Ref.	0.087
	3.00 to 3.50 m	-0.720	**	0.228	0.487	
	> 3.50 m	-0.714	**	0.238	0.490	
Speed limit	50 km/h	Ref.			Ref.	***
	< 50 km/h	0.498	***	0.132	1.645	
City type (Central place theory)	upper-level centres	Ref.			Ref.	**
	mid-level centres	-0.584	***	0.169	0.558	
McF-R^2 = 0.43						
AIC = 4002.07						

[1]Significance of the coefficient (Wald test) * < .05 ** < .01 *** .001 **** < .0001
[2]Significance model effect (likelihood ratio test) * p < .05 ** p < .01 *** p < .001 **** p < .0001

0.43, the model shows a good fit to the database.

The results of the model show a relatively small regression coefficient for the exposure variables, but their unit of cyclists resp. motorised vehicles per hour must be taken into account. At the same time, the analysis of the explanatory power of the independent variables (deviance/df) in Figure 2 shows that these two variables explain most of the deviance. For the infrastructural and operational characteristics, explanatory power is highest for the speed limit. The city type explains a higher proportion of the deviance than lane width and bicycle pictograms, which hardly cause any change in the deviance.

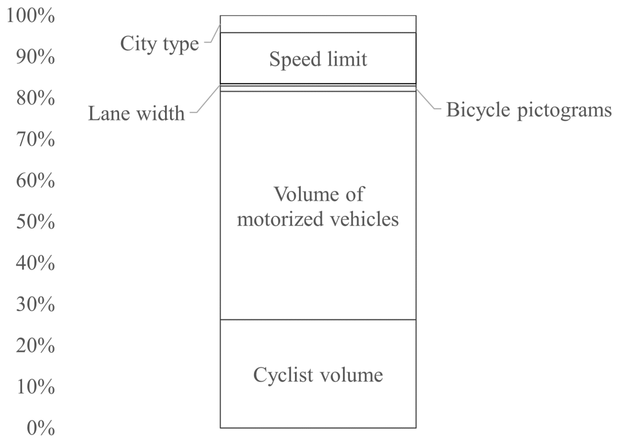

Figure 2 Explanatory power of independent variables (deviance/df) without the unexplained proportion of the total deviance

4.3 Application

The model can now be used to develop evidence-based recommendations on appropriate conditions for mixed traffic provision for cyclists, ensuring pre-defined levels of compliance, measured as the probability of cyclists using the carriageway. To illustrate this capability, we apply the model to predict the probability of cyclists using the carriageway in different scenarios with varying volumes of motorised vehicles, speed limits and the presence/absence of bicycle pictograms. Fixed values are set for the other model variables as follows:

- Cyclist volume = 43 cyclists per hour: This is the average value in the dataset that seems most appropriate, as the recommendations should apply to all levels of cycling.
- Lane width = 3.00 metres to 3.50 metres: This is the most common lane width in German cities and is also recommended in the guidelines for standard lanes with buses or heavy goods vehicles as the design vehicle.
- City type = 0.1: This is the average of the dataset, with 10% of cities classified as mid-level centres.

Figure 3 shows the predicted probability of cyclists on the carriageway as a function of the volume of motorised vehicles for speed limits of 50 kilometres per hour (black) and < 50 kilometres per hour (red) and for streets without any markings (solid) or with bicycle pictograms (dashed). The general shape of the curves shows a negative correlation between traffic volume and the probability of cyclists using the carriageway. The influence of a speed limit < 50 kilometres per hour and the bicycle pictograms, as identified in the model above, is well visible and of the same magnitude. Study sites with a speed limit of 50 kilometres per hour and bicycle pictograms achieve similar probabilities of cyclists using the carriageway as study sites with speed limits of < 50 kilometres per hour without markings.

Assuming a 90% probability of cyclists using the carriageway, cycling in mixed traffic can be recommended for a combination of a maximum of 400 motorised vehicles per hour and a speed limit of < 50 kilometres per hour. Similarly, recommendations for other compliance levels and combinations of speed limit, marking and vehicle volumes can be derived from the model application.

We would like to emphasise the effect of cyclist volumes on the probability of cyclists using the carriageway even more clearly and therefore present a second model application in Figure 4, showing the relationship between cyclist volume and the probability of cycling on the carriageway for streets with a speed limit < 50 kilometres per hour. The volume of motorised vehicles is set to 200, 400 and 600 vehicles per hour and per direction. The same fixed values are used for lane width and city type, as described above. The increase in the probability of cyclists using the carriageway with higher cyclist volume is clearly visible for all three values of the volume of motorised vehicles.

5 Discussion

The results of this study confirm and expand previous research. The large number of study sites made it possible to estimate a binary logistic regression model, taking into account the exposure of cyclists, pedestrians and motorised vehicles, as well as detailed infrastructure characteristics. In terms of exposure, the volume of motorised vehicles becomes significant, which is consistent with the descriptive findings from the literature on cyclists' compliance with mixed traffic provision (Koppers et al., 2021; Schüller et al., 2023; Zweibrücken et al., 1999) and also from the literature on cyclists' perception and evaluation of cycle facilities (Hu et al., 2023), and on cyclists' route choice (Rossetti et al., 2019).

Cyclist volume has a positive effect on the probability of cyclists using the carriageway, which we explain by individual cyclists feeling safer on the carriageway when they are part of a larger group. This indicates a positive self-reinforcing effect: Mixed traffic provision for cyclists in appropriate conditions increases the probability of cycling on the carriageway. When this increased probability leads to higher absolute numbers of cyclists on the carriageway, then cyclist volumes will in turn lead to higher compliance levels. These mechanisms must not be translated into guidelines recommending mixed traffic provision for higher volumes of motorised vehicles when cyclist volume is high, as this could lead to a negative downward trend: Some cyclists might avoid the carriageway because of the high volume of motorised vehicles, reducing compliance levels and thus the number of cyclists on the carriageway, etc. Instead, the positive effect of cyclist volumes on compliance levels should only be understood as a positive side effect of appropriate conditions for mixed traffic provision, which should be chosen to ensure high proportions of cyclists using the carriageway, which will then have a positive self-reinforcing effect, increasing cyclist volumes and thus again the proportion of cyclists on the carriageway.

Pedestrian volume does not become significant in the model. Still, due to the (moderate) correlation between pedestrian and cyclist volumes in our data, we cannot exclude that pedestrian volumes also influence the probability of cyclists using the carriageway. Previous survey-based studies (Hu et al., 2023), as well as descriptive findings from on-site studies on cyclists' compliance with mixed traffic provision (Schüller et al., 2023; Zweibrücken et al., 1999), suggest such effects of pedestrian volume, finding higher proportions of cyclists using the carriageway on streets with actively used buildings (e.g. shops), which may be a proxy for higher pedestrian numbers on the pavement. It appears that motorised vehicles push cyclists onto the pavement and pedestrians push cyclists onto the carriageway, which is plausible but further research based on data with a lower correlation between pedestrian and cyclist volumes is needed to confirm this hypothesis and determine the extent of these opposing effects.

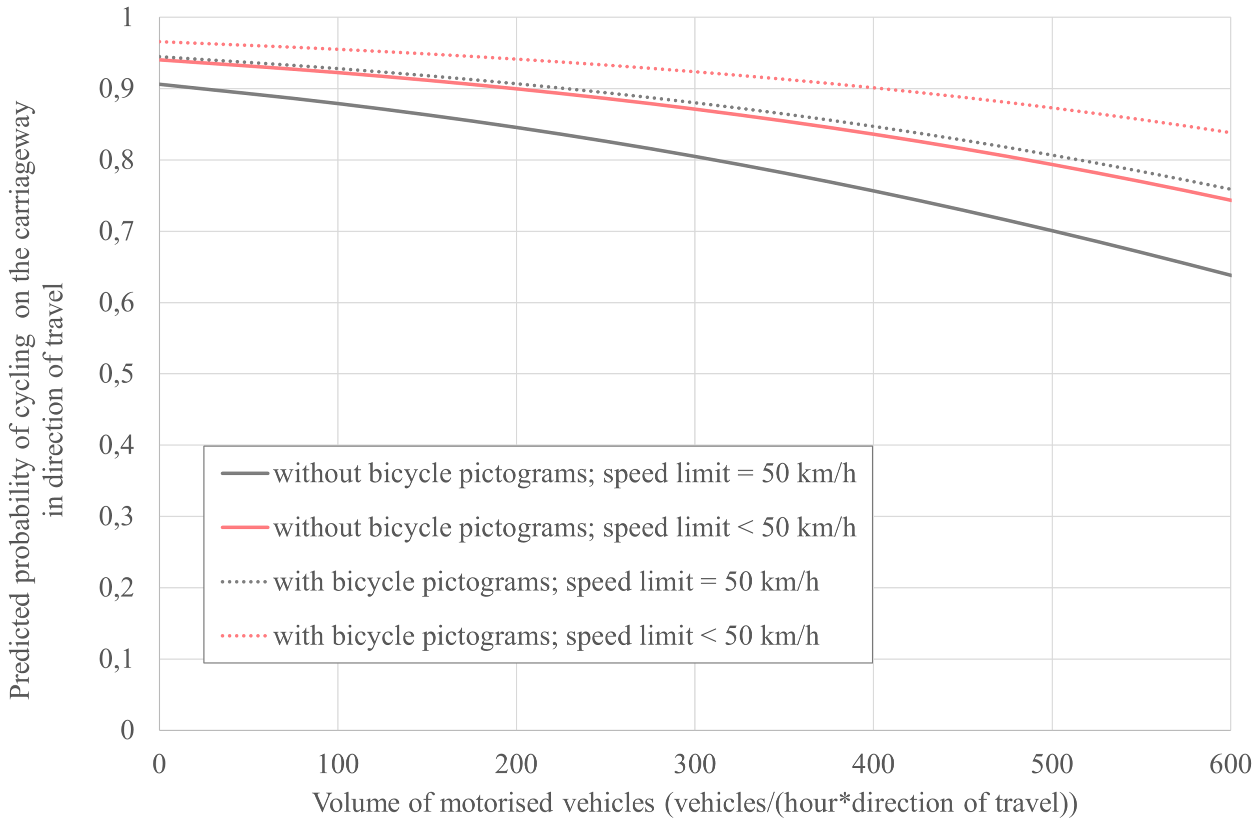

Figure 3 Predicted probability of cycling on the carriageway based on the model results by volume of motorised vehicles

In terms of infrastructure characteristics, the probability of cycling on the carriageway is highest on narrow profiles with a width of less than three metres compared to the two groups of three to 3.5 metres and with more than 3.5 metres. A possible explanation could be that overtaking manoeuvres become more frequent as lane width increases (Ohm et al., 2015), which might be perceived as more uncomfortable. The low explanatory power of lane width in the model should be noted, meaning that the above explanations describe trends that would need to be validated in further research. Pavement width has no significant effect on the proportion of cyclists on the carriageway in our data, which might be due to interactions with pedestrian volume.

No significant effects are found for other infrastructure characteristics, such as the median (marked or raised), the presence of tram tracks and parking. However, findings from the descriptive analyses, as shown in Table 3, indicate trends for the median and the presence of parking. Study sites without a marked or raised median have a higher probability of cyclists using the carriageway, which could be explained by an interaction with lower numbers of motorised vehicles and lower lane widths. The only correlations found in our data are between the presence of any type of median and volumes of motorised vehicles, which is higher at study sites with marked or raised medians, and a higher volume of motorised vehicles negatively affects the probability of cycling on the carriageway, as shown.

The presence of parking is not significant in the model but is associated with a higher probability of cyclists using the carriageway in the descriptive analysis in this study, contrary to the results of Zweibrücken et al. (1999), who find lower compliance levels in street sections with parking spaces on the carriageway, and also to studies investigating cyclists' perceived safety (Chataway et al., 2014; FixMyCity, 2020). Possible explanations are that parking is associated with more intensive use of the buildings, which is used as a proxy for pedestrian volumes in some studies and is correlated with the presence of shops and pedestrian volumes in this study. It has also been shown in the literature that the presence of parking reduces the average speeds of motorised vehicles (Schüller, 2010). It is also conceivable that parking visually narrows the width of the carriageway. This could lead to fewer

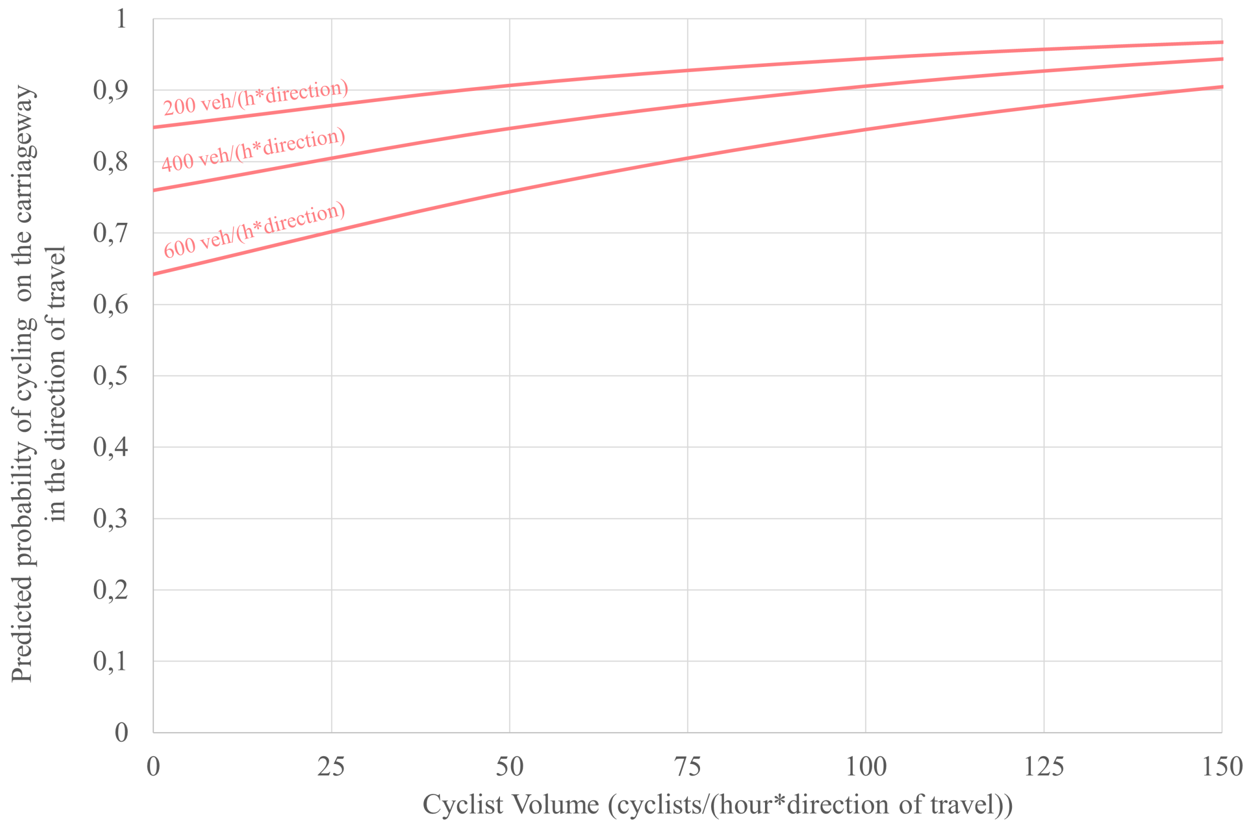

Figure 4 Predicted probability of cycling on the carriageway based on the model results by cyclist volume, volume of motorised vehicles, without bicycle pictograms and a speed limit of < 50 km/h

overtaking manoeuvres and, in turn, lower average speeds of motorised vehicles (Schüller, 2010). In addition, vehicles parked on the carriageway might be a barrier for cyclists, preventing them from moving onto pavement. It should also be noted that around 30% of accidents on street sections with mixed traffic are related to parking (Hantschel, 2022).

The highest explanatory power in terms of operational characteristics is found for the speed limit. A speed limit of < 50 kilometres per hour (40 or 30 kilometres per hour) significantly increases the probability of cycling on the carriageway in mixed traffic conditions, which is consistent with the literature. For example, Rossetti et al. (2018), Rossetti et al. (2019) and FixMyCity (2020) find negative effects of high speeds of motorised vehicles on cyclists' route choice and on cyclists' perceived safety.

Markings with bicycle pictograms significantly increase the probability of cyclists using the carriageway compared to mixed traffic without any markings, which is consistent with the literature (Birk et al., 2004; Hunter et al., 2010; Koppers et al., 2021; Pein et al., 1999) but should be interpreted with caution, as the number of street sections with pictograms is very low at 13. Conclusions from these consistently positive effects of pictograms on cyclists' compliance with mixed traffic provision in the literature and this study should be carefully considered. In principle, all streets should be designed so that all users, including cyclists, use them intuitively and in accordance with the traffic rules.

City type is an interesting variable that has not been considered before. Streets in upper-level centres show a significantly higher probability of cyclists using the carriageway than those in mid-level centres. A possible explanation for this might be that the modal share of cycling is generally higher in upper-level than mid-level centres (Gerike et al., 2020). This may lead to a higher presence of cyclists in the city (regardless of the cyclist volume at the considered study sites). A possible explanation for this might be that the modal share of cycling is generally higher in upper-level than mid-level centres (Gerike et al., 2020). This may lead to a higher presence of cyclists in the city (regardless of the cyclist volume at the considered study sites), which in turn could mean that cyclists are more familiar with motorised vehicles and vice versa. The higher modal share of cycling in upper-level centres also means that more motorists do also cycle, which might have a positive impact on cyclists' view of motorists and vice versa, which has been shown to be relevant in previous studies on how aggressive both user groups behave in the street (Kaplan et al., 2019; Piatkowski et al., 2017).

This study is based on on-site observations; one limitation is that we do not consider personal characteristics. Age, gender, cycling practice, and earlier incidents experienced by cyclists are shown in previous studies to impact how safe cyclists feel. They can also be assumed to affect how likely cyclists are to use the carriageway. The consideration of coping strategies is limited to whether or not cyclists use the carriageway. Further possible coping strategies, such as choosing other modes of transport, alternative routes to avoid street sections with mixed traffic provision or other departure times for a trip to avoid peak-hour traffic, are not considered in this study focusing on on-site behaviour. The high correlation between pedestrian and cyclist volumes is another limitation of this study. Previous studies have found that higher pedestrian volumes negatively influence cyclists' perception and compliance with mixed traffic provision. This study finds that higher cyclist volumes positively influence the proportion of cyclists using the carriageway. Further research based on data with lower correlations between pedestrian and cyclist volumes would allow these effects to be disentangled. Studies in countries with different legal frameworks would be interesting to better understand the relevance of the legal requirement to use the carriageway in Germany compared to cyclists' perceptions of the street environment.

It should be noted that this study only considered people who already cycle. It would be interesting to assess how cycle-friendly mixed traffic provisions affect the attitudes and/or concerns of 'interested but concerned' cyclists.

6 Conclusions

The results of this study provide new insights into the complex interdependencies between the different factors influencing cyclists' behaviour in mixed traffic conditions. Based on a case study in Germany, where guidelines allow mixed traffic for cyclists on streets with a speed limit > 30 kilometres per hour and where cyclists are requested by law to use the carriageway, this study is to our best knowledge the first to quantify the effects of exposure and street characteristics on cyclists' compliance with mixed traffic provision.

Returning to the three research questions, this study finds an average proportion of cyclists using the carriageway of 80% across all 273 study sites, which is relatively high compared to the literature presented in Figure 1, where mean proportions of appr. 65% are found for mixed traffic provision and appr. 85% for advisory cycle lanes. One reason for this difference might be that the studies in Figure 1 include 2-lane and 4-lane street sections, whereas this study only analyses 2-lane street sections. Other possible reasons include different countries with specific legal frameworks, small case numbers in some studies, and city size and type. On the one hand, the value of 80% is low considering that cycling on the carriageway is a legal requirement in Germany for mixed traffic. It means that one in five cyclists does not obey the traffic rules even though cyclists in Germany generally have a good knowledge of the legal framework (Schüller et al., 2023); they know where they are expected to cycle. On the other hand, it can be assumed that the cyclists in this study use the carriageway because they feel sufficiently safe and comfortable but also because they are legally obliged to do so. There may be cyclists in our sample who would prefer to cycle on the pavement but do not do so to avoid violating the traffic rules. The proportion of cyclists using the carriageway in mixed traffic provision might be even lower in countries where cyclists are free to choose where they cycle.

In terms of the determinants of the probability of cyclists using the carriageway, the high relevance of volume and speed of motorised traffic found in this study is consistent with previous studies that are mainly survey-based and analyse cyclists' perceptions of different street environments as well as route choices. Previous studies consistently show that cyclists feel unsafe on the carriageway with high volumes of motorised vehicles sharing the same space. This study finds that cyclists are less likely to use the carriageway when it is heavily loaded with motorised vehicles. It thus describes the consequence of the negative perceptions found in previous studies. Hardly any studies have considered the effect of cyclist volumes. The positive relationship between cyclist volumes and the probability of cyclists using the carriageway in this study positively reinforces compliance levels in streets with mixed traffic provision under appropriate conditions. Speed limit, lane widths and bicycle pictograms are the significant infrastructure characteristics in the model, while the presence of a median (marked or raised), tram tracks, or parking shows no significant effect on compliance levels. City type as a proxy for city size and city characteristics in terms of transport provision and travel behaviour of residents is also significant.

The developed model is directly applied to derive recommendations for mixed traffic provision, which can only be recommended up to a maximum volume of 400 motorised vehicles per hour and a speed limit of < 50 kilometres per hour, with narrow profiles being preferred. These thresholds are necessary to achieve a 90% probability of cycling on the carriageway; they can and need to be adjusted according to political preferences. These recommendations are in line with those of the Netherlands, Great Britain, France and Ireland (Cerema, 2020; CROW, 2016; DfT, 2020; NTA, 2023) and call for a clear hierarchy in the cycle network: Mixed traffic designs should only be provided for cyclists where the volume and speed of motorised vehicles are low. Separate cycle facilities should be provided where volumes of motorised vehicles are high and/or motorised vehicles travel at higher speeds.

Overall, this study contributes to the comprehensive understanding of the mechanisms of cycling provision, cyclists' perceptions and behaviour. It shows that mixed traffic provision for cyclists on main streets can achieve high compliance levels, it shows the key determinants of cyclists' willingness to comply with mixed traffic provision, and it also shows the consequences when exposure and infrastructure characteristics do not match cyclists preferences and perceived safety.

CRediT contribution statement

Sebastian Hantschel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft. **Bettina Schröter:** Writing—review & editing. **Regine Gerike:** Supervision, Writing—original draft, Writing—review & editing.

Declaration of competing interests

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.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for profit sectors.

Acknowledgements

This paper is based on the work presented earlier in a PhD dissertation 'Einflussfaktoren auf die Akzeptanz und die Verkehrssicherheit des Radverkehrs im Mischverkehr auf innerstädtischen Hauptverkehrsstraßen [Factors influencing the acceptance and road safety of cycling in mixed traffic on urban main roads]', by Sebastian Hantschel, defended at Dresden University of Technology on August 2022.

An early version of this paper was presented at the 11^{th} International Cycling Safety Conference, held in the Hague, the Netherlands, on 15–17 November 2023.

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About the authors

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Bettina Schröter is a research associate at the Chair of Mobility System Planning at TUD. After studying traffic engineering in Dresden, she is now a PhD student. Her research interests focus on bicycle safety in general and the analysis of bicycle crashes and bicyclists' safety-related behaviour in particular.

Regine Gerike is head of the Chair of Mobility System Planning at TUD. Before joining TUD, she chaired the Institute for Transport Studies at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria. From 2008 to 2012 she was assistant professor at Technische Universität München, head of the Research centre mobility and transport and of the PhD-program 'mobil.LAB Sustainable Mobility in the Metropolitan Region of Munich'. Her research interests include transport planning and traffic safety with a focus on vulnerable road users.

A Correlation matrix

	Cyclist volume in direction of travel	Pedestrian volume on the adjacent pavement	Volume of motorised vehicles in direction of travel	Proportion of heavy vehicles	Bicycle pictograms	Lane width	Pavement width	Presence of Parking	Type of parking	Location of the parking	Proportion length of car parking	Speed limit	Median	Tram tracks	Proportion length of buildings with shops	Density of minor inter-sections with traffic lights	Density of minor inter-sections w/o traffic lights	Density of centre islands (crossing facilities)	Density of signalised pedestrian crossing	Density of crosswalks	City type
Cyclist volume in direction of travel																					
Pedestrian volume on the adjacent pavement	0.54																				
Volume of motorised vehicles in direction of travel	0.23	-																			
Proportion of heavy vehicles	0.16	0.20	-																		
Bicycle pictograms	-	-	-0.22	-																	
Lane width	0.22	0.22	0.16	0.12	-0.13																
Pavement width	0.31	0.36	0.19	-	-0.15	0.35															
Presence of Parking	-	0.27	-	-	-	0.25	0.28														
Type of parking	0.16	0.29	-	-	-	0.26	0.22	0.94													
Location of the parking	-	-	-	-0.17	0.18	-	-	0.79	0.79												
Proportion length of car parking	0.14	0.27	-	-	-	0.29	0.34	0.77	0.71	0.55											
Speed limit	-0.15	-	-0.14	0.17	-	-	-0.13	-0.15	-	-	-0.15										
Median	-	-	0.35	-	-	-	-	-	-	-	-	-									
Tram tracks	0.21	0.32	-	-	-	-	-	-	-	-	-	-0.18	-								
Proportion length of buildings with shops	0.40	0.56	-	0.26	-	0.18	0.19	-	-	-	-	-	-	0.31							
Density of minor intersections with traffic lights	-	0.17	-	0.29	-	0.21	-	-	-	-	-	0.15	-	-	0.20						
Density of minor intersections w/o traffic lights	-	-	-0.26	-	-	-	-	-	-	-	-0.13	-	-0.13	0.24	0.14	-0.20					
Density of centre islands (crossing facilities)	-	-0.13	0.12	-	-	-	0.13	0.17	0.15	0.15	-	-	-	-0.14	-	-	-				
Density of signalised pedestrian crossing	-	-	-	-	-	-	-	0.13	0.17	-	-	0.14	-0.17	-	-	-	0.17	-			
Density of crosswalks	-	-	-	-	-	-	-	-0.22	-0.18	-0.19	-0.16	0.17	-	-	-	-0.13	0.20	-	-		
City type	-0.33	-0.17	-0.19	-0.26	0.25	-0.23	-0.18	-	-	0.16	-	-	-	-	-0.18	-0.13	-	-	-	-0.12	