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Determinants of bicycle crashes at urban signalized intersections

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ABSTRACT

Problem: Bicycle volumes are increasing in many regions worldwide leading to higher relevance of an in-depth understanding of bicyclist safety mechanisms. Detailed studies on bicyclist safety that consider exposure and distinguish by intersection category and crash types are missing for urban signalized intersections, which are of particular relevance for bicyclist safety. *Method:* Based on a comprehensive dataset of motorist and bicyclist volumes and infrastructure characteristics for a sample of 269 signalized intersections in two German cities, we utilize a top-down approach to analyze firstly, bicycle crashes of all types and secondly, bicycle crashes by type including turning, right-of-way and loss-of-control. A combination of descriptive statistics and Accident Prediction Models (APM) are applied as analysis methods. *Results:* Bicycle volumes are relevant for all types of intersections and crashes, whereas the effect of motor vehicle volumes differ between these different applications. The separation of bicyclists from motor vehicles in time and space increases their safety but also leads to behavioral adaption and risk compensation. The likelihood of right-of-way crashes even increases with more separation in the signaling scheme. The main predictor for loss-of-control crashes in terms of infrastructure are tram tracks. *Summary*: This study provides insights on relevant determinants of bicycle crashes at urban signalized intersections at several levels of detail. Exposure variables as well as the physical separation of bicyclists from motor vehicles show consistent effects on bicycle crash numbers whereas the effects of signaling differ between crash types. *Practical Applications:* The different types of intersections and crashes follow each specific mechanism of bicyclist safety. The separation of bicyclists and motorists in time and space are paramount at intersections with high bicycle volumes. Risk compensation such as red light running becomes more important as intersections get smaller and motor vehicle volumes decrease.

1. Problem

The strong commitment of various stakeholders around the world, combined with the desire of many people to get around in a more environmentally friendly and healthy way, has led to a significant increase in cycling in recent years. For example, the distance cycled per capita in Germany increased by 64% between 1997 and 2017. These developments are associated with several positive effects for transport systems, the environment, the economy, and public health with one primary negative effect, which is safety. The number of injuries from crashes with bicycles in Germany increased by 11% during this period (between 1997 and 2017) with a continuing upward trend (Destatis, 2022b). Similar trends can be observed in other countries (Buehler & Pucher, 2021; European Commission, 2022). These developments are not in line with political ambitions, which consistently call for a significant reduction in the number of road injuries in the coming years and, in the long term, vision zero (see e.g. United Nations, 2020). Safe road infrastructure and bicycle facilities are paramount for increasing cycling levels and for decreasing cyclist injuries. Intersections are of particular relevance because about two-thirds of all bicycle crashes in Germany occur at intersections (Gerlach et al., 2020). Compared to street sections, intersections are far more complex in possible street users' maneuvers, risks and conflicts, design and operation. Of all intersection types, signalized intersections are the most complex ones because of their sheer size but also because (bicyclist) safety is not only influenced by road design, but also by signaling. In addition, signalized intersections have the highest traffic volumes for all road user types including bicycling. Therefore, improving safety at signalized intersections is an important lever for increasing overall bicycle safety.

Previous studies on determinants of cyclist safety at intersections include cross-sectional analyses of different intersections

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(Kolrep-Rometsch et al., 2013; Liu & Marker, 2020; Madsen & Lahrmann, 2017; Schnüll, 1992), case-control studies comparing locations with and without safety issues (Harris et al., 2013; Vandenbulcke et al., 2014; Zangenehpour et al., 2016), and before-and-after studies (Jensen, 2008a, 2009; Lyons et al., 2020; Nabavi Niaki et al., 2021). Crash data from official police statistics represent bicyclists' actual risk of injury (Kolrep-Rometsch et al., 2013; Liu & Marker, 2020; Madsen & Lahrmann, 2017; Schnüll, 1992). It is complemented by hospital data to address under-reporting of official police data, particularly for crashes with slight or no injuries (Below, 2016). The problem of under-reporting does not apply to video analysis where conflicts measured as Surrogate Safety Measures (SSM) or evasive actions are analyzed (Nabavi Niaki et al., 2021). Studies that analyze on-site behavior of cyclists such as the type of facilities used or red light running are also relevant for this study. They are based on on-site observations or video data where relevant indicators per user are determined (Van der Meel, 2013).

Considering methods analyzing crashes, those are analyzed in terms of absolute numbers, ratios of crashes and traffic volumes (crash rates) as well as multivariate statistics. Abdulhafedh (2017) gives an overview of the different possible multivariate methods in the so-called Accident Prediction Models (APM). Poisson regression and negative binomial regression are most frequently used.

Of the various relevant determinants of bicycle crashes, exposure is consistently of high relevance. Both bicycle and motor vehicle volumes matter in descriptive analysis (Kolrep-Rometsch et al., 2013) and APM with coefficients mainly below one (Elvik & Goel, 2019). This demonstrates the safety-in-numbers effect, which means that the number of crashes increases disproportionately as traffic volumes increase (Elvik & Bjørnskau, 2017; Elvik & Goel, 2019; Kolrep-Rometsch et al., 2013; Liu & Marker, 2020; Nordback et al., 2014; Turner, 2011).

Evidence on the influence of the type of bicycle facilities at signalized intersections is inconclusive. The general provision of bicycle facilities (lanes or tracks) increases the number of crashes compared to no bicycle facilities without considering exposure (Jensen, 2008a; Kolrep-Rometsch et al., 2013) but reduces crash rates (Kolrep-Rometsch et al., 2013) and also the likelihood of crashes in APM (Liu & Marker, 2020). Bicycle lanes reduce the likelihood of crashes in APM compared to bicycle tracks (Liu & Marker, 2020; Thomas & DeRobertis, 2013). Two-way bicycle tracks consistently increase the number of crashes compared to one-way facilities (Alrutz et al., 2009; Harris et al., 2013; Schnüll, 1992). Only Vandenbulcke et al. (2014) find positive effects for two-way bicycle tracks and explain this with bicyclists' behavioral adaption and risk compensation.

In addition to research on the type of bicycle facility, there are also studies on the influence of specific characteristics of these facilities on bicyclist safety, in particular for bend-outs (distance between the bicycle track and the edge of the main carriageway) and for colored bicycle lanes. Kolrep-Rometsch et al. (2013) find the highest crash rates for bend-outs of 2 m to 4 m compared to smaller and larger bend-out distances. Schnüll (1992) finds the highest crash numbers for the largest bend-out of > 4 m compared to smaller bend-outs, but also presents the highest bicycle volumes for these approaches. No clear effects are identified for colored bicycle lanes, these are not significant (Kolrep-Rometsch et al., 2013; Schnüll, 1992) or even increase crash numbers (Jensen, 2008b). The preferred installation of colored bicycle lanes at black-spot locations or risk compensation of bicyclists such as higher speeds or less attention belong to the possible reasons for these mixed findings.

In terms of infrastructure characteristics beyond the type of bicycle facility, Vandenbulcke et al. (2014) develop a complexity index for intersections as a proxy for road legibility. They quantify this index as the sum of all road links radiating outwards from the intersection over a certain distance and find significant effects of this indicator, the higher the complexity index, the higher the likelihood that crashes occur at an intersection. All other studies use more detailed infrastructure characteristics. Strauss et al. (2015) find a lower likelihood of crashes for signalized intersections with three arms compared to four arms, which supports the negative effect of higher complexity on crash numbers. Tram tracks are consistently significant in APM (Liu & Marker, 2020; Vandenbulcke et al., 2014), they increase the likelihood of bicycle crashes. Strauss et al. (2015) find negative effects of public transport stops at signalized intersections, but they are not significant in Liu and Marker (2020). Limited sight distances are reported as one reason for crashes in several studies. For example, Kolrep-Rometsch et al. (2013) and Jensen (2008a) identify sight obstacles as one main problem in their manual inspections of locations with particularly high crash numbers. Sight obstacles also increase crash rates, in some cases in relation with parking (Vandenbulcke et al., 2014). A lower speed limit of 30 km/h reduces crash numbers (Harris et al., 2013; Reynolds et al., 2009) and also the likelihood of crashes in APM (Liu & Marker, 2020).

Signaling is of high relevance for bicyclists' comfort and safety with clear interdependencies. Separate signaling (also called protected signaling) for right- or left-turning motor vehicles consistently decreases crash rates (Baier et al., 2018; Kolrep-Rometsch et al., 2013; Niewöhner & Berg, 2005; Sundstrom et al., 2018) and also the likelihood of crashes in APM (Liu & Marker, 2020). At the same time, separate signaling might increase circle cycle times and thus also waiting times for bicyclists and other road users, which might then decrease acceptance. Bicyclists might start circumventing rules (e.g., with red light running; Van der Meel, 2013), which then increases their crash risks. Studies on red light running of bicyclists mainly consider personal factors such as gender, age, or rider type and situational factors such as the group size or the direction of travel (Fraboni et al., 2018; Johnson et al., 2011; Schleinitz et al., 2019; Wang et al., 2019; Wu et al., 2012; Zhang & Wu, 2013). Red light running behavior is considered to be influenced by the presence of other users: bicyclists are more likely to run a red light if no other user is present with a stronger effect for the presence of motorists than for cyclists (Johnson et al., 2011). Regarding infrastructure, longer crossing distances decrease red light running (Van der Meel, 2013). Schleinitz et al. (2019) find higher rates of red light running for bicyclists on bicycle tracks compared to mixed traffic.

Overall, the literature gives a good understanding of the main mechanisms of bicycle safety at signalized intersections, but several gaps can be identified: Exposure, particularly for bicycling, is often missing, which limits the interpretability of results. In studies considering exposure, crash rates are often used based on the implicit assumption of linear relationships between motorist and/or bicyclist volumes. However, results from APM studies show that parameters for exposure variables are mainly below one, this non-linearity should be considered. Regarding data other than exposure, studies often mix different types of crashes such as turning or loss-of-control or different types of locations such as signalized intersections and intersections controlled by road signs.

This study addresses these gaps. The aim of this study is to investigate the influence of exposure and infrastructure characteristics like design and operation at signalized intersections on bicyclist safety. Based on a comprehensive dataset of motorist and bicyclist volumes and infrastructure characteristics for a sample of 269 signalized intersections in the two German cities of Dresden and Munich, we utilize a top-down approach to analyze, firstly, bicycle crashes of all types and, secondly, bicycle crashes by type including turning, right-of-way and loss-of-control. The combination of descriptive statistics and APM gives a detailed understanding on how the different variables interact and, in their combination, how they determine bicyclist safety. The analysis level of complete intersections is consciously chosen to identify determinants of bicyclist safety for typical signalized intersections in Germany with typical combinations of bicycle facilities. These analyses form the basis for the final step of this study, which is the development of evidence-based recommendations for improving bicyclist safety at existing intersections and for ensuring high safety levels at newly planned intersections from the very beginning.

2. Method

2.1. Data collection

2.1.1. Intersections and design features

The sample of intersections to be analyzed in this study was assembled iteratively in a three-step procedure: First, the two municipal transport authorities in Dresden and Munich provided georeferenced positions of all traffic lights in their city. Second, data on exposure for motorist volumes were requested from the transport authorities for all signalized intersections. Intersections without such data were excluded from the sample. Third, the research team examined all intersections via satellite photos and excluded those that do not meet the criteria for this study of full signaling and three or four arms. As a result of these steps, the initial sample of 1,127 traffic lights in Munich was reduced to 142 signalized intersections and the sample of 789 traffic lights in Dresden was reduced to 127 signalized intersections in Dresden, which results in the final sample of 269 intersections for both cities.

The selection of infrastructure characteristics was made based on the literature review and own hypotheses on possible determinants of bicyclist safety. Intersection characteristics in terms of design and operation were gathered from OpenStreetMap (OSM), transport authorities, aerial photo image databases such as Mapillary and on-site inspections. All characteristics were matched to the georeferenced intersections in a GIS database. Data on infrastructure characteristics were collected per arm in order to account for possible differences (e.g., in the type of bicycle facilities between the different arms of one intersection). These detailed data were aggregated in the next step to variables describing the intersection as one entity, which is the level of analysis for this study. The full list of variables per intersection arm (including, e.g., the number of lanes for motorized vehicles, the color of the bicycle facility, the geometric turning radius and the distance of parking to the intersections) is provided in Schröter et al. (2023). Table 1 shows the intersection characteristics used for this study.

The number of arms of the intersection as a whole and the number of arms with bicycle lanes or tracks are the two general characteristics used for the analysis. Only mandatory bicycle lanes are considered as bicycle facilities, advisory cycle lanes are shared with motorized traffic and are therefore categorized as mixed traffic. All bicycle tracks in the sample are one-way facilities. Typical combinations have been identified for the types of bicycle facilities at each arm of the intersection, which were the basis for grouping the sample into major, medium, and minor intersections as shown in Fig. 1. Bicycle facilities are provided on all four arms at major, on the two arms of the main road at medium and on none of the arms at minor intersections. This grouping of the intersections was done based on the hypothesis that bicyclist safety at the intersection level is rather determined by combinations of intersection characteristics than by the detailed variables of each single arm of the intersection for which there are also various interrelations.

The number of arms with bicycle bend-outs (or set-backs) larger than 4 meters was included considering the insights from the literature review and the distribution of bend-out distances of bicycle tracks in the sample of intersections of this study. The number of signaling stages was chosen for describing to what extent separate signaling for right- or left-turning motor vehicles exist at each intersection. No protected right or left turns exist at intersections with two stages, two protected left turns and/or two protected right turns exist at intersections with three stages. Intersections with more protected turns are captured as four + stages. Simultaneous green stages for bicyclists are not included in the sample.

Variables on public transport facilities are analyzed as dummy-coded variables. Variables on the presence of public transport stops and of tram tracks complete the list of infrastructure characteristics to be considered for the analysis.

2.1.2. Exposure

Volumes of motor vehicles and bicycles are included as the total Annual Average Daily Traffic (AADT), which is the average number of vehicles entering or exiting an intersection per day. For the city of Munich, data on AADT for motor vehicles were provided by the local transport authority from the demand model, which is used for local transport planning and based on data from 2019. Data on AADT were provided for the whole network of main roads so that almost each of the signalized intersections throughout the city could be retained for the analysis. Motor vehicle volumes in Dresden are based on manual counting that took place between 2017 and 2019 for selected signalized intersections. Those were also provided by the local transport authority.

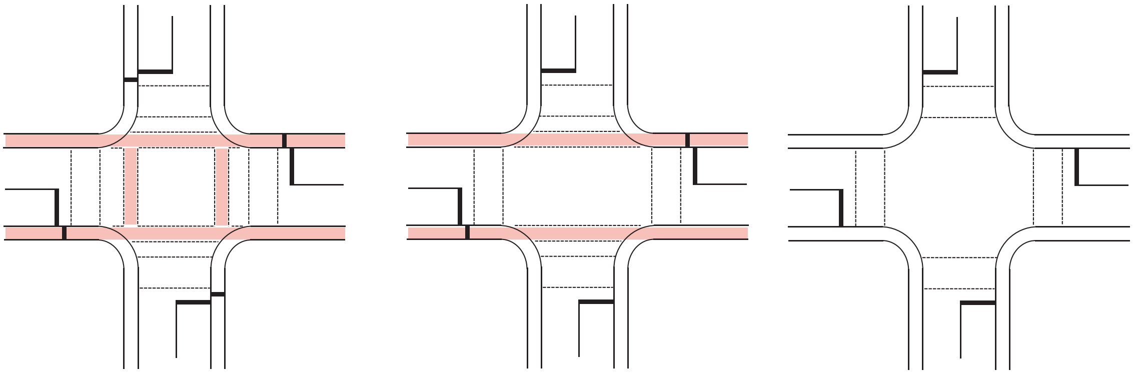
Bicycle volumes for Dresden and Munich were computed as AADT based on crowd-sourced bicycle trajectory data from the campaign *City Cycling 2019* (CITY CYCLING, 2022), which were validated with data from permanent automatic counting stations of bicycle traffic (Schröter et al., 2023). Pedestrian volumes were not available for any of the cities.

2.1.3. Crash data

Bicycle crash data were taken from the *Accident Atlas* published by the federal statistical office of Germany (Destatis, 2022c) for the

Table 1
Intersection characteristic variables.

Feature	Variable	Value
general	nr. of arms	[3,4]
bicycle facility	nr. of arms with bicycle facility	[0,1,2,3,4]
	type of bicycle facility if present	[bicycle track, bicycle lane, combination of bicycle track and bicycle lane]
	classification	[major, medium, minor] - see Fig. 1
	nr. of arms with bicycle-bend out of at least 4 m	[0,1,2,3,4]
signal stages	nr. of stages	[2,3,4 +]
public transport	public transport stops	[present, not present]
	tram tracks	[present, not present]



Major Intersections
(Cycling Facility on Both Streets)
N = 113

Medium Intersections
(Cycling Facility on Major Street)
N = 87

Minor Intersections
(No Continuous Cycling Facility)
N = 69

Fig. 1. Definition and sample size of the intersection classification.

five-year period between 2016 and 2020. This time period is longer than the time periods for which exposure data were gathered, but includes the years with exposure data. The reason behind these two different investigation periods for crashes and exposure is that exposure data were only available from cross-sectional data collection in single points of time, whereas crash data were available for any desired time period. The time period of five years was consciously chosen for crash data in order to have sufficient cases for statistical analysis, while at the same time limiting the probability of changes in the infrastructure and exposure.

Data in this georeferenced database are based on police reports and only include crashes with person injuries. Besides the georeferenced location of each crash, the database includes information on its severity and type. Crash types in German statistics are categorized based on the conflict that initially led to the crash and do not necessarily describe what happens later in the course of the crash (Destatis, 2022a). The following three crash types out of the overall seven types in German statistics are considered for this study because they have the highest relevance for bicyclist safety at signalized intersections:

- *Turning crashes:* These crashes are caused by a conflict between a vehicle turning off and another road user approaching from the same or opposite direction.
- *Right-of-way crashes:* These crashes are caused by conflicts between road users turning into a road or crossing it and having to give way with a (crossing) vehicle/bicycle having the right of way.
- *Loss-of-control crashes*: These crashes are caused by cyclists losing control of their bicycle, e.g., due to unadopted speed or misjudgment of the course or condition of the road. A collision with other road users might happen as a result of the uncontrolled vehicle movement.

Processed crash data were added to the GIS database including the total number of bicycle crashes per intersection as well as the number of crashes by type.

In addition to the open Interactive Accident Atlas, a more detailed crash database was available for the city of Dresden. This database is also based on police crash reports but includes further information such as a short verbal description of the course of the crash.

2.2. Statistical analysis

Correlations between intersection characteristics in terms of design, operation, and exposure were first analyzed using bivariate Spearman coefficients. Correlations that are significant at a significance level of 5% were considered in the analyses of intersection characteristics (see Section 3.1). Characteristics that correlate with a factor of 0.5 or more are excluded to be tested in the same model in the following analysis (see Section 3.3).

Crash data and their correlates were analyzed using Accident Prediction Models (APM) that are based on Generalized Linear Models (GLM) as used before e.g. by Elvik and Bjørnskau (2017), Elvik and Goel (2019) and Hantschel (2022). The prediction models have the following form:

$$\textit{number of crashes} = e^{\beta_0}\, AADT_{bic}{}^{\beta_{bic}}\, AADT_{mot}{}^{\beta_{mot}}\, e^{\left(\sum_n \beta_n x_n\right)}$$

where e denotes the exponential function and β the regression coefficients. The first term in the equation is the constant term. The AADT terms refer to traffic volumes (*bic* denotes bicycles, *mot* denotes motor vehicles) that are included as exposure variables into the model with the natural logarithm. The final term comprises predictor variables × other than traffic volumes, which are the variables on intersection design and operation. When one or both exposure variables do not become significant in a model, the corresponding term in the model is omitted.

Poisson regression is used to determine the effect on goodness of fit for each variable. Negative binomial regression is applied to determine the coefficients that describe the effect of each variable on the crash numbers shown in Section 3.3. Each model was built stepwise. Starting with the intercept-only model, the explanatory variables were tested on significance and effect on goodness of fit based on the Akaike Information Criterion (AIC). For each intersection model, the model with the best goodness of fit is presented in Section 3.3. The coefficients are significant at a significance level of 10%.

In this study, models are developed to analyze the effects of the different variables on crash numbers. We do not aim at predicting crash numbers, this would need validation with an additional dataset.

3. Results

3.1. Intersection characteristics

Table 2 gives an overview of the main characteristics of the final sample of intersections. The correlation matrices are provided in Appendix A. From the whole sample of 269 intersections in the two cities, 42% are classified as major, 32% as medium, and 26% as minor intersections. Seeing that the sampling procedure of the

Table 2
Intersection characteristics.

AADT [vehicles/24 h]	**Parameter**	**all**	**Major**	**Medium**	**Minor**
motor vehicles/24 h	minimum	4,600	15,500	10,250	4,600
	mean	29,307	35,847	27,297	21,132
	maximum	92,500	92,500	68,500	48,550
bicycles/24 h	minimum	100	150	110	100
	mean	3,610	5,140	3,330	1,440
	maximum	24,550	24,550	18,310	6,780
Number of Intersections [%]	**Value**	**All** (n = 269)	**Major** (n = 113)	**Medium** (n = 87)	**Minor** (n = 69)
nr. of arms	3	27	24	25	35
	4	73	76	75	65
type of bicycle facility if present	bicycle track	62	80	71	20
	bicycle lane	3	3	7	0
	combination	14	18	22	0
	none	20	0	0	80
nr. of arms with bicycle bend-out > 4 m	0	76	64	76	97
	1	10	16	9	3
	2	8	13	8	0
	3	3	4	5	0
	4	2	4	2	0
nr. of stages	2	47	47	38	58
	3	49	44	60	42
	4	4	9	2	0
public transport stops	present	72	75	67	74
	not present	28	25	33	26
tram tracks	present	47	34	56	58
	not present	53	66	44	42

intersections for this study began with the full set of signalized intersections in the two cities and that the availability of exposure data was the main criterion for excluding intersections from the sample, we are confident that the distribution of intersections along the three groups of major, medium, and minor intersections represents the overall distribution in these cities well. Most of the signalized intersections are major complex and large ones with bicycle facilities at all arms.

AADT is highest at major intersections for motorists and bicyclists compared to medium and minor intersections. This significant correlation is also reflected in the correlation matrix (see Appendix A) with coefficients of 0.45 for motorists and 0.5 for bicyclists. These differences in exposure between the three intersection categories are of high relevance for bicyclist safety and also demonstrate the suitability of the chosen classification into the three groups with their distinct typical characteristics. AADT of bicyclists is systematically lower than for motorists in all three groups.

Around three fourth of the intersections have four arms with a slightly higher share for minor intersections. 80% of major and 71% of medium intersections have bicycle tracks on the arms with bicycle facilities, the share of intersections with bicycle lanes is below 10%. This high proportion of bicycle tracks is the result of earlier German bicycle guidelines traditionally recommending to provide them (see e.g. FGSV, 1982). Bicycle lanes have only been recommended for the last decades (FGSV, 2010), which is only slowly becoming visible because most municipalities refurbish their intersections without changing much about the original design and complete re-designs are rarely done.

The proportion of intersections with combinations of bicycle tracks and lanes is lower at major intersections with 18% compared to 22% at medium intersections. This high share of these intersections with combinations of bicycle facilities shows the individual character of each intersection and their arms. Minor intersections by definition do not have any bicycle facility (80%) or if they have a facility in one arm, they only have bicycle tracks (20%).

The number of intersections with bicycle bend-outs wider than 4 m in at least one arm is with 36% highest for major intersections, followed by medium intersections with 24%, and 3% for minor intersections. These differences are reflected in significant correlations between the number of arms with bend-outs and the intersection category as well as with the type of bicycle facilities, both these correlation coefficients are equal at 0.55. This corresponds to the higher proportion of arms with bicycle tracks in the group of major intersections but also shows that the design of bicycle tracks differs between major and medium intersections. The higher proportion of arms with bend-outs at major intersections might be a combination of higher space availability and conscious decisions to increase bend-out distances because of the higher motor vehicle volumes. The high proportion of intersections with one to three arms with bicycle bend-outs (compared to zero or four) shows the individual character of the intersections in our sample once again.

The number of stages also shows interesting patterns. The number of intersections with two or three stages is almost equal for major intersections with 47% and 44%, whereas for medium intersections, the share of intersections with three stages is highest with 60% and for minor intersections, the share of two stages is highest with 58%. The proportion of intersections with four (or more) stages is generally low. A closer look at the signaling shows that, overall, there are more protected left-turn phases than right-turn phases at the intersections. Possible reasons for the high proportion of two stages at minor intersections might be that these simple signaling schemes are most suitable for the low vehicle volumes and compact intersection designs. They also result in low cycle times and thus low waiting times. The relatively high share of two stages at major intersections might have different reasons like restrictions in available time for each single stage and also for the whole cycle time. Overall, the share of unprotected turns is high, which is relevant for bicyclist safety. Over all three groups, 72% of intersections have at least one public transport stop with low variation between the groups. The proportion of intersections with tram tracks is highest for medium and minor intersections.

3.2. Descriptive analyses of crashes

Overall, 1,218 crashes occurred at the 269 intersections during the 5-year period, which corresponds to an average crash number of 0.91 crashes per intersection and year. At 1.13, the crash rate is highest for major intersections, followed by medium intersections at 0.90, and minor intersections at 0.55. This order of crash numbers from major with the highest values to minor with the lowest values holds for all sub-samples of intersections along the specific characteristics in infrastructure and operation. Table B1 in Appendix B lists the crash numbers over the whole sample of intersections as well as for the different groups. To interpret the detailed crash numbers, one needs to consider that differences in crash numbers are always determined by the mixture of differences in exposure and in the specific characteristics, and that the number of cases in some combinations is low, as shown in 2. The application of APM in Section 3.3 of this paper allows to disentangle the influences of the different factors behind the crash numbers.

The major part of the crashes in the sample (87%) resulted in slight injuries, 13% of the crashes lead to severe injuries and only five crashes with fatalities are included in the dataset. This low number of crashes with severe and fatal injuries does not allow to distinguish between the different levels of crash severity for further analysis in this study.

The distribution of crashes by type is shown in Fig. 2. Over the whole sample, turning crashes are the most relevant group. They account for 53% of all crashes, which is very well in line with the literature with consistent evidence that crashes with right turning and to a slightly lesser extent left turning motor vehicles cause the highest proportion of bicycle crashes at signalized intersections (Kolrep-Rometsch et al., 2013). For example, Alrutz et al. (2015) find, based on the analysis of 1,050 bicyclist crashes at signalized intersections in four German cities, that turning crashes account for 50% of all crashes, followed by right-of-way crashes with a share of 24%, and loss-of-control crashes with 6%. Turning crashes are also the type with the highest variation between the three intersection categories. Their proportion is with 62% for major intersections, almost twice as high as for minor intersections with 34%. The opposite effect can be identified for loss-of-control crashes, which account for 28% of all crashes for minor intersections compared to only 5% at major intersections. The differences between the intersection categories are less distinct for the crash types right-of-way and other. The latter group includes crashes of the four types in German crash statistics that are not considered for this study because of their small number and thus of limited relevance for bicyclist safety at signalized intersections. These include crashes related to crossing, vehicles moving along the carriageway, parking, and "other" possible reasons that are not covered by the any of the pre-defined types (Destatis, 2022a).

The high proportion of turning crashes and loss-of-control crashes was expected:

- Turning crashes occur when vehicles turn and cross parallel riding cyclists' way. At signalized intersections this is particularly relevant for permissive left-turn/right-turn signal control when turning cars have green at the same time as cyclists going straight ahead in parallel to the turning cars
- Loss-of-control crashes occur due to the complexity of the tasks at signalized intersections: bicyclists need to understand where to go, need to give right-of-way, to swerve or to break etc., which may result in losing control of the bicycle.

Right-of-way crashes typically occur at uncontrolled intersections and thus were not initially expected to have such a high share in the sample, because right of way is regulated by traffic lights at signalized intersections. For this reason, such crashes can only happen if users run a red light (illegally) or if there is a right turn on red sign (legally). Verbal crash reports for 100 of the right-of-way crashes were read in order to better understand the main mechanisms of these bicycle crashes. Verbal reports were only available for the city of Dresden, but a similar pattern can be assumed for the city of Munich. More than half of the 100 crashes are related to red light running mainly by bicyclists, which means that a bicycle crosses a carriageway has to give way but does not respect this and collides with a vehicle coming from right or left and having right of way. About one third of the crashes occur due to right-turn on red signs, with mainly motorists turning and colliding with a crossing bicycle that has the right of way. The remaining crashes were caused by multiple reasons, with signal turn-off during night-time hours being one example.

The descriptive distributions of crash types primarily show their relevance, the interpretation of the magnitudes and variation between intersection categories is difficult because of the variety of factors that are behind the proportions in Fig. 2. The models presented in the next sections will help to disentangle the effects of these different individual factors.

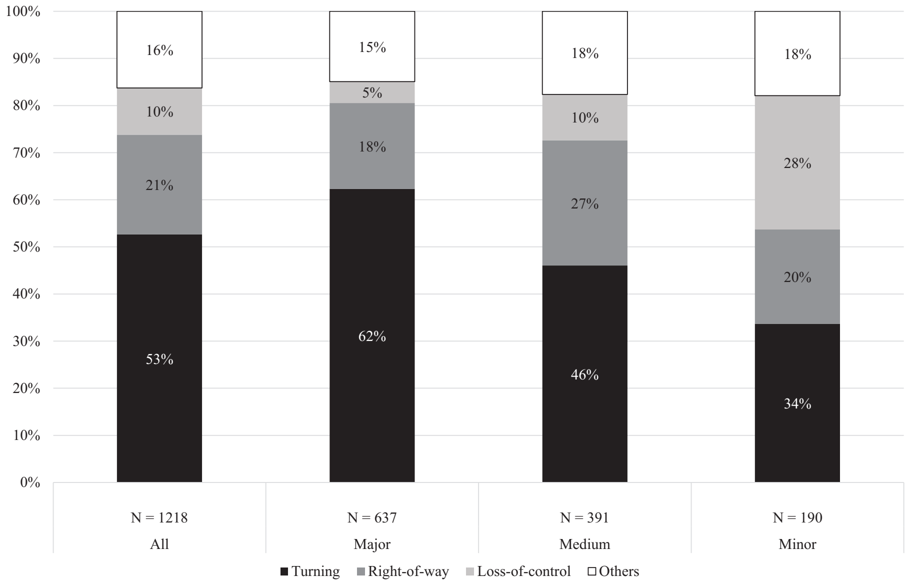


Fig. 2. Crash type distribution by intersection category.

3.3. Models

3.3.1. All crashes

The APMs for the total sample of bicycle crashes of all types for entire intersections over all intersection categories and also separately for the three groups of minor, medium, and major intersections are shown in Table 3. Exposure variables for motor vehicles and bicycles are consistently significant with coefficients in the expected direction and magnitude. Bicycle volumes influence the predicted bicycle crash numbers with a coefficient of 0.513, which confirms the safety-in-numbers hypothesis for bicycle traffic (as introduced in Section 1). The coefficient for motor vehicle volumes is higher at 0.705, which means that this relation is more linear than for bicycle volumes.

Significant differences exist between each of the three intersection categories. Major intersections have the highest and minor intersections the lowest safety levels, which is opposite to the results from descriptive statistic presented in Section 3.2. The APM shows that the high crash numbers at major intersections are mainly caused by the higher exposure compared to medium and minor intersections, whereas the infrastructure is safer at major (and medium) intersections. The higher number of arms with bicycle facilities at major and medium intersections as shown in Fig. 1 obviously decreases the likelihood of crashes compared to minor intersections with no dedicated bicycle facility when exposure is considered.

The distinction between intersections with three versus four arms is also significant. Three-arm intersections are safer; this is plausible because of their lower number of conflict points and complexity.

No infrastructure characteristics are significant in the model for all intersections because many of them, and particularly the type of bicycle provision, correlates with the intersection category by definition. For this reason, separate models are developed for each intersection category, which are also shown in Table 3. The model for major intersections shows similar significant variables as the model for all intersections, mainly because half of all intersections are major intersections. Different variables are significant in the models for medium and minor intersections, confirming their distinct characteristics.

The number of arms only becomes significant for major intersections with a coefficient that is twice as high as in the overall model. The fourth arm seems to increase the intersection complexity to a lesser extent for medium and minor intersections because of lower exposure and smaller layouts of these arms compared to the fourth arm at major intersections, which might have substantial traffic load, widths and time in signaling.

The coefficient of motor vehicle volumes is highest for medium intersections compared to major and minor intersections. One possible reason might be an unfavorable combination of high motor vehicle volumes (see Table 2) at medium intersections with large and complex designs compared to minor intersections on the one hand and fewer separate bicycle facilities compared to major intersections on the other hand.

The existence of bicycle tracks at medium intersections significantly improves bicyclist safety compared to bicycle lanes and combinations of tracks and lanes. This is an indication that more separation of bicycles has positive effects for this specific intersection category but is less relevant for major intersections.

Tram tracks are, besides exposure, the only significant variable in the model for minor intersections, which shows a substantial risks for bicyclists in arms that have tram tracks but no bicycle facility.

The models described above for all crashes are high-level models that include various types of road user movements such as turning right or left and related crash types. Determinants of each crash type might differ with reinforcing or counteracting interdependencies, they might even level out each other and might not become significant in the general models, even though they are highly relevant for specific crash types. In what follows, we develop separate models for each intersection category to account for these possible effects and to gain more detailed insights on the specific determinants of bicyclist safety at signalized intersections.

3.3.2. Turning crashes

For turning crashes, the overall model for all intersections as well as the individual models for major, medium, and minor intersections in Table 4 show significant effects of bicycle and motor vehicle volumes. Coefficients for bicycle volumes range from 0.418 to 0.519 and thus show low variation in all four models. Coefficients for motor vehicles are at 0.802 to 1.039 higher than for all crash types (see Table 3) and show a linear to disproportionate relationship between motor vehicle volumes and bicyclist crash numbers. This demonstrates the high relevance of (turning) motor vehicles, which are (besides the bicyclists who mainly go straight ahead) the main party in turning crashes. For interpreting the results, one needs to know that bicycle and motor vehicle volumes are not distinguished by the type of movement along the intersection. This means that motor vehicles going straight ahead are also included into the exposure variable used for the model.

The number of arms is only significant for major intersections, which is in line with the models on all crash types as introduced above. Turning crashes at major intersections as the most complex type in our sample are apparently more affected by the higher

Table 3
Regression coefficients of all crash types.

All Crash Types **Feature**	**Intersection Classification**			
	All	**Major**	**Medium**	**Minor**
intercept (β_0)	−11,772***	−11,418***	−13,53***	−10,425***
$AADT_{bic}$	0,513***	0,510***	0,467***	0,471***
$AADT_{mot}$	0,705***	0,652***	0,987***	0,617**
classification = minor	0,378**			
classification = medium	0,224**			
classification = major	Ref.			
nr. of approaches = 4	0,206*	0,473**		
nr. of approaches = 3	Ref.	Ref.		
bicycle facility = bicycle track			−0,597***	
bicycle facility = other			Ref.	
tram tracks = present				0,530**
tram tracks = not present				Ref.

$^{*}p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

Table 4
Regression coefficients of turning crashes.

Turning Crashes	**Intersection Classification**			
Feature	**All**	**Major**	**Medium**	**Minor**
intercept (β_0)	$-16{,}134^{***}$	$-13{,}313^{***}$	$-17{,}95^{***}$	$-16{,}493^{***}$
AADT$_{bic}$	$0{,}549^{***}$	$0{,}519^{***}$	$0{,}450^{***}$	$0{,}418^{**}$
AADT$_{mot}$	$1{,}039^{***}$	$0{,}802^{***}$	$1{,}335^{***}$	$1{,}183^{***}$
nr. of approaches = 4		$0{,}452^{**}$		
nr. of approaches = 3		Ref.		
signal stages = 4 + stages	$-0{,}457^{***}$	$-0{,}617^{**}$	$-0{,}569^{**}$	
signal stages = 3 stages		$-0{,}43^{**}$		
signal stages = 2 stages	Ref.	Ref.	Ref.	
bicycle facility = bicycle track			$-0{,}694^{**}$	
bicycle facility = other			Ref.	
$^{*}p < 0.1$; ** $p < 0.05$; *** $p < 0.01$				

complexity of the whole intersection due to the fourth arm, which is less relevant for medium and minor intersections. These are more compact and can be overseen and understood more easily even when they have four arms.

The number of signal stages is significant in all models except for minor intersections. The existence of at least one protected left or right turn significantly reduces the number of turning crashes for all and medium intersections. For major intersections, even the distinction between three and four or more stages is significant. This shows the high overall relevance of the separation of the conflict parties in time and for major intersections. This also demonstrates the specific relevance of each additional protected turn.

For medium intersections, similar to the model for all crash types as introduced above, the existence of bicycle tracks significantly reduces the likelihood of turning crashes. This seems to be an indication for positive effects of generally more separation compared to bicycle lanes and also from possible bend-outs of the bicycle tracks. Bend-outs allow turning vehicles to first complete their turn and then yield to bicyclists going straight ahead in a kind of "waiting zone" that results from the bend-out of the bicycle track.

None of the variables related to infrastructure or signaling are significant for minor intersections. For these comparably small and compact intersections, it seems to be fine to have turning motorists and bicyclists sharing the same space and green times in signaling, also because right-turning motorists drive directly in front of or behind cyclists instead of parallel, thus eliminating the conflict point when turning right.

3.3.3. Right-of-Way crashes

Bicycle volumes are significant in all three models for right-of-way crashes (see Table 5). Motor vehicle volumes are only significant for major intersections, which is different from turning crashes and comes somewhat unexpectedly. Two counteracting effects might be the reason for this result: First, there is consistent evidence in the literature that higher motorist volumes are related to higher crash risks for bicyclists (Elvik & Goel, 2019). Second, higher motorist volumes might decrease the likelihood of red light running. The first effect seems to dominate for major intersections, higher motor vehicle volumes increase the likelihood of bicycle crashes and at the same time, red light running is low due to the generally high motor vehicle volumes and also long crossing distances related to large and complex intersection designs (Van der Meel, 2013). Medium intersections are smaller, crossing distances and mean motor vehicle volumes are lower. For medium intersections, the red light running effect of lower motor vehicle volumes seems to be stronger and compensates the exposure effect so that overall, the coefficient for motorist volumes is not significant for medium intersections. Signal turn-off at night times is another reason for right-of-way crashes, which might happen more often at medium intersections and is also not related to motor vehicle volumes. Information of right turn on red signage is not available and thus cannot be analyzed in this study.

The intersection category affects right-of-way crashes only in the distinction between major intersections and others, which supports the hypothesis of less red light running at major intersections as discussed before.

For major and medium intersections, the number of signal stages affects the expected number of right-of-way crashes in the opposite direction to turning crashes, a higher number of stages increases the likelihood of bicyclist crashes. Red light running is again the most likely reason behind this result. Higher numbers of stages increase the intersection cycle times, resulting in longer waiting times that might increase red light running (Van der Meel, 2013).

For major intersections, the existence of bicycle tracks significantly decreases the likelihood of right-of-way crashes, which might be explained by shorter crossing distances because cycle

Table 5
Regression coefficients of right-of-way crashes.

Right-of-Way Crashes	**Intersection Classification**			
Feature	**All**	**Major**	**Medium**	**Minor**
intercept (β_0)	$-6{,}651^{***}$	$-15{,}421^{***}$	$-6{,}736^{***}$	no model
AADT$_{bic}$	$0{,}672^{***}$	$0{,}542^{***}$	$0{,}692^{***}$	
AADT$_{mot}$		$0{,}939^{***}$		
classification = minor	Ref.			
classification = medium				
classification = major	$-0{,}414^{**}$			
signal stages = 4 + stages	$0{,}510^{**}$	$0{,}498^{**}$	$0{,}639^{**}$	
signal stages = 3 stages				
signal stages = 2 stages	Ref.	Ref.	Ref.	
bicycle facility = bicycle track		$-0{,}586^{**}$		
bicycle facility = other		Ref.		
$^{*}p < 0.1$; ** $p < 0.05$; *** $p < 0.01$				

Table 6
Regression coefficients of loss-of-control crashes.

Loss-of-Control Crashes	Intersection Classification			
Feature	**All**	**Major**	**Medium**	**Minor**
intercept (β_0)	$-3,375^{***}$	no model	no model	$-7,633^{***}$
$AADT_{bic}$				$0,606^{**}$
classification = minor	$0,619^{**}$			
classification = medium	Ref.			
classification = major				
tram tracks = present	$1,194^{***}$			$1,881^{***}$
tram tracks = not present	Ref.			Ref.

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

tracks are located at the sidewalk and not at the carriageway; as this is the case for cycle lanes, cycle tracks are thus not to be crossed together with the lanes for the motorized vehicles. For minor intersections, the number of right-of-way crashes and the variance in their determinants is low, no model can be estimated for this category.

3.3.4. Loss-of-control crashes

Models for loss-of-control crashes could only be estimated for all and for minor intersections. They also show the lowest number of significant explanatory variables (see Table 6). The intersection category shows an effect in the distinction between minor intersections and others. Bicyclists seem to behave differently at these compact intersections with low traffic volumes and with no dedicated bicycle facility. Motor vehicle volumes do not become significant in any of the models and even bicycle volumes are found to be only significant for minor intersections, which shows their relevance.

The presence of tram tracks increases the likelihood of bicyclist crashes. The coefficient for minor intersections is higher than for all intersections, which might be the result of bicyclists being more exposed to tram tracks when cycling in mixed traffic situations and in street layouts with lower widths. When analyzing the verbal crash reports in Dresden, 29 out of 83 loss-of-control crashes were identified to occur in the context of tram tracks, which again demonstrates their relevance but also shows that trams tracks are not the only determinant for those crashes. Besides trams tracks, no other infrastructure-related variable is significant in the models. The occurrence of loss-of-control crashes seems to be influenced by infrastructural characteristics that are not considered or rather by temporal or personal factors (e.g. dirty or slippery roads or riding under the influence of alcohol), which are not included in this study. The temporal distribution of loss-of-control crashes differs from the general sample. Only 39% of loss-of-control crashes occur during peak hours (45% for all crashes) compared to 41% during nighttime (29% for all crashes). Cyclists might tend to speed with lower presence of other road users which could (especially in combination with poorer visibility at nighttime or drunk riding) lead to more crashes.

4. Discussion

Overall, the results of the descriptive statistics and the APM confirm the literature and add new insights thanks to the detailed analysis of the determinants of bicyclist crashes. Both the classification of the signalized intersections along the three categories (major, medium, and minor) and also the distinction of crashes by type proves insightful. They disclose effects that are not visible in the analyses of the overall sample of intersections and crashes due to differences in the mechanisms of bicyclist safety among intersection categories and crash types.

The overall results from the different analysis techniques confirm the literature in that exposure is the main explanatory variable for bicyclist crashes (Elvik & Bjørnskau, 2017; Elvik & Goel, 2019). Coefficients for bicycle volumes are significant in all models except for loss-of-control crashes, which shows the relevance of separate analyses by crash type. The size of the coefficients is between 0.4 and 0.7, which confirms the safety-in-numbers effect (Nordback et al., 2014). The coefficients for motor vehicle volumes show more variation and are consistently higher than for bicycle volumes, which is also in line with the literature (Elvik & Bjørnskau, 2017; Elvik & Goel, 2019).

Rebound effects are identified for right-of-way crashes, which have hardly been considered in the researched literature. Lower complexity of intersections in combination with lower motor vehicle volumes seem to encourage risky behavior of bicyclists, such as red light running. This behavioral adaption and risk compensation appears to dampen the exposure effect so that even motor vehicle volumes do not become significant for some models.

Rebound effects are also identified for infrastructure characteristics in terms of design and operation. The number of signal stages does not get significant in the models for all crash types because of two counteracting effects that become visible only in the models for turning and right-of-way crashes. A higher number of signal stages and, related to this, of protected right or left turns on the one hand decreases the likelihood of turning crashes, but on the other hand increases the likelihood of right-of-way crashes. Hence, the lack of significance of the number of signal stages in the models for all crash types does not mean that these are not relevant. Instead, this means that the negative coefficients of the model for turning crashes and the positive coefficients for right-of-way crashes compensate each other.

These rebound effects are hardly covered by the existing literature because of two separated research streams: References exist that find higher crash numbers for more complex intersections (Liu & Marker, 2020; Vandenbulcke et al., 2014). Other references find higher red light running rates for longer waiting times and shorter crossing distances (Van der Meel, 2013). Both research streams have hardly been combined so far, which seems to hide relevant interactions. For all crash types combined, more separation measured as the number of signal stages improves bicyclist safety, despite these rebound effects, because the number of turning crashes is higher than the number of right-of-way crashes.

The influence of bicycle facilities on bicyclist crashes is well captured by the three intersection categories with their typical provision for bicyclists. More intersection arms are equipped with bicycle facilities at major (and medium) intersections compared to minor intersections; this relates to a higher average number of crashes at one specific intersection in the descriptive statistics, but lower expected crash numbers in the APMs that consider bicycle volumes. Obviously, the higher degree of bicyclists' separation from motor vehicles overcompensates for the effect of higher complexity of major intersections, which would be expected to decrease bicyclist safety due to their higher traffic volumes and larger dimensions. Looking not only at the presence but also at the type of bicycle facility, the provision of bicycle tracks compared to any other type of bicycle facility is significant in several models with consistently negative coefficients. This supports the hypothesis that more separation of bicyclists from motorized vehicles improves bicyclist safety and adds to the literature, which is not clear on the effect of specific types of bicycle facilities on crash numbers. Our findings are in line with studies that find lower crash rates for intersections with bicycle facilities compared to no bicycle facilities (Kolrep-Rometsch et al., 2013) and a lower likelihood of crashes in APM (Liu & Marker, 2020). Hardly any comparison with the literature is possible for our findings on the impact of the type of bicycle facility because only few references could be identified, and these have different research designs. For example, Liu and Marker (2020) find a lower likelihood of crashes in APM for bicycle lanes compared to bicycle tracks, which indicates that separation increases the likelihood of crashes but do not compare any other type of bicycle facility with bicycle tracks and focuses on approaches and not the complete intersection, as is done in this study.

Loss-of-control crashes are overall lowest in number and also in the significant variables in the models. Besides the existence of tram tracks, the infrastructure-related mechanisms for these crashes seem to be less relevant and future research might rather focus on personal or temporal factors in order to better understand these crashes. The relevance of tram tracks as identified in this study is in line with the literature (Vandenbulcke et al., 2014).

Various other infrastructure variables beyond bicycle provision were tested, but no significant effects could be identified. Examples for these variables include the bend-out distance of bicycle tracks or the geometric turning radius. The results of this study show that these detailed characteristics of the intersections with their various interdependencies, and also variation within individual intersections, are well captured by the three intersection categories. They are expected to get more relevance in APM that model each arm of a signalized intersection separately.

5. Summary

This study presents a detailed investigation of the determinants of bicyclist safety at urban signalized intersections, including their interdependencies with reinforcing and counteracting effects. The overall sample of 269 intersections in the two cities of Dresden and Munich was classified into the three categories: major, medium, and minor intersections. Based on the analysis of the 1,218 crashes at these intersections, distinguished into the three crash types (turning, right-of-way, and loss-of-control), we identify relevant relationships between infrastructure characteristics in terms of design and operation, exposure in terms of bicycle and motor vehicle volumes, and bicyclist crashes from police reports.

The analysis level of complete intersections generates valuable insights. It shows that different mechanisms of bicyclist safety take effect at different types of intersections. The effect on bicycle safety differs and the types of suitable measures for mitigating identified safety problems differ as well. At the same time, the analysis level of complete intersections hides detailed mechanisms at each specific arm, which is a limitation of this study. Accident prediction models for individual arms of one intersection can be expected to generate new insights on the relevance of more detailed infrastructure characteristics such as the bend-out distances of bicycle tracks or protected left or right turns in signaling schemes. Exposure data in this study do not distinguish between the different directions of movement along the intersection and do not include pedestrian volumes, which is another limitation.

Seeing the substantial differences in the determinants of turning, right-of-way, and loss-of-control crashes, the analyses by crash type should be continued. More studies with similar designs as this one would help to validate the insights from this study and to critically examine the transferability of the results. This holds particularly for the identified rebound effects in terms of bicyclists' behavioral adaption for risk compensation. These are of highest relevance for planning, but only few references could be identified. In the interpretation of the model results in this study, hypotheses were developed about further variables for which little evidence exists. Geometric turning radius is one example, further investigations would help to validate these developed hypotheses.

6. Practical implications

The most relevant practical implication of this study is that the different types of intersections and crashes each follow specific mechanisms of bicyclist safety and, consequently, need specific measures. The consequent provision of separate facilities for bicyclists and separate signaling are paramount at intersections with high bicycle volumes, which in our dataset are also major intersections with high motor vehicle volumes and large dimensions. Risk compensation becomes more important as intersections get smaller and motor vehicle volumes decrease. Short cycle times are important and also the consequent monitoring of possible problems in the acceptance of traffic regulation, e.g. in the form of red light running. These possible rebound effects of more separation in time and/or space should be anticipated from the early planning phases with the final goal of continually finding the optimal balance between temporal and spatial separation, respectively, integration for each individual application anew.

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 and B. Supplementary data

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