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Analysis of the impact of different bicycle infrastructure designs on cyclist–motor vehicle interactions on local roads

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Abstract

The increasing volume of bicycle traffic has heightened the demand for safe cycling infrastructure on local roads, where space and financial resources are often limited. This research investigates how different types of cycling infrastructure affect interactions between cyclists and motorized traffic. The goal is to provide policymakers with practical and applicable insights to support safe and feasible design choices.
Four scenarios were developed in STISIM Drive® 3 (driving simulator software): no cycling infrastructure, advisory bike lanes, cycle streets, and adjacent bike lanes. These were implemented on both one-way and two-way streets. Driver behavior was analyzed using parameters such as passing distance, passing speed, overtaking distance, and overtaking time.
The simulations show that on one-way streets, adjacent bike lanes offer the highest level of safety due to greater passing distances. Cycle streets offer the most safety on two-way roads, even though 55% of drivers violated the no-overtaking rule. Nevertheless, cycle streets still demonstrated high safety due to low passing speeds and ample overtaking distances. Advisory bike lanes represent a viable alternative in cases where the low-speed limit of cycle streets (30 km/h) is less desirable. In terms of cost-effectiveness and spatial feasibility, the safest options are often achievable, particularly in planning new road infrastructure. However, no clear relationship between infrastructure and cyclist safety was observed on one-way streets.

Keywords: bicycle safety; cycling infrastructure; driving simulator; policy advice; cost-benefit analysis

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1. Introduction

Bicycle infrastructure has become an increasingly prominent element in contemporary mobility planning. With the global shift toward sustainable transportation, cycling is recognized for its role in reducing congestion, air pollution, and carbon emissions. In Belgium, the popularity of cycling continues to grow, not only due to its environmental benefits but also because of its positive impact on public health. In Flanders, the average number of bicycles per household is 2.19, based on Statistiek Vlaanderen (2023). According to Acerta, the number of commutes by bicycle has increased by 35% over the past five years (2025), and the Flemish Traffic Centre reported an 11.6% rise in cyclist counts between 2022 and 2023, according to Vlaanderen Verkeerscentrum (2023).

This growing trend reinforces the demand for safe cycling infrastructure. Poorly designed facilities or the lack thereof are associated with a higher risk of accidents involving cyclists, retrieved from Kennisnetwerk SPV & Strategisch Plan Verkeersveiligheid (2020). Local roads, in particular, accommodate a diverse range of cycling infrastructure, such as separated cycle tracks, bike lanes, and shared roadways, each influencing cyclist safety differently. In 2022, traffic accidents in Belgium resulted in 11,950 slightly injured cyclists, 1,186 seriously injured cyclists, and 102 fatalities, based on the reports from Statbel (2023). Moreover, cyclists accounted for 33% of all road deaths in 2023, according to Statistiek Vlaanderen (2024), a significant increase from previous years.

While Schepers et al. (2017) and SWOV's report (2020) stated that physically separated cycle tracks are generally safer, their implementation on local roads is often constrained by space or budgetary limitations. Alternatives such as advisory bike lanes or cycle streets are commonly used, but empirical data on their safety effectiveness remains limited. This study addresses this gap by investigating how different types of cycling infrastructure affect interactions between cyclists and motorized vehicles on local roads. The research aims to support mobility policy by identifying infrastructure types that improve cyclist safety while also being spatially and financially feasible.

2. Literature review

This literature review explores the various types of cycling infrastructure in Belgium, their impact on cyclist safety, and the factors influencing their design. It highlights the common types of cycling infrastructures, including roads without bike lanes, bike lanes, adjacent and segregated bike lanes, and cycle streets, each with distinct safety implications, as stated by the Agentschap wegen en verkeer (2024). Research shows that segregated bike lanes are generally considered the safest option, especially in high-traffic areas. In contrast, roads without bike lanes pose a higher risk of accidents, as Meuleners et al. (2019) stated. Factors such as traffic intensity, speed limits, and infrastructure design directly affect safety. Studies by Bi et al. (2023) and Jeon and Woo (2024) suggest that reducing traffic volume and speed improves cyclist safety. The strategic placement of bike lanes can minimize risks, such as "dooring" accidents, as highlighted by DiGioia (2014), Duthie et al. (2010), Johnson et al. (2013), and Van Houten & Seiderman (2005).

In evaluating different cycling infrastructure scenarios, it is essential to consider the associated construction costs. These costs vary significantly depending on the type of infrastructure and whether the intervention takes place in a one-way or two-way street.

Table 1 presents an overview of typical unit prices per linear meter for various types of cycling infrastructure. The prices distinguish between painted markings and colored asphalt, as well as between advisory lanes, cycle streets, and adjacent cycle lanes. These figures are intended to serve as a reference point for cost estimation and comparison across different urban planning scenarios. The unit prices included were obtained from a Belgian engineering firm that has requested to remain anonymous.

Table 1. Additional costs of cycling infrastructure per linear meter on one-way and two-way streets.

	Additional cost of a one-way street (€ / linear meter)	Additional cost of a two-way street (€ / linear meter)
Painted advisory bike lanes	/	94.01
Colored asphalt advisory bike lanes	/	45.76
Painted cycle streets	124.50	186.75
Colored asphalt bicycle streets	27.00	40.50
Painted adjacent bike lanes	80.19	160.38
Colored asphalt adjacent bike lanes	47.69	95.38

Additionally, the review examines cyclist behavior, showing that cyclists adjust their position on the road based on factors like infrastructure type and the presence of vehicles. Cyclists tend to ride closer to the road edge when there is a wide sidewalk, and their position on bike lanes varies depending on the width of the lane, as reported by Hatfield et al. (2018) and Schepers et al. (2023). Romanillos & Gutiérrez (2020) and Xu et al. (2015) also stated that weather conditions and demographic factors, such as age and gender, influence cycling speed.

Finally, the review evaluates the reliability of driving simulators for studying cycling infrastructure and traffic behavior. While driving simulators offer controlled environments for research, they may not perfectly replicate real-world conditions, particularly in terms of speed and lateral positioning, as reported by Alm (1995) and Törnros (1997). However, studies conducted by de Waard & Brookhuis (2004) and Törnros (1997) stated that simulators remain a valuable tool for understanding traffic interactions and infrastructure effectiveness, provided their limitations are acknowledged.

In sum, while previous studies highlight the safety benefits of certain cycling infrastructures—especially segregated lanes—there is limited and inconsistent empirical evidence on alternatives like advisory bike lanes and cycle streets, particularly in local road contexts. Much of the literature focuses on single infrastructure types rather than offering comparative insights. This reinforces the need for controlled studies that evaluate multiple infrastructure types under consistent conditions. Our study responds to this gap using simulator-based analysis informed by key design factors identified in earlier work.

3. Methodology

To evaluate driver-cyclist interactions across varying cycling infrastructures, this study employs a controlled experiment using the STISIM Drive® 3 driving simulator located at the Institute for Mobility (IMOB) at Hasselt University. This simulator replicates a real driving environment using a Ford Mondeo equipped with a steering wheel, an acceleration pedal, and a braking pedal. It provides a 180° field of view powered by three projectors. The simulation environment is specifically designed to measure behavioral responses in realistic urban traffic settings while maintaining complete control over experimental variables. The driving simulator is shown in Fig. 1. (a) and the interior of the driving simulator in Fig. 1. (b).

Four types of cycling infrastructure are tested: no cycling facility, advisory bike lanes, adjacent bike lanes, and cycle streets. Each infrastructure type is implemented in both one-way and two-way traffic configurations where legally and practically feasible. For example, advisory bike lanes are only simulated in two-way streets, as they are not applied in one-way streets under the current national practice, retrieved from Agentschap wegen en verkeer (2024) reports. Free-standing or segregated cycle tracks are excluded from the study, as they generally eliminate direct interaction between cyclists and motorized traffic.

To ensure comparability across scenarios, road widths are standardized. One-way streets are modeled with a total width of 4.5 m and two-way streets with 5.5 m. An exception is made for one-way cycle streets, which are modeled as 4.0 m wide to reflect their typical implementation in space-constrained urban settings. Advisory bike lanes follow national guidelines, with 1.7 m wide markings on each side of the roadway. Adjacent bike lanes are simulated as narrow (1.0 m wide) painted lanes immediately next to the vehicle lane, with no physical separation. These layout choices enable the simulation of realistic lateral clearance and overtaking conditions across all scenarios. The dimensions were validated through on-site measurements of the various roads and cycling infrastructures and were subsequently refined to ensure a realistic representation within the simulator environment.

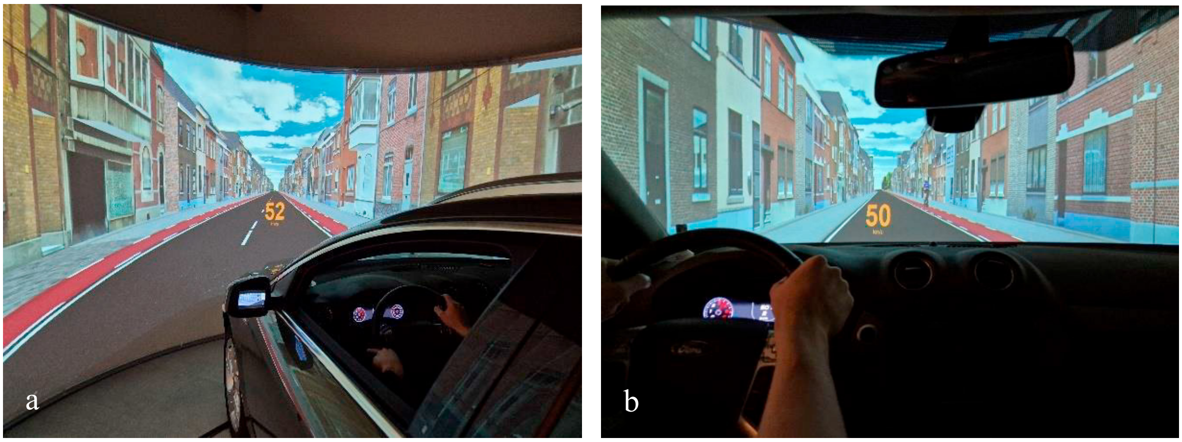

Fig. 1. (a) Driving simulator setup; (b) Interior view of the driving simulator.

The virtual environment is further enhanced by adding contiguous buildings along both sides of the road and 2 m wide sidewalks to reflect an urban context. Pedestrians are included on the sidewalks, moving at speeds between 0.8 and 1.6 m/s, to improve visual immersion and provide reference points for drivers.

Each simulation includes solo or riding in pairs of cyclists, positioned one behind the other and traveling at a consistent speed of 4 m/s. In all scenarios except those with adjacent bike lanes, cyclists ride at a lateral position of 0.75 m from the right-hand edge of the road. Cyclists are positioned centrally within the 1.0 m-wide marked lane for adjacent bike lanes. In most scenarios, four cyclists are programmed into the environment, except for the cycle street, where only a single cyclist is placed due to overtaking prohibitions. Oncoming motorized traffic appears at key moments, either just before or well in advance of a potential overtaking maneuver. This variation is designed to assess the impact of opposing traffic on driver decision-making and overtaking behavior.

In total, 54 participants (13 women and 41 men) participated in the experiment. All participants complete a short familiarization drive to get used to the driving simulator. Each participant then completes a randomized set of scenarios to minimize the influence of learning effects on the results. To be eligible, participants must possess at least a provisional category B driving license and a minimum of 20 hours of driving experience. Exclusion criteria include pregnancy, current illness, or excessive use of alcohol or drugs. All participation is voluntary and may be discontinued at any time.

Multiple performance metrics are collected for each drive. Key variables include lateral passing distance, overtaking speed, overtaking time, and overtaking distance. In cycle street scenarios, where overtaking is not allowed, the analysis also focuses on average following distance and the percentage of drivers who violate the no-overtaking rule. These variables are selected to quantify both compliance and safety-related behavior across different infrastructure types.

To ensure these variables were assessed consistently across conditions, the scenario randomization process was conducted by assigning each scenario a number and then randomizing the order of the numbers. In total, four scenarios were developed and evenly distributed across participants, with each participant completing only one scenario. Random allocation was used to minimize potential order effects, such as learning or fatigue. The trial duration was approximately 20 minutes, and all data, such as passing distance and lateral position, were recorded at intervals of 0.014 seconds.

Raw data are preprocessed using the interquartile range (IQR) method to identify and remove outliers. Participants with outlying scores in more than 15% of their data points are excluded from the analysis. Statistical analyses are then conducted using linear mixed models (LMM) in SPSS. This approach is chosen due to its suitability for analyzing repeated measures data within an unbalanced design.

4. Results

Of the 54 participants, two were identified as outliers and subsequently excluded. Therefore, the final analysis was conducted on data from 52 participants.

Table 2 presents the average passing distances, passing speeds, required space, and additional cycling infrastructure costs on two-way streets.

For roads without cycling infrastructure, the average passing distance is 0.95 m. The average passing speed is 50.41 km/h. The required space is 5.50 m, and there is no additional cost associated with this infrastructure.

A similar passing distance of 0.96 m is measured for advisory bike lanes. The average passing speed drops to 45.44 km/h. The required space remains the same for roads without cycling infrastructure, namely 5.50 m. The additional cost for this infrastructure is 45.76 euros per meter.

For adjacent bike lanes, the average passing distance decreases to 0.60 m. At the same time, the average passing speed is the highest among all types of cycling infrastructure, at 50.65 km/h. The required space increases to 7.50 m. The additional cost for this type of infrastructure is 95.38 euros per meter, the highest of all.

The greatest average passing distance in cycle streets is measured at 1.10 m. The average passing speed is the lowest, at 41.64 km/h. The required space is 5.50 m, matching the first two types. The additional cost per meter for cycle streets is 40.50 euros.

Table 2. Passing behavior and street characteristics on two-way streets by cycling infrastructure type.

Type of cycling infrastructure	Passing distance (m)	Passing speed (km/h)	Required space (m)	Additional cost (€ / linear meter)
No cycling infrastructure	0.95	50.41	5.50	0.00
Advisory bike lanes	0.96	45.44	5.50	45.76
Adjacent bike lanes	0.60	50.65	7.50	95.38
Cycle streets	1.10	41.64	5.50	40.50

Table 3 presents the average passing distances, passing speeds, required space, and additional cycling infrastructure costs on one-way streets.

Table 3. Passing behavior and street characteristics on one-way streets by cycling infrastructure type.

Type of cycling infrastructure	Passing distance (m)	Passing speed (km/h)	Required space (m)	Additional cost (€ / linear meter)
No cycling infrastructure	0.67	49.42	4.50	0.00
Adjacent bike lanes	1.40	49.79	5.50	47.69
Cycle streets	0.59	45.09	4.00	27.00

On roads without cycling infrastructure, the average passing distance is 0.67 m. The average passing speed is 49.42 km/h. The required space is 4.50 m, and there is no additional cost associated with this type of cycling infrastructure.

For adjacent bike lanes, the average passing distance increases to 1.40 m. The average passing speed is nearly equal to that of roads without infrastructure, at 49.79 km/h. The required space here is 5.50 m. The additional cost for this type of cycling infrastructure is 47.69 euros per meter.

In cycle streets, the average passing distance decreases to 0.59 m, the lowest value of the three types of cycling infrastructure. The average passing speed is 45.09 km/h, which is lower than the other infrastructure types. The required space is the smallest here, at 4.00 m. The additional cost per meter for cycle streets is 27.00 euros.

Table 4 presents the result of a linear mixed model (LMM) analysis conducted in SPSS, examining the effects of different cycling infrastructure types on the dependent variable passing distance. This model used "no cycling infrastructure (two-way)" as the reference category.

The presence of an advisory bike lane (two-way) did not produce a significant effect (p = .811). In contrast, an adjacent bike lane (two-way) was associated with a significant decrease in the outcome (Estimate = -0.344, p < .001), while cycle streets (two-way) showed a significant positive effect (Estimate = 0.149, p = .013).

Table 4: LMM analysis in SPSS (passing distance).

						95% Confidence Interval	
Parameter	Estimate	Std. Error	df	t	Sig.	Lower Bound	Upper Bound
Intercept	.946	.042	312.477	22.717	<.001	.864	1.028
No cycling infrastructure (two-way)	0[a]	0	.	.	.	.	.
Advisory bike lane (two-way)	.012	.048	758.061	.239	.811	-.083	.106
Adjacent bike lane (two-way)	-.344	.048	758.061	-7.127	<.001	-.439	-.249
Cycle streets (two-way)	.149	.060	761.928	2.501	.013	.032	.267
No cycling infrastructure (one-way)	-.277	.042	758.061	-6.625	<.001	-.359	-.195
Adjacent bike lane (one-way)	.450	.042	758.061	10.760	<.001	.368	.532
Cycle streets (one-way)	-.360	.068	763.359	-5.278	<.001	-.494	-,226

[a]: reference or baseline condition.

Among one-way street categories, no cycling infrastructure (one-way) was associated with a significant decrease (Estimate = -0.277, p < .001), while adjacent bike lane (one-way) showed a significant increase in the outcome variable (Estimate = 0.450, p < .001). Finally, cycle streets (one-way) were associated with a significant decrease (Estimate = -0.360, p < .001).

5. Discussion

The results reveal clear and statistically significant differences between the investigated types of cycling infrastructure in terms of lateral passing distance, overtaking speed, overtaking time, overtaking distance, required space, and additional cost. In two-way streets, the adjacent bike lane resulted in the shortest lateral passing distance (0.60 m), a difference that was statistically significant compared to the reference category (Estimate = -0.344, p < .001). This supports the interpretation that drivers may perceive the bike lane as a physical separation, making them less inclined to move away from the cyclist and thus maintain a smaller distance while overtaking. Additionally, the overtaking speed was highest in this scenario. The combination of short lateral passing distance and high overtaking speed increases the risk for cyclists.

The advisory bike lane and no cycling infrastructure showed similar lateral passing distances (0.96 m and 0.95 m, respectively), and this lack of difference was confirmed in the LMM (p = .811). However, the overtaking speed was significantly lower on the advisory bike lane (45.44 km/h), indicating more cautious driver behavior despite the similar lateral distance.

In contrast, the cycle street stood out with the greatest lateral passing distance (1.10 m), which was significantly greater than the reference category (Estimate = 0.149, p = .013), and the lowest overtaking speed. This suggests that drivers are more considerate of cyclists in this setting. Although 55% of drivers ignored the prohibition on overtaking, overtaking on cycle streets occurred relatively safely compared to the other infrastructure types. When overtaking did not occur, an average follow distance of 15.29 m was maintained between the driver and the cyclist. Overall, these findings statistically and behaviourally reinforce that the cycle street represents the safest option in two-way streets.

In one-way streets, the pattern is different. The adjacent bike lane resulted in the greatest lateral passing distance (1.40 m), which was significantly higher than the reference (Estimate = 0.450, p < .001). This contrasts with its effect in two-way streets and likely reflects the ability of drivers to fully shift laterally due to the absence of oncoming traffic. Cycle streets in one-way configurations showed the shortest lateral passing distance (0.59 m), significantly lower than the reference (Estimate = -0.360, p < .001), yet drivers overtook at the lowest speeds. This may suggest increased driver caution. As in two-way streets, overtaking still occurred in 36% of cases, with an average follow distance of 17.61 m between the driver and the cyclist. On roads with no cycling facility, lateral passing distance did not differ significantly from that of the cycle street. However, overtaking speed was significantly higher, increasing the potential risk for cyclists.

Required space is an essential factor in determining the applicability of each infrastructure type. The adjacent bike lane requires the most space (at least 7.5 m in two-way streets), while cycle streets generally require less. Construction costs are also higher for cycle streets and adjacent bike lanes compared to advisory bike lanes or streets with no cycling facility.

6. Conclusion

The results show clear and statistically supported differences between the investigated types of cycling infrastructure in terms of passing distance, passing speed, required space, and additional costs. The type of infrastructure influences driver behavior and has spatial and financial implications that affect its practical applicability.

For two-way streets, cycle streets prove to be the safest option, offering the greatest passing distance and lowest passing speed, both of which were statistically significant. Where cycle streets are not feasible, advisory bike lanes provide a good alternative due to the lower speed, despite a similar passing distance compared to no cycling infrastructure. Roads without cycling infrastructure rank third, as the higher speed increases the risk. Adjacent bike lanes are the least recommended for this traffic type due to the combination of short passing distance and high passing speed. However, wider bike lanes can lead to larger passing distances, and on busy roads, adjacent bike lanes may be the safest option since cyclists do not ride in the vehicle lane.

In one-way streets, adjacent bike lanes come forward as the safest option, resulting in the greatest passing distance, which was statistically significant. Cycle streets follow as they are associated with significantly lower speeds despite a small passing distance. Roads without cycling infrastructure are least advisable in one-way streets because distance and speed are unfavorable.

To achieve safer traffic situations, it is recommended to prioritize cycle streets and advisory bike lanes on two-way streets. In contrast, adjacent bike lanes and cycle streets are preferred in one-way traffic.

The required space and costs negatively correlate with perceived safety in two-way streets. In most cases, the infrastructures perceived as safest are characterized by relatively limited space requirements and low investment costs. In one-way streets, this relationship is reversed. The infrastructures perceived as safest demand the most space and the highest costs. Although costs positively correlate with perceived safety here, a negative relationship exists between required space and the feeling of safety. An exception is adjacent bike lanes, which, despite their greater spatial demand, clearly add value to the perception of safety.

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