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Finding the Correlation between Transport Infrastructure and the Fatal Accident Rate of Cyclists—An International Perspective

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Abstract: Bicycle transport stands at the forefront of sustainable mobility initiatives, a cornerstone of European Union policy. While support for cycling is crucial, its advancement hinges upon the presence of high-quality, secure infrastructure for cyclists. Safety emerges as a paramount concern, influencing the viability of cycling as a mode of transportation, yet its perception varies among user demographics. In light of this, this article endeavors to examine and contrast cycling infrastructure across various European nations, alongside analyzing statistics pertaining to fatal traffic accidents involving cyclists. The findings underscore a substantial correlation between the quality of cycling infrastructure and the incidence of accidents. This correlation underscores the pressing need for robust infrastructure development and safety measures to bolster cycling as a safe and viable transportation option. By understanding the intricate interplay between infrastructure quality and safety outcomes, policymakers can better prioritize resources and enact measures to foster safer cycling environments, thus furthering the objectives of sustainable mobility on a continental scale.

Keywords: cycling; traffic accidents; road safety; transport infrastructure; fatalities

1. Introduction

Europe presented its goals in the field of sustainable mobility, where cycling itself, as an element of active travel, plays a very important role. The goals (EU mobility Strategy 2020) are focused on the reducing of greenhouse emission, dependency from fossils fuels, and creation strong and resilient transport systems. Many experts presented various benefits of cycling. The positives that cycling brings can be evaluated from the point of view of the benefits for the transport system as well as the integration within public passenger transport with the cooperation of several transport systems or services (Gnap et al, 2023; Charreire et al. 2021). Other authors see the economic benefits of cycling (Blondiau et al. 2016) resulting in the various aspects of daily life. Various studies (Maier et al. 2021) also pointed to the effects of cutting the social cost resulting from the perspective of environmental issues such as decarbonization of traffic etc. (Brad & Schneider 2023; Zitricky et al.,2020).

In the realm of bicycle transport, there's a growing emphasis on enhancing customer comfort and satisfaction through modernizing operational structures and adopting up-to-date technological aids (Hajduk, I. E., and Poliak, M. 2023). Kliestik et al, (2021) proposes a methodological solution aimed at transport service providers to build long-term relationships with clients by leveraging modern technologies and methodologies, potentially applicable to bicycle delivery services. Strategies such as implementing a process portal utilizing big data could optimize service efficiency and contribute to building a competitive offer in the bicycle logistics chain.

There are several reasons why road users use bicycle transport. One of them is precisely the fact that bicycle transport is increasingly considered to be the most ecological and, in its own way, the fastest way to get around city centers. Research by (Šarkan et al, 2023) points out how to monitor places with deteriorating air conditions and actively participate in their improvement.

For this reason, the article is dedicated to the comparison of cycling infrastructure in selected European countries as well as the statistics of fatal traffic accidents. The results confirmed the significant dependence between the infrastructure for cyclists and the accident rate itself.

In recent years, there has been a growing emphasis on promoting cycling as a sustainable mode of transportation. As part of this effort, many countries have been investing in the development of bike infrastructure to support safe and convenient cycling routes. Increasing trend of cycling had occurred during COVID -19 pandemic in comparison with passenger reduction in public transport (Mašek et al, 2023).

However, alongside the expansion of bike infrastructure, concerns about cyclist safety persist. Fatal accidents involving cyclists are tragic events that not only result in loss of life but also raise questions about the effectiveness of existing safety measures and infrastructure design.

In this case study, we explore the relationship between the length of bike infrastructure and the number of cyclist fatalities in Poland, Slovakia, and Netherland from 2013 to 2021. By analyzing these variables, we aim to understand whether there is a correlation between the expansion of bike infrastructure and the incidence of cyclist fatalities, and to assess the effectiveness of current safety measures.

2. Safety of Cyclists

Safety is an important aspect for cycling users. This is because cyclists are among the most vulnerable road users and therefore have higher demands on safety itself (Stülpnagel & Rintelen 2024). Some authors (Ji et al. 2024) pointed out that an important factor is the existence of cycling infrastructure. Here it is necessary to emphasize that it should be a high-quality, safe, and attractive infrastructure, because then we can face the so-called the paradox of not using the infrastructure.

Perceiving of safety by users determines whether or not someone will use the cycling infrastructure. There is, however, a big difference between safety, which is represented by cycling infrastructure, and safety perceived by residents (Fuest et al. 2024). Some authors investigate the term objective safety which refers to various parameters considering by cyclists (Christ et al. 2023). This also explains the situation when the cycling infrastructure is built, but users do not use it. It can be, for example, from the point of view of cohesion, smoothness of ride, connection to the overall network, as well as the aforementioned security. Some authors analyzed the safety of public bikesharing systems (Dudziak & Caban, 2022).

The basic prerequisite for ensuring safety for cyclists is the construction of a cycling infrastructure. (Useche et al. 2024) provides evidence about the safety perspective from various cities, classified by size and the evaluation of safety for cyclists. It is ideal if it is segregated from motor traffic, in case there is not enough space, traffic markings are used for separation. In the event that it is not possible to set aside dedicated lanes for cyclists and they have to share space with motor vehicles, it is advisable to take measures to calm the traffic by reducing the speed (Olsson & Elldér 2023)

Bicycle safety shares similarities with motorcycle safety in terms of the importance of protective gear, such as helmets and padding, to mitigate the risk of head and bodily injuries in crashes. The article Bańkowski and Frej (2023) presents a review of the literature related to motorcycle crash tests and the dummies used for the tests. The work presents the most important standard that regulates how motorcycle crash tests are performed.

The specifications of the design attributes for cycling also assumes the specific safety design principles (Boulangé et al. 2017) that can attract potential users. Evaluating fatal cyclist accidents is one way to determine the overall safety of these road users. Due to the needs of this evaluation, it is necessary to develop the appropriate technique and technology of this evaluation. Jaśkiewicz et al. (2021) highlights the development of an anthropometric dummy for low-speed crash tests, emphasizing its relevance to assessing bicycle safety at speeds up to 30 km/h where standard dummies are inadequate. Jaśkiewicz (2024) discusses the durability of knee and shoulder joints in the new dummy model, suggesting its potential in enhancing safety measures for bicycle transport through reliable joint mechanisms.

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One of the basic indicators of road traffic safety is traffic accident statistics, including fatal traffic accidents involving cyclists. Table 1 shows that up to 15 monitored countries recorded an increase in the number of cyclists fatalities in 2021. Figure 1 also shows a cartograph for this year, showing this trend mainly in the countries of Central and Eastern Europe, but also in countries such as Belgium and Netherlands. This factor needs to be investigated further and it is possible that it is further related to the use of electromobility in cycling, which has become more popular in recent years, especially among the younger population.

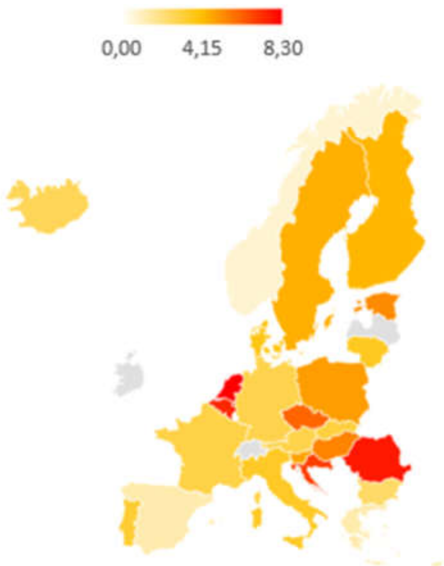

Figure 1. Cyclist fatalities per 1 million inhabitants in year 2021.

Table 1. Development of cyclist fatalities in the territory of the European 27 between 2013 and 2021 per 1 million inhabitants.

Country	2013	2014	2015	2016	2017	2018	2019	2020	2021	Graphical representation of the trend
Austria	6.15	5.29	4.54	5.52	3.65	2.72	2.48	2.13	2.91	 
Belgium	7.45	7.33	8.01	7.16	6.70	7.81	8.29	7.38	7.44	
Bulgaria	4.26	4.00	4.03	4.89	3.10	2.98	3.86	2.73	2.46	
Croatia	5.40	4.47	8.05	6.44	5.54	5.36	3.93	2.22	6.94	
Cyprus	2.31	1.17	1.18	0.00	4.68	1.16	1.14	1.13	1.12	

Czechia	7.04	6.47	7.97	5.02	5.39	5.28	4.98	4.77	6.10	
Denmark	5.89	5.33	4.59	5.43	4.70	4.84	5.34	3.26	3.77	
Estonia	0.00	0.00	0.00	3.04	0.76	2.27	1.51	0.75	5.26	
Finland	3	4.95	5.67	4.74	4.18	3.81	4.17	5.61	4.34	
France	2.24	2.40	2.24	2.43	2.59	2.61	2.78	2.40	2.99	
Germany	4.40	4.90	4.72	4.78	4.63	5.37	5.36	5.12	2.90	
Greece	1.36	1.74	1.01	1.67	1.02	1.12	2.05	1.12	1.31	
Hungary	6.86	9.92	8.42	7.43	8.27	6.95	6.45	4.09	5.45	
Iceland	0.00	0.00	3.04	0.00	5.91	0.00	0.00	0.00	2.71	
Ireland	1.08	2.80	2.14	2.12	2.93	1.86	1.63			
Italy	4.21	4.49	4.13	4.53	4.19	3.62	4.23	2.83	3.49	
Latvia	6.42	7.99	4.53	3.56	5.64	4.65	4.69	8.91		
Lithuania	6.06	6.45	7.53	4.15	4.56	2.85	3.22	4.29	3.58	
Luxembourg	0.00	0.00	0.00	1.74	0.00	4.98	0.00	4.79	0.00	
Malta			0.00	2.22	0.00	2.10	0.00	0.00	0.00	
Netherlands	6.67	7.90	7.40	7.72	8.08	9.31	8.56	9.08	8.30	

Norway	1.98	2.35	0.97	2.30	1.71	1.32	1.13	0.56	0.74	
Poland	8.04	7.52	7.89	7.14	5.79	7.50	6.79	6.56	4.89	
Portugal	2.77	3.36	2.41	3.19	2.42	2.53	2.63	1.85	3.30	
Romania	8.04	7.57	8.15	8.91	9.72	9.27	10.20	9.88	7.76	
Slovakia				3.87	4.23	3.49	3.12	4.40	3.11	
Slovenia	7.77	6.31	6.79	5.81	5.32	3.87	4.33	3.82	4.74	
Spain	1.46	1.59	1.25	1.44	1.68	1.24	1.70	1.50	1.33	
Sweden	1.47	3.42	1.74	2.23	2.60	2.27	1.66	1.55		
Switzerland	2.61	4.18	4.73	3.96	4.39	4.60	3.16	5.11	4.50	
EU27	4.29	4.56	4.40	4.47	4.30	4.42	4.52	4.05	3.59	

3. Methodology and Data Collection

3.1. Methodology

There are already published studies which investigate the cycling infrastructure in cities (Tait et al. 2022). Another study reflects to the analysis of cycling safety in Europe (Evgenikos et al. 2016) from the road accident database. But there is a lack of studies analysing the type of cycling infrastructure and correlation to road fatalities.

3.2. Data Collection

For this study, data was collected on two key variables:

X: Length of bike infrastructure from 2013 to 2021.

Y: Number of cyclists killed in fatal accidents in from 2013 to 2021.

The data was obtained from official sources such as government reports, EUROSTAT and road safety organizations. It represents a comprehensive overview of bike infrastructure development and cyclist fatalities in three countries, namely the Netherlands, Poland, and Slovakia. The aim of selecting these countries was to compare countries that have significantly developed bicycle transport (the Netherlands) with countries where this type of transport is not so popular compared to other types of personal transport. Unfortunately, not all data could be found in the required quantity and

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quality. Therefore, data collection was limited to the years 2013 (or 2016 in the case of Slovakia) to 2021.

Table 2 provides a clear overview of the X and Y values for each year, showcasing length of bike infrastructure in selected countries and the corresponding number of cyclist fatalities.

Table 2. Variables collected for the research in selected countries.

Year	Netherland		Poland		Slovakia	
	Length of Bike Infrastructure in km (X)	Cyclist Fatalities (Y)	Length of Bike Infrastructure in km (X)	Cyclist Fatalities (Y)	Length of Bike Infrastructure in km (X)	Cyclist Fatalities (Y)
2013	30763	112	7726	306	336.54	N/A
2014	31791	133	9347.5	286	437.65	N/A
2015	32850	125	10797.2	300	538.76	N/A
2016	33941	131	11258.4	271	639.87	21
2017	35063	138	12138.2	220	740.98	23
2018	36218	160	13904.7	285	747.86	19
2019	37405	148	15538.7	258	853.82	17
2020	38626	158	17254.6	249	923.59	24
2021	39880	145	18509.9	185	106.06	17

For the purposes of the study, data regarding the length of the cycling infrastructure that were not available were further calculated using spline interpolation. Data available from official sources are shown in green in Table 2. It is worth noting that the only country that had all the necessary data available from official sources in the studied area is Poland.

4. Data Analysis

4.1. Descriptive Analysis

Netherlands:

The length of bike infrastructure in the Netherlands has been steadily increasing over the years, starting from 30,763 km in 2013 and reaching 39,880 km in 2021.

The number of cyclist fatalities in the Netherlands fluctuates but generally shows a decreasing trend, with a peak of 160 fatalities in 2018 and a low of 112 in 2013. The number slightly increases in the last year, reaching 145 in 2021.

Poland:

Poland also shows an increasing trend in the length of bike infrastructure, starting at 7,726 km in 2013 and reaching 18,509.9 km in 2021.

The number of cyclist fatalities in Poland varies, with some fluctuations throughout the years. There is a notable decrease in fatalities from 2016 to 2017, followed by an increase in 2018 and then a decreasing trend until 2021.

Slovakia:

Slovakia has the lowest length of bike infrastructure among the three countries, starting at 336.537 km in 2013 and reaching 1,062.06 km in 2021.

The number of cyclist fatalities in Slovakia is relatively low compared to the other two countries. There is a slight fluctuation in the number of fatalities over the years, with a peak of 24 in 2020.

General Trends:

Overall, all three countries show an increasing trend in the length of bike infrastructure over the years.

The number of cyclist fatalities varies between the countries, with the Netherlands generally having higher numbers compared to Poland and Slovakia.

Missing Data:

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There are some missing values for cyclist infrastructure for certain years, particularly in the earlier years of the dataset. This could be due to incomplete data collection or reporting issues.

Interpretation:

The increasing length of bike infrastructure indicates a positive trend towards promoting cycling as a safe and sustainable mode of transportation. However, the effectiveness of this infrastructure in improving cyclist safety must be assessed by examining its impact on reducing cyclist fatalities.

Fluctuations in the number of cyclist fatalities highlight the ongoing challenges in ensuring cyclist safety on the roads. While infrastructure development plays a crucial role in improving safety, additional measures such as education, enforcement, and community engagement are also essential components of a comprehensive road safety strategy.

Further analysis, including statistical modeling and trend analysis, may provide deeper insights into the relationship between bike infrastructure development and cyclist fatalities, helping to inform evidence-based policy.

4.2. Statistical Analysis

Input data were verified by the Shapiro-Wilk test for normal distribution. Since the results of this test proved that $p>\alpha$ in all cases, we confirm the null hypothesis H_0, that all the investigated data did not show a significant departure from normality, and therefore the Pearson correlation coefficient was used to calculate the correlation, including the verification of statistical significance.

Pearson Correlation Coefficient (r):

The Pearson correlation coefficient (r) measures the strength and direction of the linear relationship between two variables. It ranges from -1 to 1, where:

r=1 indicates a perfect positive linear relationship,

r=−1 indicates a perfect negative linear relationship, and

r=0 indicates no linear relationship.

The formula for calculating the Pearson correlation coefficient (r) is:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x^2)][n\sum y^2 - (\sum y^2)]}} \tag{1}$$

Where:

n is the number of data points,
$\sum xy$ is the sum of the products of the corresponding values of x and y,
$\sum x$ is the sum of the values of x,
$\sum y$ is the sum of the values of y,
$\sum x^2$ is the sum of the squares of the values of x,
$\sum y^2$ is the sum of the squares of the values of y.

Statistical Significance Test:

To assess the statistical significance of the correlation coefficient, we perform a hypothesis test using the t-distribution. The null hypothesis is that there is no correlation in the population (i.e., r=0).

We calculate the t-statistic using the formula:

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}} \tag{2}$$

Where:

r is the calculated Pearson correlation coefficient,
n is the number of data points, and
n−2 represents the degrees of freedom.

We then determine the critical value from the t-distribution for a specified significance level (e.g., α=0.05) and degrees of freedom.

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If the absolute value of the calculated t-statistic exceeds the critical value, we reject the null hypothesis and conclude that the correlation coefficient is statistically significant.

5. Results and Interpretation

In the following text descriptive analysis of the research results is provided.

Netherlands

Correlation-test, using T(df:7) distribution (two-tailed)

Since the null correlation is zero, we use the t-distribution to test the correlation. The correlation's distribution is not symmetrical when $r \neq 0$, hence we use the Z distribution over Fisher transformation to create the confidence interval.

Since the p-value < α, H0 is rejected. The p-value equals 0.007319, ($P(x \leq 3.7341) = 0.9963$). It means that the chance of type I error (rejecting a correct H0) is small: 0.007319 (0.73%). The smaller the p-value the more it supports H1. The test statistic T equals 3.7341, which is not in the 95% region of acceptance: [-2.3646, 2.3646].

The correlation (0.8159) is not in the 95% region of acceptance: [-0.6664, 0.6664].

The 95% confidence interval of correlation is: [0.3314, 0.9599]. Therefore, there is strong evidence to suggest that the correlation in the population is statistically significant, and it is not equal to 0. The calculated correlation coefficient is considered significant as it lies outside the 95% confidence interval.

Poland

Correlation-test, using T(df:7) distribution (two-tailed)

Since the null correlation is zero, we use the t-distribution to test the correlation. The correlation's distribution is not symmetrical when $r \neq 0$, hence we use the Z distribution over Fisher transformation to create the confidence interval.

Since the p-value < α, H0 is rejected. The p-value equals 0.02169, ($P(x \leq -2.9409) = 0.01084$). It means that the chance of type I error (rejecting a correct H0) is small: 0.02169 (2.17%). The smaller the p-value the more it supports H1. The test statistic T equals -2.9409, which is not in the 95% region of acceptance: [-2.3646, 2.3646].

The correlation (-0.7434) is not in the 95% region of acceptance: [-0.6664, 0.6664].

The 95% confidence interval of correlation is: [-0.9423, -0.1566]. Therefore, there is strong evidence to suggest that the correlation in the population is statistically significant, and it is not equal to 0. The calculated correlation coefficient is considered significant as it lies outside the 95% confidence interval. Moreover, its negative value suggests a negative correlation between the variables being studied.

Slovakia

Correlation-test, using T(df:7) distribution (two-tailed)

Since the null correlation is zero, we use the t-distribution to test the correlation.

The correlation's distribution is not symmetrical when $r \neq 0$, hence we use the Z distribution over Fisher transformation to create the confidence interval.

Since the p-value > α, H0 cannot be rejected.

The population's correlation is considered to be equal to the expected correlation (0).

In other words, the difference between the sample correlation and the expected correlation is not big enough to be statistically significant.

A non-significance result cannot prove that H0 is correct, only that the null assumption can not be rejected. The p-value equals 0.511, ($P(x \leq -0.7207) = 0.2555$). It means that the chance of type I error, rejecting a correct H0, is too high: 0.511 (51.1%). The larger the p-value the more it supports H0.

The test statistic T equals -0.7207, which is in the 95% region of acceptance: [-2.7764, 2.7764].

The correlation (-0.339) is in the 95% region of acceptance: [-0.8114, 0.8114].

The 95% confidence interval of correlation is: [-0.9023, 0.6519].

Based on the results of the correlation test, there is insufficient evidence to reject the null hypothesis. The data does not provide significant support for a correlation between the variables being studied. The observed correlation coefficient falls within the confidence interval, indicating

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that the relationship between the variables is not statistically significant. Therefore, the null hypothesis cannot be rejected, and it is concluded that there is no significant correlation between the variables at the given confidence level.

For a better overview, individual statistical values are compared in Table 3.

Table 3. Summary table of statistical analysis results.

Country	Netherland	Poland	Slovakia
Parameter	**Value**	**Value**	**Value**
Pearson correlation coefficient (r)	0.8159	- 0.7434	- 0.3390
r^2	0.6658	0.55270	0.11490
P-value	0.007319	0.02169	0.51100
Covariance	39716.2222	- 10 662.92220	- 153.27200
Sample size (n)	9	9	6

The Netherlands and Poland exhibit statistically significant correlations between the variables being studied, with strong positive and strong negative correlations respectively. Slovakia, on the other hand, shows a moderate positive correlation, but the correlation is not statistically significant given the obtained p-value. The coefficients of determination provide insights into the proportion of variability in the data explained by the linear relationships. Covariance indicates the direction and magnitude of the relationship between the variables.

6. Conclusion and Discussion

The investigation made clear that it is important to include several factors when examining the problem of bicycle-related traffic accidents. It is impossible to assess the severity of bicycle fatal accidents. It is necessary to establish a connection between them and the distance covered by bicycles in terms of infrastructure or kilometers. On the one hand, this is also the reason we selected nations like Slovakia and Poland. They represent the countries with less advanced cycling nations. Conversely, the Netherlands boasts a well-advanced network of bike infrastructure.

6.1. Main findings

Based on the results of the correlation tests conducted for Netherlands, Poland, and Slovakia regarding the length of bike infrastructure and fatalities, significant findings emerge:

Netherlands: The correlation analysis reveals a strong positive correlation (0.8159) between the length of bike infrastructure and fatalities. The p-value (0.007319) is below the significance level, indicating strong evidence to reject the null hypothesis. The calculated correlation coefficient falls outside the 95% confidence interval, further supporting the significance of the correlation. This suggests that as the length of bike infrastructure increases in the Netherlands, the number of fatalities tends to increase as well.

Poland: In Poland, a significant negative correlation (-0.7434) between the length of bike infrastructure and fatalities is observed. The p-value (0.02169) is below the significance level, providing strong evidence to reject the null hypothesis. The correlation coefficient falls outside the 95% confidence interval, indicating statistical significance. This negative correlation suggests that as the length of bike infrastructure increases in Poland, the number of fatalities tends to decrease.

Slovakia: Conversely, for Slovakia, the correlation analysis does not yield statistically significant results. The p-value (0.511) is above the significance level, suggesting insufficient evidence to reject the null hypothesis. The correlation coefficient falls within the 95% confidence interval, indicating that the relationship between the length of bike infrastructure and fatalities is not statistically significant. Thus, no significant correlation is found between these variables in Slovakia.

6.2. Descriptive Analysis

Overall Implications

The findings suggest that the relationship between the length of bike infrastructure and fatalities varies across the studied countries. While Netherlands and Poland exhibit significant correlations, indicating the potential impact of infrastructure length on fatalities, Slovakia does not show a significant relationship. These results emphasize the importance of context-specific analysis and tailored interventions in addressing cyclist safety. Policymakers should consider these findings when designing and implementing cycling infrastructure projects to enhance safety and promote cycling as a sustainable mode of transportation. Further research may be needed to understand the underlying factors contributing to the observed correlations and disparities among different regions.

6.3. Future Directions

Further Research: Future research could explore the specific mechanisms through which bike infrastructure influences cyclist safety and identify best practices for infrastructure design and implementation. Longitudinal studies tracking changes in infrastructure development and cyclist fatalities over time could provide valuable insights into the long-term impacts of infrastructure investments on road safety outcomes.

Evaluation and Monitoring: Continuous evaluation and monitoring of bike infrastructure projects are essential to assess their effectiveness and identify areas for improvement. Regular data collection on cyclist fatalities, infrastructure usage, and user satisfaction can inform evidence-based decision-making and ensure that resources are allocated efficiently. (Ondrus-Kolla 2018)

While this study provides valuable insights into the relationship between bike infrastructure length and cyclist fatalities, it is important to acknowledge several limitations that may affect the interpretation and generalization of the findings:

Data Limitations: The analysis relies on secondary data obtained from official sources, such as government reports and transportation departments. The accuracy and completeness of these datasets may vary, and there may be inconsistencies or errors in reporting. The availability of data may be limited to certain time periods or geographic regions, which could affect the representativeness of the findings. A big disadvantage is the fact that not all detailed data are available for individual countries, so we have considered only those that are available.

Spatial and Temporal Variability: The analysis aggregates data at the national level, which may mask spatial variations in infrastructure quality, traffic conditions, and safety outcomes across different countries. Local factors, such as urban density, road design, and socioeconomic status, could influence the relationship between infrastructure development and cyclist safety. The study examines trends over a fixed time period (2013-2021), but infrastructure projects and safety initiatives may have different implementation timelines and lead times. Short-term fluctuations in infrastructure investment or safety interventions may not be fully captured by the analysis.

Acknowledging these limitations is crucial for interpreting the findings of the study accurately and for informing future research efforts aimed at addressing these challenges and advancing our understanding of the relationship between bike infrastructure and cyclist safety.

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