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Article

The Correlation between Cycling Infrastructure and the Fatal Accident Rate of Cyclists – Comparison of Slovakia, Poland and The Netherlands

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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. Considering this, this article endeavours to examine and contrast cycling infrastructure across various European nations, alongside analysing statistics pertaining to fatal traffic accidents involving cyclists. In our paper, we have chosen the Netherlands as a representative of building quality cycling infrastructure with many years of experience, and two countries that are developing conditions for cyclists, Slovakia and Poland. We have applied a correlation between the length of the transport infrastructure and the number of cyclists killed. The findings point to the 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. We have employed the Shapiro-Wilk test for normal distribution to verify the input data and process the Pearson correlation to investigate the correlation between cycling infrastructure and road accident fatalities of cyclists.

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 [1] are focused on reducing greenhouse emissions, dependency on fossil fuels, and the creation of 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 [2]. Other authors see the economic benefits of cycling [3] resulting in the various aspects of daily life. Various studies [4] also pointed to the effects of cutting social costs resulting from the perspective of environmental issues such as the decarbonisation of traffic [5]. In the realm of bicycle transport, there is a growing emphasis on enhancing customer comfort and satisfaction [6]. Strategies such as implementing a process portal utilising big data could optimise 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 centres. Research by [7] 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

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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. An increasing trend of cycling occurred during the COVID-19 pandemic in comparison with passenger reduction in public transport [8]. 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 the Netherlands from 2013 to 2021. By analysing 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.

From a research perspective, there is a lack of peer-reviewed studies comparing cycling infrastructure and cyclist fatalities. This is particularly the case when there is a comparison between countries with a high level of cycling infrastructure and countries that do not have good cycling infrastructure. In addition, this article looks at the relationship between the Netherlands, a country with a high-quality cycling network, and two countries, Slovakia and Poland, which are trying to develop conditions for cyclists.

The paper is structured as follows: section 2 provides a literature review of the topic of road traffic accidents and cyclists. The section 3 describes the applied methodology. In the section 4 is presented the data and statistical analysis of selected countries. The results are presented in section 5. The discussion is presented in section 6 with an accent on how the results can be interpreted and the challenges for future research in this area.

2. Literature Review

Safety is an important aspect for cycling users [9]. This is because cyclists are among the most vulnerable road users and, therefore, have higher demands on safety itself [10]. Some authors [11] pointed out that cycling infrastructure is an important factor. Here it is necessary to emphasise that it should be a high-quality, safe, and attractive infrastructure because then we can face the paradox of not using the infrastructure. Users ' perception of safety determines whether or not someone will use the cycling infrastructure [12]. However, there is a big difference between safety, represented by cycling infrastructure, and safety perceived by residents [13]. Some authors investigate the term objective safety which refers to various parameters considered by cyclists [14]. 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, and connection to the overall network, as well as the aforementioned security. Some authors analysed the safety of public bikesharing systems [15]. The essential prerequisite for ensuring cyclists' safety is the construction of a cycling infrastructure. [16] 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; if 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 [17]. 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 authors [18] present a review of the literature related to motorcycle crash tests and the dummies used for the tests. The work presents the most crucial standard that regulates how motorcycle crash tests are performed. Larsen et al [19] pointed out the problem with the lack of room for building the cycling infrastructure. The specifications of the design attributes for cycling also assume the specific safety design principles [20] that can attract potential users. Evaluating fatal cyclist accidents is one way to determine the overall safety of these road users. One of the basic indicators of road traffic safety is traffic accident statistics, including fatal traffic accidents involving cyclists. Table 1 in Appendix 1 shows that up to 15 monitored countries recorded

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an increase in the number of cyclist fatalities in 2021. In the geographical comparison the, Figure 1 depicts the cyclists fatalities per 1 million per 2021, showing this trend mainly in the countries of Central and Eastern Europe, but also in countries such as Belgium and the Netherlands. This factor needs to be investigated further, and it is possible that it is related to the use of electromobility in cycling, which has become more popular in recent years, especially among the younger population.

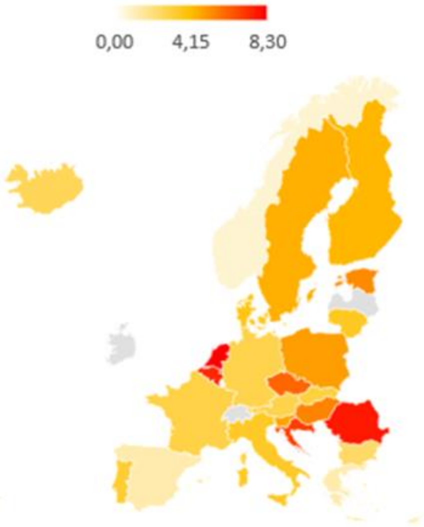

Figure 1. Cyclist fatalities per 1 million inhabitants in year 2021, source [21].

3. Methodology

There are already published studies which investigate the cycling infrastructure in cities [22]. Another study reflects the analysis of cycling safety in Europe [23] review 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 less popular than other types of personal transport. Unfortunately, not all data could be found in the required quantity and quality. Therefore, data collection was limited to the years 2013 (or 2016 in the case of Slovakia) to 2021.

Table 1 provides a clear overview of each year's X and Y values, showcasing the length of bike infrastructure in selected countries and the corresponding number of cyclist fatalities. The methodology consisted of collecting data from individual countries for selected years. Where these data were not available, the missing data were interpolated to allow statistical analysis and correlation calculations.

Table 1. Variables collected for the research in selected countries. [24–27].

Year	The 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	30 763	112	7 726	306	336.54	15
2014	31 791	133	9 347.5	286	437.65	24
2015	32 850	125	10 797.2	300	538.76	16
2016	33 941	131	11 258.4	271	639.87	21
2017	35 063	138	12 138.2	220	740.98	23

2018	36 218	160	13 904.7	285	747.86	19
2019	37 405	148	15 538.7	258	853.82	17
2020	38 626	158	17 254.6	249	923.59	24
2021	39 880	145	18 509.9	185	1 060.6	17

For the purposes of the study, data regarding the length of the cycling infrastructure that was 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 Poland is the only country with all the necessary data available from official sources in the studied area.

Table 2. Summary table of statistical analysis results.

Country	The Netherlands	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

4. Data Analysis

This section briefly describes the key indicators for the selection of countries, namely the development of the length of cycling infrastructure. We can see that the increase in the length of cycling infrastructure varies due to the size of the country, the different needs for infrastructure, and the approach to the development of cycling infrastructure itself. The situation is similar for cycling fatalities, which are generally on a downward trend.

The 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 increased 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 than Poland and Slovakia.

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

4.1. Statistical Analysis

Input data were verified by the Shapiro-Wilk test for normal distribution. Since the results of this test proved that p>α in all cases, we confirm the null hypothesis H0, 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:

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

Where:

n is the number of data points,

∑xy is the sum of the products of the corresponding values of x and y,

∑x is the sum of the values of x,

∑y is the sum of the values of y,

∑x2 is the sum of the squares of the values of x,

∑y2 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.

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

The following section presents the results of the statistical analysis.

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The 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≤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. This suggests that the extensive cycling infrastructure might attract a higher number of daily cyclists, which could increase the exposure risk and, consequently, the number of fatalities despite the infrastructure.

Poland

Correlatio 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≤-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. This implies that improvements in cycling infrastructure are effectively enhancing the safety of cyclists, as increased infrastructure corresponds to fewer fatalities.

Slovakia

Correlatio 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≤-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]. However, this relationship is not statistically significant, suggesting that the current level of cycling infrastructure development is insufficient to impact cyclist safety significantly or other factors might be influencing the fatality rates.

Based on the correlation test results, 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 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 2.

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6. Discussion

Different aspects of the research discussion should be used to evaluate the findings from the data analysis. The Netherlands and Poland exhibit statistically significant correlations between the studied variables, with strong positive and 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. In the case of the Netherlands, which has the longest segregated cycling infrastructure, the number of fatalities is probably also related to the high number of inhabitants who use a bicycle on a daily basis. In the case of Poland, it is more indicative of a still inadequate safe cycling network, similarly, for Slovakia, where the proportion of cyclists who cycle daily is lower than in the Netherlands. Usage data for the whole of Europe is only available from the Eurobarometer 2020 survey [28]. However, individual countries also conduct their own surveys on travel behaviour. The problem is that the methodologies are not harmonised across countries, so the data are not fully comparable. Eurobarometer provided the option to compare the usage of cycling daily, where the Netherlands is on the second place, Slovakia on the 10th and Poland on the 20th place. While we do not need to discuss the position of the Netherlands, the position of Slovakia could mean that the country has good conditions for cyclists with adequate cycling infrastructure, which is not the case. Like Poland, it still needs to develop its cycling infrastructure, but the country states its VISION ZERO related to traffic accident fatalities [29], similar to the Netherlands [30].

Of course, the construction of cycling infrastructure can have an impact on reducing fatal accidents for cyclists, but the quality of the built cycling routes is also an important aspect [31]. An important aspect is, therefore the funding of cycling infrastructure. It is important to emphasise that countries that have developed a comprehensive network of cycle routes, such as the Netherlands [32], have a long history of investing in the promotion of cycling (source). In contrast, countries with fewer cycle lanes (e.g. Eastern Europe) rely less on support from EU funds. Poland is planning to allocate almost €800 million of EU structural funds for investment in the cycling sector in the financial period from 2021 to 2027 [33]. In 2022, the Dutch government has allocated a one-off budget of €780 million to improve cycling access to new housing developments. For the first time, there is now a structural budget for cycle routes: €6 million per year [34].

The Recovery and Resilience Plan will provide €105 million to support the development of cycling in Slovakia. In some cases, politics will also hinder the development of cycling infrastructure. The shift from car-centric planning to sustainable mobility tends to be difficult for some countries.

The aspect of traffic accident analysis from the point of view of the locations where fatal cyclist accidents occur is also important. We are mainly thinking of the difference between traffic accidents in the urban environment and accidents outside the city, in the suburbs [35] and also the surface of roads [36]. It is also possible to find out the correlation between the built environment and cyclists' accidents [37]. It is also important to have a common dataset to analyse the trend of cycling accidents or accidents of vulnerable users in one place [38]. There are many more factors contributing to bicycle accidents that need to be investigated [39]. In the future, it is expected that information technology (40) will be able to improve the safety of cyclists. It would also be advisable to develop a single database or adapt existing databases (41,42) with comprehensive statistical data on cyclist accidents. A fundamental problem in comparing countries is the lack of consistent statistics, especially when it comes to historical data on cycling infrastructure. Therefore, we also selected countries where this data could be obtained. The challenge would be to compare the length of cycling infrastructure with a detailed breakdown of different types across Europe. This data would help to better monitor the strategic targets set by both the European Union and individual countries. Of course, an added value would be to calculate multiple regressions and investigate other parameters that impact cyclist safety. Again, this is due to the incompleteness of all the necessary data for individual countries. The unavailability of these data could be partly overcome by interpolation using the data available to date.

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7. Conclusions

The main output of this study was to investigate the correlation between the length of cycling infrastructure and cyclist fatalities in selected countries. Data from the Netherlands, Poland, and Slovakia were selected for comparison, as a correlation was found between countries with different conditions for cyclists. The results of the correlation show a correlation between the length of cycling infrastructure and cyclist fatalities (the Netherlands and Poland) but also point to other aspects that need to be taken into account (Slovakia). These include funding cycling infrastructure, determining the location of fatalities, and determining the overall modal split of cycling infrastructure.

This study investigates the correlation between the length of cycling infrastructure and cyclist fatalities in three selected countries: the Netherlands, Poland, and Slovakia. The findings are based on statistical analysis, including Pearson correlation coefficients and p-values, providing insight into the strength and significance of these correlations.

In the Netherlands, the study reveals a strong positive correlation between the length of cycling infrastructure and cyclist fatalities, with a correlation coefficient of 0.8159. This correlation is statistically significant, as indicated by the p-value of 0.007319, which is well below the 0.05 significance threshold. Furthermore, the 95% confidence interval for the correlation coefficient, which ranges from 0.3314 to 0.9599, does not include zero. This result suggests that as the length of cycling infrastructure increases, the number of cyclist fatalities also tends to increase. This could be attributed to the higher numbers of daily cyclists in the Netherlands, which might increase the exposure risk despite the extensive infrastructure.

In Poland, the study finds a strong negative correlation, with a correlation coefficient of -0.7434. The p-value of 0.02169 indicates that this correlation is statistically significant at the 0.05 level. The negative correlation suggests that as the length of cycling infrastructure increases, the number of cyclist fatalities decreases. The 95% confidence interval for this correlation, which ranges from -0.9423 to -0.1566, does not include zero, confirming the significance of the correlation. This finding implies that improvements in cycling infrastructure in Poland are effectively enhancing cyclist safety.

In contrast, Slovakia presents a moderate negative correlation with a correlation coefficient of -0.3390. However, the p-value of 0.511 indicates that this correlation is not statistically significant. The 95% confidence interval for this correlation includes zero, ranging from -0.9023 to 0.6519, suggesting no significant evidence to support a relationship between the length of cycling infrastructure and cyclist fatalities in Slovakia. This result implies that the current level of cycling infrastructure development in Slovakia may not be sufficient to impact cyclist safety significantly, or other factors might be influencing the fatality rates.

The findings highlight that the Netherlands shows a significant positive correlation between cycling infrastructure length and cyclist fatalities, likely due to a higher number of daily cyclists. Poland exhibits a significant negative correlation, indicating that increased infrastructure is associated with fewer fatalities and suggesting effective safety improvements. Slovakia, however, does not show a significant correlation, indicating that other factors might be at play or that the infrastructure development is not yet impactful. These insights emphasise the importance of considering various factors, including infrastructure extent, funding, and daily cycling habits, when evaluating cyclist safety and the effectiveness of infrastructure. To develop comprehensive cycling safety strategies, further research is needed to explore these relationships in other countries and under different conditions.

By understanding the intricate interplay between infrastructure quality and safety outcomes, policymakers can better prioritise resources and enact measures to foster safer cycling environments, thus furthering the objectives of sustainable mobility on a continental scale.

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