Sustainable Futures 10 (2025) 101223

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Sustainably breaking the cycle: How closely are countries' development and welfare indicators related to their cycling safety outcomes?

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ARTICLE INFO

ABSTRACT

While urban cycling is gaining ground worldwide as an active and sustainable mode of transport, various safety-related risks continue to threaten cyclists. In this regard, some studies suggest that cycling risk-related outcomes

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https://doi.org/10.1016/j.sftr.2025.101223
Received 31 December 2024; Received in revised form 23 July 2025; Accepted 23 August 2025
Available online 28 August 2025

Dataset link: https://doi.org/10.7910/DVN/EP6QLN

Keywords:
Sustainable transport
Cycling behavior
Country-based development indicators
Inequities
Safety

could be closely linked to development indicators beyond cycling infrastructure, including health, income, and welfare indices. This study aimed to analyze the relationships between different country-level development indicators (e.g., income level, life expectancy, internet access, healthcare coverage, and national health expenditure) and cyclists' behavioral and safety-related outcomes in 19 countries with diverse socio-economic backgrounds. The findings of this multinational study indicate that country-level development indicators are significantly and consistently related to both cycling safety behaviors and crash records, with the situation being more pronounced in developing (LMIC) countries. Overall, these differences highlight (although not linearly) the inequity and the high vulnerability faced by cyclists in countries with low or medium levels of economic development and point to the need for targeted interventions in areas such as information access, healthcare, and road safety training. Such measures could support the promotion of cycling and other active transport modes from a user-centered perspective. All in all, this may help multidimensionally enhance the promotion of the bicycle as a sustainable means of transport, fostering increased safety and equity among countries.

1. Introduction

Given its countless contributions to community welfare, urban cycling is currently promoted in most countries as a sustainable, healthy, and accessible alternative to motorized transport means [1,2]. Among these literature-based "benefits", the accumulated literature endorses that regular cycling improves users' health and fitness [3] and contributes to the reduction of traffic congestion [4], polluting gas emissions, and noise in urban areas [5], making it reasonable to foster its choice for regular commutes [6].

Nevertheless, particularly in Low and Middle-Income Countries (LMICs), significant progress can still be made in increasing the number of people who choose bicycles over motorized vehicles, as well as invigorating developments in other quality-of-life-related indicators and social equity through safer and more inclusive cycling [7–9]. In addition, from a scientific perspective, it is critical to generate knowledge and promote the use of sustainable means of transportation to support these hypothesized cycling-related benefits, especially given that the persistent risks associated with cycling crashes and fatalities continue to discourage both current and potential bicycle riders [1,10].

Moreover, some recent studies support the idea that strengthening policies and public investments in key issues both inside (e.g., infrastructures, shared bike systems) and outside active transport (e.g., healthcare quality, access to information) may contribute to developing a "sustainable and sustained" improvement of cycling share in these countries [11,12,13,14]. Additionally, the individuals' socioeconomic level influences their transportation choices in different regions [8,15, 16]) and, despite the efforts made by emerging countries to improve cycling environments, there are still significant between-country differences in the number of bicycle users, their behavioral trends, and safety outcomes [17,18].

Apart from the income-based classification HIC and LMIC, other indexes help to better shape the socioeconomic context of countries. For instance, the World Development Indicators are produced by the Development Data Group in collaboration with the Bank's regions and Global Practices, as well as external partners (Link 1). These indicators mainly cover poverty and inequality, people issues (including healthcare), the environment, the economy, states and markets, and global links. Therefore, the question arises as to whether parameters related to the socioeconomic context of a country such as life expectancy, connectivity, and health expenditure, may affect active transport dynamics (i.e., behavioral, environmental, and structural factors that shape the use of non-motorized means of transportation), as well as cycling-related risky behaviors and their outcomes [19].

With this in mind, the current study aims to analyze the relationships between different country-level development indicators (e.g., income level, life expectancy, percentage of population with internet access, physicians per 1000 inhabitants, and national health expenditure) and cyclists' behavior (violations and errors) in 19 countries with different socio-economic backgrounds. Based on the scientific background presented in the introduction and previous research from our research group [20,18], we hypothesized that, besides income levels (and even controlling by them), cyclists riding in countries with greater investment in these development indicators may also tend to report safer cycling behaviors.

2. Methods and materials

2.1. Participants

A total of 7001 cyclists from 19 countries on five continents participated in this study. Participants were contacted through diverse recruitment strategies, including social media advertising, classroom questionnaire-sharing, mailing lists, and national cyclist federations, with an estimated response rate of 60–70 %. Additionally, the snowball procedure was applied asking participants to reshare the survey to obtain as many responses as possible. We used an electronic survey method (online questionnaire) translated into each country's most spoken language(s). The platform employed to gather the data differed in some countries according to country or institutional-based convenience or unavailability. Finally, no economic incentives were offered to the participants of the study. Table 1 shows these characteristics organized by participating countries. Specific sociodemographic and cycling characteristics of participants can be found in Tables 2 and 3.

2.2. Variables and instruments

The study participants responded to an online-based general survey consisting of two sections. The first section enquired about sociodemographics (age, gender, occupation, education) and cycling features

Table 1
Countries and questionnaire information.

Continent	Country	N	Questionnaire Language	Data collection method
Africa	Cameroon	119	French	Google Forms
South-America	Brazil	226	Portuguese	Google Forms
	Chile	303	Spanish	Google Forms
	Colombia	603	Spanish	Google Forms
	Dominican Republic	386	Spanish	Google Forms
	Mexico	330	Spanish	Google Forms
Asia	China	541	Chinese	Wenjuanxing
	Malaysia	183	Malay	Google Forms
Europe	Austria	131	German	Google Forms
	Belgium	342	Dutch	Google Forms
	Denmark	576	Danish	SurveyXact
	Finland	213	Finnish	Google Forms
	Germany	458	German	Google Forms
	Poland	116	English + Polish	Google Forms
	Russia	374	Russian	Google Forms
	Slovakia	233	Slovak	Google Forms
	Spain	335	Spanish	Google Forms
	United Kingdom	428	English	Google Forms
Oceania	Australia	1104	English	Qualtrics

Table 2
Sociodemographic features by country and income group.

Continent	Country	Income Group(1)	N	Age (years)		Gender (%)		Occupation (%)							Education (%)			
				Mean	SD(4)	Male	Female	Student	Employed	Self-employed	Unemployed	Retired	Home-maker	Other (Occupation)	Secondary/ high school	Technical/ intermediate	Undergraduate	Postgraduate
Africa	Cameroon	LMIC(2)	119	24.77	6.59	84.0	16.0	50.4	0	21.8	14.3	0	1.7	11.8	28.6	0	70.6	0
South-America	Brazil	LMIC	226	38.89	11.76	48.7	50.9	14.6	55.8	17.7	2.2	3.1	0.4	6.2	7.1	3.1	33.6	57.5
	Chile	HIC(3)	303	37.43	9.37	69.0	30.4	8.6	59.1	22.4	6.3	0.3	0.7	2.6	2.3	5.0	53.5	39.3
	Colombia	LMIC	603	25.92	9.85	63.8	36.0	58.5	21.1	13.6	2.8	1.2	1.5	1.3	22.6	16.7	50.7	9.8
	Dominican Republic	LMIC	386	24.38	10.47	64.2	35.2	68.1	19.4	8.8	1.3	1.3	0.5	0.5	19.9	11.9	56.0	11.7
	Mexico	LMIC	330	36.75	10.69	69.4	29.7	12.7	50.0	27.3	5.2	1.2	1.2	2.4	7.0	10.9	53.3	28.8
Asia	China	LMIC	541	28.21	5.83	80.2	19.8	31.8	40.1	14.8	6.8	2.6	1.7	2.2	19.0	64.7	11.1	0.6
	Malaysia	LMIC	183	45.08	10.66	90.2	9.8	3.3	61.2	18.0	3.8	9.8	0	3.8	7.1	7.7	56.3	29.0
Europe	Austria	HIC	131	38.40	10.21	51.9	46.6	14.5	67.9	11.5	2.3	2.3	0.8	0.8	11.5	27.5	19.8	38.2
	Belgium	HIC	342	38.49	11.97	39.5	60.5	6.4	69.0	7.9	6.1	1.5	0	9.1	8.8	13.8	50.0	2.6
	Denmark	HIC	576	46.89	14.44	42.5	56.1	12.2	68.4	4.5	2.3	10.1	0.5	2.1	12.3	6.1	26.9	53.5
	Finland	HIC	213	43.77	11.78	51.6	45.1	7.5	71.8	8.5	2.3	5.6	0.9	3.3	9.9	19.7	61.0	8.9
	Germany	HIC	458	28.21	9.74	29.5	69.0	65.5	29.0	3.1	0.7	0.9	0	0.9	26.9	8.1	39.1	26.0
	Poland	HIC	116	27.79	8.26	86.2	13.8	37.1	57.8	2.6	0	0	1.7	0.9	7.8	14.7	74.1	3.4
	Russia	LMIC	374	21.61	4.87	67.6	31.0	79.7	12.3	1.9	2.1	0	1.6	2.4	20.1	5.6	73.5	0.8
	Slovakia	HIC	233	30.81	11.52	60.1	39.9	50.6	37.8	7.7	1.7	0.4	0.9	0.9	33.5	22.7	0	4.3
	Spain	HIC	335	33.74	14.69	57.9	41.8	45.1	40.9	6.0	3.6	2.1	0.3	2.1	20.9	11.9	46.9	19.7
	United Kingdom	HIC	428	44.78	13.22	51.6	47.7	9.6	70.1	6.1	0.5	10.0	1.9	1.9	4.7	9.8	40.4	45.1
Oceania	Australia	HIC	1104	50.35	12.67	70.1	29.2	4.5	62.8	9.9	4.3	16.4	0.8	1.4	7.4	18.1	37.0	37.5

Notes for the Table: The values for gender, occupation, and education are presented as a percentage. * Percentages of sex that do not sum 100 % correspond to gender "other." Percentages of education that do not sum 100 % correspond to education "primary or lower." Conversely, if these parameters sum 100 %, there are no subjects with gender "other" and education "primary or lower".

(weekly hours, typical trip length, self-rated cycling performance on a scale from 0 to 10 points, reasons for cycling) and crashes in the previous five years. The second section consisted of the CBQ. Finally, the socio-economic factors of each country were manually obtained from official sources (see Section 2.2.2).

2.2.1. *Violations and errors: the cycling behavior questionnaire (CBQ)*

The CBQ is a self-report cycling behavioral survey initially developed by Useche et al. [18] to analyze self-reported cyclists' behavior on a Likert scale from 0 (never) to 4 (almost always). The CBQ comprises 29 items grouped into risky ([factor 1] violations and [factor 2] errors) and protective ([factor 3] positive) behaviors. These factors are calculated by averaging the result of each item composing the factor. For the current study, we addressed the CBQ's risky behaviors, namely:

Traffic Violations (Cronbach's $\alpha = 0.869$; McDonald's $\omega = 0.870$): consisting of 8 items evaluating the incidence of situations in which cyclists are deliberately not complying with traffic rules (e.g., consumption of substances, inadequate and/or excessive speed).

Riding Errors (Cronbach's $\alpha = 0.852$; McDonald's $\omega = 0.856$): made up of 15 items that measure cyclists' non-deliberate risky behaviors (e.g., misjudgments of traffic situations, sudden and/or abrupt braking).

At a methodological level, the behavior of cyclists is widely assessed using behavioral checklists such as the Bicycle Rider Behavior Questionnaire (BRBQ) and, more widely, the Cycling Behavior Questionnaire (CBQ) [21], both of them validated tools to measure risky (violations and errors) and protective (positive) behaviors of cyclists across different countries [20]. For this study, we focused specifically on violations and errors due to their empirically-supported link to self-reported crash risk (see [22–24]).

The CBQ has been validated with adequate internal consistency indices in its Spanish [21], Chinese [25], French and Dutch [26], and English versions [27]. Therefore, the questionnaire can be theoretically applied to urban cyclists regardless of their country of residence. In this study, the CBQ was translated and culturally adapted through a forward–backward process by native-speaking researchers in each participating country. Where available, previously validated versions of the questionnaire were used to ensure linguistic accuracy and conceptual equivalence. This translation process followed a coordinated protocol across countries to ensure cross-cultural comparability of the data. Finally, it is worth highlighting that the cross-cultural validity and utility of the CBQ have been confirmed through its administration in >44 countries.

2.2.2. *Development indicators*

To arrange the independent variables, objective development indicators (life expectancy, percentage of population with internet access, physicians per 1000 inhabitants, and national health expenditure) were manually extracted from public sources (see Link 2, Link 3, and Link 4). Furthermore, countries were classified into income groups according to LMIC and high-income countries (HIC). For such purpose, we consulted the latest World Bank Country and Lending Groups report (Link 5).

2.3. *Data processing*

Statistical analyses were conducted using IBM SPSS (Statistical Package for Social Sciences), version 29.0 (Armonk, NY, United States).

This study, first, described and characterized the risk-related CBQ factor scores (traffic violations and riding errors) using descriptive analysis and Welch's *t*-test to look for significant differences between LMIC and HIC. The effect sizes were reported as the estimate and 95 % confidence interval (CI) using different measures (η^2= Eta-squared, ε^2= Epsilon-squared, Ω^2_F Omega-squared [Fixed-effect], and Ω^2_R= Omega-squared [Random-effect]) and interpreted as small (< 0.060), medium ($\leq$ 0.140), and large (> 0.140). A value of $p < .05$ was uniformly established as a cut-off criterion for statistical significance.

Thereafter, classification trees were performed to observe the clustering that occurs in each of the factors according to the region and income group. This method segments the dataset into branches based on decision rules, creating an inverted tree-like structure with a root node. It provides an interpretable model to explore complex interactions and patterns in the data [28,29].

Pearson's correlations were also performed to assess if there were statistical correlations among the safety outcomes and development indicators. Results were interpreted using traditional criteria [30]: negligible ($r \leq 0.100$), weak (r =0.101 – 0.399), moderate (r = 0.400 – 0.699), strong (r = 0.700 – 0.899), and very strong ($r \geq 0.900$).

Finally, hierarchical multiple linear regression was used to explore the predictors of cycling safety outcomes, examining the unique and incremental contributions of country-level literature-endorsed factors as potential predictors. The behavioral dimensions (violations and errors) were treated as observed variables, computed as mean composite scores based on the validated CBQ items. The model was built entering life expectancy, percentage of the population with internet access, physicians per 1000 inhabitants, national health expenditure, and self-reported cycling, allowing for the evaluation of incremental explanatory power. This approach facilitates the identification of unique contributions of predictors [31].

2.4. Ethics

The Ethics Committee of the Research Institute on Traffic and Road Safety at the University of Valencia verified and approved the study protocol's compliance with the Declaration of Helsinki, its general ethical standards, and the contents of the informed consent form presented to all the participants. The ethical approval of this study was granted with the IRB number HE0003170921.

3. Results

3.1. Descriptive country-based socio-demographic and cycling information

Tables 2 and 3 present specific sociodemographic and cycling features of the 7001 participants of the study.

3.2. Descriptive country-based behavioral outcomes

The descriptive results of the 19 countries included in the study are presented in Table 4 and Fig. 1. As hypothesized regarding income levels, High-Income Countries (HICs) presented significantly ($p<$ .001) lower scores in cycling risk-taking than Low and Middle-Income Countries (LMICs). In other words, risky behaviors by cyclists (traffic violations and riding errors) tend to be self-reported more frequently in developing countries.

It is noteworthy that countries clustered as 'Low and Middle-Income Countries' tend to register higher rates of both deliberate (i.e., traffic violations) and unintentional (i.e., riding errors) risky cycling behavior than their higher-income counterparts. In addition, the effect sizes of traffic violations (0.014–.027) are slightly lower than those reported for riding errors (0.046–.066).

3.3. Country-Based clustering of cycling behavior: classification trees

To explore how behavioral outcomes vary across countries, we applied a Classification and Regression Tree (CART) methodology. This supervised method segments the dataset into groups based on predictor variables, offering a visual representation of how these factors relate to cycling behaviors. It is important to clarify that, although referred to as "classification," this approach should not be confused with unsupervised clustering techniques commonly used in machine learning. The tree structure consists of a root node (top level of Figs. 2 and 3), internal decision nodes (intermediate levels), and terminal nodes (leaf levels).

The classification tree for Factor 1, Traffic Violations (deliberate risky behaviors), resulted in seven nodes. Each continent formed a distinct node, reflecting regional differences in this behavioral outcome. Europe was the only region subdivided further, distinguishing countries by income level. In this case, European countries with higher income levels reported lower levels of traffic violations than those with lower economic levels (see Fig. 2).

The classification tree for Factor 2 "Riding Errors" (unintentional risky behaviors) suggests the existence of ten nodes. Asia and Africa are represented by a separate node for each. In Latin America, there are two nodes, indicating differences in this factor according to economic level. Thus, Latin American countries with higher income levels show fewer cycling errors than Latin American countries with lower income levels.

Table 3
Cycling features by country and income group.

Continent	Country	Income Group(1)	N	Cycling weekly hours		Typical trip length (minutes)		Self-rated performance (0–10 points)		Cycling for leisure (%)		Cycling for sport (%)		Cycling for job (%)	
				Mean	SD	Mean	SD	Mean	SD	No	Yes	No	Yes	No	Yes
Africa	Cameroon	LMIC(2)	119	7.39	5.20	41.72	26.57	6.04	2.09	26.1	73.9	34.5	65.5	70.6	29.4
South-America	Brazil	LMIC	226	6.35	5.95	68.89	49.45	7.85	1.41	4.0	96.0	25.7	74.3	86.3	13.7
	Chile	HIC(3)	303	6.71	5.40	43.27	32.47	8.08	1.12	12.2	87.8	42.6	57.4	87.8	12.2
	Colombia	LMIC	603	7.59	7.24	56.53	44.24	7.74	1.76	16.3	83.7	30.5	69.5	79.8	20.2
	Dominican Republic	LMIC	386	4.42	5.52	46.62	37.84	7.15	2.31	30.6	69.4	33.2	66.8	90.9	9.1
	Mexico	LMIC	330	8.50	7.02	48.90	32.98	8.25	1.20	11.8	88.2	36.4	63.6	73.0	27.0
Asia	China	LMIC	541	2.50	2.19	28.75	14.69	4.33	2.95	43.8	56.2	21.8	78.2	43.3	56.7
	Malaysia	LMIC	183	6.52	6.16	100.05	54.73	8.12	1.30	7.7	92.3	4.9	95.1	91.8	8.2
Europe	Austria	HIC	131	5.16	4.41	50.50	42.92	8.03	1.25	13.0	87.0	54.0	55.0	77.1	22.9
	Belgium	HIC	342	4.93	3.24	32.22	24.65	8.28	0.94	–	–	–	–	86.3	13.7
	Denmark	HIC	576	6.06	6.14	33.77	25.76	8.93	0.87	19.8	80.2	57.1	42.9	69.1	30.9
	Finland	HIC	213	6.56	4.64	39.18	31.84	8.03	1.13	9.4	90.6	24.4	75.6	93.0	7.0
	Germany	HIC	458	4.11	3.90	36.09	32.27	7.92	1.28	21.6	78.4	68.8	31.2	83.4	16.6
	Poland	HIC	116	4.18	5.45	68.23	49.56	7.32	2.05	21.6	78.4	58.6	41.4	94.8	5.2
	Russia	LMIC	374	3.18	4.89	48.07	45.19	7.08	3.02	40.1	59.9	52.7	47.3	74.3	25.7
	Slovakia	HIC	233	5.26	4.40	57.17	41.33	7.00	1.55	9.0	91.0	39.9	60.1	93.6	6.4
	Spain	HIC	335	3.58	4.96	34.96	34.52	7.34	2.15	39.7	60.3	64.2	35.8	94.6	5.4
	United Kingdom	HIC	428	6.26	4.32	52.78	42.81	7.65	1.06	10.0	90.0	36.0	64.0	86.4	13.6
Oceania	Australia	HIC	1104	10.09	6.56	73.75	45.42	7.87	1.31	6.3	93.8	11.7	88.3	97.5	2.5

Notes for the Table:
"-" denotes missing data. The values for cycling for leisure, cycling for sport, and cycling for job are presented as a percentage.

Table 4
Traffic violation and riding errors by country and income group.

Continent	Country	Income Group[(1)]	N	Factor 1: Traffic Violations		Factor 2: Riding Errors		Comparative Tests		Effect Sizes [(7)]		95 % CI [(8)]	
				Mean	SD[(4)]	Mean	SD	Test Value [(5)]	Sig. [(6)]	Parameter	Estimate	Lower	Upper
Africa	Cameroon	LMIC[(2)]	119	1.65	.99	1.71	.95	**Factor 1: TrafficViolations**					
South-America	Brazil	LMIC	226	.77	.50	.36	.37	120.67	***	η^2	.020	.014	.027
	Chile	HIC[(3)]	303	.68	.47	.41	.37						
	Colombia	LMIC	603	.80	.69	.60	.56			ε^2	.020	.014	.027
	Dominican Republic	LMIC	386	.68	.78	.68	.82						
	Mexico	LMIC	330	.69	.44	.46	.39			Ω^2_F	.020	.014	.027
Asia	China	LMIC	541	.85	.51	.80	.43						
	Malaysia	LMIC	183	.57	.49	.44	.47			Ω^2_R	.020	.014	.027
Europe	Austria	HIC	131	.72	.47	.40	.37						
	Belgium	HIC	342	.77	.44	.47	.30	**Factor 2: Riding Errors**					
	Denmark	HIC	576	.65	.42	.32	.31	327.30	***	η^2	.056	.046	.066
	Finland	HIC	213	.66	.43	.34	.38						
	Germany	HIC	458	.89	.56	.45	.41			ε^2	.056	.046	.066
	Poland	HIC	116	.52	.61	.42	.58						
	Russia	LMIC	374	.74	.99	.67	.98			Ω^2_F	.056	.046	.066
	Slovakia	HIC	233	.61	.49	.47	.46						
	Spain	HIC	335	.49	.51	.38	.39			Ω^2_R	.056	.046	.066
	United Kingdom	HIC	428	.44	.37	.32	.30						
Oceania	Australia	HIC	1104	.53	.42	.43	.35						

Notes for the table: (1) Income group classification was extracted from the latest World Bank Country and Lending Groups report (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups); (2) LMICs= Low and Middle-Income Countries; (3) HICs= High-Income Countries; (4) SD: standard deviation; (5) Test value of Welch's test; (6) Significance level: ***= <0.001; (7) Estimated based on the fixed-effect model; (8) Confidence Interval at the level 95 %; η^2= Eta-squared; ε^2= Epsilon-squared; Ω^2_F Omega-squared (Fixed-effect); Ω^2_R= Omega-squared (Random-effect).

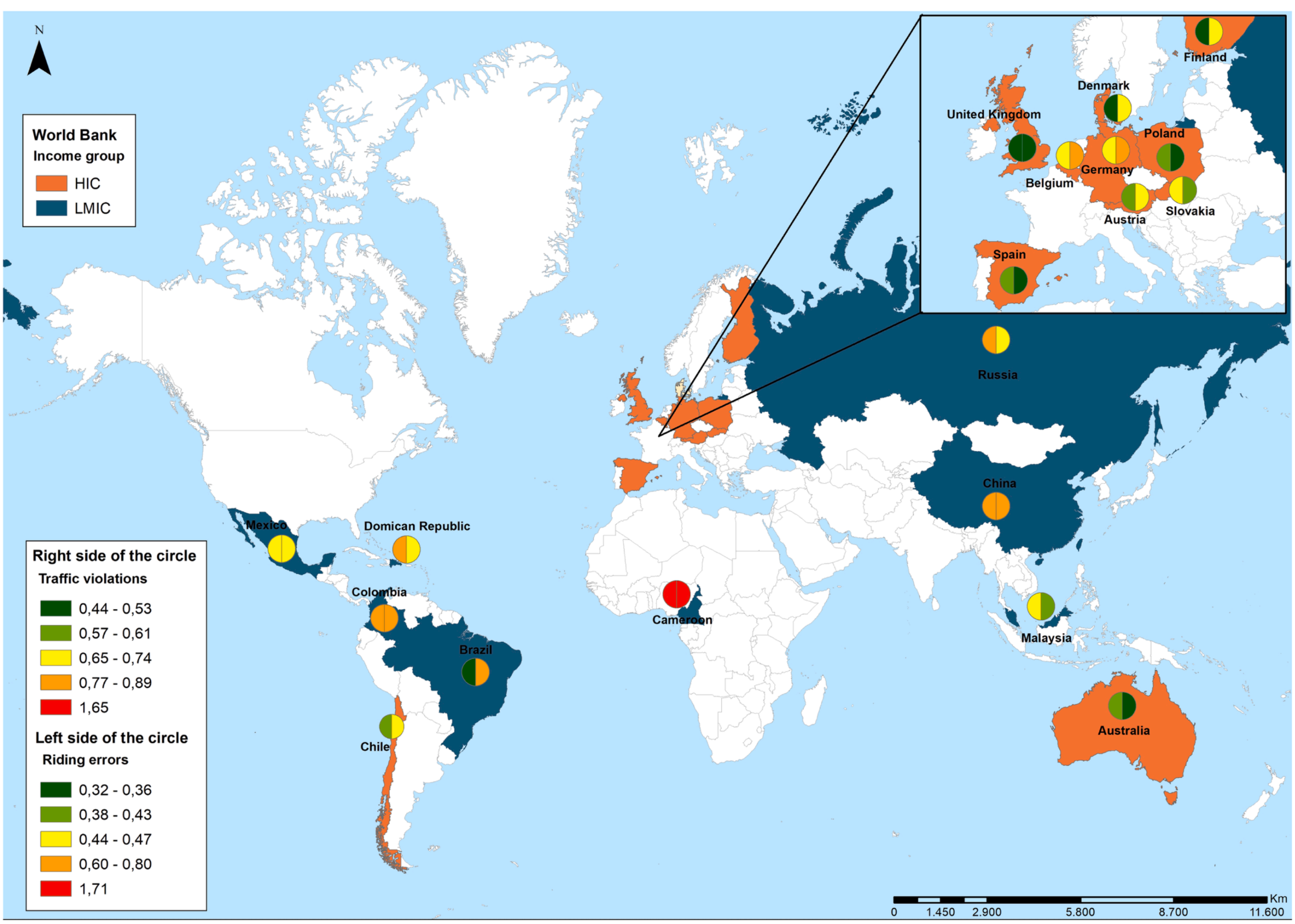

Fig. 1. Means of self-reported cycling violations and errors in each of the included countries. LMIC: low- and middle-income country; HIC: high-income country.

Finally, Oceania and Europe are grouped into a single node. Subsequently, there are two disaggregations according to, first, to socio-

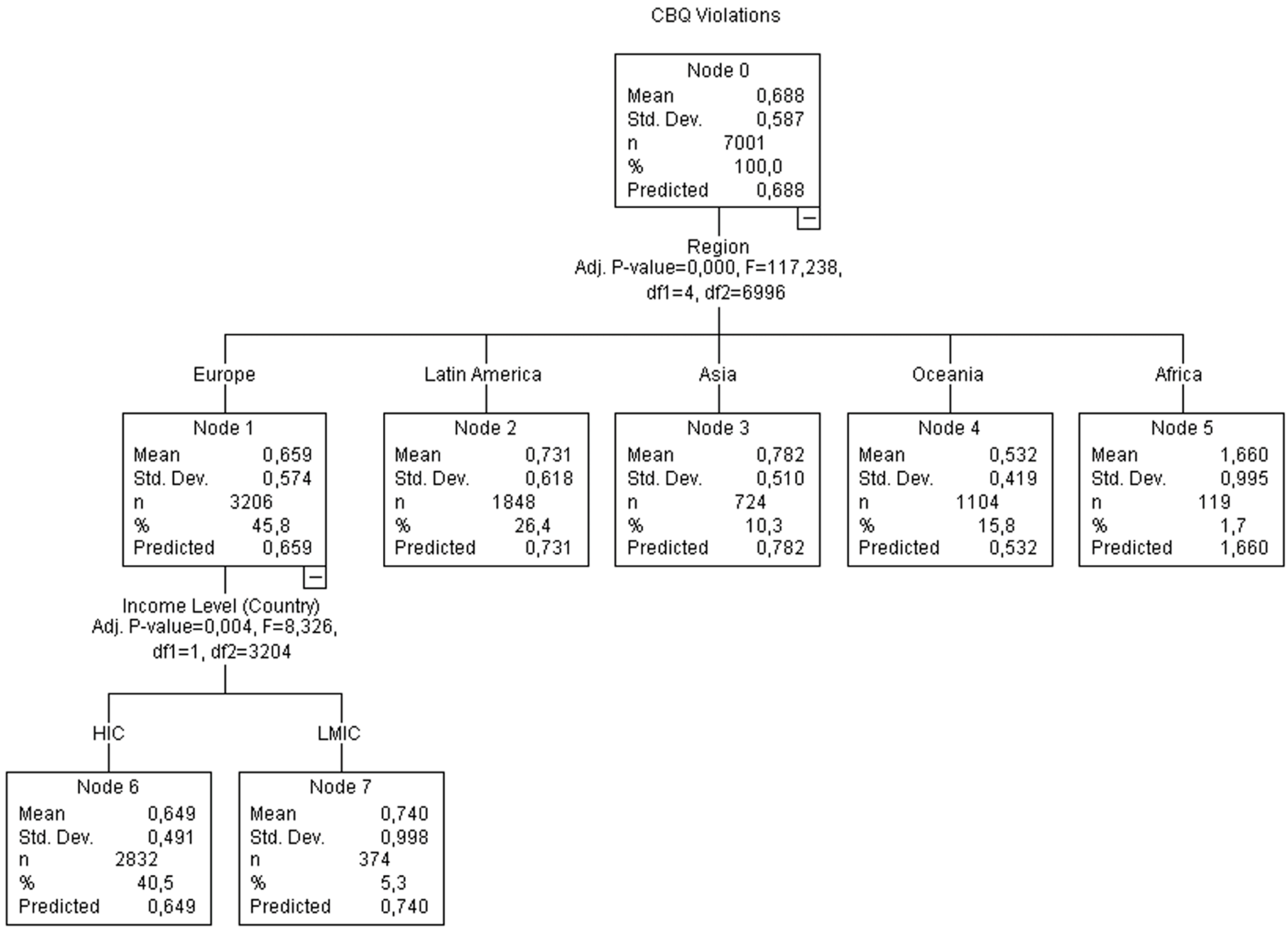

Fig. 2. Classification tree for factor 1 "traffic violations" according to country income level and region.

economic status and, second, according to the region (see Fig. 3).

3.4. Inter-Factor correlations

Fig. 4 graphically represents the relationships among the variables. It is to be noted that riding violations and errors were positively correlated between them and with cycling crashes (all $p < .001$). Similarly, the development indicators (life expectancy, percentage of population with internet access, physicians per 1000 inhabitants, and national health expenditure) were significantly correlated between them (positive correlation) and with cycling crashes (negative correlation) (all $p < .001$). Finally, risky behaviors (traffic violations and riding errors) were significantly negatively correlated with development indicators.

It is to be noted that correlations ranged from weak to strong [$r = 0.045 – 0.754$] (values closer to 0 indicating weaker associations and to 1.0 denoting stronger correlations), and that these are unadjusted associations which do not account for the influence of other variables (e.g., undocumented demographics or exogenous factors) that were not controlled for in the study.

3.5. Multiple regression analyses

Multiple linear regressions were performed to predict cycling violations and errors based on development indicators and cycling crashes. A significant regression equation was found for both variables (traffic violations: $F_{(5,5682)} = 195.34$, $p < .001$, with an adjusted R^2 of 0.146; and riding errors: $F_{(5,5682)} = 287.52$, $p < .001$, with an adjusted R^2 of 0.201). Table 3 represents the regression analyses, where the significant indicators and their coefficients are described. Table 5

4. Discussion

This research aimed to analyze the relationships between various country-level development indicators (e.g., income level, life expectancy, percentage of the population with internet access, physicians per 1000 inhabitants, and national health expenditure) and cycling safety outcomes (violations, errors, and crashes) in 19 countries across five continents with diverse socio-economic backgrounds. Overall, the results support the hypothesis that country-level development indicators are related to both cycling safety behaviors (i.e., violations and errors) and reported crashes. In this regard, LMIC tend to register higher rates of both deliberate (i.e., traffic violations) and unintentional (i.e., riding errors) risky cycling behavior than their higher-income counterparts, which agrees with previous research [32].

From a literature-based approach, the first potential explanation for these results is that standards of living and habits are linked with the socioeconomic development of a country [33,34]. In this regard, high-income communities invest more in developing and maintaining cycling infrastructures [35], better cycling infrastructures entail a higher prevalence of cycling [36,37], and a higher prevalence of cyclists promotes the 'safety in numbers' effect (i.e., safer environments for road users that are more commonly seen on the road) (Alonso, Faus, Cendales, et al., 2021; [38–40]). This discussion will be developed around the role of transport policies in making the bicycle a legitimate mode of transport, how this relates to the development indexes selected in this study, and how this might affect people's willingness to comply with

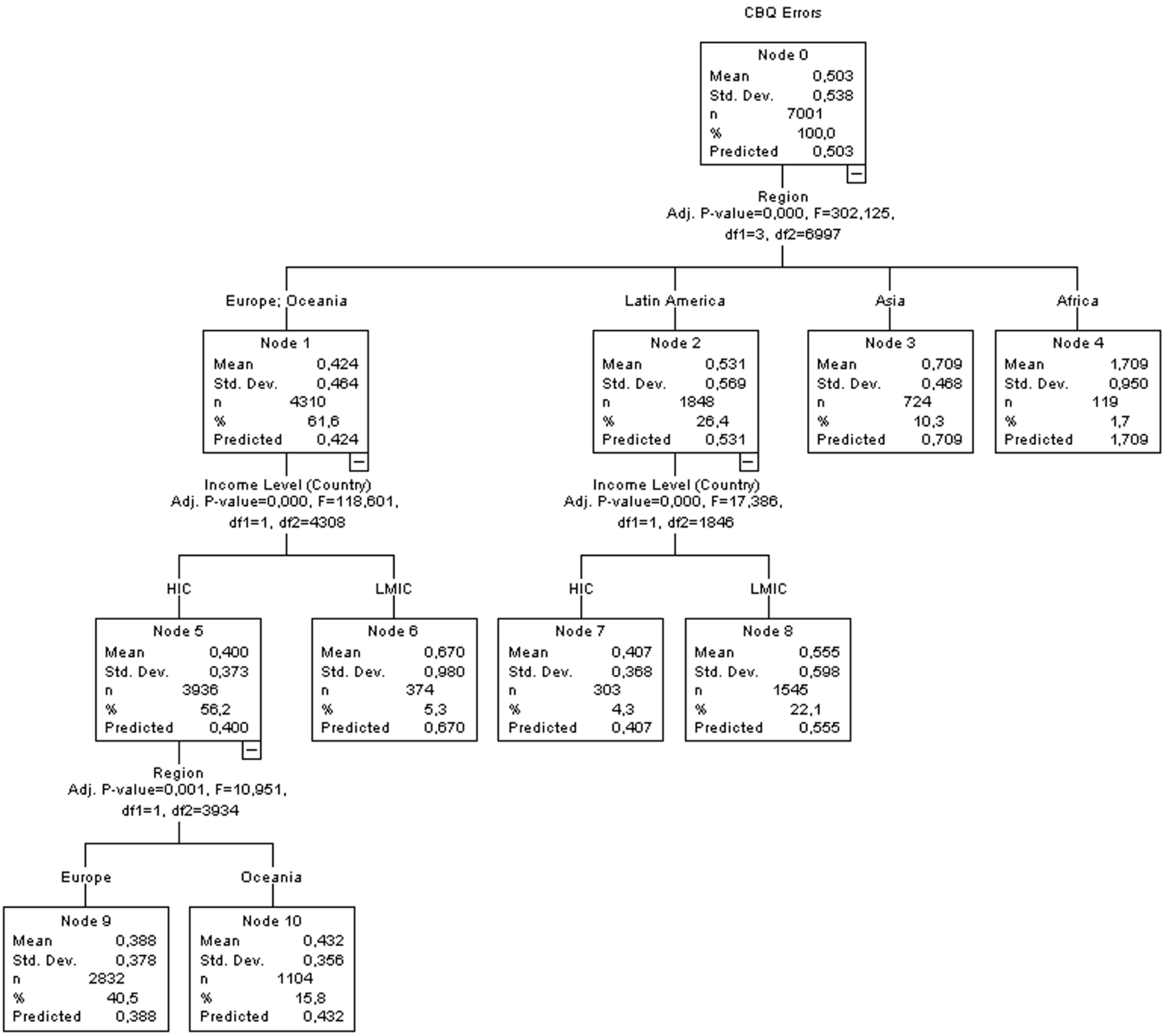

Fig. 3. Classification tree for factor 2 “riding errors” according to income level and region.

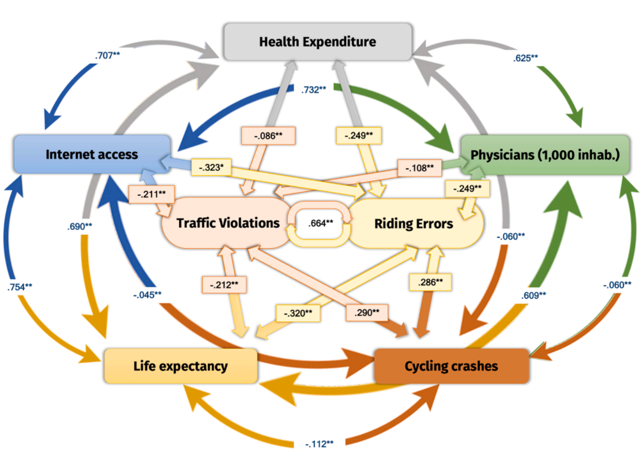

Fig. 4. Pearson’s correlation of CBQ factors (self-reported cycling behavior) with socio-economic and health variables. Notes: **: significant correlations at the level $p<$ .001.

traffic rules.

At a theoretical level, the interpretation of such figures seems linear, but it is not. While it could be suggested that high-income communities present safer environments for cyclists, there are some particularities and peculiarities, same as registered in previous studies addressing cycling and sustainable transport issues at a mid- or large-scale [41]. In the following sections, we discuss the potential effects that each one of these factors (income group, life expectancy, percentage of population with internet access, physicians per 1000 inhabitants, and national health expenditure) may have on transport policies and cycling safety (i.e., risk-behavioral and crash-related) indicators.

4.1. *Countries’ income level condition the risky behaviors of their cyclists*

Overall, the results of this study show how cyclists from LMIC reported both traffic violations and riding errors more frequently than their counterparts in HIC. These differences were statistically significant, and the effect sizes observed for errors were consistently larger than those for violations, suggesting that unintentional behaviors may play a more prominent role in differentiating countries on the basis of

Table 5
Multiple linear regression of the factors "traffic violations" and "riding errors", using country-level literature-endorsed factors as potential predictors.

Variable 1: Traffic Violations							
Predictor	Unstandardized Coefficients		Standardized Coefficients	t[(4)]	Sig.[(5)]	Adj. R^2 [(6)]	ΔR^2 [(7)]
	B[(1)]	S.E.[(2)]	β [(3)]				
(Constant)	2.390	.180		13.305	<0.001	.146	.147
Life expectancy	-0.017	.003	-0.119	−6.147	<0.001		
Internet access	-0.012	.001	-0.302	−13.543	<0.001		
Physicians per 1000 inhabitants	.059	.009	.116	6.476	<0.001		
Health expenditure	.040	.005	.159	8.769	<0.001		
Cycling crashes	.130	.006	.279	22.594	<0.001		
Variable 2: Riding Errors							
Predictor	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Adj. R^2	ΔR^2
	B	S.E.	β				
(Constant)	2.820	.162		17.419	<0.001	.201	.202
Life expectancy	-0.023	.003	-0.169	−9.002	<0.001		
Internet access	-0.009	.001	-0.258	−11.928	<0.001		
Physicians per 1000 inhabitants	.041	.008	.087	5.028	<0.001		
Health expenditure	-0.001	.004	-0.005	-0.296	.767		
Cycling crashes	.113	.005	.261	21.825	<0.001		

Notes for the Table: B[(1)] = Unstandardized effect coefficient; S.E.[(2)] = Standard Error; β [(3)] = Standardized effect coefficient (Beta –can be interpreted as controlling for effects of other variables); t[(4)] = Value of the Student's *t*-test; Sig. [(5)] = *p*-value of the test; Adj. R^2 [(6)] = Adjusted R-square; $\Delta R^{2(7)}$ = Changes in R-square.

development level.

The patterns observed in the classification trees reinforce this discrepancy. Beyond infrastructure adequacy –which tends to be more favorable in HIC settings [42,43] other contextual variables may contribute to the observed behavioral differences [44,45]. Cultural factors, such as those described by the tightness – looseness framework, may also be relevant. This theory proposes that some countries enforce strict social norms and sanctions (tight cultures), while others show more permissive regulatory environments (loose cultures), which may influence compliance with traffic norms [46,47].

In this context, road safety education and awareness campaigns can play a meaningful role in promoting rule compliance and shaping behavioral norms across user groups, including in LMIC settings [48,49]. Their effectiveness is often enhanced when combined with enforcement mechanisms such as police controls or sanctioning systems [50,51]. Considering that many LMICs have weaker institutional frameworks for road safety [52], increased policy attention –possibly supported by international collaboration– may contribute to narrowing the behavioral gap observed across income groups.

From a broader policy perspective, strategies that position the bicycle as a legitimate transport mode –supported by sustained investment in cycling infrastructure– may contribute to improved safety outcomes. Previous studies suggest that such investment is associated with reductions in injuries and increased modal legitimacy [19]. A relevant issue that remains unaddressed is whether cyclists from HIC maintain safer behavioral patterns when riding in LMIC contexts, where cycling environments may lack the conditions necessary for safe travel.

4.2. Do development indices influence the risky behavioral patterns of cyclists? which ones, and to what extent?

Most of the development-related indicators examined in this study –namely life expectancy, internet access, number of physicians per 1000 inhabitants, and national health expenditure– showed negative bivariate associations with violations, errors, and self-reported crashes. Furthermore, several of these variables arose as significant predictors of risky behaviors in the adjusted regression models. Overall, these findings reinforce the trend previously described: cyclists in countries with lower development indices tend to report more frequent risk-taking and worse safety outcomes.

Life expectancy, as a macro-level health indicator, may relate to cycling safety outcomes through at least two pathways. On the one hand, lower life expectancy is typically observed in LMICs, where both traffic risk behaviors and injury rates tend to be higher [53–55]. Similar trends are observed within countries across income strata, with populations facing poverty displaying both shorter life expectancy and riskier health-related behaviors [56]. On the other hand, high rates of road traffic injuries –including those involving cyclists– can themselves have a measurable impact on national life expectancy. According to available data, road injuries ranked as the eighth leading cause of death worldwide in 2015, accounting for over 13 million deaths [53], with cycling crashes representing over 4 % of those fatalities. Regional estimates suggest that cycling-related deaths accounted for 3 % of total road fatalities in Latin America [57] and as much as 10 % in Europe [58].

Internet access, a robust proxy of development and connectivity in the digital era, also showed meaningful associations. In 2023, internet penetration reached 93 % in HICs, compared to just 60 % in LMICs [59]. Limited access to online resources may restrict the diffusion of road safety content, awareness campaigns, and educational materials [60, 61]. Moreover, countries with lower connectivity often lack automated enforcement technologies –such as traffic cameras– which are associated with substantial reductions in fatal crashes [62]. In such contexts, the likelihood of traffic violations may increase simply due to a reduced sense of surveillance or accountability. Internet exposure, especially among younger generations, may also contribute indirectly to safer riding by familiarizing users with recommended behaviors through institutional or peer-driven content [63,64].

It is worth noting that in some instances, the direction of bivariate correlations differed from that of the corresponding regression coefficients. A notable example is the number of physicians per 1000 inhabitants, which showed a negative bivariate correlation with traffic violations but a positive adjusted effect in the regression model. This likely reflects a suppression effect, whereby intercorrelations among predictors alter the net contribution of a single variable once others are held constant. Such statistical patterns are common when working with country-level development indicators and should be interpreted with caution. For this reason, the regression models were used to estimate adjusted associations, while the correlation matrix was included for descriptive reference.

Health-related variables (expenditure and medical personnel) were significantly correlated with risky cycling behaviors and crashes, which is consistent with previous findings [65]. This may reflect the broader educational and preventive functions that healthcare systems can play in shaping public attitudes toward safety [66–68]. The presence of a well-established medical infrastructure may facilitate the diffusion of safety-related guidance – whether through direct physician interaction or institutional messaging [69]. However, it should also be acknowledged that the correlations between health system indicators and safety outcomes, although statistically significant, were weak in magnitude.

Interestingly, while health variables were significant predictors of traffic violations, they did not show the same pattern in relation to riding errors. One possible explanation is that deliberate rule violations are more amenable to preventive strategies (e.g., public health messaging), whereas unintentional behaviors—such as errors—are more likely to stem from attentional failures or perceptual misjudgments. As such, the influence of medical professionals may extend to the former, but not the latter. These findings suggest a possible role for healthcare systems in promoting road safety, but also highlight the need for complementary interventions—such as cyclist training, infrastructure adaptation, and broader public awareness campaigns—to address non-deliberate risks [69,70].

Taken together, the results of this study reinforce a broader point: that risky cycling behaviors are closely tied to countries' development conditions. Since economic development itself is shaped by structural factors (e.g.,income inequality, public investment, and institutional capacity) road safety in lower-income settings is unlikely to improve without parallel advances in these areas [71,72]. This relationship reflects the so-called vicious circle of poverty, whereby underdevelopment in one domain reinforces constraints in others [73,74].

From a policy standpoint, this underscores the importance of supporting cycling safety not only through sector-specific measures, but also through broader efforts to strengthen healthcare, education, infrastructure, and information access. While this study focuses on macro-level associations and does not consider internal sociodemographic variability within countries, the findings offer a starting point for identifying structural settings that may shape cycling risk from a population-level perspective.

4.3. Limitations and future research

Although the execution of this study followed a coordinated protocol and the data were carefully curated, several limitations should be considered at interpreting the findings. First, the countries included in the analysis were those for which comparable datasets were available through the Bike-Barometer project. This means that –from a post-study perspective– the study sample, while diverse, does not cover all world regions or reflect global cycling distributions.

Second, as shown in Table 2, the gender composition of the national samples is uneven. Some countries (particularly among LMICs) show a marked overrepresentation of male cyclists. Given previous findings on gender differences in risk behavior, this may have influenced the reported averages. However, since the study is descriptive and based on country-level data, we did not apply statistical corrections for individual-level factors. We acknowledge this as a boundary of the design, and suggest that future research explores these dynamics using stratified or multilevel approaches.

Third, although the CBQ includes a third factor assessing positive cycling behaviors, this study focused on violations and errors due to their stronger (and empirically consistent) association with crash risk. Still, examining protective habits in future studies could be of value – particularly given the increasing relevance of promoting safer, more equitable, and inclusive cycling environments in urban contexts, where phenomena such as occupational use (e.g., delivery riding) impose additional risk-related intersections [75,76–78].

The interpretation of results should also consider the level of analysis. Country-level indicators offer a useful perspective, but individual characteristics (e.g., age, gender or riding experience) may also contribute to observed patterns. In this regard, future studies may be able to integrate both levels to better address possible nested effects.

Moreover, it is worth noting that all behavioral and crash-related data were self-reported, which implies a potential for recall bias or social desirability effects [79–82]. While the use of validated instruments and the assurance of anonymity reduce this risk, it cannot be completely ruled out. Similarly, trip durations reported by participants also showed considerable variation across countries. In contexts such as Malaysia or Australia, longer average durations may reflect the presence of sport-oriented cyclists rather than commuters. These values were retained to preserve consistency across the sample but should be interpreted with care when making cross-country comparisons.

Finally, although development indicators were selected from the World Bank's WDI framework to ensure comparability, other structural variables (such as traffic enforcement, police presence, or surveillance systems) may also influence cycling behavior. These were not included due to data availability issues, but future studies may consider incorporating them to gain further insights on the influence of transport dynamics, measures, and countermeasures on cycling outcomes.

5. Conclusions

The findings of this multinational study suggest that (1) country-level development indicators are associated with both cycling safety behaviors (i.e., violations and errors) and crash involvement, and that (2) cyclists from more developed countries tend to report fewer risky behaviors (i.e., errors and violations) compared to those from less developed regions.

These differences highlight an underlying inequity in the vulnerability faced by cyclists in low- and middle-income countries, and point to several complementary areas where targeted interventions may be needed (namely access to information, healthcare systems, and road safety training). With these findings, the study provides a starting point for designing and establishing preventive measures aimed at reducing risky cycling behaviors and improving user-based safety records.

Taken together, the results provide a basis for designing preventive strategies to reduce risky cycling behaviors and improve safety outcomes from a multidimensional perspective, while also strengthening user-based safety records and enhancing the promotion of the bicycle as a sustainable means of transport across its different modalities (e.g., occupational, commuting, leisure, sports/fitness), with greater safety and equity outcomes among countries.

CRediT authorship contribution statement

Sergio A. Useche: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Alonso:** Visualization, Validation, Supervision, Software, Resources, Funding acquisition, Formal analysis, Data curation. **Alev Aktaş:** Methodology, Investigation, Data curation. **Kayck D. Araujo:** Methodology, Investigation, Data curation. **Predrag Brlek:** Methodology, Investigation, Data curation. **Maria A. Calota:** Methodology, Investigation, Data curation. **Boris Cendales:** Methodology, Investigation, Data curation. **Ruben Domenech:** Methodology, Investigation, Data curation. **Mireia Faus:** Methodology, Investigation, Formal analysis, Data curation. **Andres Gené-Sampedro:** Methodology, Investigation, Data curation. **Giuseppe Guido:** Methodology, Investigation, Data curation. **Isti Hidayati:** Methodology, Investigation, Data curation. **Sreten Jevremović:** Methodology, Investigation, Data curation. **Katerina Koliou:** Methodology, Investigation, Data curation. **Luciana C. Lima:** Methodology, Investigation, Data curation. **Irina Makarova:** Methodology, Investigation, Data curation. **Milad Mehdizadeh:** Methodology, Investigation, Data curation. **Mette Møller:** Methodology, Investigation, Data curation. **Eduard Mukhametdinov:** Methodology, Investigation, Data curation. **Dimitrios Nalmpantis:** Methodology, Investigation, Data curation. **Mihai R. Nita:** Methodology, Investigation, Data curation. **Steve O'Hern:** Methodology, Investigation, Data curation. **Puspa R. Pant:** Methodology, Investigation, Data curation. **Noleen Pisa:** Methodology, Investigation, Data curation. **German M. Rojas:** Methodology, Investigation, Data curation. **Felix W. Siebert:** Methodology, Investigation, Data curation. **Ioanna Spyropoulou:** Methodology, Investigation, Data curation. **Amanda N.**

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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.

Acknowledgments

This paper was supported by the project PID2023-152606OA-I00, funded by MCIN/AEI/10.13039/501100011033/ and by FEDER 'A way of making Europe,' EU. The authors also wish to thank Dr. Arash Javadinejad (licensed translator) for the professional edition of the final version of the manuscript, as well as all the study partakers and collaborators involved in the distribution of this cross-cultural survey.

Data availability statement

Data related to the Bike-Barometer are of free access/use for researchers and academics (https://doi.org/10.7910/DVN/EP6QLN).

Data availability

https://doi.org/10.7910/DVN/EP6QLN (see)

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