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COMPARATIVE DYNAMICS OF ROAD FATALITY RISK IN POLAND, CZECHIA, AND SLOVAKIA: A LONGITUDINAL STUDY, 2014-2024

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Resume
In this study are compared population-normalized road-fatality rates in Poland, Czechia and Slovakia for 2014-2024 using the harmonized 30-day data, which measure population burden rather than exposure-adjusted risk. OLS and Theil-Sen trends, non-parametric tests, country-by-year interactions, sigma convergence, segmented 2020 trends and a Road Safety Transition Performance Index (RSTPI) were applied. Significant annual declines were found in Poland (-3.48 per million; R^2 = 0.892), Czechia (-2.20; R^2 = 0.818) and Slovakia (-0.84; R^2 = 0.510), i.e. reductions of 38.1%, 31.8% and 12.7%, respectively. Between-country dispersion fell by 66.1%, although Slovakia's post-2020 slope turned positive. Equal-weight RSTPI scores were 86.4 (Czechia), 85.3 (Poland) and 51.5 (Slovakia); the order of the first two depends on weighting, so the index complements fatality-rate comparisons but requires external validation.

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1 Introduction

The road traffic injuries remain a major public-health, transport-policy, and economic problem. Cross-country comparisons often rely on absolute crash or casualty totals, although those measures depend on population, travel exposure, motorization, and reporting practices. Poland, Czechia, and Slovakia share important historical and institutional characteristics but have experienced different road-safety trajectories. In previous studies were examined infrastructure, human behaviour, vulnerable road users, freight transport, and predictive methods. Nevertheless, many studies focus on a single country, region, road-user group, or intervention, limiting direct assessment of convergence across neighbouring countries [1-3].

In a few harmonized longitudinal studies were compared these three countries' fatality levels, trends, and stability within one inferential framework. National accident totals are not directly comparable since the reporting rules differ. The CARE/Eurostat 30-day fatalities per million inhabitants reduce population-size effects, but measure societal burden rather than exposure-adjusted risk per vehicle-kilometre [4-6]. The objective was to compare 2014-2024 trends in Poland, Czechia, and Slovakia and examine whether the rates fell, which country improved most, whether national slopes differed, and how trajectories changed after 2020. Contributions include descriptive and indexed trends; OLS, Theil-Sen, Kendall, Friedman, and country-year interaction tests; sigma convergence and its exploratory half-life; segmented analysis of the 2020 level and trend changes; and a Road Safety Transition Performance Index (RSTPI) evaluated for sensitivity to its component weights.

2 Literature background

Road design and infrastructure condition are repeatedly associated with crash occurrence and severity. Cross-section configuration, intersection type, interchange design, bypass geometry, road markings, roadside hazards, and visibility at crossings influence

both conflict probability and injury outcome. This evidence supports proactive network assessment rather than reliance on historical crash counts alone. It also indicates that national trends may reflect cumulative infrastructure investment, although aggregate data cannot isolate individual measures [1, 7-8].

Mobile-phone use, signal violations, speeding, risk-taking, reduced night-time visibility, and insufficient attention at crossings are recurrent behavioural risk factors. Pedestrians, cyclists, and motorcyclists remain especially sensitive to speed and infrastructure quality. Educational programmes and enforcement are therefore most effective when combined with forgiving road design, safe crossing facilities, lighting, and speed management [3, 9-10]. Recent regional research examines advanced driver-assistance systems (ADAS), intelligent transport systems, automatic incident detection, front brake lights, neural-network forecasts, time-series models, and composite safety indicators. These approaches expand the analytical toolkit, but many are prototypes, case studies, or model-based assessments. The long-term national outcome studies remain necessary to establish whether technological and policy changes coincide with measurable population-level progress [2, 11-12].

3 Materials and methods

The longitudinal ecological dataset comprised 11 country-years (2014-2024) for each of Poland, Czechia, and Slovakia (33 observations); the EU average served solely as a benchmark. The outcome was road fatalities per million inhabitants under the harmonized 30-day definition (death immediately or within 30 days of a crash), drawn from European Commission Road Safety Observatory and Eurostat sources [4-5, 13]. This population-based rate is not exposure-adjusted risk per vehicle- or passenger-kilometre; cross-national differences may also reflect traffic volumes and modal composition. The series ends in 2024, the latest harmonized complete year, excluding provisional 2025 values. National 2024 accident totals provide context only because reporting thresholds differ [6, 14-15].

For each series, the central tendency and temporal dispersion were characterized by the mean, standard deviation, median, minimum, maximum, range, coefficient of variation (CV), and 95% confidence interval for the mean. Change over the observation window was expressed as the absolute baseline-to-endpoint difference, relative percentage change, and compound annual growth rate (CAGR). Ordinary least-squares regression was used to estimate the annual linear change, with year as the independent variable and fatalities per million inhabitants as the dependent variable. The slope, its standard error and 95% confidence interval, coefficient of determination (R^2), and p-value were reported. Since the short annual series can be influenced by unusually high or low observations, the Theil-Sen median slope and its 95% confidence interval were calculated as a robust estimator. Kendall's τ was additionally used to test whether the direction of change was monotonically decreasing without requiring normally distributed residuals.

Differences between the three matched national trajectories were tested with the Friedman test, treating year as the repeated block. Kendall's W was reported as an omnibus effect-size measure. When the omnibus result was significant, paired two-sided Wilcoxon signed-rank tests were applied, with Holm adjustment for three comparisons. The Friedman procedure evaluates persistent differences in annual levels, but it does not directly test whether the rates of improvement differ. Therefore, a pooled country-year regression was also estimated with year centred at 2014, country indicators, and country-by-year interaction terms. HC3 heteroscedasticity-robust standard errors were used. Pairwise linear contrasts of the interaction coefficients quantified whether one national trend was significantly steeper than another.

EU-benchmark gaps were summarized by the mean signed difference, mean absolute error (MAE), root-mean-square error (RMSE), and years at or below the EU level. The first differences, $\Delta F(t) = F(t) - F(t - 1)$, characterized annual variability. The proportion of the full reduction concentrated in 2019-2020, was calculated and exploratory segmented regressions was estimated with a pre-2020 trend, a 2020 level shift, and a post-2020 slope change; pre/post means were compared, as well. Mobility and exposure changes in 2020 prevent attributing these descriptive discontinuities to COVID-19 restrictions. Given only 11 observations per series, structural-break estimates require caution. Significance was set at $\alpha = 0.05$; agreement of OLS, Kendall and Theil-Sen estimates served as a robustness check.

3.1 RSTPI construction and weight-sensitivity analysis

The Road Safety Transition Performance Index (RSTPI) is proposed as a descriptive composite measure of national safety transitions rather than a direct estimate of crash risk or of policy effectiveness. It combines four complementary domains: progress towards a reduction target (TP), proximity to the EU reference level (EP), consistency of the annual linear trend (TC), and retention of the post-2020 improvement (PR). Each component has an attainable scale of 0-100 points, so differences across domains can be inspected before aggregation. The baseline index is their arithmetic mean:

$$RST\ PI_c = \frac{1}{4}(\ TP_c + EP_c + TC_c + PR_c)\,. \qquad (1)$$

Throughout, c identifies one of the three countries, t is a calendar year (2014-2024), $F_{c,t}$ denotes 30-day road

fatalities per million inhabitants in country c, and $F_{EU,t}$ is the corresponding EU rate. The higher component scores indicate more favourable performance. To prevent extrapolation beyond the common scale, the clipping operator is defined as:

$$C(x) = \min\{100, \max\{0, x\}\}. \quad (2)$$

Target progress (TP). This component benchmarks the observed reduction between 2014 and 2024 against a 50% decrease from the 2014 baseline. Scaling by the required reduction, rather than by the baseline rate alone, gives 100 points when at least half the initial rate is eliminated. A stagnation or increase yields zero after clipping:

$$TP_c = C\left(\frac{100(F_{c,2014} - F_{c,2024})}{0.50\, F_{c,2014}}\right). \quad (3)$$

The 50% threshold is a transparent decadal reference applied uniformly to the study window; it must not be interpreted as formal attainment of an EU target using a different base year. From Table 1, the Polish decline from 84 to 52 corresponds to TP = 76.2 points; the Czech and Slovak results are 63.6 and 25.5 points, respectively.

EU proximity (EP). This component describes the distance between the national endpoint and the 2024 EU rate. To retain a common scale, the denominator is the maximum absolute country-EU gap observed in the same sample and time window:

$$G_{\max} = \max_{c,t} abs(F_{c,t} - F_{EU,t}) = 29, \quad (4)$$

$$EP_c = C\left(100\left[1 - \frac{abs(F_{c,2024} - F_{EU,2024})}{G_{\max}}\right]\right). \quad (5)$$

The normalization constant is 29 fatalities per million (Poland relative to the EU in 2014); it is not a universal safety threshold. Equality with the EU endpoint gives EP = 100, while a larger positive or negative gap reduces the score. Reporting G_{max} is essential for replication; comparisons with other country groups or periods require recalibration or a fixed reference denominator.

Trend consistency (TC). The coefficient of determination of each country-specific ordinary least-squares regression is transformed to a percentage scale:

$$TC_c = 100 R^2{}_c. \quad (6)$$

Here $R^2(c)$ measures how closely the 11 annual observations follow their fitted linear trajectory. This component rewards regularity, not the direction of change; an increasing trend could also have high R^2. Accordingly, TC must be interpreted jointly with TP and the estimated trend slope, rather than as a stand-alone road-safety measure.

Post-shock retention (PR). The lowest rate in 2020-2021 is used as a descriptive reference for the immediate change around the mobility shock; the 2019 rate represents the pre-shock level. The observed initial gain is D_c:

$$B_c = \min\{F_{c,2020}, F_{c,2021}\}; D_c = F_{c,2019} - B_c. \quad (7)$$

When D_c is positive, the proportion of this initial gain still present in 2024 is converted to a bounded score. Rebound above B_c reduces retention; subsequent improvement beyond B_c does not increase the component beyond 100:

$$PR_c = C\left(100\left[1 - \frac{\max\{0, F_{c,2024} - B_c\}}{D_c}\right]\right) \quad (8)$$

for $D_c > 0$,

$$PR_c = 0 \text{ for } D_c \le 0. \quad (9)$$

The second rule avoids division by zero and assigns no retained gain where the 2019-to-2020/2021 improvement is absent. For Slovakia, B = 45, D = 50 - 45 = 5, and the increase to 48 in 2024 produces PR = 40.0; Poland and Czechia each receive 100.0. These figures describe persistence of population-based outcomes and cannot identify the causal effects of pandemic restrictions or road-safety policies.

Weights and sensitivity analysis. Equal weights are chosen to make the baseline construction auditable and to avoid introducing unsupported judgements about the relative policy importance of the four domains. Their selection is a methodological convention, not a statistically estimated optimum. With K = {TP, EP, TC, PR}, the generalized index is:

$$RST\ PI_c(w) = \sum_{k \in K} w_k I_{c,k},\ \sum_{k \in K} w_k = 1. \quad (10)$$

Here $I_{c,k}$ denotes the score of country c on component k; weights w_k are non-negative and sum to one. Four one-at-a-time scenarios assign 40% to a selected component and 20% to each remaining component, while leaving source data and normalized scores unchanged:

$$w_j = 0.40;\ w_{k \ne j} = 0.20\ (j \in K). \quad (11)$$

For each weighting scheme, national scores and ranks are recalculated (Table 6). Poland moves ahead of Czechia when TP or TC receives 40%, whereas Czechia leads when EP or PR receives 40%; Slovakia remains last throughout. Thus, the top-two ordering is sensitive to defensible weighting choices, while the broad separation from Slovakia is robust across these specified scenarios. This analysis evaluates weight sensitivity only; it does not quantify uncertainty from rounded input rates, indicator selection, alternative normalization, or model specification.

For replication, Equations (2)-(9) generate the four country-specific scores, which are aggregated using Equation (1) or the alternative weights in Equation

(10). Tables 5-6 report values rounded to one decimal. Interpretation should always retain the component profile, because clipping may conceal differences at the limits.

4 Results

In this section are presented the empirical results in five steps. In Section 4.1 are described the annual fatality rates and their position relative to the EU benchmark; in Section 4.2 are reported the magnitude and statistical significance of the national trends; in Section 4.3 were examined the robustness, dispersion and year-to-year changes; in Section 4.4 were tested the between-country differences in levels and slopes; and in Section 4.5 were analyzed the convergence, structural change after 2020 and the proposed RSTPI.

4.1 Annual fatality rates

An additional benchmark-gap analysis was performed to assess the endpoint positions and cumulative distance from the EU average over the full study period. Summed signed country-EU gaps for 2014-2024 were 204 rate points in Poland (mean +18.55 fatalities per million annually), 65 in Czechia (+5.91), and 3 in Slovakia (+0.27). These sums are not counts of additional deaths. Poland's endpoint EU gap narrowed from 29 in 2014 to 7 in 2024 (-75.9%); Czechia's fell from 11 to zero, whereas Slovakia moved from parity with the EU to three fatalities per million above it. Annual decreases occurred in five of ten intervals in Poland, seven in Czechia, and four in Slovakia. Czechia had the highest standard deviation of annual changes (5.67, versus 4.78 in Poland and 3.47 in Slovakia). Thus, the EU proximity and the rate or consistency of

Table 1 *Road fatalities per million inhabitants, 2014-2024*

Year	Poland	Czechia	Slovakia	EU average
2014	84	66	55	55
2015	77	70	58	55
2016	80	58	51	54
2017	75	55	51	53
2018	75	62	48	53
2019	77	58	50	51
2020	66	49	45	42
2021	60	51	45	45
2022	52	50	49	47
2023	52	47	49	46
2024	52	45	48	45

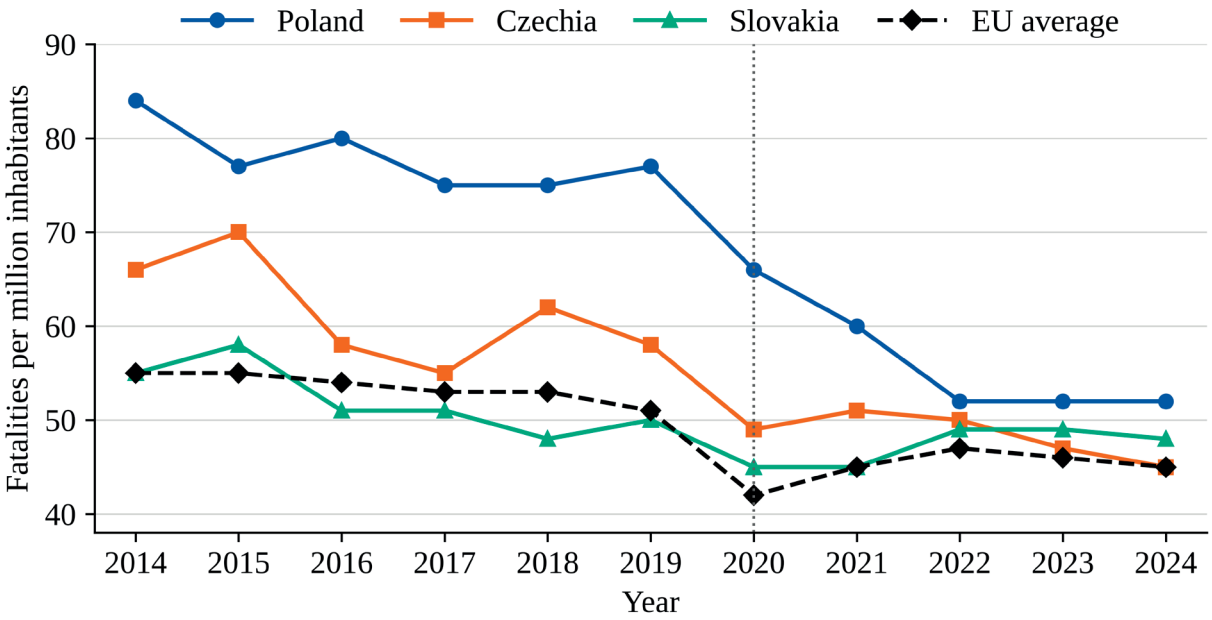


Figure 1 *Population-normalized road-fatality trends, 2014-2024*

improvement describe different dimensions.

The 2019-2020 fall represented 34.4% of Poland's net decade-long reduction, 42.9% of Czechia's, and 71.4% of Slovakia's, suggesting different dependence on that disruption. In Table 1 are reported the full annual series: Poland declined from 84 to 52 fatalities per million, Czechia from 66 to 45, Slovakia from 55 to 48, and the EU average from 55 to 45.

Across the entire period, Poland had the highest mean rate (68.18 ± 12.23 fatalities per million), followed by Czechia (55.55 ± 8.07) and Slovakia (49.91 ± 3.88). The ordering changed by the end of the period: Czechia reached the EU benchmark, whereas Poland and Slovakia remained seven and three fatalities per million above it, respectively. The trajectories in Figure 1 additionally reveal that the improvement was not uniform over time. All four series declined sharply in 2020, but their subsequent development differed: the Polish rate continued to decrease, the Czech rate declined more moderately, and the Slovak rate partially rebounded.

Figure 1 shows the 2020 discontinuity. Average 2014-2019 versus 2020-2024 rates decreased from 78.0 to 56.4 in Poland (-27.7%), from 61.5 to 48.4 in Czechia (-21.3%), from 52.17 to 47.2 in Slovakia (-9.5%), and from 53.5 to 45.0 in the EU (-15.9%). These descriptive changes do not establish a causal pandemic effect, since travel exposure and other simultaneous factors were not modelled.

4.2 Trend magnitude and statistical significance

The descriptive and regression results summarized in Table 2 confirm that the visual decreases were statistically significant. Poland achieved the steepest and most regular improvement, Czechia recorded the second strongest decrease, while Slovakia combined the smallest slope with the lowest trend consistency. Table 2 also shows that only Poland and Czechia achieved larger relative reductions than the EU average over the complete period.

All four series show statistically significant downward linear trends. Poland improved most rapidly, with an estimated annual reduction of 3.48 fatalities per million (95% CI: -4.40 to -2.57; $R^2 = 0.892$; $p < 0.001$). Czechia declined by 2.20 per million annually (95% CI: -2.98 to -1.42; $R^2 = 0.818$; $p < 0.001$). Slovakia's decline was smaller, at 0.84 per million annually (95% CI: -1.45 to -0.22; $R^2 = 0.510$; $p = 0.014$). Kendall tests confirmed monotonic decreases in Poland ($\tau = -0.839$; $p < 0.001$), Czechia ($\tau = -0.771$; $p = 0.001$), and Slovakia ($\tau = -0.585$;

Table 2 *Descriptive and linear-trend statistics*

Series	Mean ± SD	Median	2014-2024 change	CAGR	Slope/year	95% CI	R^2	p
Poland	68.18 ± 12.23	75.0	-38.1%	-4.68%	-3.48	-4.40 to -2.57	0.892	<0.001
Czechia	55.55 ± 8.07	55.0	-31.8%	-3.76%	-2.20	-2.98 to -1.42	0.818	<0.001
Slovakia	49.91 ± 3.88	49.0	-12.7%	-1.35%	-0.84	-1.45 to -0.22	0.510	0.014
EU average	49.64 ± 4.72	51.0	-18.2%	-1.99%	-1.22	-1.77 to -0.66	0.733	<0.001

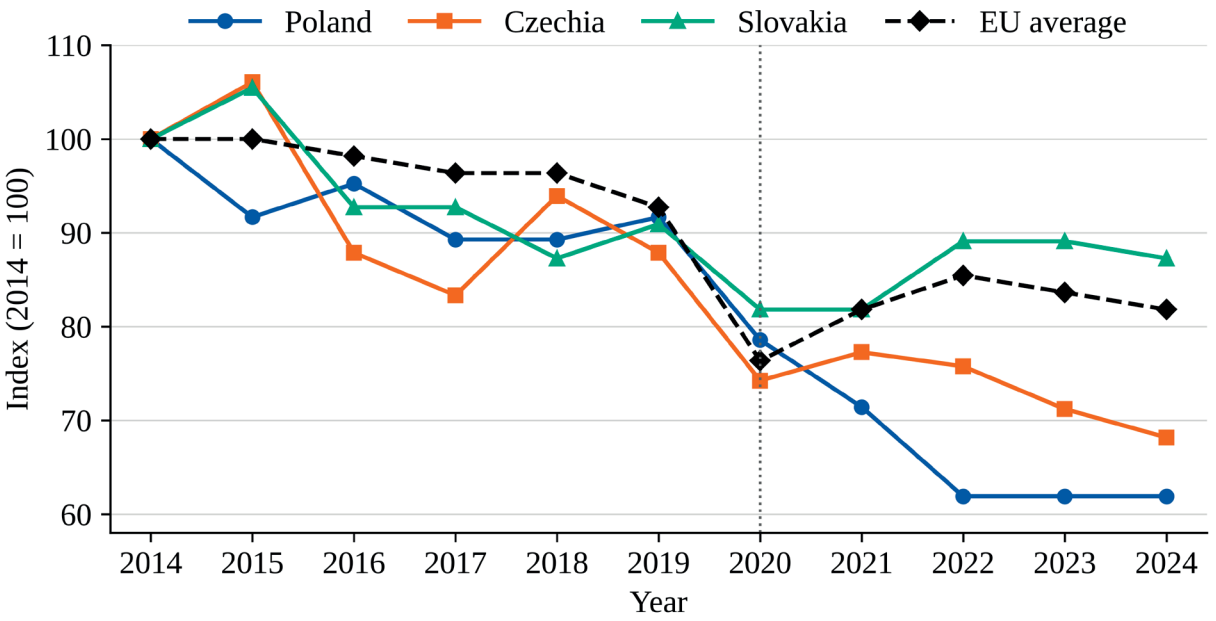


Figure 2 *Relative change in road-fatality rates (2014 = 100)*

p = 0.015). In Figure 2 are expressed those changes relative to a common 2014 baseline and consequently separates the pace of improvement from differences in the initial fatality level. Indexing each series to 2014 demonstrates the different pace of progress. By 2024 Poland reached 61.9% of its 2014 level, Czechia 68.2%, Slovakia 87.3%, and the EU average 81.8%. Poland and Czechia therefore achieved larger relative reductions than the EU benchmark, whereas Slovakia's 12.7% reduction was smaller than the EU-wide 18.2% decline.

4.3 Robustness, dispersion, and distance from the EU benchmark

The additional statistics in Table 3 distinguishes three concepts that are often conflated in road-safety comparisons: the average fatality burden, the stability of the annual series, and the speed of improvement. Poland had the widest observed range (52-84) and the highest temporal CV (17.94%), reflecting both its high initial burden and its pronounced subsequent decline. Czechia also showed substantial variation (CV = 14.52%; range 45-70). Slovakia had the lowest CV (7.78%) and the narrowest relative dispersion, but this should not be interpreted automatically as superior performance: in this case, low variability largely reflects a comparatively flat trajectory rather than sustained improvement. The EU series had an intermediate CV of 9.50%.

Theil-Sen slopes reproduced the OLS ordering: Poland -3.50 (95% CI -4.60 to -2.25), Czechia -2.14 (-3.00 to -1.33), Slovakia -0.70 (-1.50 to -0.25), and the EU -1.11 (-1.40 to -0.80) fatalities per million per year (Table 3). All intervals excluded zero, supporting the Kendall results. Residual screening yielded Shapiro-Wilk p = 0.528-0.927 and Durbin-Watson values of 1.27-2.44; diagnostics were interpreted cautiously with only 11 annual observations.

The EU benchmark proximity ranked the countries differently from trend improvement. Poland's mean signed gap was +18.55 and RMSE 20.35, but its endpoint gap shrank by 75.9%. Czechia's mean gap was +5.91 (RMSE 7.33) and reached zero in 2024. Slovakia was the closest on average (+0.27; MAE 2.27; RMSE 2.68) and was at or below the EU rate in six years, but ended three fatalities per million above it. Table 4 complements these level comparisons with annual first differences (negative = improvement).

Poland recorded the strongest mean annual improvement (-3.20 fatalities per million), but the sequence was not uniformly decreasing: five intervals improved, three were unchanged, and two worsened. Czechia improved in seven of ten intervals, the highest frequency among the analyzed countries, although its year-to-year standard deviation was also the largest (5.67) because the series included both a reduction of 12 fatalities per million in 2015-2016 and an increase of 7 in 2017-2018. Slovakia had a median annual change of zero and almost balanced counts of improving, stable, and worsening intervals (4/3/3), which is consistent with the weaker monotonic trend and lower R^2. The EU benchmark improved in six intervals but also increased in 2021 and 2022 as mobility recovered.

The 2019-2020 decline represented 34.4%, 42.9%, 71.4%, and 90.0% of the total 2014-2024 reduction in Poland, Czechia, Slovakia, and the EU, respectively. Excluding that interval, mean annual changes

Table 3 *Robust trend, dispersion, and EU benchmark statistics*

Series	95% CI for mean	CV, %	Observed range	Theil-Sen slope/ year (95% CI)	Mean gap to EU	RMSE vs EU
Poland	59.97-76.40	17.94	52-84	-3.50 (-4.60 to -2.25)	+18.55	20.35
Czechia	50.13-60.96	14.52	45-70	-2.14 (-3.00 to -1.33)	+5.91	7.33
Slovakia	47.30-52.52	7.78	45-58	-0.70 (-1.50 to -0.25)	+0.27	2.68
EU average	46.47-52.81	9.50	42-55	-1.11 (-1.40 to -0.80)	—	—

Table 4 *Year-to-year change and shock-concentration diagnostics*

Series	Mean Δ/year	Median Δ	SD of Δ	Improved / stable / worsened years	Largest reduction	Largest increase	2019-2020 share of total reduction, %
Poland	-3.20	-2.50	4.78	5 / 3 / 2	-11	+3	34.4
Czechia	-2.10	-2.50	5.67	7 / 0 / 3	-12	+7	42.9
Slovakia	-0.70	0.00	3.47	4 / 3 / 3	-7	+4	71.4
EU average	-1.00	-1.00	3.20	6 / 2 / 2	-9	+3	90.0

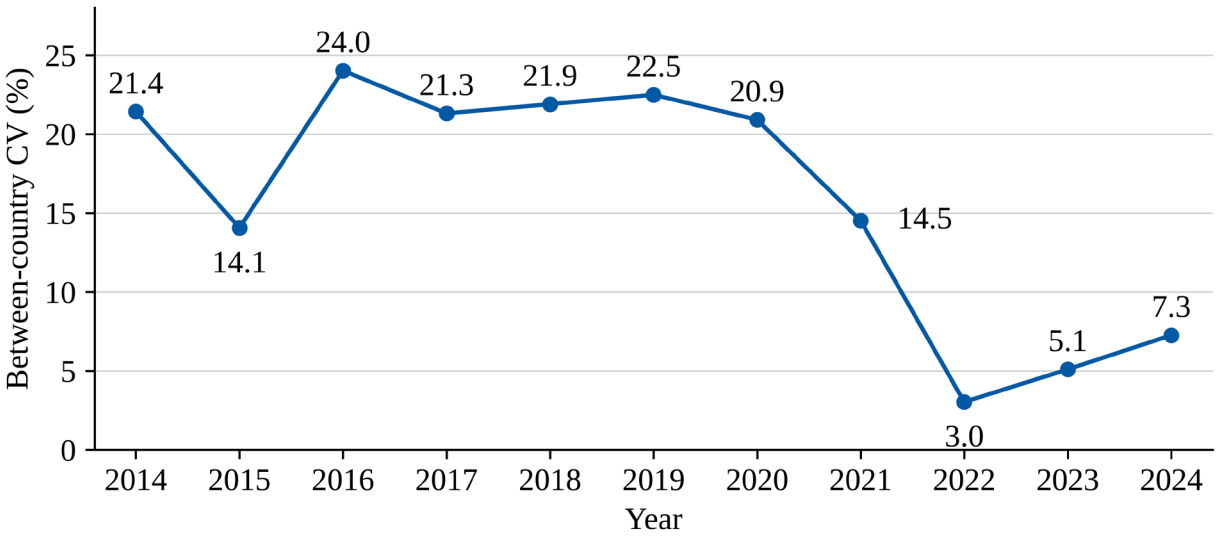


Figure 3 *Sigma convergence of population-normalized fatality rates*

remained negative in Poland (-2.33) and Czechia (-1.33), but approached zero in Slovakia (-0.22) and the EU (-0.11). This is a descriptive sensitivity check, not a causal estimate of pandemic-related effects.

4.4 Between-country differences

The Friedman test demonstrated a significant difference among the three national series ($\chi^2 = 18.73$; df = 2; $p < 0.001$). Kendall's W was 0.851, indicating a large and highly persistent separation of the ranked annual rates. Post-hoc paired Wilcoxon tests showed significant differences for Poland versus Czechia (W = 0; unadjusted p = 0.00098; Holm-adjusted p = 0.0029), Poland versus Slovakia (W = 0; unadjusted p = 0.00098; adjusted p = 0.0029), and Czechia versus Slovakia (W = 5; unadjusted p = 0.0088; adjusted p = 0.0088). Poland's rate exceeded both neighbouring countries in each observed year. Czechia exceeded Slovakia during 2014-2022, whereas Slovakia recorded slightly higher values in 2023 and 2024. These rank-based tests concern the distributions of paired annual rates rather than merely the endpoints.

The pooled country-by-year model explained 91.6% of the variability in the 33 national observations (R^2 = 0.916; HC3 robust F = 57.93; $p < 0.001$) and confirmed that the slopes were not parallel. Poland's trend was 1.28 fatalities per million per year more negative than Czechia's (95% CI: -2.28 to -0.28; p = 0.014) and 2.65 more negative than Slovakia's (95% CI: -3.63 to -1.66; $p < 0.001$). Slovakia's trend was 1.36 fatalities per million per year less negative than Czechia's (95% CI: 0.42 to 2.31; p = 0.006). The interaction analysis therefore strengthens the conclusion from the Friedman procedure: the countries differed not only in their typical fatality levels but also in the velocity of their safety transitions.

4.5 Convergence, structural change, and the proposed RSTPI

A sigma-convergence test assessed whether national fatality rates became more similar. In each year, cross-country dispersion was calculated as CV_t = SD(F_PL,t, F_CZ,t, F_SK,t) / mean(F_PL,t, F_CZ,t, F_SK,t), where F denotes fatalities per million inhabitants. The coefficient declined from 21.42% in 2014 to 7.27% in 2024, a reduction of 66.1%. Its linear slope was -1.67 percentage points per year (R^2 = 0.521; p = 0.012). in Figure 3 is shown the convergence after 2021, when dispersion fell below 10%, followed by a rebound in 2023-2024.

The Safety Convergence Half-Life (SCHL) expresses the speed of convergence in years. The exponential model $\ln(CV_t) = a + bt$ gave b = -0.1498 (R^2 = 0.493; p = 0.016), yielding SCHL = ln(2)/|b| = 4.63 years. This exploratory projection assumes that the observed convergence rate persists.

To distinguish the convergence from a temporary common shock, slopes were estimated separately for 2014-2019 and 2020-2024. Poland accelerated from -1.31 to -3.60 fatalities per million per year; Czechia changed from -1.91 to -1.20; Slovakia reversed from -1.57 to +1.00. In an exploratory segmented regression that simultaneously allowed a 2020 level shift, the Slovak change in slope was +2.57 fatalities per million per year (95% HC3 CI: 0.17 to 4.97; p = 0.039). The slope-change terms were not statistically significant for Poland (-2.29; p = 0.327) or Czechia (+0.71; p = 0.625). The positive Slovak post-2020 slope therefore represents more than a minor visual fluctuation within this short series, although the limited number of observations precludes a causal attribution. The cross-country coefficient of variation reached its minimum of 3.03% in 2022 and then rose to 5.10% in 2023 and 7.27% in 2024. Regional convergence was consequently substantial but not yet irreversible.

Table 5 *Components and results of the Road Safety Transition Performance Index*

Country	TP	EP	TC	PR	RSTPI
Poland	76.2	75.9	89.2	100.0	85.3
Czechia	63.6	100.0	81.8	100.0	86.4
Slovakia	25.5	89.7	51.0	40.0	51.5

Table 6 *Sensitivity of RSTPI to alternative component weights*

Country	Equal (25% each)	TP 40%; others 20%	EP 40%; others 20%	TC 40%; others 20%	PR 40%; others 20%
Poland	85.3	83.5	83.4	86.1	88.3
Czechia	86.4	81.8	89.1	85.5	89.1
Slovakia	51.5	46.3	59.1	51.4	49.2

The RSTPI, specified in Section 3.1 and Equation (1), integrates target progress, EU proximity, linear-trend consistency and retention of gains following the 2020 decline. Table 5 displays the four 0-100 components and the equal-weight index values. Czechia and Poland obtained nearly identical overall scores through different profiles: Czechia reached the EU benchmark in 2024, while Poland performed better on target progress and trend consistency. Slovakia's score was lower chiefly because of weaker relative improvement and partial reversal of its early post-2020 reduction.

Under equal weights Czechia scored 86.4, Poland 85.3, and Slovakia 51.5 (Table 5). Since the first two scores are close, in Table 6 are compared the baseline with four alternative weight sets to assess the ranking stability.

Under alternative weights, Poland ranked first when target progress (TP) or trend consistency (TC) received 40% weight; Czechia led when EU proximity (EP) or post-shock retention (PR) received 40%. Poland's scores ranged from 83.4 to 88.3 and Czechia's from 81.8 to 89.1, while Slovakia remained third (46.3-59.1). Thus, the ranking of the first two countries is weight-sensitive, whereas their separation from Slovakia is stable in the tested scenarios. The RSTPI requires validation and should not be treated as a definitive ranking.

5 Discussion

The empirical findings reveal three distinct road-safety trajectories. Poland began with the highest population-normalized fatality burden but achieved the largest absolute and relative improvement. Its linear trend was more than four times steeper than Slovakia's, and the 2024 rate was 38.1% below the 2014 level. Czechia also improved faster than the EU benchmark and reached the EU average by 2024. Slovakia recorded a statistically significant decline, but both the slope and CAGR show that progress was comparatively slow. The central policy implication is therefore not that one uniform regional intervention is required, but that common Safe System principles should be combined with country-specific diagnosis.

The rankings distinguish present status from transition dynamics. Slovakia was closest to the EU benchmark on average but improved least and exhibited an adverse post-2020 slope change. Poland improved fastest despite remaining above the EU benchmark; Czechia combined substantial progress with attainment of the EU rate in 2024. RSTPI integrates these distinct dimensions, but the Czechia-Poland ranking depends on weights (Table 6); equal weights cannot be interpreted as empirically established policy importance.

The strong Polish reduction is consistent with literature emphasizing infrastructure modernization, speed enforcement, road-network safety management, and pedestrian protection. However, the aggregate design cannot attribute the decline to any single intervention. Changes in vehicle safety, emergency response, mobility, enforcement, economic activity, and road investment occurred simultaneously. Czechia's trajectory supports continued use of proactive hazardous-location identification and composite indicators. Slovakia's flatter path warrants closer examination of speed management, pedestrian safety, and network-specific risk [16-18].

The sharp 2019-2020 decline coincided with COVID-19 mobility restrictions [19-20]. Reduced exposure may lower population-based fatality rates without reducing risk per kilometre. The 2020 interval contributed 34.4%, 42.9%, 71.4%, and 90.0% of the overall decline in Poland, Czechia, Slovakia, and the EU (Table 4). After excluding that interval, average annual changes remained -2.33 in Poland and -1.33 in Czechia, versus -0.22 in Slovakia. Poland stayed at 52 fatalities per million during 2022-2024, whereas Slovakia rebounded from 45 in 2020-2021 to 48 in 2024. These are descriptive differences in retention, not causal evidence of policy effects or pandemic impacts without harmonized traffic-exposure data.

The Sigma convergence was substantial (-66.1% cross-country dispersion; SCHL 4.63 years), yet dispersion rose after its 2022 minimum. A shared fall during restricted mobility may temporarily compress national gaps; sustained convergence instead requires progress after exposure patterns recover. Segment and

benchmark analyses offer complementary diagnostics but do not establish causation.

Police-recorded accident totals should not be the primary measure in international comparisons. In 2024, national sources reported 21,519 accidents in Poland, 92,217 in Czechia, and 11,434 in Slovakia. Different reporting and classification rules partly explain the striking discrepancies relative to closer fatality rates. Harmonized fatality measures improve comparability, although rates per population do not adjust for distance travelled, modal share, road type, or urbanization [6, 14-15].

For international benchmarking, the RSTPI should be reported with its four components, the EU reference value, Gmax, and weight sensitivity, alongside population-based rates and available exposure metrics. Its decomposition can highlight whether priority questions concern reduction towards a target (TP), EU proximity (EP), trend regularity (TC), or retention after a disruption (PR), but cannot score causal intervention effectiveness. Poland should consolidate gains, while closing the EU gap; Czechia should sustain progress and investigate fluctuations; Slovakia needs closer examination of persistent obstacles. Evaluation requires exposure, serious-injury, enforcement, and infrastructure data [2, 11, 21].

6 Limitations

The ecological design does not support individual- or intervention-level causal inference. Eleven annual values per series limit inference on serial correlation and 2020 breakpoints; HC3 addresses heteroscedasticity but not all temporal dependence, and non-parametric or robust trends cannot eliminate omitted-variable bias. Fatalities per million reflect population burden rather than the exposure-adjusted travel risk, while the EU benchmark partly includes the three countries and published integer rates reduce numerical precision. The RSTPI is exploratory: indicator choice, equal weights, sample-specific Gmax, use of R^2, and post-2020 retention definitions have not been externally validated. In Table 6 are examined the weight changes but not the measurement uncertainty or alternative normalizations. The 2024 endpoint excludes provisional 2025 values. Further research should add harmonized travel exposure, serious injuries, enforcement, and intervention timing.

7 Conclusions

In this study is provided the empirical evidence that fatalities per million inhabitants declined significantly in Poland, Czechia, and Slovakia from 2014 to 2024, but at different rates. Poland showed the greatest improvement (-38.1%; OLS slope -3.48 fatalities per million per year), followed by Czechia (-31.8%; -2.20) and Slovakia (-12.7%; -0.84). The Theil-Sen estimates confirmed this ordering, and country-by-year interactions showed a significantly steeper decline in Poland than in the other two countries. Matched national trajectories differed significantly (Friedman test, Kendall's $W = 0.851$). In 2024, Czechia matched the EU benchmark of 45 fatalities per million, while Slovakia and Poland recorded 48 and 52, respectively.

The cross-country dispersion decreased by 66.1%, consistent with sigma convergence, although the rebound after 2022 and the different post-2020 trajectories show that convergence was not uniformly sustained. The proposed RSTPI integrates benchmark proximity with the pace and persistence of improvement. Czechia and Poland received similar equal-weight scores (86.4 and 85.3), but their ordering reversed under some alternative component weights; Slovakia remained third across all tested configurations. Consequently, the RSTPI is the best reported together with its components and a sensitivity analysis, rather than used as a stand-alone country ranking. Further work should integrate exposure, severe-injury, enforcement, infrastructure-investment and intervention-timing data to move from descriptive comparisons toward stronger policy evaluation.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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