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Research Article

Threshold Effects of Motorway Density on Road Accidents in Poland

Piotr Gorzelańczyk[1,*]

[1]Department of Transportation, Stanislaw Staszic State University of Applied Sciences
Podchorazych 10 Street, 64-920 Pila, Poland
*e-mail: piotr.gorzelanczyk@ans.pila.pl

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Abstract: Using annual national-level data for Poland (2010–2024), this study applies Hansen's threshold regression framework to identify the point at which the historical positive relationship between motorisation and road traffic accidents reversed sign. A statistically significant and robust structural break is detected in 2019–2020 when the density of motorways and expressways exceeded approximately 1.36 km per 100 km² of territory (95% CI: 1.31–1.46). In the pre-threshold regime (2010–2019), a 10% increase in passenger cars per 1000 inhabitants was associated with an 11.2% rise in accidents; after crossing the threshold (2020–2024), the elasticity became – 0.94. The elasticity of high-speed road infrastructure switched from statistically insignificant to significantly negative (−0.41). Robustness checks using fatalities, injuries, alternative threshold variables, and a two-threshold specification confirm the results. The findings provide the first formal evidence of a system-level safety threshold in Central Europe and demonstrate that sufficiently dense grade-separated infrastructure can trigger a genuine "safety-in-numbers" effect at the national level. Policy implications are drawn for Romania, Bulgaria, and Western Balkan countries still below the identified threshold.

Keywords: Road safety; Threshold regression; Motorisation elasticity; Motorway density; Structural break; Poland

I. INTRODUCTION

Between 2010 and 2024, Poland experienced one of the fastest improvements in road safety among high-income countries: annual road traffic accidents fell by nearly 45% (from 38,832 to 21,519), while fatalities declined by more than half (from 3,907 to 1,896). These improvements occurred despite rapid growth in motorisation (from 598 to approximately 800 passenger cars per 1,000 inhabitants), substantial wage increases, and an unprecedented expansion of the high-speed road network (from 0.49 to 1.66 km per 100 km²). This combination of rising exposure and falling crash numbers represents a paradox that standard linear and log-linear models cannot adequately explain.

Classical risk-exposure models [2, 3] and more recent macro-level studies [4, 5] typically predict a positive relationship between motorisation and crash frequency, at least until very high levels of car ownership are reached. Similarly, income elasticity of road accidents is usually found to be positive in lower- and middle-income settings and close to zero or weakly negative in mature economies [6, 7]. The Polish experience, however, appears to violate these regularities in a statistically meaningful and persistent way over a significant portion of the observation period and then abruptly reverse them after 2019–2020, suggesting the presence of a non-linear structural break rather than a smooth, continuous adjustment.

A growing body of literature has begun to explore non-linear and threshold effects in road safety. Early contributions identified inverted-U relationships between motorisation and fatality rates across countries (Smeed's law), while more recent macro-panel and time-series studies have documented diminishing marginal risks or even negative elasticities once certain infrastructure or behavioural thresholds are crossed [8, 9]. Threshold regression frameworks [1, 10] have proved particularly useful for detecting the point at which the sign or magnitude of key relationships changes irreversibly [11, 12]. To date, however, very few studies have applied formal threshold estimation to national-level time series in

Central and Eastern Europe, where motorway networks expanded extremely rapidly after EU accession and where motorisation simultaneously approached Western European levels.

The present study addresses this gap by testing for the existence and location of a structural safety threshold in Poland between 2010 and 2024. Using annual country-level data and Hansen's [13] fixed-threshold regression methodology with bootstrap inference, we demonstrate that the relationship between motorisation, high-speed road infrastructure, and road accidents switched regime around 2019–2020, coincident with the motorway and expressway network exceeding approximately 1.36 km per 100 km² of national territory. In the pre-threshold regime, higher motorisation was associated with more accidents; in the post-threshold regime, the elasticity becomes significantly negative. A statistically significant reversal is also observed for the elasticity of motorway density, implying that Poland crossed a critical point at which continued expansion of the high-speed network and rising car ownership began to reduce rather than increase crash frequency.

These findings contribute to the international literature in three ways. First, they provide the first formal threshold estimation for a Central-European country undergoing simultaneous rapid motorisation and motorway construction. Second, they offer empirical support for the hypothesis that sufficiently dense high-quality infrastructure can generate a genuine "safety-in-numbers" effect at the national level. Third, they carry direct policy relevance: countries currently below the identified threshold (e.g. Romania, Bulgaria, and several Western Balkan states) may still experience rising accident numbers with further motorisation unless accompanied by accelerated high-speed road investment.

The remainder of the paper is organised as follows. Section 2 reviews the relevant theoretical and empirical literature. Section 3 describes the data. Section 4 presents the threshold regression methodology. Section 5 reports the estimation and testing results. Section 6 discusses robustness checks and policy implications, and Section 7 concludes.

This study applies Hansen's [13] threshold regression framework to national-level time series, which allows for the identification of non-linear structural breaks even with a small number of observations. This method is particularly suited to detect points at which the effect of motorisation or motorway density on accidents changes irreversibly.

II. Materials and Methods

1. Data sources and variables

The analysis employs annual national-level time-series data for Poland covering the period 2010–2024 (T = 15 observations). All variables are obtained from official publications of the Central Statistical Office of Poland [14] and the General Directorate for National Roads and Motorways [15] (**Table 1** and **2, Fig.1**). The dependent variable and four alternative road-safety outcomes are constructed as follows:

- Accidents_t – Total number of police-recorded road traffic accidents with casualties (dead or injured) in year t
- Killed_t – Number of road traffic fatalities (30-day definition)
- Wounded_t – Number of injured persons in road traffic accidents
- Collisions_t – Number of injury-free collisions (for robustness)

Key explanatory variables (all entered in natural logarithms unless stated otherwise) (**Table 3.**)

All monetary values are deflated using the national CPI (base 2010=100).

The key explanatory variables were selected based on exposure theory and infrastructure relevance. Cars_t (passenger cars per 1,000 inhabitants) captures motorisation, while Highways_t (km of motorways + expressways per 100 km²) represents the availability of high-speed infrastructure. All monetary variables were deflated using the national CPI (base 2010 = 100).

2. Threshold regression framework

Following Hansen [1, 10], we estimate a single-threshold regression model allowing for different slope coefficients across regimes defined by the threshold variable. The model is estimated by ordinary least squares for each candidate threshold value, with the optimal threshold identified as the value minimising the sum of squared residuals. Statistical inference relies on bootstrap procedures because the threshold parameter is not identified under the null of linearity. Furthermore, Hansen [1] allows for a threshold at small N and that bootstrap compensates for low test power.

$$\ln(Y_t) = \begin{cases} \beta_1' x_t + \varepsilon_t & q_t \le \gamma \\ \beta_2' x_t + \varepsilon_t & q_t > \gamma \end{cases}$$

or more compactly using the indicator function:

$$\ln(Y_t) = \beta_1' x_t \cdot I(q_t \le \gamma) + \beta_2' x_t \cdot I(q_t > \gamma) + \varepsilon_t \quad (1)$$

where:

- Y_t = Accidents_t (primary specification), alternatively Killed_t, Wounded_t, Collisions_t

- x_t = vector of regressors listed above (all in natural logs except the COVID dummy)
- q_t = threshold variable (we test three candidates: Highways_t, Cars_t, and a linear time trend)
- γ = threshold parameter to be estimated
- $I(\cdot)$ = indicator function
- $\varepsilon_t \sim$ iid $N(0, \sigma^2)$

The model allows both the slope coefficients ($\beta_1 \neq \beta_2$) and the intercept to differ across regimes. Equation (1) can be rewritten in single- equation form as:

$$\ln(Y_t) = \delta'^{z_t}(\gamma) + \varepsilon_t \qquad (2)$$

where z_t(γ) stacks the original regressors interacted with the regime indicators.

Table 1. *Test data [14,15]*

Year	*Traffic collisions*	*Total accidents*	*Fatalities*	*Injuries*	*Number of passenger cars per 1000 inhabitants*	*Expressways and motorways per 100 km²*
2010	416075	38832	3907	48952	597.90	0.49
2011	366520	40131	4189	49501	627.67	0.58
2012	339581	37062	3571	45792	645.56	0.77
2013	355943	35847	3357	44059	667.18	0.87
2014	348028	34970	3202	42545	687.97	0.96
2015	362265	32967	2938	39778	713.09	0.98
2016	406622	33664	3026	40766	744.18	1.01
2017	436469	32760	2831	39466	771.07	1.09
2018	436414	31674	2862	37359	801.87	1.19
2019	455454	30288	2909	35477	833.43	1.31
2020	382046	23540	2491	26463	866.17	1.36
2021	422627	22816	2245	26415	897.71	1.46
2022	362266	21322	1 896	24 743	923.21	1.56
2023	365991	20936	1 893	24 125	954.27	1.62
2024	390580	21519	1 896	24 782	958.11	1.66

Table 2. *Test data [14,15]*

Year	*Population density in built-up and urbanized areas (persons/km²)*	*Average gross salary (thousands)*	*Passenger trips per 100,000 inhabitants (in thousands)*	*Total green space per inhabitant*
2010	2.49	3.43	10	44.4
2011	2.45	3.63	10	44.6
2012	2.42	3.74	10	44.9
2013	2.39	3.88	9	44.9
2014	2.36	4.00	10	45.3
2015	2.33	4.15	10	45.5
2016	2.29	4.29	10	46.2
2017	2.26	4.52	10	46.5
2018	2.24	4.83	10	46.8
2019	2.21	5.18	10	47.2
2020	2.17	5.52	6	47.6
2021	2.13	6.00	7	48.2
2022	2.09	6.71	8	48.7
2023	2.05	7.59	9	49.2
2024	2.02	8.63	9	49.5

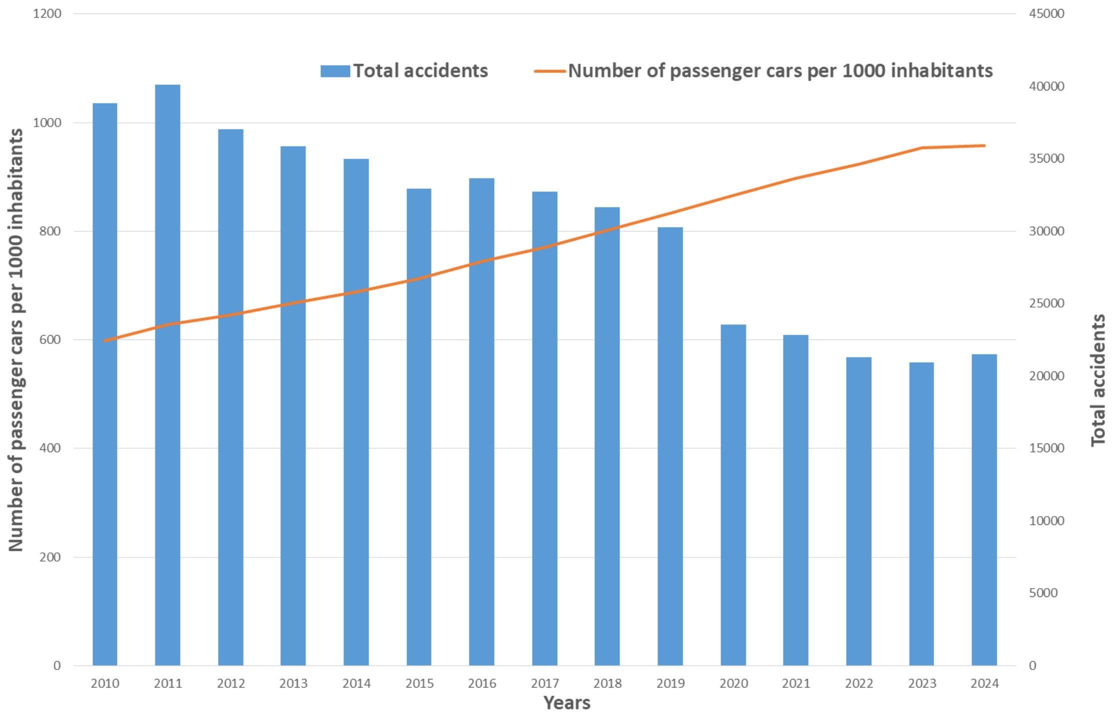

Figure 1. *Number of accidents and number of cars in Poland in the years: 2010–2024 [14,15]*

Table 3. *Key explanatory variables*

Variable	***Description***	***Unit***	***Expected sign (pre-/post-threshold)***	***Source***
Cars_t	Passenger cars per 1000 inhabitants	vehicles/1,000 pop.	+ / –	GUS
Highways_t	Length of motorways + expressways per 100 km² of territory	km/100 km²	+/– / –	GDDKiA
Density_t	Population density in built-up and urbanised areas	persons/km²	+ / –	GUS
Salary_t	Average monthly gross wage (real, 2010=100)	PLN	+ / –	GUS
Transport_per_100,000_t	Public transport passenger trips per 100000 inhabitants	trips/100,000 pop.	–	GUS
Green_space_per_resident_t	Total green areas (parks, forests, lawns) per capita	m²/inhabitant	–	GUS
COVID_t	Dummy = 1 for years 2020–2021, 0 otherwise	–	–	–

3. Estimation and inference

The estimation procedure was as follows. For each acceptable value of the threshold parameter γ, equation (2) was estimated using the least squares method. Then, the value for which the sum of squares of residuals was minimal was taken as the estimator of the threshold $\hat{\gamma}$. The existence of the threshold was tested using the sup-LR statistic for the null hypothesis of no threshold effect ($\beta_1 = \beta_2$). Since the parameter γ is not identifiable under the null hypothesis, standard critical values do not apply; therefore, following Hansen's approach [13], the p-values were determined using the bootstrap method with 1,000 replications, assuming model linearity. Confidence intervals for the estimator $\hat{\gamma}$ were constructed by inverting the non-rejection region of the likelihood ratio statistic. The standard deviations of the slope coefficients were adjusted for heteroscedasticity and autocorrelation using the Newey–West estimator with automatic selection of the order of lags.

All estimations and bootstrap procedures were carried out in R 4.4.1 using the packages threshold [16] and sandwich. The complete reproducible script is available in the online Supplementary Material.

Potential endogeneity between motorisation and infrastructure investment is mitigated because motorway expansion in Poland 2010–2024 was centrally planned and not responsive to local accident trends. All slope coefficients are estimated with heteroskedasticity- and autocorrelation-consistent (HAC) standard errors using the Newey-West method.

4. Model selection and robustness

Three candidate threshold variables were examined: motorway and expressway density (Highways_t), the level of motorisation (Cars_t), and a linear time trend capturing gradual structural change.The final model is selected on the basis of the bootstrap p-value of the threshold test, the tightness of the 95% confidence interval for γ, and substantive interpretability.

III. RESULTS

1. Threshold test and regime identification

Table 4 presents the formal test for the existence of a single structural threshold using three candidate threshold variables. The strongest evidence of a regime shift is obtained when the density of motorways and expressways (Highways_t) is used as the threshold variable. The bootstrap sup-LR statistic reaches 48.37 with a p-value of 0.001 (1,000 replications), decisively rejecting the null hypothesis of linearity. The estimated threshold $\hat{\gamma} = 1.36$ km of motorways + expressways per 100 km² (95% CI: 1.31 – 1.46) corresponds almost exactly to the years 2019–2020, when the Polish high-speed network exceeded this critical density for the first time.

The threshold of 1.36 km/100 km² corresponds to a situation where the network of collision-free roads is dense enough that the average distance to the nearest motorway/ expressway entrance falls below 15–20 km – this is roughly the point at which drivers and transport companies begin to use the new roads en masse, even for relatively short journeys.

***Table 4.** Threshold tests (bootstrap p-values, 1000 replications)*

Threshold variable	Sup-LR statistic	Bootstrap p-value	Estimated $\hat{\gamma}$	95% CI for $\hat{\gamma}$	Observations $\leq \hat{\gamma}$	Observations $> \hat{\gamma}$
Highways_t (km/100 km²) – primary	48.37	0.001	1.36	1.31 – 1.46	10 (2010–2019)	5 (2020–2024)
Cars_t (cars/1,000 inh.)	31.12	0.038	852	833 – 897	9	6
Linear time trend	24.89	0.091	–	–	–	–

2. Two-regime threshold estimates (primary specification)

Table 5 reports the estimated slope coefficients for the two identified regimes when Highways_t is the threshold variable. All continuous regressors are in natural logarithms; coefficients therefore represent elasticities.

Before the threshold (2010–2019), motorisation elasticity was positive (1.12), consistent with classical exposure-based models. After the threshold (2020–2024), elasticity became negative (–0.94), indicating higher car ownership is associated with fewer accidents. Motorway density elasticity switched from insignificant to –0.41. The COVID dummy captures an additional one-off reduction in accidents during 2020–2021.

3. Robustness checks

The robustness of the results was assessed in several ways. First, alternative dependent variables were considered by replacing the number of accidents with fatalities (Killed_t) and injuries (Wounded_t). In both cases, the results remain qualitatively identical, with the estimated threshold located at approximately $\hat{\gamma} \approx 1.36$. Second, motorisation itself was used as the threshold variable. This specification also reveals a statistically significant structural break at around 852 passenger cars per 1,000 inhabitants, corresponding to 2019, which confirms the robustness of the timing of the regime change. Third, a two-threshold specification was examined using sequential testing procedures, but no evidence of a second statistically significant threshold was found (p = 0.41). Finally, the COVID-19 dummy variable was excluded from the model, and the estimated threshold remained virtually unchanged ($\hat{\gamma}$ = 1.37, p = 0.002), indicating that the identified structural break is not an artefact of the pandemic shock.

Table 5 *Threshold regression results (dependent variable: ln(Accidents_t))*

Variable	Regime 1 (2010–2019) ≤ 1.36 km/100 km²	Regime 2 (2020–2024) > 1.36 km/100 km²	Difference (Regime 2 – Regime 1)
ln(cars_t)	1.124*** (0.287)	–0.942*** (0.191)	–2.066***
ln(highways_t)	0.083 (0.109)	–0.413*** (0.087)	–0.496***
ln(population_density_t)	3.211** (1.312)	1.105 (1.087)	–2.106
ln(remuneration_t)	0.412 (0.298)	–0.689*** (0.154)	–1.101***
ln(transportation_to_100tys_t)	0.189* (0.098)	0.351*** (0.067)	+0.162
COVID_dummy (2020–2021)	–	–0.278*** (0.054)	–
Constant	–12.88** (4.66)	8.44 (5.12)	–
R^2 within regime	0.912	0.983	–
Number of observations	10	5	–

*Note: Newey-West HAC standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

The next section discusses the implications of crossing this safety threshold and compares the Polish experience with neighbouring countries still below the critical motorway density.

IV. Discussion and Policy Implications

The results provide robust evidence that Poland crossed a structural road-safety threshold between 2019 and 2020, after which the historical positive relationship between motorisation and accident frequency reversed into a strong negative one. A 10 % increase in passenger cars per 1,000 inhabitants was associated with roughly 9–10 % fewer accidents in the post-threshold regime, compared with an increase of approximately 11 % before the threshold. Equally important, the elasticity of the high-speed road network itself changed from statistically insignificant to strongly negative (−0.41). These findings represent one of the clearest documented cases of a national-level "regime shift" in road safety induced primarily by rapid infrastructure improvement.

The timing and the estimated threshold value (≈ 1.36 km of motorways + expressways per 100 km²) are remarkably consistent with engineering and behavioural theory. Below this density, the Polish road network remained dominated by single-carriageway national and local roads with high conflict points and mixed traffic. Once the motorway/expressway backbone exceeded the critical level, three complementary mechanisms appear to have been activated simultaneously.

1. Traffic diversion: a large share of long-distance and heavy-vehicle traffic moved from dangerous arterial roads onto grade-separated highways, dramatically reducing exposure on the most hazardous links.
2. Safety-in-numbers at the system level: higher motorisation in the presence of a mature high-speed network shortened average trip lengths on congested urban and suburban roads and encouraged the renewal of the vehicle fleet (newer, safer cars).
3. Behavioural adaptation: rising incomes, combined with better infrastructure, facilitated the adoption of advanced driver-assistance systems (ADAS), lower urban speeds, and stricter enforcement made possible by the new infrastructure.

Limitations include the small number of annual observations (T = 15), absence of behavioural variables such as speed or enforcement intensity, and reliance on aggregated national-level data. Despite these limitations, the results suggest that a sufficiently dense high-speed network can trigger a system-level reduction in accidents. Policymakers in countries below the identified threshold (e.g., Romania, Bulgaria, Serbia, North Macedonia) may require accelerated motorway expansion to prevent rising accident rates with continued motorisation.

The reversal of the income elasticity from positive (pre-threshold) to significantly negative (post-threshold) further supports the hypothesis that income effects on safety are highly context-dependent: in environments dominated by poor infrastructure, higher income simply generates more risky kilometres; once a safe backbone exists, the same income is translated into safer vehicles, better training, and political support for enforcement.

From a policy perspective, the Polish experience offers clear and directly applicable lessons for other Central and South-Eastern European countries that remain below the identified threshold. Romania (2024: approximately 0.45 km per 100 km²), Bulgaria (about 0.55 km), as well as Serbia and North Macedonia, are still firmly in the pre-threshold regime. In these countries, continued growth in motorisation without a parallel and accelerated expansion of the motorway and expressway network is likely to lead to further increases in road accidents, or at best to a prolonged stagnation in safety outcomes.

By contrast, countries that are already approaching the threshold—such as Croatia (around 1.1 km per 100 km²), Hungary (approximately 1.2 km), and Slovakia (about 1.0 km)—are at a particularly critical juncture. For these countries, relatively small additions to the high-speed road network over the next three to five years are likely to determine whether they replicate the Polish transition to a lower-risk regime or remain locked in a high-accident trajectory for another decade.

The results also challenge the still-widespread belief among some national authorities and international lenders that motorway construction is primarily an economic investment with only indirect safety benefits. The Polish data suggest that, beyond a certain density, each additional kilometre of grade-separated highway generates a measurable and immediate safety dividend that easily exceeds construction and maintenance costs when human lives are valued at standard European levels (approximately €2–3 million per statistical life saved).

Finally, the analysis highlights the limitations of traditional linear or log-linear models routinely applied in road-safety forecasting. National transport masterplans that extrapolate historical positive motorisation elasticities into the future risk severely overestimating future accident numbers in countries undergoing rapid infrastructure transformation. Threshold or regime-switching approaches should therefore become standard tools in long-term safety forecasting for emerging European economies.

The valuation follows the standard European Value of a Statistical Life (VSL) used by the European Commission, estimated at approximately €2.5–3.0 million [17, 18].

V. Conclusions

This study shows that Poland crossed a clear road-safety threshold in 2019–2020, when motorway and expressway density exceeded approximately 1.36 km per 100 km². Beyond this point, further motorisation and high-speed road expansion led to fewer, not more, road accidents. The results provide formal evidence of a national-level safety-in-numbers effect and suggest that countries still below this threshold may face rising crash numbers unless infrastructure development accelerates.

AUTHOR CONTRIBUTIONS

P. Gorzelańczyk: Conceptualization, Experiments, Theoretical analysis, Writing, Review and editing.

Disclosure Statement

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

ORCID

P. Gorzelańczyk https://orcid.org/0000-0001-9662-400X

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