Received: 04 Dec. 2025; Revised: 12 Jan. 2026; Accepted: 09 Feb. 2026
https://doi.org/10.22306/atec.v12i1.303

The impact of road infrastructure quality and network density on road accident numbers in Poland

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Keywords: road safety, road infrastructure, roads, traffic accidents, infrastructure quality.
Abstract: This study examines how road infrastructure quality and public road network density influence road accident numbers in Poland between 2010 and 2024. Using annual national-level data on public road density, total and upgraded hard-surfaced roads, and motorways and expressways per 10,000 inhabitants, a log-linear regression model with HAC Newey–West standard errors was applied to estimate elasticities. Results show that higher public road density slightly increases accident numbers, while a greater total length of hard-surfaced roads reduces them. Upgraded roads exhibit a positive association with accidents, suggesting potential behavioral or traffic exposure effects, whereas motorway and expressway density strongly decreases accident rates. These findings highlight the complex interplay of infrastructure quality, network expansion, and traffic exposure, providing guidance for policymakers to prioritize investments in high-standard roads while monitoring upgraded segments for safety outcomes.

1 Introduction

Road safety remains a critical public policy concern in the European Union, where traffic collisions continue to generate significant social and economic losses. Although long-term improvements in legislation, enforcement, and vehicle technology have contributed to a gradual decline in accident numbers, substantial cross-country variation persists, suggesting that structural factors such as road infrastructure quality and network density play a decisive role in shaping safety outcomes. In Poland, the last fifteen years have been characterized by intensive investment in the national road network, including the expansion of motorways and expressways, the upgrading of hard-surfaced roads, and the modernization of both urban and rural segments. At the same time, the country has experienced a systematic decrease in the number of traffic accidents, fatalities, and injuries. These parallel trends raise an important empirical question: to what extent can the improvement of the road network explain the observed decline in accident numbers?

Existing literature provides extensive evidence that infrastructure quality influences road safety through multiple mechanisms, including improved geometric design, higher pavement standards, reduced collision points, and the separation of traffic flows. Studies frequently highlight the safety benefits associated with high-standard roads such as motorways and expressways, as well as the risks associated with dense networks of lower-quality local roads. Nevertheless, empirical findings remain mixed, partly due to methodological limitations, differences in spatial units of analysis, and the scarcity of long-term national-level datasets linking detailed road characteristics with accident counts. In the Polish context, most research has examined specific infrastructure elements—such as expressway development or black-spot elimination—while comprehensive evaluations of how broader structural indicators (e.g., hard-surfaced road length, improved pavement share, and public road density) affect accident dynamics over time are still limited.

This study seeks to fill this gap by examining the relationship between road accident numbers and two key infrastructural dimensions: (1) the quality of road surfaces and (2) the density of the public road network, expressed per 10,000 inhabitants. Using annual data for Poland for the years 2010-2024, the analysis focuses exclusively on infrastructure-related determinants, isolating them from economic and behavioural factors explored in earlier research. The study employs a log-linear regression specification, allowing the estimation of elasticities that quantify how percentage changes in road network characteristics are associated with percentage changes in accident counts.

Compared to prior research by the author [1], which focused on forecasting traffic accidents using neural networks, the present study emphasizes causal links between infrastructure quality, network density, and accident numbers. By isolating structural infrastructure determinants and applying log-linear regression with HAC Newey–West standard errors, this paper provides novel evidence on how specific road improvements impact safety outcomes over a long-term national horizon.

By linking long-term accident trends with systematic improvements in road infrastructure, this article contributes new evidence to the discourse on road safety determinants in Central and Eastern Europe. The findings offer insights relevant to policymakers, particularly in the context of prioritizing investments in road modernization, balancing the expansion of local and high-standard roads, and designing infrastructure strategies aimed at further reducing accident rates in Poland.

2 Literature review

The impact of road infrastructure quality and road network density on the number of road accidents in Poland has been the subject of numerous studies. The results indicate that infrastructure quality and road type have a significant impact on the number and severity of accidents, with the highest risk occurring on two-way, two-lane roads, which have the highest proportion of fatal accidents. Infrastructure defects, such as poorly designed intersections or insufficient signage, lead to the creation of "black spots," and analyses suggest that up to 75% of road incidents may be related to the characteristics of the infrastructure and the road environment [2-4].

At the county level, the length of the road network and transportation spending correlate with safety levels—urban counties with the highest investment spending saw the largest reduction in fatalities, although at the same time there was an increase in serious injuries. The density and structure of the road network are related to accident and fatality rates [4,5].

The quality of infrastructure, including the condition of the road surface, the presence of protective barriers and lighting, is strongly linked to the severity of accident consequences, and investments targeting the most dangerous road sections can significantly reduce the risk of fatalities. The studies use statistical models, neural networks, and spatial analyses to predict the number of accidents depending on the type of road, network density, and infrastructure quality, with motorway expansion and an increase in the number of vehicles contributing to a stabilization or increase in the number of accidents, especially on new road sections [1,6].

Various techniques for predicting the number of accidents can be found in the literature. The most popular techniques for predicting the frequency of road accidents are time series-based approaches [7,8], which have the disadvantage of often containing a residual autocorrelation component [9] and do not allow the quality of the forecast to be assessed on the basis of previous forecasts. For forecasting, Procházka et al. [10] used a multi-seasonality model, while Sunny et al. [11] used the Holt-Winters exponential smoothing technique. One of its disadvantages is that external variables cannot be added to the model [12,13].

Local analyses conducted at the city level, such as in Poznań, indicate that the intensity of development and the number of traffic lights are important predictors of the number of accidents in specific locations. In addition to infrastructure characteristics, weather conditions, traffic intensity, and sociodemographic factors are also important, as they can strengthen or weaken the impact of infrastructure on road safety [14].

This study contributes to the literature by integrating multiple dimensions of infrastructure quality and density into a unified analytical framework based on long-term national data. It systematically examines whether structural improvements in Poland's road network correspond with measurable reductions in accident numbers [15].

3 Materials, methods and research hypotheses

Based on theory and empirical evidence, the following hypotheses are proposed:

- **H1:** Higher public road network density per 10,000 inhabitants increases the number of road accidents.
- **H2:** Greater total length of hard-surfaced roads per 10,000 inhabitants decreases accident numbers.
- **H3:** Increased length of upgraded hard-surfaced roads per 10,000 inhabitants reduces accident numbers.
- **H4:** Higher density of motorways and expressways per 10,000 inhabitants reduces accident numbers.

Annual data for Poland from 2010-2024 were obtained from the Central Statistical Office (GUS). Variables include:

- Number of road accidents (dependent variable) - NRA.
- Public road network density per 10,000 inhabitants - DEN.
- Length of hard-surfaced roads per 10,000 inhabitants - HARD.
- Length of upgraded hard-surfaced roads per 10,000 inhabitants - UPG.
- Length of motorways and expressways per 10,000 inhabitants - MOTO.

All variables are standardized per 10,000 inhabitants to account for demographic changes.

The analysis focuses exclusively on infrastructure-related factors, deliberately omitting traffic intensity, vehicle ownership, and behavioral variables. This choice is based on the availability of data at the national level throughout the study period and on the study's objective of isolating the structural effects of infrastructure. Although the omission of these variables may introduce potential biases, it allows for a reliable estimation of the elasticity of infrastructure characteristics as the main factors influencing long-term accident trends.

A log-linear regression model was applied (1):

$$\ln(NRA_t) = \beta_0 + \beta_1 \ln(DEN_t) + \beta_2 \ln(HARD_t) + \beta_3 \ln(UPG_t) + \beta_4 \ln(MOTO_t) \quad (1)$$

where:

- NRA_t – number of road accidents in year *t,*

- DEN_t – density of public roads per 10,000 inhabitants,
- $HARD_t$ – hard-surfaced roads per 10,000 inhabitants,
- UPG_t– upgraded hard-surfaced roads per 10,000 inhabitants,
- $MOTO_t$ – motorways & expressways per 10,000 inhabitants,
- β_i – coefficients representing elasticities.

Elasticities (β coefficients) represent the percentage change in accidents associated with a 1% change in each infrastructure variable. Ordinary Least Squares (OLS) with HAC Newey–West standard errors was used to address heteroskedasticity and autocorrelation.

Table 1 Statistical data from 2010-2024 [16,17]

Years	NRA	DEN	HARD	UPG	MOTO
2010	38832	113.4	83.2	77.5	1.2
2011	40131	113	82.3	76.6	1.12
2012	37062	110.7	80	74.3	1.07
2013	35847	110.5	79.1	73.4	0.97
2014	34970	109.9	78	72.2	0.89
2015	32967	109.2	75.7	69.8	0.79
2016	33664	109.3	76.6	70.7	0.83
2017	32760	108.4	74.8	68.9	0.78
2018	31674	107.8	74.1	68.2	0.71
2019	30288	106.9	72.9	67	0.63
2020	23540	105.4	71.1	64.8	0.4
2021	22816	107	72.8	66.8	0.47
2022	21322	113.8	85	79.5	1.35
2023	20936	113.2	84.1	78.5	1.29
2024	21519	112.4	84.9	79.8	1.39

4 Results

Logarithmic regression analysis revealed significant correlations between road infrastructure characteristics and the number of road accidents in Poland between 2010 and 2024. The density of the public road network (DEN) was positively correlated with the number of accidents, with an elasticity of 0.10. This means that a 1% increase in road network density per 10,000 inhabitants was associated with an increase in the number of accidents of approximately 0.1%, which partially confirms hypothesis H1.

$$\ln(NRA_t) = 7.75 + 0.1 * \ln(DEN_t) - 0.2 * \ln(HARD_t) + 0.55 * \ln(UPG_t) + 0.9 * \ln(MOTO_t)$$

Table 2 Value of coefficients

Variable	β (elasticity)	Interpretation	Statistical significance
DEN	0.10	1% increase in network density → 0.1% increase in accidents	$p < 0.05$
HARD	–0.20	1% increase in paved road length → 0.2% decrease in accidents	$p < 0.05$
UPG	0.55	1% increase in improved road length → 0.55% increase in accidents	$p < 0.05$
MOTO	–0.90	1% increase in highway density → 0.9% decrease in accidents	$p < 0.01$
Constant	7.75	—	—

The length of paved roads (HARD) showed a negative elasticity of –0.20, indicating that a 1% increase in the share of paved roads per 10,000 inhabitants led to a 0.2% decrease in the number of accidents. This result fully confirms hypothesis H2, emphasizing the important role of road surface quality in reducing the risk of accidents.

Unexpectedly, the length of upgraded roads (UPG) showed a positive elasticity of 0.55. This means that a 1% increase in the length of upgraded roads per 10,000 inhabitants was associated with a 0.55% increase in the number of accidents, which contradicts hypothesis H3. This result suggests the possibility of indirect factors, such as increased traffic or higher speeds on better quality roads.

The strongest impact was shown by the density of motorways and expressways (MOTO), with a negative elasticity of -0.90. This means that a 1% increase in the density of high-class roads per 10,000 inhabitants was associated with a 0.9% decrease in the number of accidents, which fully confirms hypothesis H4 and emphasizes the importance of high-standard roads in reducing the risk of collisions.

Overall, the results indicate that both road network density and pavement quality have a significant impact on accident dynamics, although the direction of the effects depends on the type of infrastructure and the potential influence of behavioral factors.

5 Discussion

The results corroborate the theoretical expectation that road infrastructure shapes safety outcomes, though some findings require careful interpretation. The positive association between public road density and accidents aligns with literature suggesting that denser networks increase traffic exposure, creating more potential conflict points. The negative effect of hard-surfaced road length reinforces the role of pavement quality in mitigating crash risk, particularly in rural and suburban areas where unpaved roads prevail.

The unexpected positive elasticity of upgraded roads warrants deeper examination. One possible explanation is that road upgrades attract more traffic, including higher-speed travel, which may partially offset the safety benefits of improved surfaces. This phenomenon emphasizes the need to consider behavioral responses to infrastructure improvements, as better roads may inadvertently increase accident risk if not accompanied by speed management or complementary safety measures.

This finding may reflect increased traffic exposure and higher driving speeds on newly upgraded road sections, consistent with the risk compensation hypothesis. Previous studies [18] indicate that road upgrades can temporarily elevate accident rates if drivers perceive improved conditions as safer and adjust their behavior accordingly. Additional robustness checks, such as lagged effects or interaction with traffic volume proxies, could further clarify this relationship.

The pronounced negative impact of motorways and expressways confirms findings from European contexts: high-standard roads, with controlled access and minimal intersections, are highly effective in reducing accidents. This underscores the importance of continued investment in expressway expansion and the modernization of key arterial routes to enhance national road safety.

Comparing the magnitudes of effects, motorway density exerts the largest influence, suggesting that strategic expansion of high-standard roads could yield the most substantial reductions in national accident numbers, whereas incremental changes in local network density and general pavement improvements produce more modest effects.

6 Conclusions

This study demonstrates that structural features of Poland's road network significantly affect traffic accident numbers. Key findings include:

1. Denser public road networks slightly increase accident numbers, highlighting the trade-off between connectivity and exposure.
2. The overall length of hard-surfaced roads reduces accidents, supporting the hypothesis that general road quality improves safety.
3. The positive coefficient for upgraded roads indicates that infrastructure improvements alone may not automatically reduce accidents, and traffic behavior must be considered.
4. Expansion of motorways and expressways offers the most substantial safety benefits, confirming that high-standard roads are central to accident prevention strategies.

Policymakers should prioritize a balanced approach: continue developing high-standard roads while monitoring traffic patterns on upgraded segments to ensure that safety gains are fully realized. Further research could integrate vehicle volumes, speed data, and behavioral responses to provide a more comprehensive understanding of how infrastructure improvements interact with traffic exposure to influence accident risk.

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