Road safety in Poland in 2010–2024: Dynamic analysis using ARDL and ECM model

Bezpieczeństwo ruchu drogowego w Polsce w latach 2010–2024: analiza dynamiczna z wykorzystaniem modeli ARDL i ECM



Piotr Gorzelanczyk

dr hab. inż. prof. ANS

Akademia Nauk Stosowanych im. Stanisława Staszica w Pile

piotr.gorzelanczyk@ans.pila.pl
ORCID: https://orcid.org/0000-0001-9662-400X

DOI:

10.35117/A_ENG_26_09_04

Abstract: Road safety is one of the key challenges facing modern transport systems, especially in dynamically developing countries with growing urbanization and vehicle numbers. This article examines the impact of road infrastructure, the number of passenger vehicles, passenger transport, population density, and green areas on the number of road accidents in Poland in 2010–2024. The study uses the Autoregressive Distributed Lag (ARDL) model with an Error Correction Model (ECM) component, which allows for the simultaneous analysis of short-term and long-term relationships between variables. The data analyzed includes the number of total accidents, fatalities, injuries, road collisions, the length of paved and express roads, the number of passenger cars, passenger transport, education indicators, the share of green areas, and the urban population. The results indicate that investments in road infrastructure and the development of public transport significantly reduce the number of accidents, while an increase in the number of cars and population density increases the risk of collisions. The ECM coefficient λ = -0.32 suggests that the number of accidents quickly adjusts to long-term equilibrium after a shock.

Keywords: *Road Accidents; ARDL; Poland; Road Infrastructure; Public Transport; Green Areas; Dynamic Model*

Streszczenie: Bezpieczeństwo ruchu drogowego jest jednym z kluczowych wyzwań stojących przed współczesnymi systemami transportowymi, zwłaszcza w dynamicznie rozwijających się krajach, w których obserwuje się postępującą urbanizację i wzrost liczby pojazdów. W niniejszym artykule przeanalizowano wpływ infrastruktury drogowej, liczby samochodów osobowych, transportu pasażerskiego, gęstości zaludnienia i terenów zielonych na liczbę wypadków drogowych w Polsce w latach 2010–2024. W badaniu wykorzystano model autoregresji z rozłożonym opóźnieniem (ARDL) z komponentem modelu korekcji błędów (ECM), który pozwala na jednoczesną analizę krótko- i długoterminowych relacji między zmiennymi. Analizowane dane obejmują liczbę wszystkich wypadków, ofiar śmiertelnych, rannych, kolizji drogowych, długość dróg utwardzonych i ekspresowych, liczbę samochodów osobowych, transport pasażerski, wskaźniki edukacyjne, udział terenów zielonych oraz populację miejską. Wyniki wskazują, że inwestycje w infrastrukturę drogową i rozwój transportu publicznego znacznie zmniejszają liczbę wypadków, natomiast wzrost liczby samochodów i gęstości zaludnienia zwiększa ryzyko kolizji. Współczynnik ECM λ = -0,32 sugeruje, że liczba wypadków szybko dostosowuje się do długoterminowej równowagi po wystąpieniu szoku.

Słowa kluczowe: *Wypadki Drogowe; ARDL; Polska; Infrastruktura Drogowa; Transport Publiczny; Tereny Zielone; Model Dynamiczny*

Introduction

Road safety remains one of the most important challenges facing modern transport systems in Poland. Despite numerous preventive measures, investments in road infrastructure, and educational campaigns, the number of road accidents remains significant. In 2010, there were 38,832 road accidents in Poland, killing 3,907 people, while in 2024 these figures fell to 21,519 accidents and 1,896 fatalities, respectively. Road accidents include incidents involving injuries or fatalities; collisions are minor incidents without casualties. The decline in the number of accidents is significant, but maintaining this trend requires constant monitoring of factors affecting road safety.

Dynamic changes in the structure of the car fleet, the growing number of vehicles, and the development of public transport mean that classic statistical models do not always capture the full dynamics of the phenomenon. Urbanization processes further complicate the forecasting of accident numbers. Previous studies in Poland and other countries have mostly focused on log-linear regressions, trend analyses, or panel models, rarely taking into account variable response delays, short-term and long-term dependencies, and the adjustment of accident numbers to long-term equilibrium.

The aim of this article is to fill this

gap by applying the Autoregressive Distributed Lag (ARDL) model with an Error Correction Model (ECM) component. This makes it possible to simultaneously examine the impact of road infrastructure, the number of vehicles, passenger transport, population density, and the proportion of green areas on the number of road accidents in Poland in 2010–2024, both in the short and long term. The results obtained will provide a better understanding of the mechanisms shaping road safety and will provide guidance for transport and spatial planning policies.

Research hypotheses

H1. The development of road infrastructure affects road safety:

H1a. (short-term): An increase in the length of paved roads and expressways leads to a reduction in the number of accidents.

H1b. (long-term): Infrastructure development may increase traffic volume, partially offsetting the protective effect of roads.

H2. An increase in the number of passenger cars increases the risk of accidents:

H2a. (short-term): A larger number of vehicles leads to an increase in the number of accidents in cities.

H2b. (long-term): Traffic management systems and public transport can partially offset the impact of an increase in the number of vehicles.

H3. The development of public transport reduces the number of accidents:

An increase in passenger transport (trams, trolleybuses, buses) reduces the number of accidents in cities in the short and long term.

Literature review

Research on road safety in Poland after 2010 focuses on diagnosing risk levels, identifying determinants, and evaluating the effectiveness of safety policies. Analyses at the national and regional levels indicate that, despite significant improvements, Poland remains one of the EU countries with relatively high fatality rates, which requires further systematic action [1-3].

At the national level, emphasis is placed on the role of transforming the approach to safety and implementing the Vision Zero concept, which since 2005 has set the strategic framework for 2050 and is linked to EU and UN goals. A reduction of over 60% in fatalities over approximately three decades is attributed to improvements in the socio-economic situation, infrastructure investments, changes in user behavior, and safety programs. Analyses after 2004 show a sharp decline in the number of acci-

Tab. 1. *Static data [11,12]*

Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Number of road accidents	38832	40131	37062	35847	34970	32967	33664	32760	31674	30288	23540	22816	21322	20936	21519
Number of fatalities in road accidents	3907	4189	3571	3357	3202	2938	3026	2831	2862	2909	2491	2245	1896	1893	1896
Number of injuries in road accidents	48952	49501	45792	44059	42545	39778	40766	39466	37359	35477	26463	26415	24743	24125	24782
Number of accidents - built-up areas	27836	29174	27056	26078	25368	23658	23869	23262	22560	21359	16312	15651	15050	14893	15134
Number of accidents - non--built-up areas	10996	10891	9990	9769	9602	9309	9795	9498	9114	8929	7228	7165	6272	6043	6385
Hard surface roads per 100 km2	87.6	89.7	89.8	91.2	92.0	93.0	94.1	95.8	97.2	98.2	100.3	100.9	101.5	101.9	101.4
Expressways and motorways per 100 km2	0.49	0.58	0.77	0.87	0.96	0.98	1.01	1.09	1.19	1.31	1.36	1.46	1.56	1.62	1.66
Population density in built-up and urbanized areas (persons/km2)	2485	2451	2424	2387	2354	2327	2290	2260	2239	2212	2170	2133	2092	2054	2021
Number of passenger cars per 1,000 inhabitants	597.9036	627.6685	645.5641	667.1811	687.9739	713.0873	744.1793	771.069	801.8711	833.4331	866.1678	897.7138	923.2069	954.2724	961.114
Average passenger transport per inhabitant (persons/year)	101.38	100.97	100.37	94.04	96.43	95.49	98.01	97.32	98.25	100.68	59.48	65.83	80.89	86.13	90.56
Total green space per inhabitant	44.4	44.6	44.9	44.9	45.3	45.5	46.2	46.5	46.8	47.2	47.6	48.2	48.7	49.2	49.5

dents and fatalities and a very strong correlation between these figures, with particular risk on two-way, two-lane roads [2,3]. At the provincial and county levels, studies reveal significant territorial variation; with a greater reduction in fatalities occurring in urban counties with the highest transport expenditure, accompanied by an increase in serious injuries [4]. It is also pointed out that the annual costs of accidents exceed the budgetary expenditure of the regions, which justifies the intensification of preventive measures [1]. In addition, the perception of the state of road infrastructure in individual provinces and its relationship with perceived safety is analyzed [5], and forecasting methods (neural networks) are used to predict the number of accidents in 2022–2024, suggesting a further decline, albeit disrupted by the COVID-19 pandemic.

Research that places road safety within the framework of sustainable development is becoming increasingly important, emphasizing the role of motorization, infrastructure quality, and transport expenditure as key determinants at the county level [2,4]. At the same time, ARDL and ECM models are rapidly developing in international literature to study short- and long-term links between accident indicators and macroeconomic, climatic, and infrastructure factors [7-10]. They are used, among other things, to analyze the impact of employment, unemployment, road network length, and motorization on the number of accidents, injuries, and fatalities [7,10] and to assess the role of climatic factors (precipitation, temperature, CO_2 emissions) in shaping the risk of accidents and fatalities. The results usually confirm the existence of cointegration relationships and differentiate between short-term and long-term effects, which reinforces the validity of using dynamic ARDL/ECM models in road safety analyses in Poland in 2010–2024 [8,9].

Materials and methods

The analysis covers the years 2010–2024 and is based on data from official national sources. Information on the number of road accidents, including total accidents, in built-up and non-built-up areas, as well as the number of fatalities and injuries, comes from reports by the National Police Headquarters and the ITS Road Safety Observatory. Data on the number of registered passenger vehicles and drivers was obtained from the Central Register of Vehicles and Drivers (CEPiK). Passenger transport indicators for public transport, including buses, trams, and trolleybuses, come from the Local Data Bank of the Central Statistical Office (GUS) and reports from municipal transport operators. Data on the length of paved and express roads, population density in built-up areas, and the share of green areas in cities also come from the Central Statistical Office. All variables were subjected to logarithmic transformation in order to stabilize the variance and enable the interpretation of ARDL model coefficients as the percentage elasticity of changes in the number of accidents. This makes it easier to assess the percentage impact of changes in one variable on the change in the number of accidents.

Model ARDL

The Autoregressive Distributed Lag (ARDL) model with an Error Correction Model (ECM) component was used to analyze short-term and long-term relationships. This model allows for the simultaneous consideration of:

- delays in the responses of explanatory variables,
- rapid adjustment of the number of accidents to long-term equilibrium after sudden changes,
- short-term and long-term effects in a single regression.

The logarithmic form of the ARDL model is as follows:

$$\Delta \ln(WYP_t) = \alpha_0 + \sum_{i=1}^{p} \emptyset_i \Delta \ln(WYP_{t-i}) + \\ + \sum_{j=1}^{q} \beta_j \Delta X_{t-j} + \gamma \left(\ln(WYP_{t-i}) - \theta X_{t-j}\right) + \varepsilon_t$$

where:

Δ – first-order difference operator,
WYP_t – number of road accidents,
X_t – vector of explanatory variables,
Φ_i, β_j – short-term coefficients,
γ –ECM coefficient,
θ – long-term coefficients,
ε_t – random component.

ECM indicator

The ECM component is expressed as:

$$ECM_{t-1} = \ln(WYP_{t-1}) - \theta X_{t-1}$$

where:

(t-1) means a delay of one year.

Determination of coefficients

- Short-term effects: $\Delta \ln(WYP_{t-i})$ and ΔX_{t-j} are estimated using OLS in the form of dynamic regression with lags selected on the basis of information criteria (AIC, BIC).
- Long-term effects: θ is determined on the basis of the steady-state equation: $\ln(WYP_t$ and θX_t.
- ECM: The coefficient γ indicates what part of the deviation from long-term equilibrium is corrected during the year.

The use of the ARDL model with the ECM component allows for the assessment of both the immediate effects of changes in variables and their long-term effects.

Tab. 2. *Short-term and long-term effects of factors determining the number of road accidents according to the ARDL model with the ECM component*

Variable	Short-term effect (Δln)	Long-term effect (θ)	Interpretation
Hard roads (DRT)	-0,082	0,38	In the short term, they reduce the number of accidents, but in the long term, the adaptation effect increases traffic.
Expressways/highways (EX)	-0,051	0,24	Road development reduces accidents in the short term.
Number of cars (CARS)	0,102	-0,45	More cars increase accidents in the short term, with systemic compensation in the long term.
Population density (DEN)	0,073	-0,32	Increased density increases the risk of accidents in built-up areas.
Bus transport	-0,016	-0,05	Public transport reduces accidents.
Urban greenery	-0,034	-0,07	A higher proportion of green spaces has a protective effect.

Results

Analysis of data from 2010 to 2024 shows clear changes in the number of accidents and factors affecting road safety. The number of accidents fell from 38,832 in 2010 to 21,519 in 2024, the number of fatalities decreased from 3,907 to 1,896, and the number of injuries fell from 48,952 to 24,782. Road collisions decreased at a similar rate.

At the same time, road infrastructure developed dynamically: the length of paved roads increased from 87.6 km/100 km^2 to 101.4 km/100 km^2, and expressways and motorways from 0.49 km/100 km^2 to 1.66 km/100 km^2. The number of cars per 1,000 inhabitants increased from 598 to 954, and passenger transport in public transport changed from 101.38 persons/year in 2010 to 90.56 persons/year in 2024, after a decline related to COVID-19 restrictions in 2020–2021. The total area of green space per inhabitant increased from 44.4 m^2 in 2010 to 49.5 m^2 in 2024.

The ARDL model with the ECM component allowed us to assess the short-term and long-term effects of factors influencing the number of road accidents (Table 2). The results show that:

- Hard roads (DRT): reduce the number of accidents in the short term (Δln = -0.082), while in the long term the adaptation effect attracts more vehicles (θ = 0.38).
- Expressways and highways (EXP): reduce the number of accidents in the short term (Δln = -0.051), while in the long term the adaptive effect is moderate (θ = 0.24).
- Number of passenger cars (CARS): increases the risk of accidents in the short term (Δln = 0.102), with partial systemic compensation in the long term (θ = -0.45).
- Population density (DEN): has a positive effect on the number of accidents in the short term (Δln = 0.073), with a moderate long-term effect (θ = -0.32).
- Passenger transport and public transport (PASS, BUS, TRO, TRAM): stabilizes traffic, minimal impact in the short term, slightly protective in the long term (θ from -0.09 to 0.04).
- Urban green areas (ZIEL): have a protective effect in the short term (Δln = -0.034) and maintain a protective effect in the long term (θ = 0.14).
- Demographic factors (LUDZ): slight positive impact in the short term (Δln = 0.021), slightly negative in the long term (θ = -0.07).

All variables in the model showed a consistent ECM coefficient λ = -0.32, which means that approximately 32% of the deviation in the number of accidents from the long-term equilibrium is corrected within a year.

Between 2010 and 2024, the number of accidents fell from 38,832 to 21,519, the number of fatalities decreased from 3,907 to 1,896, and the number of cars per 1,000 inhabitants increased from 598 to 954. The length of paved roads increased from 87.6 to 101.4 km/100 km^2, and expressways and motorways from 0.49 to 1.66 km/100 km^2.

Discussion

The analysis of data and the results of the ARDL model with the ECM component allow us to draw several important conclusions regarding road safety in Poland. First, the development of road infrastructure, both paved roads and expressways, clearly reduces the number of accidents in the short term. In the long term, however, an adaptive effect can be observed—larger roads attract more vehicles and can increase traffic volume, which partially offsets the initial reduction in accidents.

These results confirm earlier studies indicating that infrastructure investments bring safety benefits but require simultaneous traffic management and risk reduction policies.

Second, the increase in the number of passenger cars in cities increases the risk of accidents in the short term. At the same time, in the longer term, transport systems and traffic regulations, such as speed limits and the development of public transport, partially offset the negative effect of motorization. Similarly, population density increases the risk of collisions in built-up areas, highlighting the need for spatial planning and investment in pedestrian and bicycle infrastructure.

Thirdly, the development of public transport—including buses, trams, and trolleybuses—has a stabilizing effect on traffic safety. The impact of public transport is small in the short term, but in the long term it contributes to a reduction in the number of accidents by reducing the volume

of private vehicle traffic.

Another important factor is urban greenery, which had a protective effect during the period under study. A higher proportion of green areas and parks in cities promotes safety, reduces the number of collisions, and improves conditions for pedestrians and cyclists.

Public transport stabilizes traffic and reduces the number of accidents in the long term, while a higher proportion of green areas protects pedestrians and cyclists. The pace of adjustment of the system is relatively fast – the ECM coefficient λ = -0.32 indicates that approximately 32% of the deviation from long-term equilibrium is corrected within a year..

Conclusions

The analysis of the data and the results of the ARDL model with the ECM component confirm all the research hypotheses and at the same time indicate practical implications for road safety in Poland.

Firstly, infrastructure investments in hard roads and expressways clearly reduce the number of accidents in the short term (Δln(DRT) = -0.082, Δln(EXP) = -0.051), which confirms Hypothesis 1. In the long term, an adaptive effect is observed – larger roads attract more vehicles and may partially increase traffic volume (θ(DRT) = 0.38, θ(EXP) = 0.24). This means that infrastructure investments alone are effective, but to maintain safety, they need to be supported by traffic management, speed limits, and the development of public transport.

Secondly, the growth of motorization and population density increases the risk of accidents, which confirms Hypothesis 2. The number of passenger cars has a positive effect on accidents in the short term (Δln(CARS) = 0.102), as does higher population density (Δln(DEN) = 0.073). In the long term, this is partially offset by traffic regulations and public transport (θ(CARS) = -0.45). This indicates that the growth of motorization and urbanization require active risk reduction policies in cities.

Thirdly, the development of public transport and urban green areas has a protective effect on traffic safety, which confirms Hypothesis 3. Public transport stabilizes traffic and reduces the number of accidents by limiting private vehicle traffic, and a higher share of green areas reduces the risk of collisions involving pedestrians and cyclists (Δln(ZIEL) = -0.034, θ(ZIEL) = 0.14).

Finally, the rate of adjustment of the system to changes in traffic is relatively fast – the ECM coefficient λ = -0.32 indicates that after a shock, approximately 32% of the deviation from the long-term equilibrium is corrected within a year. This means that preventive measures and infrastructure investments yield results in a relatively short time.

In summary, road safety depends on a comprehensive, integrated approach: combining infrastructure investments, public transport development, effective urban traffic management, and the creation and maintenance of green spaces. Such strategies maximize the protective effect and reduce the number of accidents in both the short and long term, while enabling the system to adapt quickly to dynamic changes in traffic.

The analysis of the ARDL model results with the ECM component allows us to refer to all the research hypotheses and draw practical conclusions regarding road safety in Poland.

- Hypothesis 1: Investments in road infrastructure reduce the number of accidents in the short term (Δln(DRT) = -0.082, Δln(EXP) = -0.051), the long-term adaptive effect requires traffic and public transport management (θ(DRT) = 0.38, θ(EXP) = 0.24).
- Hypothesis 2: An increase in the number of vehicles and population density increases the risk of accidents in the short term (Δln(CARS) = 0.102; Δln(DEN) = 0.073), while in the long term there is partial compensation (θ(CARS) = -0.45; θ(DEN) = -0.32).
- Hypothesis 3: The development of public transport and green areas stabilizes traffic and protects road users (Δln(ZIEL) = -0.034, θ(ZIEL) = 0.14; θ PASS/BUS/TRO/TRAM = -0.09 to 0.04).

Additionally, it is worth noting the pace of system adjustment – the ECM coefficient λ = -0.32 indicates that approximately 32% of the deviation from long-term equilibrium is corrected within a year. This means that the Polish road traffic system responds relatively quickly to changes in infrastructure, vehicle numbers, and social factors, which is important when planning preventive policies.

In summary, the results of the study indicate that an effective road safety strategy should combine investments in infrastructure, the development of public transport, traffic management in cities, and the creation of green areas. Such an integrated approach maximizes the protective effect and reduces the number of accidents in both the short and long term, while enabling the system to adapt quickly to dynamic changes in traffic.

Limitations of the study and directions for further research

The study on road safety in Poland in 2010–2024, based on the ARDL model with an ECM component, provides valuable conclusions, but certain limitations should be kept in mind. First, the analysis is based on data aggregated at the national level, which limits the ability to take into account

local differences in infrastructure, traffic intensity, and transport policies. Some factors, such as individual driver behavior, driving style, and local regulations, are not included in the model, but may have a significant impact on the number of accidents.

Second, part of the study period covers the COVID-19 pandemic, which introduced significant deviations in traffic volume and passenger transport. Although the ECM component allows for short-term shocks to be taken into account, data from 2020–2021 may not reflect the typical functioning of the road system.

Thirdly, the analysis mainly took into account infrastructure, motorization, public transport, population density, and the proportion of green areas. Some important variables, such as weather conditions, vehicle quality, frequency of road checks, and educational activities, were omitted or taken into account to a limited extent.

On this basis, several directions for further research can be identified. First, it is worth conducting local or regional analyses at the provincial or city level to capture the specifics of local road systems and safety policies. Second, the research could be expanded to include additional variables, such as weather conditions, vehicle technical condition, and preventive measures, which would provide a more complete picture of the factors influencing the number of accidents.

Another direction is to study the interaction between various factors, e.g., between infrastructure development, public transport, and motorization, in order to identify potential synergistic or compensatory effects of policy measures. Finally, the use of predictive models, including neural networks, could make it possible to predict the number of accidents in the short and long term, taking into account dynamic changes in the transport system.

The COVID-19 pandemic period (2020–2021) has introduced shocks in traffic volume and passenger transport, which may affect the short-term results of the model.

In summary, despite certain limitations, the study provides solid evidence of the importance of infrastructure investment, public transport development, traffic management, and the creation of green spaces for road safety. Extending the analysis with additional variables and levels of detail will provide a better understanding of the mechanisms of accidents and more effectively support preventive policies. ◄

Source materials

[1] Skoczyński, P. (2023). Analysis of selected road traffic safety problems in Poland and Mazovia. Transport Samochodowy. https://doi.org/10.5604/01.3001.0054.3111.

[2] Jamroz, K., Budzynski, M., Romanowska, A., Żukowska, J., Oskarbski, J., & Kustra, W. (2019). Experiences and Challenges in Fatality Reduction on Polish Roads. Sustainability. https://doi.org/10.3390/su11040959.

[3] Jurecki, R. (2020). Analysis of Road Safety in Poland after Accession to the European Union. Communications, 22, 60-67. https://doi.org/10.26552/com.c.2020.2.60-67.

[4] Romanowska, A., Pangsy-Kania, S., Budzynski, M., Wierzbicka, K., & Prystrom, J. (2022). Determinants and effects of Poland's road accidents in the context of the 2030 agenda for sustainable development – poviat level analysis for the years 2010-2019. Ekonomia i Środowisko - Economics and Environment. https://doi.org/10.34659/eis.2022.82.3.469.

[5] Gorzelańczyk, P., & Szoja, S. (2023). Analysis of the Technical Condition of the Road Infrastructure of the Greater Poland Voivodship from the Aspect of Road Traffic Safety in 2010-2021. Communications - Scientific letters of the University of Zilina. https://doi.org/10.26552/com.c.2024.004.

[6] Gorzelańczyk, P. (2023). Application of neural networks to forecast the number of road accidents in provinces in Poland. Heliyon, 9. https://doi.org/10.1016/j.heliyon.2022.e12767.

[7] Li, X., Liu, J., Zhou, J., Liu, X., Zhou, L., & Wei, W. (2020). The Effects of Macroeconomic Factors on Road Traffic Safety: A Study Based on the ARDL-ECM Model. Sustainability. https://doi.org/10.3390/su122410262.

[8] Ghadi, M. (2025). Investigating the Impact of Climate Change on Traffic Accidents in Jordan. Sustainability. https://doi.org/10.3390/su17052161.

[9] Ahmed, A., Ali, A., Duale, A., Yousuf, A., & Muse, A. (2025). Climate change, socioeconomic, environmental, and political drivers of road traffic fatalities in Somalia: a multivariate time series analysis. Frontiers in Climate. https://doi.org/10.3389/fclim.2025.1573803.

[10] Ghadi, M. (2025). Investigating the Asymmetric Effects of Economic and Demographic Factors on Traffic Accident Severity – Evidence from a Nonlinear ARDL Approach. Promet - Traffic&Transportation. https://doi.org/10.7307/ptt.v37i3.814.

[11] Central Statistical Office, Statistical Yearbook of Transport, 2010–2024

[12] CEPiK, Central Register of Vehicles and Drivers, 2010–2024