# ECONOMIC AND INFRASTRUCTURE DETERMINANTS OF ROAD TRAFFIC FATALITIES: PANEL EVIDENCE FROM THE VISEGRAD COUNTRIES

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***Resume***

In this study are analysed the determinants of road traffic fatalities in the Visegrad Group countries during 2000-2024, using a balanced panel and fixed-effects models with Driscoll-Kraay standard errors. The results show that the higher motorization and a longer high-standard road network are associated with lower fatalities. By contrast, the GDP per capita and unemployment increase fatalities in the baseline model, although these effects are sensitive to alternative specifications. Public expenditure on road infrastructure has no robust immediate effect, with only limited evidence of delayed benefits. Overall, the findings suggest that the road safety depends not only on economic growth, but on the quality and structure of infrastructure development, as well.

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## 1 Introduction

Traffic accidents are one of the most serious global challenges today, with consequences that go far beyond transport itself and have a significant impact on public health, economic development, and the sustainability of public finances. The road traffic deaths and injuries generate significant social costs in terms of loss of human capital, reduced labor productivity, increased healthcare spending, and pressure on public budgets. From an economic perspective, the road safety is not just a technical or behavioral issue, but a complex problem of efficient resource allocation and transport system performance. With increasing urbanization, intensified mobility, and diversification of transport modes, the complexity of the relationships between the transport infrastructure, economic activity, and road safety is increasing. Traditional approaches to assessing transport safety, which focus exclusively on absolute numbers of accidents or fatalities, are proving inadequate as they do not take into account differences in exposure to transport, the structure of transport systems, or the broader socioeconomic context. As pointed out in [1], the risk assessment based solely on driver fatalities can lead to biased conclusions, as it does not capture the external costs passed on to other road users, particularly pedestrians and cyclists. Including the so-called "third parties" in the analysis is therefore a necessary step towards a more accurate measurement of the social impact of different forms of transport.

The importance of infrastructure and its functional layout is particularly evident in urban environments and on high-capacity roads. Highways and expressways are primarily designed to maximize traffic flow and speed, but this can lead to an increased risk of serious accidents, especially in cases of illegal pedestrian movement or vehicle malfunctions. Empirical evidence from the US shows that high speed limits, multi-lane road layouts, and inadequate lighting contribute significantly to fatal pedestrian accidents, especially at night and in rural areas [2]. Those findings highlight the tension between the goals of transport efficiency and safety, which must be addressed through comprehensive evaluation frameworks. In response to this complexity, integrated analytical approaches that combine the evaluation of technical efficiency, productivity, and safety outcomes of transport systems are increasingly being promoted in the literature. In that study is highlighted the value of slack-based network models, combined with the Malmquist and Luenberger productivity indices for evaluating the performance of urban road transport systems. Its results point not only to significant heterogeneity between cities, but to differences between the static efficiency and actual growth in total factor productivity, as well, which has important implications for transport policy and strategic decision-making in the public sector [3].

Another dimension of road safety is the macroeconomic view of safety, which is further underscored by evidence of causal relationships between road fatalities, economic growth, and public spending. An analysis [4] shows that the GDP growth per capita can be associated with an increase in road fatalities in both the short and long term, suggesting that economic growth without adequate investment in safety can lead to negative externalities. Conversely, higher health care spending and higher population density in many regions appear to be factors that reduce the risk of traffic fatalities, highlighting the importance of public policies and urban structure. The structure of traffic patterns and their safety implications also deserve special attention. Results from studies in developing countries suggest that promoting walking, cycling, and intermediate forms of public transport can lead to lower road fatalities, while the growth of motorization, particularly in the form of two-wheeled motor vehicles and private car transport, increases the risk of fatal accidents [5]. Those findings are particularly relevant in the context of transforming economies, where changes in the transport behavior of the population are occurring faster than the adaptation of infrastructure and regulatory frameworks.

At the micro level, the behavior of road users remains one of the key determinants of the severity of traffic accidents. Advanced machine learning methods reveal the importance of the seat belt use, accident timing patterns, and driver demographics in explaining road fatalities [6]. At the same time, it appears that times of crisis, such as the COVID-19 pandemic, can fundamentally change the risk factors for traffic accidents, especially in urban and socially disadvantaged areas, requiring flexible and data-driven policy interventions [7]. Despite the extensive empirical literature, however, there is still a need for integrated analytical frameworks that can simultaneously assess the performance of transport systems, the productivity of public investments, and their safety implications. In this study is provided an economically oriented quantitative analysis that helps to better understand the trade-offs between transport efficiency, economic growth, and the protection of human lives.

## 2 Literature review

The road safety assessment represents a significant social and economic challenge, as traffic accidents generate not only human casualties, but the considerable direct and indirect costs for the economy, public finances, and labor productivity as well. Current literature increasingly advocates a comprehensive approach to traffic accident analysis that integrates macroeconomic, infrastructural, demographic, and behavioral factors, with an emphasis on the use of advanced quantitative methods and panel data. Several empirical studies confirmed that economic development and socio-economic conditions play a key role in shaping long-term trends in road traffic fatalities. At the same time, research findings suggest that economic growth alone does not automatically lead to improved road safety unless it is accompanied by effective redistribution policies, investments in safety infrastructure, and increased social justice. The negative short-term effects of economic shocks, such as mass layoffs, point to the importance of psychological stress, economic uncertainty, and social destabilization as indirect determinants of traffic safety [8-9].

At the level of European countries, the economic dimension of road safety is also reflected in differences in the performance of national systems. Empirical analyses, based on a combination of envelope curve analysis and Tobit regression, indicate that the socioeconomic context and level of transport exposure significantly influence the resulting level of road safety. These findings support the need for comparative analyses that can capture heterogeneity between countries and identify structural weaknesses in transport policy. The role of transport infrastructure, technical development, and the efficiency of transport systems also receives significant attention in the literature, with evidence suggesting that the greater road transport efficiency in terms of energy and economic indicators does not necessarily lead to fewer traffic fatalities. Investments in road infrastructure and the expansion of the road network can thus have ambivalent effects on one hand, they improve the technical condition of roads and traffic flow, but on the other hand, they can stimulate higher traffic intensity and driving speeds, which increases the risk of serious accidents [10-11].

Technological innovations, particularly in the field of automated vehicles, are often presented as a potential solution to the problem of traffic accidents. Simulation models suggest that the growing penetration of automated vehicles may contribute to a reduction in the number of multi-vehicle accidents. At the same time, however, there remains a high degree of uncertainty associated with the real-world deployment of these technologies, their interaction with conventional vehicles, and driver behavior. These findings suggest that technological advances in mobility must be supported by an appropriate regulatory, institutional, and infrastructural framework in order for their potential safety benefits to be fully realized [12].

In addition to macroeconomic and technical factors, demographic and behavioral determinants of traffic accidents remain an important part of research. Advanced time series and panel causal modelling methods identify a higher risk of fatal accidents in older age groups, in remote regions, during night hours, and in high-speed environments, emphasizing the importance of flexible panel approaches for evidence-based road safety policy making. At the micro level, research focuses on specific types of road users, particularly motorcyclists and young drivers, highlighting the importance of seasonal factors, reaction time, perceived behavioral control, and risk-taking behavior for accident probability and severity [13-16].

Current literature also pays increasing attention to environmental and climatic factors, which are increasingly shaping the road safety conditions. Empirical analyses identify a significant impact of extreme weather events and climate anomalies on the number of fatal traffic accidents, pointing to the growing complexity of the road safety environment in the context of global warming. Traffic accidents thus appear to be the result of a dynamic interaction between the economic, infrastructural, social, behavioral, and environmental factors, which places high demands on the interdisciplinary nature of research and public policy-making [17].

## 3 Methodology

The empirical analysis is based on an annual panel of four Visegrad Group countries: the Czech Republic, Hungary, Poland, and Slovakia for the period 2000-2024. The dataset was compiled based on data from the Eurostat database. The panel is balanced, with each country being monitored in each year of the sample period. All estimates were performed in Python. The panel data models were estimated using the linear models package for fixed and random effects specifications with Driscoll-Kraay standard errors. The dependent variable is the annual number of road traffic deaths in each country. This indicator captures all deaths resulting from traffic accidents that occurred within the country during the calendar year. The key explanatory variables are:

- Motorization: number of registered passenger cars per 1,000 inhabitants. This indicator captures the level of motorization and potential exposure to road risks.
- Economic development: gross domestic product per capita in euros, expressed in constant prices. This variable represents the level of economic development and overall income in each country.
- Labor market conditions: unemployment rate in percent. This variable captures macroeconomic and social pressures that may be related to road safety outcomes.
- Road infrastructure expenditure: annual public expenditure on road infrastructure in euros. This includes the construction, reconstruction, and maintenance of the road network.
- Length of high-standard roads: total length of motorways and European-class roads (e-roads) in kilometers. This variable reflects the quantitative development of high-standard road infrastructure.

The selection of explanatory variables included in the econometric model was based on three main criteria: theoretical relevance, empirical evidence from previous studies, and the availability of consistent long-term data for all V4 countries. The literature on the road safety and transport economics commonly identifies economic development, motorization, labour market conditions, and infrastructure quality as key determinants influencing traffic accident rates and the road fatalities.

Motorization, measured as the number of passenger cars per 1,000 inhabitants, reflects traffic intensity and the level of mobility within a country, which may increase exposure to traffic accidents but is also associated with improvements in vehicle safety over time.

The GDP per capita was included as an indicator of the overall level of economic development, which may affect the road safety through several channels, including infrastructure quality, technological progress in vehicle safety, and improvements in healthcare systems.

The unemployment rate was included as a control variable capturing macroeconomic conditions that may influence travel demand, commuting patterns, and overall traffic intensity. In periods of higher unemployment, mobility demand may decrease, potentially affecting the number of road accidents.

Finally, variables related to transport infrastructure, including the road infrastructure expenditures and the length of motorways and E-roads, were incorporated to capture the potential impact of infrastructure development on the road safety outcomes. High-quality road infrastructure is generally associated with safer traffic conditions and lower accident severity.

Together, these variables allow the model to capture the main economic and infrastructural mechanisms that are discussed in the road safety literature and that are particularly relevant for the development dynamics of the V4 countries.

All the variables are measured at a country and a year level. Where necessary, the series were checked for breaks and inconsistencies and harmonized over time to ensure comparability between the four countries.

To analyze the determinants of the road traffic deaths, the study uses a panel data regression model with country fixed effects. The basic specification can be written as:

$$Deaths_{it} = \alpha_i + \beta_1 Cars_{it} + \beta_2 GDPpc_{it} + \\ + \beta_3 Unemp_{it} + \beta_4 ExpRoad_{it} + \beta_5 Length_{it} + \varepsilon_{it}, \quad (1)$$

where: $Deaths_{it}$ is number of deaths,
$i$ is countries,
$t$ is years,

$\alpha_i$ are the fixed effects specific to a given country.

Fixed effects estimation is used as the main method since it controls for unobserved, time-invariant heterogeneity across countries that would otherwise distort the estimated coefficients. Specifically, differences in historical safety culture, legal traditions, or the long-term infrastructure subsidies are absorbed by country-specific intercepts. As a robustness check and to justify the focus on fixed effects, the model was also estimated using a random effects specification. Hausman's test, comparing the fixed and random effects estimates, showed that the fixed effects model is preferred, supporting the choice of using country fixed effects as the baseline specification.

The panel data on a small number of countries observed over a relatively long period of time are prone to several complications in terms of confounding effects: heteroscedasticity between panels, serial correlation over time within a country, and cross-sectional dependence due to common shocks or regional effects. To address these issues, the study reports the Driscoll-Kraay standard errors for fixed effects estimates. This estimate is robust to:

- heteroscedasticity,
- autocorrelation of unknown form within panels, and
- cross-panel dependence between panels.

The use of Driscoll-Kraay standard errors is particularly appropriate given the small number of countries (four) and the longer time dimension. It allows for consistent conclusions even when the shocks, such as Europe-wide policy changes, fuel price shocks, or significant regulatory reforms, affect all Visegrad Group countries simultaneously. For comparison, the same specification with fixed effects was also estimated with conventional heteroscedasticity-resistant standard errors and with standard errors pooled at the country level. The main coefficients of interest (motorization, GDP per capita, unemployment, travel distance) retained their sign and remained statistically significant in these alternative specifications, confirming the robustness of the results.

All the panel data estimates were performed using a fixed effects estimation with country dummy variables and without additional time dummy variables in the baseline to focus on the impact of the observed explanatory variables. The estimation was performed in three steps. First, descriptive statistics were used to examine trends in road deaths, motorization, GDP per capita, unemployment, road infrastructure spending, and length of highways/electric roads in each country. This preliminary analysis confirmed substantial time differences in all variables and a significant decline in deaths during the period under review. Second, standard panel data diagnostics was performed. The ordinary least squares (OLS), random effects, and fixed effects models were estimated and compared. The Hausman test favored the fixed effects specification, suggesting that unobserved country-specific factors correlate with the explanatory variables and that random effects would be inconsistent. Third, the preferred fixed effects model was estimated using Driscoll-Kraay standard errors. The coefficients were interpreted in terms of their sign, magnitude, and statistical significance at the conventional significance level of 0.05. To assess robustness, alternative specifications were considered, including models with different standard error estimates and reduced sets of covariates. These checks did not substantially alter the main conclusions. The interpretation of the empirical results focuses on the partial effects of each explanatory variable on the road traffic deaths, conditional on other variables and time-invariant country characteristics. The fixed effects setting means that the coefficients reflect how changes in motorization, economic development, labor market conditions, and infrastructure within a country over time are associated with changes in the number of road deaths, rather than the simple differences between countries. Particular attention is paid to the sign and magnitude of the coefficients for motorization (number of cars per 1,000 inhabitants), GDP per capita, unemployment, and length of highways/expressways, as these variables are directly related to the main research questions about the role of economic development and infrastructure in road safety in the V4 region.

## 4 Results

Figure 1 illustrates the long-term evolution of the road traffic fatalities in the Visegrad Group countries (Slovakia, the Czech Republic, Poland, and Hungary) during the period 2000-2024. A common downward trend can be observed across all countries, although the pace and timing of the decline differ.

At the beginning of the observed period, Poland recorded by far the highest number of the road fatalities, exceeding 6,000 deaths annually in the early 2000s. However, a substantial and continuous decline can be observed over the following years, with the number of fatalities decreasing to approximately 1,900 by 2024. This represents the most pronounced absolute reduction among the V4 countries and reflects significant improvements in the road infrastructure, vehicle safety, and regulatory frameworks.

A similar downward trend is visible in the Czech Republic, where fatalities declined from nearly 1,500 in 2000 to around 438 in 2024. The decline was particularly pronounced after 2008, which coincides with the introduction of stricter traffic regulations and improvements in enforcement and the road safety policies.

In Slovakia, the number of the road fatalities decreased from approximately 628 in 2000 to 262 in 2024. The most significant reduction occurred between 2008 and 2011, when the number of fatalities dropped sharply. Since the mid-2010s, the trend has stabilised

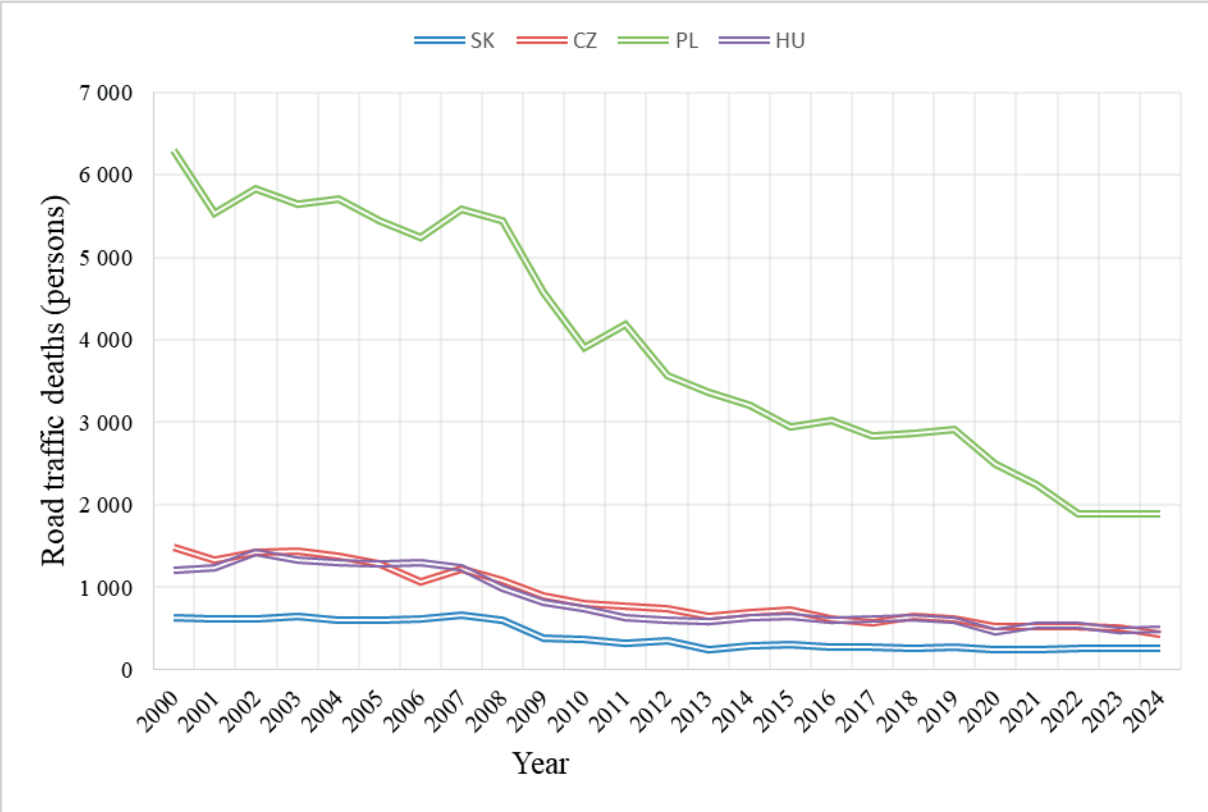


***Figure 1*** *Trends in road deaths in V4 countries*

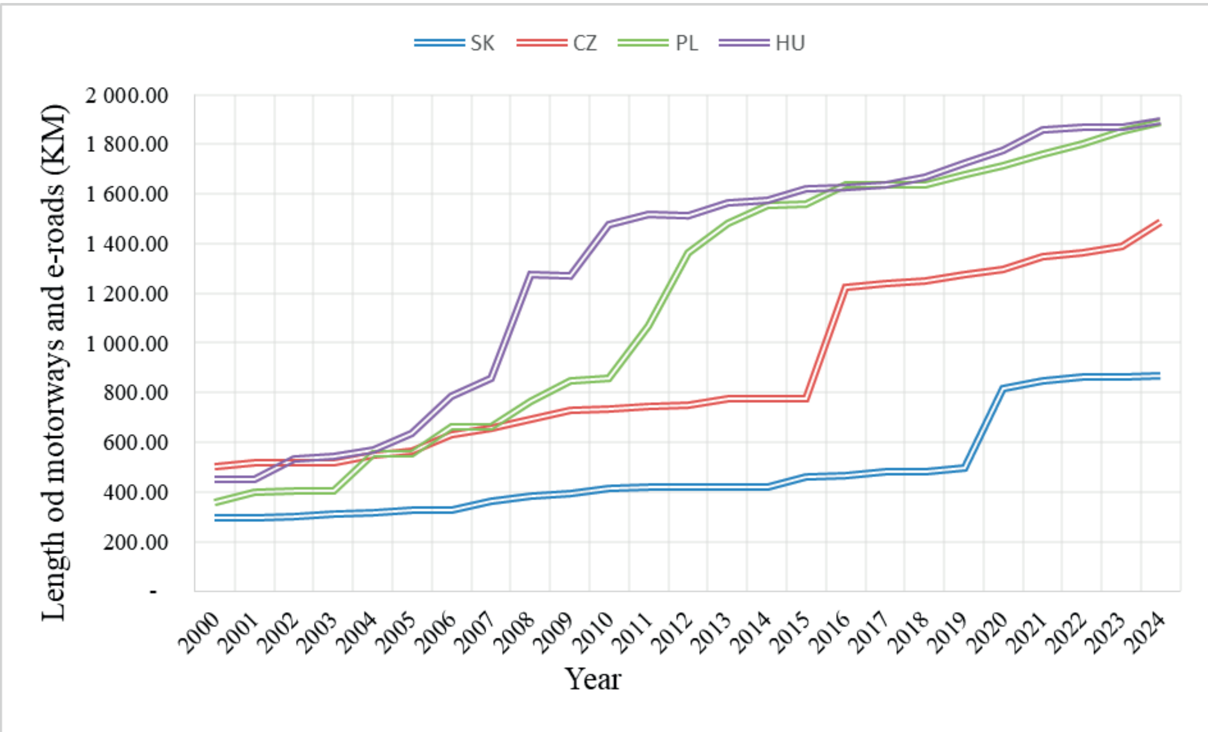


***Figure 2*** *Development of motorways and e-roads in V4 countries*

at a relatively lower level, with minor year-to-year fluctuations.

Hungary shows a comparable pattern, with fatalities declining from about 1,200 in 2000 to roughly 497 in 2024. The most substantial improvement occurred between 2008 and 2013, after which the number of deaths fluctuated around a lower but relatively stable level.

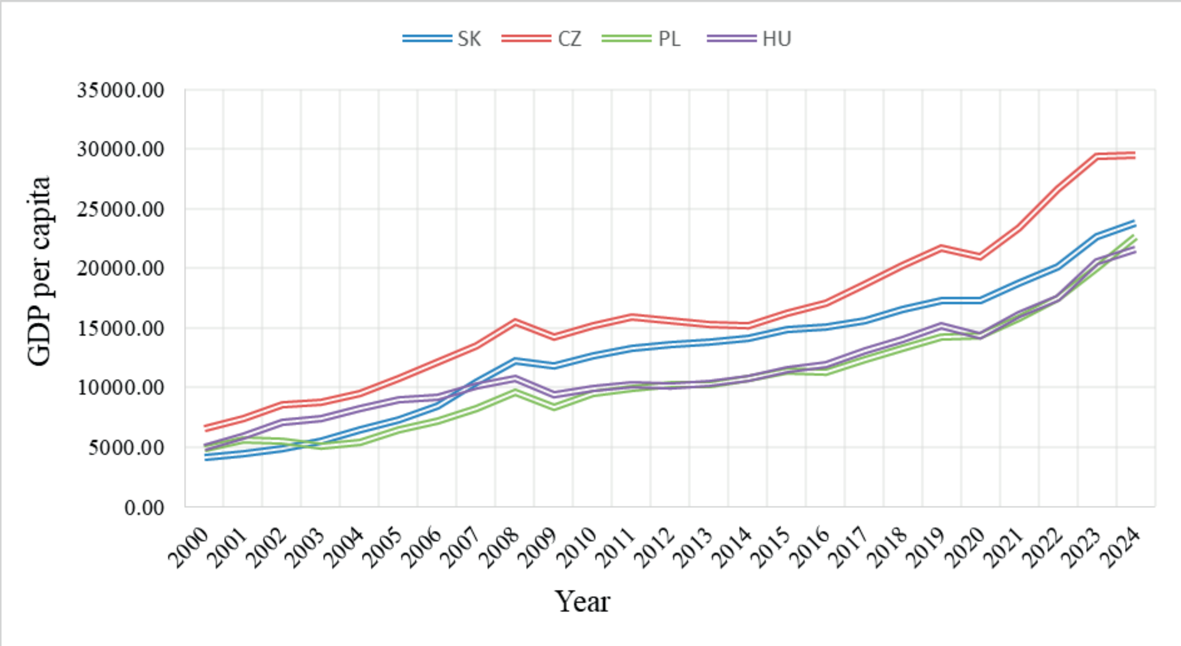


***Figure 3*** *Development of GDP per capita in V4 countries*

Figure 1 also indicates a temporary decline in fatalities during the period 2020-2021 across most countries, which may be associated with reduced traffic intensity during the COVID-19 pandemic. Overall, the graphical evidence suggests that despite differences in national dynamics, the road safety has improved significantly across the V4 region over the past two decades. These trends provide an important empirical background for the subsequent econometric analysis examining the macroeconomic and infrastructure determinants of the road traffic fatalities.

Figure 2 presents the development of the total length of motorways and E-roads in the Visegrad Group countries (Slovakia, the Czech Republic, Poland, and Hungary) between 2000 and 2024. Figure 2 reveals a substantial expansion of the motorway infrastructure across the region, although the pace and scale of development differ considerably among the countries.

At the beginning of the observed period, the Czech Republic possessed the most developed motorway network among the V4 countries, with approximately 499 km of motorways and E-roads in 2000. This network expanded gradually over the following years, reaching nearly 1,486 km by 2024. The growth was relatively steady, reflecting the long-term development of transport infrastructure and the strategic role of the Czech Republic as a transit country in Central Europe.

Poland experienced one of the most dynamic expansions of motorway infrastructure during the analysed period. The network increased from about 358 km in 2000 to nearly 1,888 km in 2024. The most significant expansion occurred after 2010, when the large-scale investments in transport infrastructure were implemented, partly supported by European Union structural funds.

Hungary also recorded significant infrastructure growth, with the motorway network expanding from approximately 448 km in 2000 to around 1,897 km in 2024. The most rapid development occurred between 2005 and 2015, reflecting substantial investments aimed at improving national and international transport connectivity.

Slovakia shows a similar upward trend, although the overall scale of infrastructure remains smaller compared to the other V4 countries. The total length of motorways and E-roads increased from roughly 296 km in 2000 to about 866 km in 2024. A particularly notable increase can be observed after 2019, when several motorway sections were completed, leading to a sharp rise in the total network length.

Figure 3 illustrates the development of GDP per capita in the Visegrad Group countries (Slovakia, the Czech Republic, Poland, and Hungary) over the period 2000-2024. Figure 3 reveals a clear upward trend in all four economies, reflecting the long-term economic convergence of the V4 region toward the more developed economies of the European Union.

At the beginning of the analysed period, the Czech Republic recorded the highest GDP per capita among the V4 countries, reaching approximately €6,560 in 2000. Over time, this indicator increased steadily, surpassing €29,000 by 2024. The Czech economy thus maintained its leading position within the V4 region throughout the entire period.

Slovakia experienced one of the most dynamic growth trajectories. The GDP per capita increased from roughly €4,140 in 2000 to approximately €23,850 in 2024. The most rapid growth occurred between 2004 and 2008, reflecting strong economic expansion following the country's accession to the European Union and the

***Table 1*** *Descriptive statistics*

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| Road traffic deaths | 4,285.6 | 2,311.4 | 1.126 | 9.820 |
| Passenger cars (per 1,000 inhabitants) | 472.3 | 96.8 | 256.4 | 702.1 |
| GDP per capita (EUR) | 16,940 | 7,820 | 5,420 | 32,110 |
| Unemployment rate (%) | 8.6 | 3.4 | 2.0 | 19.2 |
| Expenditure on road infrastructure (mil. EUR) | 3,420 | 2,115 | 410 | 8,960 |
| Length of motorways and E-roads (km) | 3,185 | 1,940 | 580 | 6,980 |

***Table 2*** *Correlation matrix*

| Variable | deaths | cars_per_1000 | gdp_pc | unemp | exp_road | length_roads |
|---|---|---|---|---|---|---|
| deaths | 1.000 | -0.015 | -0.452 | 0.348 | -0.108 | -0.064 |
| cars_per_1000 | -0.015 | 1.000 | 0.789 | -0.697 | 0.657 | 0.603 |
| gdp_pc | -0.452 | 0.789 | 1.000 | -0.692 | 0.698 | 0.484 |
| unemp | 0.348 | -0.697 | -0.692 | 1.000 | -0.594 | -0.629 |
| exp_road | -0.108 | 0.657 | 0.698 | -0.594 | 1.000 | 0.543 |
| length_roads | -0.064 | 0.603 | 0.484 | -0.629 | 0.543 | 1.000 |

inflow of foreign direct investment.

Poland also recorded substantial economic growth during the analysed period. The GDP per capita rose from about €4,900 in 2000 to more than €22,600 in 2024. Although Poland started from a relatively lower level, its steady growth trajectory indicates significant economic transformation and structural modernization of the economy.

Hungary shows a similar long-term upward trend, with the GDP per capita increasing from approximately €5,020 in 2000 to around €21,550 in 2024. However, the growth path appears somewhat less dynamic compared to Slovakia and Poland, particularly during the period following the global financial crisis.

A temporary slowdown in economic growth can be observed around 2009, reflecting the impact of the global financial crisis, as well as in 2020, when the COVID-19 pandemic affected economic activity across Europe. Despite these short-term fluctuations, the overall trend remains strongly positive in all V4 countries.

From the perspective of the road safety, rising GDP per capita may influence traffic accident dynamics through several mechanisms. Higher income levels typically lead to increased motorisation and traffic intensity, which may initially increase accident risk. However, economic development also enables greater investments in transport infrastructure, vehicle safety technologies, and the road safety policies, which may contribute to a long-term reduction in the road traffic fatalities. These relationships are further examined in the subsequent econometric analysis.

The empirical analysis is based on a balanced panel of four Visegrad Group countries (the Czech Republic, Hungary, Poland, and Slovakia) for the period 2000-2024. The dependent variable is the annual number of road traffic deaths in each country. The explanatory variables include the number of passenger cars per 1,000 inhabitants, the GDP per capita (in euros), unemployment rate (in percent), public expenditure on road infrastructure (in euros), and total length of motorways and European class roads (e-roads, in kilometers).

Descriptive statistics (Table 1) shows significant differences in all variables between countries and over time. The number of road traffic deaths decreased significantly during the period under review, which is in line with broader European trends in road safety. During the same period, motorization rates (passenger cars per 1,000 inhabitants) and GDP per capita generally increased, reflecting convergence and economic growth. Spending on the road infrastructure is relatively volatile, with phases of intense investment and phases of consolidation. The length of motorways and European roads is on a predominantly upward trend, as all four countries have expanded their high-standard road networks.

Correlation analysis (Table 2) reveals intuitive patterns. The road traffic deaths are negatively correlated with the number of passenger cars per 1,000 inhabitants and with the length of highways/expressways and positively correlated with GDP per capita. The correlation between the road infrastructure expenditure and other regression variables is moderate, suggesting that there is no serious multicollinearity. These preliminary findings are consistent with a situation where economic development, motorization, and infrastructure expansion occur simultaneously, with road safety outcomes improving over time. A basic fixed-effects country model is used to exploit the panel structure and control for unobserved heterogeneity. This approach removes all time-invariant country characteristics (e.g., geography, long-term institutional

***Table 3** Estimates of road traffic deaths with fixed effects (Driscoll-Kraay standard errors)*

| Variable | Coefficient | Std. error | t-statistic | p-value |
|---|---|---|---|---|
| cars_per_1000 | -5.472 | 1.597 | -3.427 | 0.0009 |
| gdp_pc | 0.096 | 0.027 | 3.551 | 0.0006 |
| unemp | 39.969 | 19.693 | 2.030 | 0.0453 |
| exp_road | $-3.98\times10^{-8}$ | $2.82\times10^{-7}$ | -0.141 | 0.8881 |
| length_roads | -1.167 | 0.197 | -5.936 | 0.0000 |
| Country fixed effects | yes | | | |
| Year fixed effects | yes | | | |
| Covariance estimator | Driscoll-Kraay | | | |
| Observations | 100 | | | |
| $R^2$ (within) | 0.77 | | | |

quality, driver culture) that may correlate with both road safety and explanatory variables. Given the time dimension of the panel and the likelihood of heteroscedasticity, serial correlation, and cross-sectional dependence, the fixed effects model is estimated using Driscoll-Kraay standard errors. These standard errors are robust to a wide range of correlation patterns in the residuals and are therefore preferred over conventional or cluster alternatives in this context. For robustness, a random effects specification was also estimated, and a Hausman test was performed to decide between the fixed and random effects. In addition, basic diagnostic tests for heteroscedasticity and serial correlation were performed on the clustered OLS residuals. Table 3 presents the results of the fixed effects estimation with standard errors according to Driscoll-Kraay. The dependent variable is the annual number of road traffic deaths in each country.

All the coefficients were estimated over time from changes within individual countries. This means that they describe how changes in each explanatory variable in a given country are associated with changes in deaths, while other regressors and all time-flag characteristics of the country are constant. The coefficient for the number of cars per capita (-5.472) is statistically significant at the 0.05 significance level. From an economic point of view, this means that in a given country, an increase of 1 passenger car per 1,000 inhabitants is associated with a reduction in the road deaths of 5.5 people per year, ceteris paribus. At the first glance, this result may appear counterintuitive, particularly because the simple correlation between the motorisation and the road fatalities is close to zero. However, this apparent discrepancy can be explained by the Simpson's paradox, where the relationship observed in aggregated data differs from the relationship identified after controlling for other variables or fixed effects. In the present case, the panel regression controls for country-specific heterogeneity and macroeconomic factors, which allows the underlying within-country relationship between the motorisation and the road safety to emerge. A possible explanation is that higher levels of motorisation are typically associated with more developed economies, better road infrastructure, safer vehicles, and improved traffic management systems. Consequently, although increased car ownership may lead to higher traffic intensity, it may simultaneously coincide with structural improvements that contribute to a reduction in the road traffic fatalities over time.

The GDP per capita coefficient is positive (0.096) and statistically significant at the 0.05 significance level. An increase in GDP per capita of €1 is associated with an increase of approximately 0.096 deaths per year in an average Visegrad Four country, if other factors remain unchanged. The unemployment coefficient (39.969) is positive and significant at the 0.05 significance level. This suggests that a 1% increase in the unemployment rate is associated with approximately 40 additional road deaths per year in each country. The coefficient for the road infrastructure expenditure is very small, statistically insignificant ($p \approx 0.89$), and its sign does not differ reliably from zero. In the current specification, annual public spending on the road infrastructure does not show a clear current impact on the number of road deaths. The coefficient for the road length is -1.167, which is statistically highly significant ($p < 0.05$). This means that each additional kilometer of motorways/expressways in the country is associated with a reduction in road deaths of approximately 1.2 per year, if other factors remain unchanged.

A summary of the results suggests that in the Visegrad Four countries between 2000 and 2024:

- Higher motorization is associated with lower road deaths, which is consistent with general improvements in vehicle technology, infrastructure, and institutions.
- Economic growth measured by GDP per capita has a positive impact on the number of deaths, suggesting that increased mobility and exposure to risk still outweigh improvements in safety.
- Higher unemployment is associated with higher fatalities, underscoring that labour market conditions and economic pressure can have an adverse impact on road safety.

- Total annual expenditure on road infrastructure does not have a clear short-term impact on fatalities in this specification.
- The expansion of motorways and expressways is strongly associated with a reduction in road traffic deaths, highlighting the key role of high-quality road infrastructure.

The value of the coefficient of determination $R^2$ = 0.77 indicates that the model explains a substantial part of the changes in the number of road traffic deaths in individual countries over time. Fixed country effects and annual dummy variables together capture unobserved heterogeneity and common regional shocks, while the main regression variables provide statistically and economically significant explanatory power. Alternative specifications (not reported in detail) using random effects or pooled OLS provide qualitatively similar features but differ in magnitude and standard errors. Hausman tests strongly reject random effects in favor of fixed effects, and conventional tests of heteroscedasticity and serial correlation on pooled OLS residuals confirm the need for robust inference. The use of Driscoll-Kraay standard errors ensures that the t-statistics and p-values reported are robust to these problems, lending credibility to the substantive conclusions.

As a part of the robustness analysis, the baseline model was re-estimated using an alternative dependent variable, namely the road traffic deaths per one million inhabitants, to control for population size and obtain a relative measure of the road safety.

The results reveal several important differences compared to the baseline specification using absolute fatalities. In particular, the coefficient of passenger cars per 1,000 inhabitants remains negative and highly statistically significant (-0.192, $p < 0.001$), confirming the robustness of the finding that higher levels of motorization are associated with lower fatality rates. Similarly, the effect of motorway and road length remains negative and strongly significant (-0.034, $p < 0.001$), suggesting that the expansion of road infrastructure contributes to improved road safety outcomes in relative terms.

However, notable differences emerge in the case of GDP per capita. While the baseline model indicates a positive and statistically significant relationship ($\beta \approx 0.096$, $p < 0.001$), the robustness specification yields a negative coefficient ($\beta \approx -0.0022$) that is only weakly significant ($p \approx 0.09$). This reversal in sign suggests that the relationship between economic development and road safety is sensitive to the choice of dependent variables and may reflect scale effects present in the absolute measure of fatalities.

A similar shift can be observed for the unemployment rate, which is positive and significant in the baseline model (€ ≈ 39.97, $p < 0.05$) but becomes negative and statistically significant in the robustness specification (€ ≈ -1.85, $p < 0.05$). This indicates that the higher unemployment may be associated with lower fatality rates when expressed in relative terms, potentially due to reduced mobility and traffic intensity during periods of weaker economic activity.

In contrast, the effect of road infrastructure expenditure remains inconsistent across specifications. While it is statistically insignificant in the baseline model ($p \approx 0.89$), it becomes positive and statistically significant in the robustness model ($p < 0.01$), albeit with a very small coefficient. This suggests that the estimated impact of public spending on road safety is not stable and may depend on model specification or scaling effects.

Overall, the comparison of results indicates that while certain relationships, particularly those related to motorization and road infrastructure length remain robust, other key variables such as GDP per capita, unemployment, and infrastructure expenditure exhibit considerable sensitivity to the choice of dependent variable. This underscores the importance of employing alternative specifications when evaluating the determinants of road safety and suggests that conclusions based solely on absolute fatality counts may be incomplete.

In the next step of the analysis, attention was directed towards examining the potential nonlinear relationship between the economic development and the road traffic fatalities. Specifically, the study proceeded to test the Kuznets-type hypothesis, which assumes that the impact of income growth on road safety may change across different stages of economic development. To capture this possibility, the model was extended by including both the linear and quadratic terms of GDP per capita, allowing for the identification of a potential non-monotonic relationship.

In the case of absolute road traffic deaths, the estimated coefficient of GDP per capita is positive (0.079), while the quadratic term is also positive but statistically insignificant. This configuration implies a convex and monotonically increasing relationship, rather than the expected inverted U-shape. Moreover, the implied turning point is negative (approximately -49,179), which lies entirely outside the economically meaningful range of the data. Despite the joint significance of the GDP terms, as indicated by a very low p-value (≈ 0.00001), the resulting functional form lacks practical interpretability and does not support the Kuznets hypothesis.

In contrast, when using the road traffic deaths per one million inhabitants, the results provide stronger evidence of a nonlinear relationship. The linear term of GDP per capita is negative and statistically significant (-0.0078), while the quadratic term is positive and significant (0.0000001756), indicating a U-shaped relationship. This suggests that increases in income are initially associated with a reduction in traffic fatalities, followed by a reversal at higher income levels. The estimated turning point is approximately 22,147 EUR per capita, which lies within a plausible range of the observed data. The joint significance of the GDP

***Table 4** Infrastructure spending (contemporaneous and lagged effects)*

| Outcome | Model | road_exp_mil_eur | road_exp_l1 | road_exp_l2 |
|---|---|---|---|---|
| rtd | Baseline | 0.7406 | | |
| rtd | With lag 1 | 0.7002 | 0.9103 | |
| rtd | With lag 1 and 2 | 0.6099 | 0.3249 | 0.1557 |
| rtd_per1m | Baseline | 0.3678 | | |
| rtd_per1m | With lag 1 | 0.2504 | 0.2902 | |
| rtd_per1m | With lag 1 and 2 | 0.4255 | 0.8062 | 0.0285 |

terms ($p \approx 0.0039$) further supports the presence of this nonlinear pattern.

Overall, the results do not confirm the existence of a conventional Kuznets curve in the form of an inverted U-shape. Instead, the findings suggest either a monotonically increasing relationship (in the case of absolute fatalities) or a U-shaped relationship (in the relative specification), indicating that the nature of the relationship between income the road safety nexus is sensitive to the choice of dependent variable.

To further verify whether the estimated relationships are driven by the exceptional conditions of the COVID-19 period, an additional robustness check was performed by re-estimating the baseline fixed effects model using only pre-pandemic data (2000-2019). The results indicate that the core findings remain largely unchanged. In particular, the effect of motorization (passenger cars per 1,000 inhabitants) remains negative and highly statistically significant, confirming its robust association with lower road traffic fatalities. Similarly, GDP per capita retains a positive and statistically significant coefficient ($p \approx 0.026$), suggesting that the relationship between economic development and fatalities observed in the baseline model is not driven solely by the inclusion of pandemic years.

The coefficient on motorway and the road length also remains negative and significant, reinforcing the conclusion that infrastructure expansion contributes to improving the road safety outcomes. In contrast, the effect of lagged infrastructure expenditure becomes only marginally significant ($p \approx 0.058$), indicating weaker and less stable evidence of delayed investment effects once the COVID period is excluded. Furthermore, the unemployment rate loses its statistical significance, suggesting that its previously observed impact may be sensitive to the inclusion of pandemic-related labor market disruptions.

These findings confirm that the main determinants of the road traffic fatalities are not driven by the COVID-19 period but rather reflect more stable structural relationships present throughout the pre-pandemic period.

A similar pattern is observed when using the road traffic deaths per one million inhabitants, where both the contemporaneous and first lag of infrastructure expenditure remain statistically insignificant. However, in the specification including both lagged terms, the second lag (t-2) becomes negative and statistically significant, indicating a delayed reduction in fatality rates following infrastructure investments. This result suggests that the impact of infrastructure spending on road safety may materialize only after a longer time horizon, rather than immediately or within a single year (Table 4).

A more detailed insight into the statistical significance of infrastructure expenditure effects is provided by the corresponding p-values. In the case of absolute road traffic deaths, the p-values of the contemporaneous, as well as lagged expenditure variables, remain well above conventional significance thresholds across all model specifications (e.g., 0.7406 in the baseline model, 0.7002 and 0.9103 with one lag, and 0.6099, 0.3249, and 0.1557 when both lags are included). These results confirm that infrastructure spending does not exhibit a statistically significant effect on fatalities in absolute terms, regardless of whether lag structures are considered.

A similar pattern is observed for the road traffic deaths per one million inhabitants, where the majority of coefficients remain statistically insignificant. However, in the specification including both lagged variables, the second lag (t-2) yields a p-value of 0.0285, indicating statistical significance at the 5% level. This finding provides limited evidence that infrastructure investments may contribute to reducing fatality rates with a longer time delay.

Nevertheless, the overall lack of consistent statistical significance across models suggests that this effect is not robust, and should therefore be interpreted with caution. The results imply that, while there may be some delayed benefits of infrastructure expenditure, these are neither immediate nor systematically observable across different model specifications.

## 5 Discussion

The findings of this study make an important contribution to the discussion on the macroeconomic and infrastructural determinants of the road traffic safety in the V4 countries. An empirical analysis based on a fixed-effects panel model showed that growth in economic performance, measured by GDP per capita, is associated with a decline in the number of the road fatalities in Slovakia, the Czech Republic, Poland, and Hungary, while increased motorization raises the risk of fatal accidents. Unemployment appears in the results as a factor with a predominantly dampening effect on mortality, and the significance of variables representing transport infrastructure appears to be determined more by the quality of their use than by the physical extent of the network itself.

The strongest correlation with the results of the present study was observed for the motorization variable. Several studies have confirmed that an increase in the number of vehicles leads to greater traffic exposure, higher traffic volume, and consequently a higher risk of traffic accidents and fatalities. In the European context, it has been noted that economic growth is often accompanied by an increase in motorization, and particularly in less developed economies, the rate of growth in the vehicle fleet may exceed the rate of improvement in safety [18]. A Nigerian study identified a unidirectional causal relationship from motorization to traffic accidents and also demonstrated that economic growth increases motorization, which subsequently acts as a mediating mechanism for the rise in accident rates [19]. Similar conclusions were drawn regarding Chinese provinces, where motorization was found to have a positive effect on traffic accidents [20]. Similarly, an analysis of Beijing demonstrated that private vehicle ownership increased the number of accidents over the long term [21]. Based on the above, it can be concluded that the finding of the present study that increased motorization raises the risk of fatal accidents has been largely confirmed by the existing literature.

Significantly more varied results were found when assessing the effect of GDP per capita. Some studies supported the conclusion that, under certain conditions, economic development can act as a factor reducing traffic fatalities. A Polish panel study identified a negative relationship between the GDP per capita and accident and fatality rates [22]. Similarly, a Chinese provincial analysis demonstrated that economic development had a predominantly inhibitory effect on traffic accidents [20]. A broader review of empirical findings also cited results from Russia and certain international panels, according to which growth in regional product or GDP per capita led to a decline in traffic fatalities. These findings can be considered consistent with the results of the present study, in which economic growth was interpreted as a factor promoting a higher quality of the vehicle fleet, better access to healthcare, a more modern regulatory framework, and a higher level of safety technologies.

At the same time, however, it was found that other studies had reached the opposite conclusion. A Thai study demonstrated that growth in provincial GDP per capita was associated with an increase in both traffic injuries and fatalities [23]. A comparative analysis of upper-middle-income countries found that growth in GDP per capita increased traffic fatalities in Asia, Europe, and the Americas [4]. In the case of Cameroon, an inverted U-shaped relationship was identified, suggesting that safety deteriorates in the early stages of economic growth, while it improves after a certain level of development is reached [24]. Another Thai study also confirmed this non-linearity, observing an inverted U-shape for accidents and injuries, while a U-shape was identified for fatalities [25]. For this reason, the relationship between economic performance and traffic safety could not be interpreted as universally linear. Rather, it was confirmed that this is a development-dependent relationship, sensitive to the level of economic maturity, the quality of institutions, the technical level of the vehicle fleet, and the degree of regulatory effectiveness. In this context, the results of the present study can be interpreted to mean that the V4 countries are likely at a stage of development where the positive externalities of economic growth have begun to outweigh the negative consequences of increasing mobility.

A relatively high degree of agreement was also found regarding the interpretation of the effect of unemployment. In the present study, unemployment was identified as a factor that could be associated with a lower number of fatalities, which was interpreted primarily through a reduction in mobility, commuting to work, and economically motivated travel. This conclusion was also supported by a Chinese study, which identified a predominantly negative effect of unemployment on traffic accidents [20]. Similarly, a broader literature review cited findings indicating a negative correlation between unemployment and traffic fatalities, which in some cases was even stronger than that observed for GDP. Earlier macroeconomic analyses from the U.S. also suggested that rising unemployment is often accompanied by a decline in the number of traffic fatalities, although methodological caution was recommended when interpreting such findings [26]. It can therefore be concluded that the results of the present study are not isolated in this field but are supported by several studies that have highlighted the procyclical nature of traffic accidents and fatalities.

The greatest divergence of opinion was found in the variables representing transport infrastructure and infrastructure investments. The present study suggests that simply increasing spending on the road infrastructure or expanding the highway network does not automatically lead to a reduction in the number of fatalities, as the quality of the implemented projects, the technical condition of the network, its functional layout, the manner of its use, and the time lag in the safety effect appear to be decisive factors, [26]. This conclusion has also been largely confirmed by the existing literature. A European analysis focusing on the relationship between the infrastructure spending and safety pointed out that the results of previous studies are inconsistent and that the effect of investments is strongly dependent on the method of measurement, the country's economic level, and the time horizon of the evaluation. Similarly, a Chinese study found that transportation investments themselves were positively correlated with the number of deaths, while the road length and lighting quality had a negative effect on fatalities. Such findings suggest that investments may increase traffic capacity and risk exposure in the short term, while their safety effect may only manifest later or in combination with other measures.

On the other hand, studies were also identified in which a positive safety effect was attributed to transport infrastructure. A Polish panel analysis demonstrated a negative impact of the road network length and maintenance expenditures on accident rates, suggesting that high-quality and well-maintained infrastructure can contribute to improved safety [27]. A study analyzing highways and vehicle counts in selected European countries found that in some countries, a reduction in fatalities was associated with the expansion of the highway network, with the Czech Republic explicitly mentioned, and Slovakia cited in relation to accident rates [28]. A Slovak analysis of a high-risk the road section also suggested that diverting traffic, particularly freight traffic, to the D3 highway could reduce traffic intensity in the high-risk area and thereby improve the safety situation [29]. These findings allowed for the results to be interpreted not as a rejection of the importance of infrastructure, but as confirmation that the positive effect of infrastructure manifests itself only under certain conditions, particularly when investments are focused on safety-critical sections, high-quality maintenance, and the separation of conflicting traffic flows.

Special attention also had to be paid to behavioral and institutional factors, which were identified in several studies as important mediating mechanisms. A Slovak study on mortality trends from 1996 to 2014 highlighted the importance of legislative measures, particularly the new Road Traffic Act of 2009, in accelerating the decline in mortality [30]. An Australian study, in turn, showed that fatal accidents are significantly influenced by age, rural settings, night driving, and high-speed sections [31]. An American climate macroanalysis confirmed the growing importance of temperature, precipitation, extreme weather events, and regulatory measures [32]. Although these results did not directly focus on the same variables as the present study, they supported a broader interpretive framework according to which the macroeconomic determinants operate only through a complex network of behavioral, technical, and institutional relationships.

The COVID-19 pandemic period had a significant impact on development of traffic safety, as it was accompanied in many countries by restrictions on mobility, a decline in traffic volume, and changes in the road traffic patterns. In the present study, the results were interpreted with the understanding that part of the observed period was influenced by pandemic restrictions, which may have temporarily weakened the usual links between the economic activity, unemployment, and the number of fatalities. This interpretation is supported by several studies. An Australian analysis recorded a decline in mortality in 2020, which was linked to mobility restrictions during the pandemic, although the long-term trend was also explained by broader structural factors related to the road traffic safety [31]. Similarly, a Thai study reported a slight decrease in accidents and injuries in 2020, with this trend interpreted as a consequence of pandemic-related travel restrictions, rather than a sign of lasting systemic improvement [33]. The professional literature has also pointed out that economic recessions and extraordinary social shocks are often accompanied by a decline in traffic fatalities, primarily due to lower risk exposure. For this reason, the results for the pandemic years had to be interpreted with caution, as a part of the decline in mortality could have been caused by exogenous traffic restrictions, rather than solely by improvements in infrastructure quality, regulation, or the behavior of the road users.

Based on a comparison to previous studies, it can be concluded that the results of the present study were most consistent with the literature regarding the interpretation of motorization as a risk factor, unemployment as a variable associated with a decline in traffic fatalities, and the COVID-19 pandemic as a period in which the decline in mortality was largely mediated by reduced mobility and lower risk exposure. Regarding economic performance, the existence of two opposing lines of research was confirmed, with these results aligning more closely with the group of studies in which economic growth in more mature economies was associated with improved safety. The highest degree of heterogeneity was confirmed for the transportation infrastructure, as both positive and negative effects were identified in studies depending on a country's level of development, type of investment, quality of maintenance, time horizon, and accompanying regulatory measures.

## 6 Conclusions

The empirical analysis of the Visegrad Group countries over the period 2000-2024 confirmed that the road traffic mortality is shaped by a combination of economic, infrastructural, and labour-market factors, whose effects are not always linear and whose interpretation depends on the specification used. The estimated fixed-effects models showed that higher motorization was consistently associated with lowering the road traffic fatalities, while the expansion of motorways and European-class roads also exhibited a statistically significant mortality-reducing effect. By contrast, the GDP per capita and unemployment were positively associated with fatalities in the baseline specification using absolute deaths, although both variables proved to be sensitive to the choice of dependent variable and to the exclusion of the COVID-19 period. Public expenditure on the road infrastructure did not display a robust contemporaneous effect, while lagged estimates suggested only limited evidence of delayed safety benefits.

These findings imply that road safety in the V4 countries cannot be explained solely by the scale of economic growth or by the volume of public investment. Rather, what appears to be decisive is the structural quality of development, including the modernization of the vehicle fleet, the functional design of transport infrastructure, the timing of investment effects, and the broader institutional environment in which mobility expands. The results therefore support the view that the road fatalities should be interpreted not as an isolated transport outcome, but as a by-product of wider processes of economic transformation, changing mobility patterns, and public policy choices.

At the same time, the comparison between baseline and robust specifications revealed that some determinants are considerably more stable than others. The protective effect of motorization and high-standard road length remained robust across alternative models, suggesting that in the V4 context these variables may reflect broader structural improvements in vehicle safety, infrastructure quality, and transport organization. In contrast, the effects of the GDP per capita, unemployment, and infrastructure expenditure varied according to whether fatalities were measured in absolute or relative terms and whether pandemic years were included. This indicates that caution is needed when deriving policy conclusions from a single model specification and confirms the importance of using multiple indicators of road safety performance.

From the perspective of economic policy, several practical implications emerge. First, the significant negative effect of motorway and expressway expansion suggests that continued investment in high-standard road infrastructure should remain an important component of transport and regional development policy. However, priority should not be placed on network expansion alone, but rather on those projects that demonstrably reduce conflict points, separate traffic flows, bypass hazardous settlements, and shift traffic from lower-quality roads to safer corridors. In this sense, infrastructure policy should be guided less by the quantity of kilometers delivered and more by measurable safety outcomes.

Second, the weak and unstable effect of aggregate the road infrastructure expenditure indicates that simply increasing annual public spending is unlikely to produce immediate and predictable reductions in fatalities. For policymakers, this means that expenditure efficiency should be emphasized more strongly than expenditure volume. Greater attention should be devoted to the composition of the road spending, especially to maintenance quality, black-spot treatment, intelligent traffic management systems, road lighting, signage modernization, and targeted upgrades of high-risk sections. In addition, evaluation frameworks should explicitly account for time lags, since part of the safety return from infrastructure investment may materialize only after several years.

Third, the positive association between the GDP per capita and absolute fatalities in the baseline model suggests that economic growth may continue to generate additional traffic exposure even in relatively advanced Central European economies. This implies that growth-oriented economic policy should be complemented by preventing the road safety policy, particularly during periods of rising mobility, expanding freight transport, and increasing household car ownership. Economic prosperity alone should not be assumed to automatically improve the safety outcomes. Instead, growth strategies should be accompanied by stronger enforcement, safer vehicle standards, investments in data-based traffic management, and systematic road safety auditing of major transport projects.

Fourth, the sensitivity of unemployment effects points to the importance of monitoring the mobility-related risks over the business cycle. Since labour-market fluctuations may affect commuting intensity, freight volumes, and behavioral stress, road safety policy should be designed in a countercyclical and adaptive manner. During periods of rapid economic expansion, when mobility rises, preventive campaigns and enforcement efforts may need to be intensified. During the crisis periods, by contrast, attention should be paid to shifts in travel patterns, fiscal constraints, and delayed maintenance effects, which may create new forms of risk even if aggregate mobility declines.

Fifth, the experience of the COVID-19 period highlights the need for resilience-oriented transport governance. Although the main structural findings were not driven solely by the pandemic, the crisis clearly demonstrated that extraordinary disruptions can temporarily alter the relationship between economic activity, unemployment, infrastructure use, and road fatalities. Policymakers should therefore support the development of integrated monitoring systems capable of linking economic indicators, labour-market developments, traffic volumes, and safety outcomes in real time. Such systems would allow for a faster policy response during future crises, including pandemics, energy shocks, or abrupt recessions.

In policy terms, at least three broader strategic recommendations may be derived from the present findings. First, the road safety should be treated as an integral part of economic policy rather than as a narrow transport-sector issue. Second, infrastructure decisions should be evaluated not only in terms of connectivity and growth effects, but in terms of their measurable contribution to mortality reduction, as well. Third, the road safety policy in the V4 countries should increasingly move towards the evidence-based and differentiated interventions, reflecting the fact that the determinants of fatalities differ across absolute and relative measures and may vary over time.

This study has several limitations that should be acknowledged. First, the analysis is based on a relatively small balanced panel of four Visegrad Group countries, which limits the generalizability of the findings and reduces the variability of institutional and structural conditions across observations. Second, the use of aggregate national-level data does not allow for the capture of regional differences, behavioral factors, traffic intensity, vehicle age structure, enforcement quality, or weather conditions, all of which may also affect road safety outcomes. Third, some estimated relationships, particularly those related to the GDP per capita, unemployment, and road infrastructure expenditure, proved sensitive to model specification and the choice of dependent variable. Finally, although the lagged effects and pre-pandemic robustness checks were considered, the results may still be influenced by unobserved shocks and measurement differences that could not be fully controlled for within the available dataset.

In conclusion, the study has shown that the determinants of the road traffic fatalities in the Visegrad Group are multifaceted and specification-sensitive, but not random. The most consistent evidence was found for the protective role of high-standard road network expansion and for the stable relationship between motorization and improved safety outcomes within countries over time. Less stable, but still policy-relevant, were the effects of income growth, unemployment, and infrastructure expenditure. These results underline that effective road safety improvement requires a coordinated policy mix combining infrastructure quality, institutional capacity, preventive regulation, and continuous evaluation of economic and mobility trends. For policymakers in the V4 region, the key message is that the safer roads would not result automatically from economic growth or higher public spending alone; they must be produced through targeted, well-timed, and evidence-based policy intervention.

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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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