Growth, Employment and Road Traffic Injuries: Nonlinear Short-Run Dynamics and Long-Run Stability

Arzu Safarova
Azerbaijan State University of Economics, AZ1001, Azerbaijan
arzu_safarova@unec.edu.az
https://orcid.org/0000-0002-8260-5497

Abstract. At the first stage of the study, a linear ARDL model was estimated to examine both the long-run and short-run relationships between macroeconomic indicators and road safety. The results confirmed the presence of a long-run cointegration relationship between unemployment, GDP per capita, and road traffic injury rates. However, the short-run linear effect of GDP on road traffic injuries appeared to be statistically unstable.
Given the theoretical foundations of the Kuznets hypothesis (1955) and the possibility of a structural transformation in the impact of economic growth on road safety, a nonlinear specification of the same variables was subsequently estimated by including a quadratic term of GDP (an inverted U-shaped model). The findings revealed not only a statistically significant long-run negative relationship between unemployment, GDP per capita, and road traffic injuries, but also a short-run nonlinear relationship with GDP. In particular, the results indicate the existence of a turning point (around 2005 in the case of Azerbaijan), after which further economic growth began to contribute to a reduction in road traffic injuries.

Keywords: Road Traffic Accidents (RTAs), ARDL-ECM Model, Inverted U-Shaped Model, GDP per Capita, Unemployment Rate.

1 Introduction

Road safety has traditionally been viewed as a social and public health issue; however, in recent years it has increasingly been examined within a macroeconomic framework. Studies from both developed and developing countries show that road traffic injuries have a measurable impact on economic growth through channels such as losses in human capital and productivity [7], [8]. At the same time, the reverse relationship—the influence of macroeconomic dynamics on road safety outcomes—has become an active area of empirical research. A growing body of literature demonstrates that economic factors, including income levels, employment, motorization, and transport infrastructure development, exert a statistically significant effect on road traffic accident indicators. Empirical studies conducted for European countries, OECD members, and China reveal both short-run and long-run effects of macroeconomic variables on the number of crashes, injuries, and fatalities [6].

Economic growth is typically accompanied by an expansion of transport activity and increased traffic intensity, which may initially contribute to higher accident rates, especially in the early stages of development. Additional research points to the cyclical nature of road safety: during periods of economic expansion, mobility and transport volumes tend to rise, whereas in recession phases accident rates may decline. For instance, Fred Wegman et al. (2017) show that rising unemployment during economic downturns is associated with a faster decline in road traffic fatalities, highlighting the strong sensitivity of road safety outcomes to macroeconomic fluctuations [9].

Despite the growing body of international evidence, the interaction between short-run nonlinear responses of accident indicators and the long-run stabilizing effects of economic development remains insufficiently explored for transition economies. Moreover, limited attention has been paid to the role of the labor market as a transmission channel linking economic cycles to road safety outcomes. Over the past decades, Azerbaijan has experienced a period of rapid economic growth, structural transformation, and subsequent macroeconomic shocks, accompanied by changes in income levels, employment, and transport activity. In this context, several research questions arise:

1. Does a short-run nonlinear response of road traffic injuries and fatalities to economic growth exist in this country?
2. Is this relationship compatible with the long-run stabilizing effect of development?
3. Does the labor market act as an adjustment mechanism in the dynamics of road safety?

This study addresses these gaps by combining the ARDL-ECM approach to long-run cointegration analysis with an examination of short-run nonlinear dynamics and an interpretation of the turning point within a modified Kuznets framework for the case of Azerbaijan.

2 Problem statement

The relationship between economic development and road safety is interpreted in different ways in the literature. On the one hand, economic expansion increases transport activity and traffic intensity, which in the short run may lead to higher accident rates and injury incidence. On the other hand, sustained development generates a long-term "protective" effect through infrastructure modernization, fleet renewal, improved safety standards, and better quality of medical services [4]. This duality highlights the need for models capable of capturing both short-run dynamics and long-run equilibrium.

To analyze these dynamics, the ARDL approach with an error correction mechanism (ECM) is widely used, as it allows for the estimation of short-run deviations and long-run cointegration even with relatively small time series [1], [6]. Studies applying ARDL to accident rates, injuries, and fatalities emphasize that the same macroeconomic factor may produce different short-run and long-run effects. This distinction is particularly important when separating injury and fatality indicators, as their underlying mechanisms differ [5].

The inclusion of labor market indicators—primarily unemployment—is considered a way to account for changes in mobility patterns. Rising unemployment typically reduces the intensity of daily travel and may lead to a short-run decline in road accidents and injuries [1]. Thus, unemployment acts not only as an independent macroeconomic indicator but also as a transmission channel through which economic cycles affect road safety outcomes.

To identify short-run patterns, the Kuznets-type logic is often adapted to road safety analysis, assuming an inverted U-shaped relationship between income levels and road accident indicators: at early stages of development, income growth is associated with increased motorization and accident rates, whereas at higher levels of development, compensatory safety mechanisms begin to dominate [3]. Empirical evidence from developing countries supports the existence of a turning point beyond which further economic growth is associated with a decline in accident rates or fatalities [2].

However, despite the growing body of evidence, the interaction between short-run nonlinear dynamics and long-run equilibrium effects remains insufficiently explored, particularly for transition economies. Moreover, limited attention has been paid to the role of the labor market as a transmission mechanism linking macroeconomic fluctuations to road safety outcomes.

3 Data and research methods

The study employs data on the number of road traffic injuries and fatalities, real GDP per capita (in constant 2015 US dollars), and the unemployment rate over the period 1995–2024. The data were obtained from the State Statistical Committee of the Republic of Azerbaijan and the World Bank database [10]. According to World Bank estimates, official statistics on the total number of road traffic accidents in Azerbaijan may significantly deviate from actual values; therefore, this indicator was excluded from the analysis [11].

As shown in Figure 1, the logarithmic series of road traffic injuries ($LRTA\_INJ$), unemployment ($LUNEMPLOYMENT$), and GDP per capita ($LGDP\_PERCAPITA$) exhibit broadly similar dynamics, in contrast to fatalities ($LRTA\_FATAL$). The r $LRTA\_INJ$ series displays a pronounced trend pattern. An increase is observed from the late 1990s to the mid-2000s, reaching peak values during the period of rapid economic expansion. From approximately 2013–2015 onward, a steady decline in this indicator can be observed. This trajectory reflects a cyclical pattern consistent with the phases of economic development in the country. The increase in r $LRTA\_INJ$ during periods of economic growth may be explained by rising transport activity, increased motorization, and the expansion of economic activity. LGDP_PERCAPITA shows a persistent upward trend, particularly pronounced in the mid-2000s, corresponding to a phase of accelerated economic growth. In subsequent years, the series stabilizes while maintaining an overall positive trend.

The $LUNEMPLOYMENT$ indicator follows an opposite pattern: an increase in the late 1990s is followed by a steady decline in the 2000s and subsequent stabilization at relatively low levels. The reduction in unemployment reflects increased economic activity and higher employment, which in turn may lead to greater transport intensity.

A degree of synchronicity is observed between r $LRTA\_INJ$ and $LGDP\_PERCAPITA$ during periods of economic growth. This may reflect the following mechanism: income growth → increased motorization → higher transport activity → a rise in road traffic injuries. Such a relationship is consistent with the Kuznets-type logic applied to the social costs of economic growth, whereby negative externalities tend to increase at early stages of development.

The dynamics of $LUNEMPLOYMENT$ reveal an inverse relationship with road accident indicators: declining unemployment is accompanied by an increase in the number of injuries and fatalities. This supports the interpretation of unemployment as a proxy for economic activity, where higher employment implies greater daily mobility and increased traffic intensity. In contrast to $LRTA\_INJ$, the $LRTA\_FATAL$ series does not exhibit a stable synchronicity with macroeconomic variables. Its dynamics appear smoother and do not reflect clear fluctuations aligned with macroeconomic cycles.

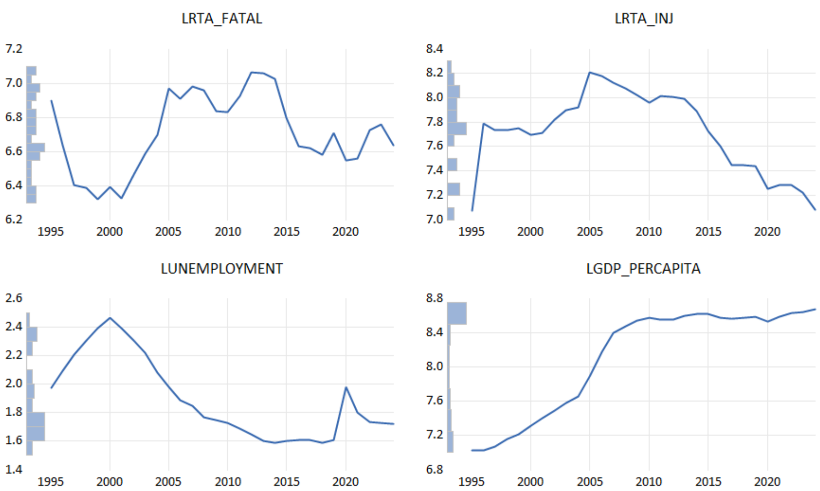

Fig. 1. Dynamics of the logarithmic values of macroeconomic indicators and road safety indicators, 1995–2024

3.1 Granger Causality Test

To determine the direction of causal relationships between the variables, pairwise Granger causality tests were conducted. The results indicate the presence of a unidirectional predictive relationship running from unemployment to road traffic injuries, with no evidence of reverse causality. In addition, a unidirectional Granger causality from GDP per capita to unemployment was identified, which is consistent with standard macroeconomic reasoning.

For road traffic fatalities, the Granger causality tests did not reveal any statistically significant directional relationships with either GDP per capita or unemployment. This suggests the absence of short-run predictability of fatalities from macroeconomic factors and is consistent with the regression results, which indicate that fatal outcomes are driven by different mechanisms. Therefore, the fatality indicator was excluded from further analysis.

3.2 Stationarity Test

Standard unit root tests produced consistent results for $LRTA\_INJ$ and $LUNEMPLOYMENT$, but mixed evidence for LGDP_PERCAPITA. While the Augmented Dickey–Fuller test (ADF) indicated persistent non-stationarity, the KPSS test—widely used in applied macroeconomics and more robust for small samples—failed to reject the null hypothesis of stationarity for the first difference of the series. This suggests that GDP per capita is integrated of order not higher than one, i.e., I(1). Therefore, the application of the ARDL bounds testing approach is appropriate, as it allows for variables that are stationary in levels or in first differences.

3.3 Cointegration Test and ARDL-ECM Model

The unit root test results indicate that all variables under consideration—road traffic injuries, GDP per capita, and unemployment—are non-stationary in levels but become stationary after first differencing, i.e., they are integrated of order I(1). Under such conditions, it is necessary to test for the existence of a long-run equilibrium relationship, as regression in levels is economically meaningful only in the presence of cointegration.

The results of the ARDL bounds test also confirm the existence of a long-run relationship, but only for the model in which road traffic injuries are specified as the dependent variable. The F-statistic is approximately 6.54, exceeding the upper critical bounds at all conventional significance levels, including 1%. This provides strong evidence of a stable long-run equilibrium relationship between injuries, economic development (GDP per capita), and unemployment in Azerbaijan, and justifies the use of the ECM framework.

To identify both short-run and long-run linear relationships, an ARDL-ECM (Autoregressive Distributed Lag – Error Correction Model) specification was estimated at the first stage, with economic growth (GDP per capita) and unemployment as explanatory variables. All variables were transformed into natural logarithms. The following model specification was obtained:

Long-run relationship:

$$LRTA\_INJ_t = \alpha_0 + \sum \beta_i \, LRTA\_INJ_{t-i} + \sum \gamma_j \, LGDP\_PERCAPITA_t + \\ + \sum \delta_k \, LUNEMPLOYMENT_t + D2016 \quad (1)$$

Short-run relationship:

$$\Delta LRTA\_INJ_t = cointeg(-1) + \Delta LUNEMPLOYMENT_t \; + D2016 \quad (2)$$

where

- D2016- is a dummy variable reflecting the currency devaluation that occurred at the end of 2015 and early 2016;
- $LRTA\_INJ_{t-i}$ –denotes i-th lag of the dependent variable;
- $cointeg(-1)$ –represents the lagged error correction term.

3.4 Nonlinear Short-Run Specification

However, no statistically significant short-run effect of GDP per capita was identified, which is consistent with the logic of road safety models, where the impact of economic growth tends to materialize primarily in the long run (through improvements in infrastructure, transport modernization, and the quality of medical services, among others). At the same time, this does not preclude the existence of a nonlinear relationship, which motivated the consideration of an alternative nonlinear specification.

Accordingly, a nonlinear model in the form of an inverted U-shaped relationship (a modified Kuznets framework) was estimated, allowing for nonlinearity in the relationship between the variables:

$$\Delta LRTA\_INJ_t = \alpha_0 + \beta_1 LGDP_t + \; \beta_2 LGDP_t{}^2 + \Delta LUNEMP_t + C \quad (3)$$

where

- $\Delta LRTA_{INJ_t}$ and $\Delta LUNEMP_t$ denote changes in the natural logarithms of road traffic injuries and the unemployment rate, respectively;

- β represents the estimated parameters; and C is a constant term.

In the nonlinear short-run specification, unemployment is included in first differences, which allows its effect to be interpreted as reflecting current changes in mobility and economic activity. Since the dependent variable is also expressed in differences, this specification ensures dynamic consistency of the model. Such a formulation is consistent with the ARDL/ECM framework, where short-run effects are captured through changes in explanatory variables.

4 Calculations

4.1 ARDL-ECM Model (Long-Run Effect)

The combination of results—namely, the integration of variables not exceeding order one (I(0)/I(1)), positive outcomes of the ARDL bounds test, a negative and statistically significant error correction term ECM(−1), and the stationarity of residuals—provides robust evidence of a long-run equilibrium relationship between macroeconomic conditions and road traffic injuries (Table 1).
In this specification, only D2016 is included as a fixed (exogenous) dummy variable with a static lag, while all other variables are estimated with automatically selected lag lengths based on the Schwarz Information Criterion.

Table 1. ARDL-ECM Model Results

Long-run relationship (lag structure: (1,0,1))		Short-run relationship	
	Dependent variable		Dependent variable
Independent variables	LRTA_INJ	Independent variables	D(LRTA_INJ)
LRTA_INJ(-1)	0.517155**	D(LUNEMPLOYMENT)	-0.749564***
LGDP_PERCAPITA	-0.211589**	ECM(-1)	-0.482845***
LUNEMPLOYMENT	-0.749564***	D2016	-0.300681***
LUNEMPLOYMENT(-1)	0.312542 *(не значимый)*		
D2016	-0.300681*		
C	5.455196***		
n=29	*R-squared = 0.90*	*n=29*	*R-squared = 0.66*

*, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively.

Note: Although one of the lagged terms of the unemployment variable in levels is statistically insignificant, it was retained in the model due to the automatic lag selection based on the Schwarz Information Criterion, which identified this specification as optimal.

In the initial model (without the inclusion of a dummy variable), the results of the CUSUM test for the baseline ARDL specification indicated parameter instability over the sample period. The crossing of the 5% significance bounds suggested a possible structural break, likely associated with macroeconomic shocks in the economy of Azerbaijan in the mid-2010s (the currency devaluations of December 2015 and February 2016).

To account for this structural shift, a dummy variable D2016 was introduced into the model, capturing changes in the institutional and economic environment after 2016. The inclusion of this variable resolved the issue of parameter instability: repeated testing using the CUSUM test and the CUSUM of Squares test showed that the recursive residuals remained within the 5% critical bounds, confirming the stability of the estimated coefficients.

The long-run coefficients of the ARDL model (with specification ARDL(1,0,1), selected using the Schwarz Information Criterion) indicate a statistically significant effect of economic development on road safety indicators. In particular, the elasticity of injuries with respect to GDP per capita is estimated at −0.21, implying that a 1% increase in real income per capita leads, on average, to a 0.21% decrease in road traffic injuries, ceteris paribus. The effect of unemployment in the long run is also statistically significant and negative: a 1% increase in unemployment is associated with an approximate 0.75% reduction in injuries. This suggests that deteriorating labor market conditions are accompanied by reduced transport activity and, consequently, fewer injury-related road traffic accidents.

The coefficient on the first difference of unemployment is also −0.75 ($p < 0.01$), indicating a substantial decline in injuries following short-term increases in unemployment, an effect that can be explained by reduced mobility and fewer trips. The error correction term (ECM), estimated at −0.483 ($p = 0.000$), is negative and statistically significant, confirming the presence of a stable adjustment mechanism toward long-run equilibrium. The magnitude of this coefficient implies that approximately 48% of deviations from equilibrium are corrected within one year. This indicates a relatively gradual but steady adjustment process in road traffic injuries in response to changes in economic development and labor market conditions. In practical terms, about 4–5 years are required to eliminate approximately 95% of the initial disequilibrium (73% in the second year, 87% in the third year, and 93% in the fourth year), reflecting a smooth but persistent convergence process.

4.2 Inverted U-Shaped Relationship between GDP per Capita and Road Traffic Injuries

When allowing for a nonlinear specification, an inverted U-shaped short-run relationship emerges. This indicates that the effect of economic activity on road traffic injuries is not linear but varies across different stages of the economic cycle.

Table 2. Results of the Inverted U-Shaped Model

Short-run nonlinear effect	
	Dependent variable
Independent variables	D(LRTA_INJ)
LGDP_PERCAPITA	2.481750^{***}
LGDP_PERCAPITA^2	-0.160905^{***}
D(LUNEMPLOYMENT)	-0.398144^{**}

C	-9.514724**
n=28	*R-squared = 0.54*

, and * indicate the significance level at 5%, and 1%, respectively.

The positive coefficient on the logarithm of GDP per capita (2.48, $p < 0.05$) and the negative coefficient on its squared term (−0.16, $p < 0.05$) indicate a phased (nonlinear) response of road traffic injuries to economic growth. The turning point of the function is given by $\mathrm{LGDP}^{ext} = \frac{2.48}{2 \cdot 0.1609} \approx 7.7$.

The estimated turning point suggests that when the logarithm of GDP per capita reaches approximately 7.7, further economic growth begins to be associated with a slowdown in the growth rate of injuries (corresponding to around 2005).

The short-run effect of changes in unemployment is negative and statistically significant (−0.40, $p < 0.05$), indicating a reduction in the growth rate of injuries when labor market conditions deteriorate. This finding is consistent with the results of the baseline model. Specifically, a one percentage point increase in unemployment in the current period is associated with an approximately 0.40% decrease in the growth rate of road traffic injuries.

4.3 Model Diagnostic Tests

The CUSUM of Squares test confirms the stability of the model parameters, as the cumulative sum of squared recursive residuals remains within the 5% confidence bounds throughout the entire sample period.

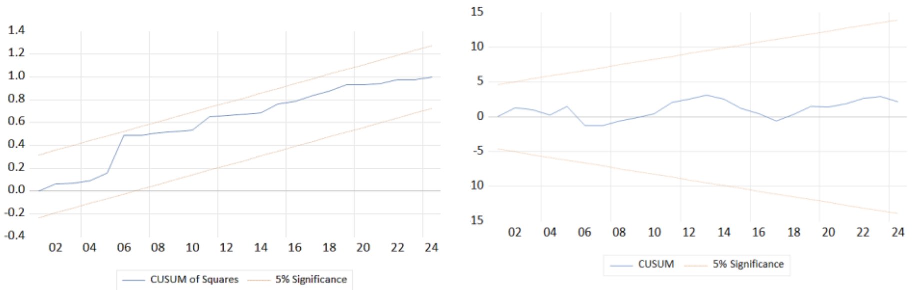

Fig. 2. Parameter stability test for the inverted U-shaped Model

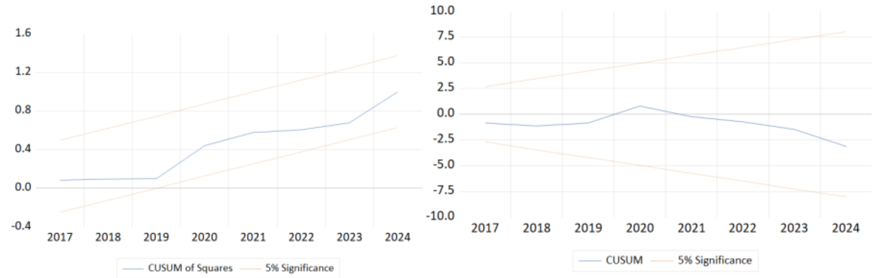

Fig. 3. Parameter Stability Test for the ARDL-ECM Model

The results of the diagnostic tests (Table 3) confirm the adequacy of both model specifications. The ADF test applied to the residuals indicates stationarity in levels (I(0)), providing evidence of cointegration among the variables.

Table 3. Model Diagnostics

	ARDL-ECM model	ARDL-ECM model
ADF test on residuals	$p = 0.0008^{***}$ I(0)	$p = 0.0002^{***}$ I(0)
Breusch–Godfrey LM test	$p > 0.6$	$p > 0.8$
Ramsey RESET test	$p > 0.4$	$p > 0.9$
Residual normality test (Jarque–Bera test)	p = 0.8 (Jarque-Bera 0.63)	p = 0.08 (Jarque-Bera 4.89)
Breusch–Pagan–Godfrey test (HAC standard errors applied)	p = 0.158	p = 0.07

*** indicate the significance level at 1%

The Breusch–Godfrey LM test does not reveal any signs of residual autocorrelation. Similarly, the Ramsey RESET test does not detect misspecification, supporting the correctness of the chosen functional form.

Normality tests suggest that the null hypothesis of normally distributed residuals cannot be rejected at the 5% significance level in both models.

The Breusch–Pagan–Godfrey test does not indicate statistically significant heteroskedasticity in the ARDL-ECM model ($p = 0.158$). For the inverted U-shaped model, the result is borderline ($p \approx 0.07$); however, in all specifications, robust Newey–West estimator (HAC) standard errors are employed, ensuring the robustness of the estimates to potential violations of classical regression assumptions.

Overall, the diagnostic test results confirm the statistical validity and robustness of the estimated models.

5 Discussion

In the linear ARDL specification, the short-run effect of GDP per capita does not appear as a statistically significant monotonic relationship. However, when allowing for a nonlinear response, an inverted U-shaped short-run relationship emerges, reflecting an increase in injuries during the early stages of economic expansion and their subsequent decline as development progresses. In the long run, GDP exerts a structural stabilizing effect, which may be explained by improvements in transport infrastructure, fleet modernization, enhanced medical services, and stronger institutional mechanisms for road safety regulation.

The estimated turning point in the quadratic model corresponds to a log GDP per capita value of approximately 7.7 (as noted above, this aligns with around 2005). Since actual values have exceeded this threshold since the mid-2000s, the economy can be considered to lie on the downward-sloping segment of the curve. This implies that, in the current period, short-run economic growth is associated with a reduction in the growth rate of road traffic injuries. This finding is consistent with the long-run effect estimated in the ARDL model and indicates no contradiction between short-run nonlinear dynamics and the structural long-run impact of economic development.

In both specifications, the short-run effect of unemployment on injuries is consistently negative. In the ARDL model, an increase in unemployment is associated with a more pronounced decline in injuries, reflecting dynamic effects captured through the lag structure and the error correction mechanism. In the nonlinear short-run model, the effect remains negative and statistically significant, although somewhat smaller in magnitude. The consistency in sign and significance across specifications suggests that unemployment acts as a stabilizing factor, reflecting reduced transport activity during periods of economic slowdown.

The absence of cointegration and Granger-causal relationships for fatalities indicates that the dynamics of fatal outcomes are driven by different mechanisms, which are less sensitive to macroeconomic fluctuations and likely more dependent on institutional, medical, and behavioral factors.

6 Conclusion

Thus, based on data for 1996–2024, only the model with road traffic injuries demonstrates a stable long-run relationship with macroeconomic indicators in Azerbaijan. Economic growth contributes to improvements in road safety outcomes, reflected in a reduction in the number of injured individuals, while rising unemployment exerts both long-run and short-run restraining effects on injuries through reduced transport activity.

The negative and statistically significant error correction term confirms the system's ability to adjust toward long-run equilibrium within approximately 4–5 years.

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