TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

FACULTY OF RAILWAYS, ROADS AND BRIDGES

DOCTORAL THESIS

Abstract

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Contributions regarding the determination of road traffic evolution functions on the Romanian national road and motorway network

SCIENTIFIC LEADER

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Contents

Chapter 1. INTRODUCTION

This paper makes original contributions to the field of transport engineering by developing an integrated methodology for road traffic forecasting on the national road network in Romania, with applicability until 2050.

The main scientific novelty consists in the development of an approach that combines macroeconomic analysis with technical modeling of road traffic. This methodology allows the simultaneous integration of socio-economic factors (GDP, GDP/capita, degree of motorization) and technical characteristics of road infrastructure into a unified predictive model.

1.1. Research Field and Subject Matter

Road transport represents one of the most important components of the European and national transport system, having a decisive impact on economic, social and territorial development. In the current context, characterized by the accelerated growth of mobility, sustained economic development and European integration, the forecast of road traffic e becomes an essential tool for strategic infrastructure planning and for substantiating investment decisions of the road transport network.

The field of this research is located at the intersection of transportation engineering, economic analysis and predictive modeling, aiming to develop a comprehensive methodology for road traffic forecasting in Romania. This interdisciplinary approach is necessary to encompass the complexity of factors influencing traffic evolution, from macroeconomic indicators to demographic and social changes.

Romania, as a member of the European Union and an integral part of the Trans-European Transport Network (TEN-T), faces specific challenges regarding the modernization and development of road infrastructure. The gap with the European average in terms of motorization, highway network density and road infrastructure quality requires a strategic approach based on realistic and scientifically substantiated forecasts.

1.2. The necessity and relevance of the research topic

Road transport of goods and passengers is experiencing steady growth at European level, a trend that is even more pronounced in Central and Eastern European countries, including Romania. According to Eurostat data, the volume of road freight transport increased by approximately 20% between 2010 and 2020, while passenger transport recorded similar increases.

In Romania, this trend is amplified by the specific factors of the economy in transition and European integration: GDP growth by an average of 3-4% annually during the period 2010-2022, Improvement of population incomes and increase in purchasing power, Development of foreign trade and intensification of trade and Accelerated motorization process, with an increase in the car fleet of over 50% in the last 15 years.

Road traffic forecasting faces several methodological and practical challenges that justify the need for this research:

The methodological problems identified:

- Inconsistency of historical data and changes in vehicle classification and data collection methods between census cycles (1980-2022) create difficulties in analyzing long-term trends;
- Limitations of existing models - current linear regression models do not integrate all stochastic and socio-economic aspects that influence traffic;
- Gaps in modeling all vehicle categories resulting from the lack of a complete history for newly introduced vehicle categories in the census classifications.

The practical problems identified:

- Diversity of collection methods - simultaneous use of censuses and automatic traffic counters causes inconsistencies in the data used for modeling;
- Saturation and congestion in major corridors due to increased traffic and traffic distribution;
- Unequal accessibility of road infrastructure in urban versus rural areas.

1.3. Purpose and objectives

The main purpose of this thesis is to develop a methodology for forecasting the evolution of road traffic in Romania, based on the analysis of the correlation between socio-economic indicators and national traffic volumes, in order to justify strategic decisions regarding the development of road infrastructure.

The research objectives are:

To achieve the proposed goal, the following specific objectives were formulated:

- Objective 1: Development of analysis and forecasting methodology
  - Developing a coherent methodology for road traffic analysis and forecasting that integrates economic, social and technical aspects;
  - Applying multiple linear regression methods to identify relationships between the determining factors and traffic volumes;
  - Development of robust predictive models for different time horizons (2025 -2050)
- Objective 2: Identification and evaluation of key indicators
  - Identification and analysis of the main relevant macroeconomic indicators: GDP, GDP per capita, motorization rate and population;
  - Assessing the impact of these indicators on traffic evolution through statistical and economical analyses;

- Establishing correlations and dependencies between economic variables and traffic volumes.

- Objective 3: Determining the evolution coefficients
  - Calculation of evolution coefficients for motorways and different categories of roads in Romania;
  - Development of differentiated forecasts by vehicle categories (passenger cars, commercial vehicles, heavy vehicles).

- Objective 4: Developing the forecast scenarios
  - Developing multiple traffic growth scenarios (optimistic, moderate, and pessimistic) for the 2022-2050 period;
  - Integrating economic and social uncertainties into the forecast model.

1.4. The scientific novelty of the obtained results

This paper makes original contributions to the field of transport engineering by developing an integrated methodology for road traffic forecasting on the national road network in Romania, with a projection horizon until 2050.

The main scientific novelty consists in the development of an approach that combines macroeconomic analysis with technical modeling of road traffic. This methodology allows the integration of socio-economic factors (GDP, GDP/capita, degree of motorization and population) and technical characteristics of road infrastructure into a unified predictive model.

Methodologically, a multiple linear regression model was developed to model the initial rapid growth and subsequent saturation of road networks using logarithmic functions. This approach provides a more realistic representation of long-term traffic evolution, considering the physical limitations of the infrastructure.

The research results provide concrete tools for decision-making in the strategic planning of road infrastructure and the allocation of European funds, opening new research perspectives in the field of the impact of emerging technologies on traffic demand.

1.5. Practical application of the obtained results

The outcomes of this study served as a basis for updating the *"Standard for determining the calculation traffic for road design from the point of view of bearing capacity and circulation capacity AND 584/2025"*.

Given that analytical pavement design methods rely on the 'Standard for Determining Design Traffic' (AND 584), any variations in the traffic evolution functions will fundamentally impact the assessment of bearing capacity and traffic flow performance

Understanding traffic characteristics across the road network is essential for effective infrastructure planning and structural design of road infrastructure investments and road maintenance and repair works, providing the rationale for traffic management measures and tracking the evolution dynamics of traffic on the road network, as well as the development of studies for: assessing air quality by estimating road traffic emissions and environmental impact.

1.6. Theoretical framework and the applied impact of the research

Theoretical contributions

This research makes the following original contributions to the field of transportation engineering:

- Developing an integrated methodology that combines economic analysis with technical traffic modeling;
- Refining vehicle classification methods according to European TLS standards;
- Creating a predictive model adapted to the specifics of Romania that can be expanded and applied to other countries with similar characteristics;
- Integrating uncertainty scenarios into long-term forecasting models.

Practical applicability

The results of this research have direct applicability in strategic planning, namely, Substantiating the National Transport Strategy for the period 2020-2050 or Elaborating investment programs in road infrastructure or Optimizing resource allocation for the development of the road network.

At the same time, it can also be used to make political and institutional decisions, being a support for government decisions regarding transport priorities to substantiate proposals for European funding (TEN-T, Structural Funds) and to assess the economic impact of infrastructure investments.

1.7. Structure of the doctoral thesis

The work is organized into six main chapters, with a total of 196 pages, 108 tables and 52 figures, its structure being designed to ensure a logical progression from theoretical foundations to practical applications:

- Chapter 1 - Introduction

It presents the investigated field, the topicality of the problem, the purpose, objectives and methodology of the research. The chapter establishes the theoretical and practical context of road traffic forecasting, identifying gaps in current research and justifying the need to develop an integrated methodology for Romania.

It highlights the strategic importance of road transport in the context of European integration and presents the methodological challenges related to the inconsistency of historical data, the limitations of existing models and the need to adapt forecasting tools. The chapter defines the conceptual framework of scientific research and sets out specific objectives for the development of road traffic evolution coefficients.

- Chapter 2 - Road traffic elements

Explores the theoretical foundations of road traffic, presenting the main characteristics and methods of traffic analysis. The chapter details key traffic indicators: intensity, flow, speed, axle load and origin-destination surveys, providing the technical basis for understanding traffic phenomena.

The statistical distributions of traffic characteristics are analyzed, treating traffic intensity as a choice variable and presenting the relevant statistical models (Poisson, Gauss, Gamma). The chapter addresses vehicle equivalence methods for determining capacity and analyzing road traffic capacity, establishing the technical foundations necessary for forecast calculations and optimizing traffic flows.

- Chapter 3 - Evolution of road traffic worldwide

It analyses global trends in road transport and identifies the determining factors at the international level. The chapter presents global influencing indicators: economic development (GDP), average income, population and motorization, demonstrating the correlations between these factors and the demand for road transport at the global level.

European forecasts for 2020-2030 are examined using the TRANS-TOOLS model and the impact of sustainable policies on traffic evolution is analyzed. The chapter presents differentiated regional trends, highlighting that in Central and Eastern Europe, road transport demand (both for goods and passengers) will grow faster than in developed economies in the western countries, providing the international context for the specifics of Romania.

- Chapter 4 - Analysis of the evolution of road traffic in Romania

It focuses on the national context, analyzing the Romanian specifics in road transports. The chapter presents the determining macroeconomic indicators: national GDP, GDP per capita, motorization rate, average salary, population and regional economic growth, establishing the correlations between these factors and the evolution of national road traffic.

Specific forecasts are developed for the period 2020-2050, analyzing the impact of demographic changes (14% population decline and increased road mobility) and the effects of the COVID-19 pandemic. The chapter demonstrates that robust economic growth combined with increased motorization will generate will lead to increased demand

on the road network, while the shift from rural areas to urban centers will drive the need for additional regional infrastructure development.

- Chapter 5 - Determination of road traffic evolution coefficients

It presents the methodology developed for road traffic forecasting and the results of its application. The chapter describes the multiple linear regression model based on the historical evolution (2000-2020) of the indicators GDP, GDP/capita, motorization rate and net income, adapted to the Romanian road specifics.

Three distinct scenarios (optimistic, medium, pessimistic) are developed for each vehicle category, presenting forecasts for 2050 with traffic increases according to each scenario. The results are corrected by logarithmic functions to reflect network saturation, providing practical tools for substantiating investments in road infrastructure.

- Chapter 6 - Final conclusions, original contributions, dissemination of results and future research directions

It synthesizes the original research contributions and presents recommendations for the practical application of the results. The chapter provides a summary of the evolution coefficients for main, secondary and European roads, grouped by the three scenarios reflecting different increases in mobility demand and provides the necessary tools for strategic planning.

The main original contributions are highlighted: defining the first long-term growth models for Romania, integrating economic and demographic elements into road models, and developing a methodology that can be used for other countries with similar characteristics to Romania. The chapter emphasizes that Romania has significant room for improvement through intelligent targeting of investments in regional infrastructure and presents recommendations for future research in the field of transport.

Combining variations in key assumptions results in a forecast with an increase in Average Daily Traffic (MZA) of between 40% and 100%. For 2050 compared to 2022, in the central forecast, an increase of about 60% is expected.

These data were obtained through the multiple linear regression method based on the historical evolution, between 2000 and 2020 (MZA 2020 was estimated from MZA 2022, the year in which the General Circulation Census was conducted) of four very important economic indicators, namely: Gross domestic product (PIB), Gross domestic product per capita (PIB/loc), Motorization grade (GM) and Average net income (VM)for which predicted values could be found from the sources mentioned in the paper.

These indicators were chosen because there is a close correlation between them (the closer the value is to 1, the better the correlation, see Table 2-1) as can be seen in the following table, there is a close correlation between these indicators.

Table 2-1 Indicators selected for analysis

	An	*PIB*	*PIB/loc*	*Grd mot*	*Vm*	*MZA*
An	1					
PIB	0.975923	1				
PIB/loc	0.972809	0.990552	1			
Grd mot	0.977834	0.953963	0.97752	1		
Vm	0.979957	0.997782	0.989996	0.96248	1	
MZA	0.94465	0.971738	0.989735	0.971518	0.97424	1

In this doctoral thesis, the multiple linear regression method was used to analyze the evolution of road traffic on the national road network, which allows highlighting the simultaneous influence of several economic and social factors on the dependent variable. This econometric method is frequently used in the analysis of complex economic phenomena, as it allows estimating the relationship between a dependent variable and several explanatory variables.

The dependent variable is represented by the MZA (annual average daily traffic expressed in physical vehicles), which reflects the level of road traffic. The independent variables considered in the model are: Gross Domestic Product (PIB), GDP per capita (PIB/loc), motorization rate (GM – number of vehicles per 1000 inhabitants) and average income (VM). These variables were selected because the specialized literature highlights a direct link between economic development, the level of motorization of the population and the intensity of road traffic.

The data used to estimate the model were collected for the period 2000–2020 and are presented in Table 2-2. Based on these data, the multiple linear regression equation was determined using the least squares method, a method that determines the model coefficients such that the sum of the squared errors between the observed and estimated values is minimal.

Table 2-2 Fundamental data

An	START ($ billions)	GDP/person ($)	GM (vehicles/1000 inhabitants)	VM ($)	MZA (physical vehicles)
2000	37	1659	124	99	3776
2005	98	4617	158	206	4150
2010	170	8397	214	390	5441
2015	178	8976	261	465	5498
2020	230	13600	350	636	6812

To evaluate the relationship between the analyzed variables and to verify the quality of the interdependence of the elements of the multiple regression equation, the correlation coefficient and the coefficient of determination are used.

The correlation coefficient (R) expresses the degree of intensity of the linear relationship between the dependent variable and the independent variables included in the model. Its value ranges from −1 to +1. A value close to +1 indicates a direct and very strong relationship between the variables, while a value close to −1 indicates a strong inverse relationship. If the correlation coefficient is close to 0, the linear relationship between the variables is weak or non-existent.

The coefficient of determination (R^2) is the square of the correlation coefficient and indicates the proportion of the total variation in the dependent variable that is explained by the independent variables included in the regression model. Its value ranges from 0 to 1 and is usually expressed as a percentage.

Thus, the coefficient of determination indicates the extent to which the econometric model accounts for the variation in the analyzed phenomenon. A high value of the coefficient of determination indicates that the explanatory variables included in the model have a good capacity to explain the variation of the dependent variable, which confirms the clarity of the model for analyzing the phenomenon under study.

In the context of the analysis of road traffic evolution, the coefficient of determination highlights the extent to which variations in the economic and social indicators considered (PIB, PIB/loc, GM and VM) explain changes in the level of road traffic expressed by the annual daily average of vehicles (MZA). The coefficients of determination can be found in Table 2-3.

Table 2-3 Multiple linear regression equation coefficients

Regression Statistics	
Multiple R	0.98838
R Square	0.9769

The correlation coefficient indicates how strong the linear relationship is.
The coefficient of determination which shows how many values (%) fall on the regression line

	Coefficients
Intercept	3668.049418
PIB	-11.93145679
PIB/loc	0.16439594
GM	-3.52534779
VM	6.740570812

The multiple regression equation for the development of traffic evolution coefficients is:

MZA = 3668.05 – 11.93 x GDP + 0.164 x GDP/loc – 3.53 x GM + 6.74 x VM (1)

The hypotheses for the three evolution variants, respectively average, optimistic and pessimistic, for a linear evolution of the growth rates for the 4 indicators are presented in Table 2-4, in accordance with the forecasts presented in the previous paragraphs.

Table 2-4 Growth rates for the 3 evolution scenarios

	Scenariu de evoluție		
	Pesimist	Mediu	Optimist
PIB	2.6	3.1	4.3
PIB/loc	3.5	4.2	5.2
GM	2	2.2	3
VM	2.6	3	4

Based on the multiple regression equation and the values of the four independent factors, the forecast values for the total MZA of the national road network were obtained, in the three variants: average, optimistic and pessimistic, for the period 2025-2050 and are presented in Table 2-5.

Table 2-5 Forecast values of PI, GDP/capita, Mot. Grd. Average Income and MZA

Pessimistic					
An	GDP (billion $)	GDP/person ($)	GM (vehicles/1000 inhabitants)	VM ($)	MZA (physical vehicles)
2025	261	16153	386	723	6722
2030	297	19185	426	822	7317
2035	338	22786	470	935	8027
2040	384	27063	519	1063	8871
2045	437	32142	573	1209	9867
2050	497	38175	633	1375	11051
average					
An	GDP (billion $)	GDP/person ($)	GM (vehicles/1000 inhabitants)	VM ($)	MZA (physical vehicles)
2025	268	16706	390	737	6810
2030	312	20522	435	854	7542
2035	363	25209	485	990	8445
2040	423	30967	541	1148	9543
2045	493	38040	603	1331	10885
2050	574	46728	672	1543	12533
Optimistic					
An	GDP (billion $)	GDP/person ($)	GM (vehicles/1000 inhabitants)	VM ($)	MZA (physical vehicles)
2025	284	17523	406	774	6946
2030	351	22578	471	942	7881
2035	433	29091	546	1146	9084
2040	534	37483	633	1394	10624
2045	659	48296	734	1696	12589
2050	813	62229	851	2063	15104

Table 2-6 Road traffic forecast – 2050

Road traffic forecast compared to 2022	Scenarios	Traffic (MZA)
Forecast 2050	Low demand	40%
	Average demand	60%
	High demand	100%

According to the MZA values, in the three hypotheses, optimistic, average and pessimistic, the evolution of road traffic for the period 2022-2050 is presented in Figure 51, the appearance of the graphs corresponding to an exponential evolution.

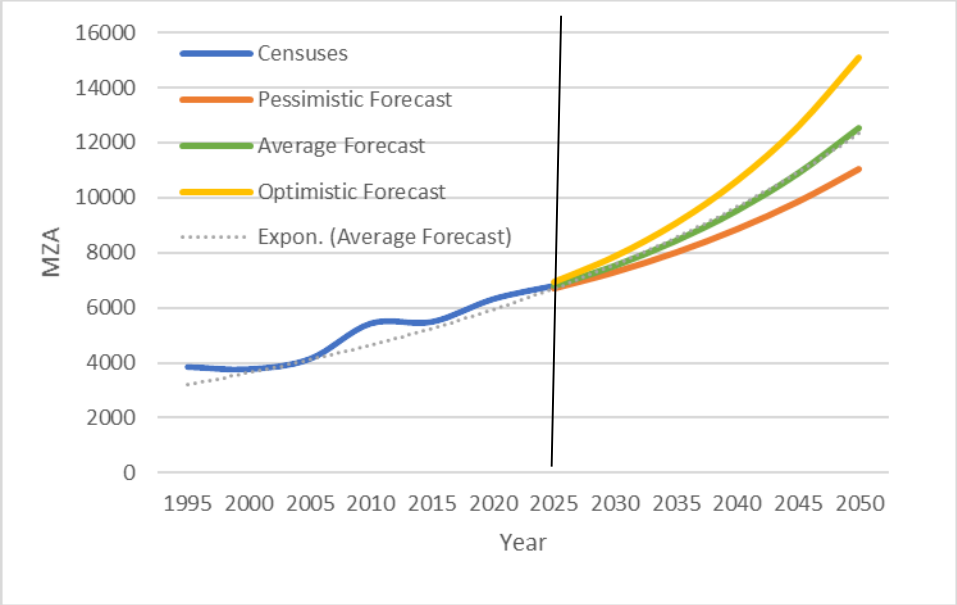

Figure 1 Evolution of road traffic 1995 – 2050

The real evolution of road traffic for the period 2022 - 2050 cannot follow the shape of the graph in Figure 50 because both the road network and the main indicators on which road traffic depends show, starting from a certain moment, a saturation trend.

As a result, given that at the beginning of the forecast period there is a sufficiently large reserve regarding traffic capacity on the entire national road network, that there are very large gaps between the average level of GDP/capita, motorization rate and average income in Romania compared to most European countries, we will consider more significant increases at the beginning of this period and smaller increases towards the end.

In the new hypothesis, the traffic evolution, keeping the values obtained through multiple linear regression for the end of the forecast period, but applying a logarithmic equation to the traffic growth trend, takes on the appearance shown in Figure 1.

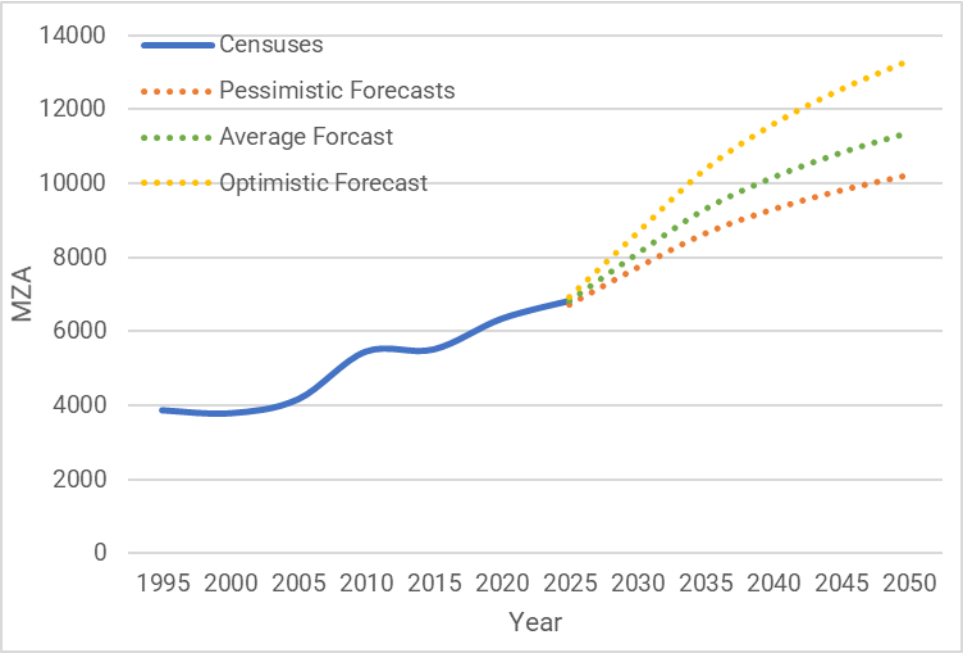

Figure 2 Road traffic evolution 2020 – 2050 – adjusted

1.1. Development of traffic evolution coefficients

1.1.1. Evolution coefficients for the European motorway and national road network

Elaborating road traffic evolution coefficients by vehicle categories for the period 2025-2050 is an extremely difficult task due to the fact that, over time, in accordance with the composition of the vehicle fleet in Romania, the vehicle categories have undergone permanent revisions.

Analyzing the vehicle categories used in censuses between 1980 and 2022, we can draw the following conclusions:

- There is no category of vehicles proposed for census in 2022 whose evolution can be analyzed over a period longer than 10 years (over 2 censuses);
- According to *Recommendations ECE/TRANS/WP.6/2019/11* the census must cover at least the following categories of motor vehicles: 1. Motorcycles; 2. Passenger cars (including minibuses with a maximum of 8+1 seats); 3. Pickup trucks with MTMA < 3.5t; 4. Lorries with MTMA > 3.5t; 5. Articulated vehicles; 6. Tractors and special vehicles. 7. Lorries with trailers. 8. Buses and coaches; [47]
- The categories recommended by ECE/TRANS/WP.6/2019/11 represent the European TLS classification system and ensure a sufficiently precise analysis of all vehicle categories found in the traffic censuses from 1980-2022.

The vehicle categories for which evolution coefficients were determined in this doctoral thesis are the following:

a. Bicycles and motorcycles;

b. Cars;
c. Minibuses with max. 8+1 seats;
d. Trucks and special vehicles with MTMA ≤ 3.5t;
e. Trucks and derivatives with 2 axles;
f. Trucks and derivatives with 3 or 4 axles;
g. Articulated vehicles (TIR type) and other vehicles with more than 4 axles;
h. Buses, coaches, minibuses with over 8+1 seats;
i. Tractors with/without trailers;
j. Trucks and derivatives with MTMA > 3.5t with trailers;
k. Passenger cars, motor vehicles with MTMA ≤ 3.5t with trailer;
l. Animal-drawn vehicles.

These vehicle classes were used in the 2022 General Road Traffic Census

1.1.2. Development of forecast coefficients for motorways and European road network - Total vehicles

The development of the evolution coefficients for motorways and European national road network is carried out using the same set of indicators as for the entire national road network, but having as dependent variable the historical evolution of the average daily annual traffic recorded in the general traffic censuses starting with 2000 and ending with the last census, in year 2022, for this particular network, as presented in Table 2-7.

Table 2-7 Evolution of the average daily annual traffic on the European motorway and national road network during the period 2000 – 2022

An	2000	2005	2010	2015	2022
MZA Physical vehicles	5518	6540	8963	9034	10283

By using the same multiple regression function and by adjusting the data using a logarithmic equation to the results obtained, in order to take into account the saturation trend of the road network, the obtained data is presented in Table 2-8 and Figure 3.

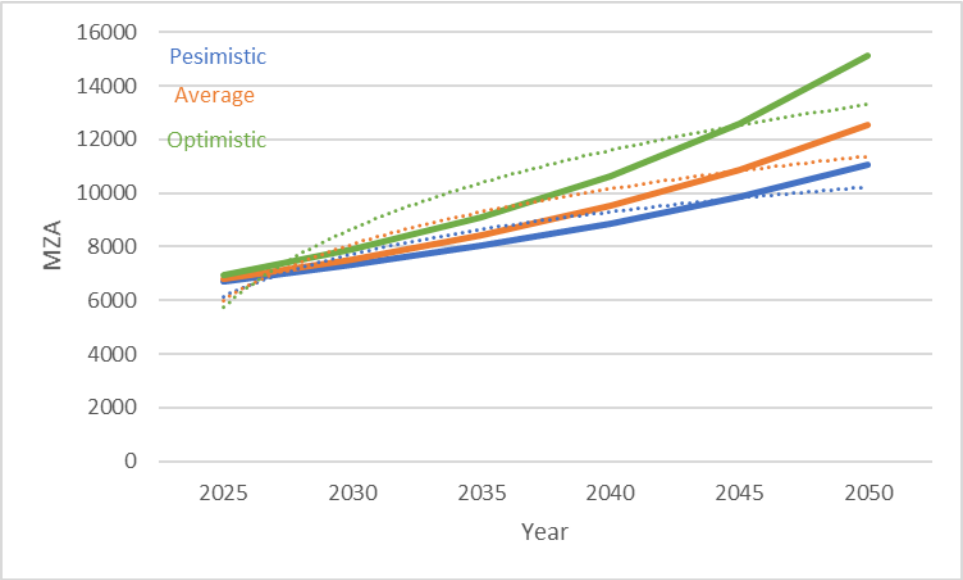

Figure 3 Road traffic evolution 2025 – 2050 - adjusted using the logarithmic equation

Table 5-8 The forecasted evolution of the average daily annual traffic on the European motorway and national road network, at the level Total vehicles

	Evolution scenarios		
	Pessimistic	Average	Optimistic
2022	1.00	1.00	1.00
2025	1.05	1.06	1.10
2030	1.12	1.14	1.21
2035	1.19	1.23	1.35
2040	1.26	1.31	1.47
2045	1.33	1.39	1.58
2050	1.39	1.47	1.68

Using the same calculation methodology, the traffic evolution coefficients for all aforementioned vehicle classes were determined in the thesis, in three scenarios of the evolution of macroeconomic indicators, for the period 2025-2050 by road types (European Roads and Motorways, Main National Roads and Secondary National Roads).

Capitolul 2. Final conclusions

The main objective of this research was to develop a methodology for forecasting the evolution of road traffic in Romania, based on the analysis of the correlation between socio-economic indicators and traffic volumes recorded on the road network. By applying an integrated approach that combines economic analysis with technical modeling

significant results were obtained for the substantiation of national road infrastructure development strategies.

The main results of the research demonstrate the existence of strong correlations between macroeconomic indicators (GDP, GDP/capita, motorization rate and average net income) and road traffic evolution. The developed multiple linear regression model provides robust forecasts for different vehicle categories and road types until 2050.

Conclusions on the specialized literature considered in the thesis:

- Chapter 3 is dedicated to the evolution of road traffic at a global level, provides an insight into the complex dynamics governing contemporary road transport. The analysis carried out demonstrates that understanding the global determinants is an essential condition for the development of accurate forecasts and effective strategies for the development of transport infrastructure.
- It is highlighted the existence of a strong and statistically significant correlation between socio-economic development and road traffic intensity. Economic indicators, especially Gross Domestic Product per capita, prove to be a primary factor in determining the demand for road transport. This direct relationship suggests that economic prosperity generates an increase in population mobility and the need for high freight transport.
- Demographic dynamics and changes in the occupational structure of the workforce are substantially influencing the global traffic patterns. The aging of population in developed countries is changing mobility patterns, while accelerated urbanization in emerging economies is concentrating transport demand in certain geographical areas. The geographical redistribution of jobs, a phenomenon associated with economic globalization, is generating new transport flows and changing traffic intensity on certain corridors.
- The degree of motorization and the evolution of the world's car fleet show distinct trends that reflect the level of development of different regions. Developed countries have reached a degree of relative saturation, with over 600 vehicles per 1000 inhabitants, while emerging economies are experiencing an accelerated expansion of the car fleet. This disparity generates major differences in the growth rates of road traffic between regions.
- The application of advanced statistical methods, in particular multiple linear regression, has proven effective in quantifying the relationships between economic indicators and road traffic evolution. The determination of evolution coefficients based on historical data allows the development of predictive models with a reasonable degree of accuracy. The use of the TRANS-TOOLS model at European level demonstrates the capacity of modeling tools to simulate complex scenarios and to provide credible estimates for future traffic evolution.

- Empirical validation of the identified causal relationships confirms the robustness of the methodological approach. The observed correlation between economic growth and road traffic intensification remains consistent over different time periods and geographical areas, suggesting the existence of fundamental mechanisms governing this relationship.
- Forecasts for the period 2020-2050 indicate sustained growth in global road traffic, with rates varying by region depending on the level of economic development. Emerging economies will experience significantly faster growth rates compared to developed countries, where existing infrastructure is approaching maximum capacity.
- The freight transport sector is particularly dynamic, with continuous expansion driven by increased global consumption and the increasing complexity of international logistics chains. Road transport maintains its central role in these transport chains, generating additional pressure on existing infrastructure, especially in the case of heavy and articulated vehicles.
- The mismatch between available transport infrastructure and growing demand is a major challenge for most countries. This discrepancy is particularly pronounced in emerging economies, where rapidly growing transport demand is outstripping the capacity for infrastructure development.
- Regional disparities in transport infrastructure development create jams in meeting global mobility demand. These inequities require an internationally coordinated approach to ensure efficient connectivity between regions and prevent the creation of jams in global transport flows.
- The rapid growth of road traffic raises serious sustainability and environmental issues. Greenhouse gas emissions from road transport, increasing urban congestion and the consumption of natural resources require finding an optimal balance between mobility needs and environmental protection.
- Rapid technological changes in the field of transportation, including the development of electric vehicles and intelligent transportation systems, will substantially modify traditional traffic forecasting models. These developments require continuous adaptation of analysis methodologies and increased flexibility in long-term planning.
- The success of future transport planning depends on adopting an integrated approach that simultaneously considers economic, demographic, technological and environmental factors. Effective linkage between national economic policies and transport development strategies becomes essential for optimizing infrastructure investments.
- Prioritizing infrastructure investments based on traffic forecasts is a necessary condition for the efficient allocation of public resources. Developing transport

networks that are both economically efficient and environmentally sustainable requires long-term planning based on rigorous analysis.

- International cooperation in the field of transport planning is becoming increasingly important in the context of the increasing globalization of the economy. Standardizing forecasting methodologies, sharing experience and good practices between countries, and developing common strategies for transnational challenges are key elements for the future success of global transport systems.
- The analysis of the evolution of road traffic worldwide confirms the complexity of the phenomenon and the need for a multidisciplinary approach for its complete understanding. The relationships identified between economic, demographic and technological factors provide a solid basis for the development of credible forecasts and effective development strategies.
- The results obtained in this chapter constitute the conceptual and methodological foundation for the specific analysis of traffic evolution on the national road network in Romania. The global context presented provides the necessary perspective for understanding local trends and for integrating them into the broader framework of international developments in the field of transport.
- The strategic importance of traffic forecasts for supporting infrastructure investment decisions becomes evident in the context of increasing pressures on existing transport networks. The ability to correctly anticipate future developments in transport demand is a crucial element for the long-term success of public transport policies.
- In order to assess the maximum variation around the central forecast, we model scenarios based on a combination of these indicators. The high demand scenario combines high GDP, namely a high GDP per capita, a high degree of motorization, a moderate population decline, an increase in employment, low oil prices and high fuel economy. Additionally, we can take into account the fact that there is a reserve of over 55% in terms of the traffic capacity of the national road network and the improvement of the quality of the road infrastructure. Consequently, each of these assumptions determines the increase in transport demand. The low demand case assumes a low GDP, and therefore low income per capita, a sharp decrease in population and employment, a degradation of the quality of the road infrastructure, high oil prices and a low level of fuel economy. Each of these assumptions determines the decrease in transport demand. A well-validated transport model, or travel demand model, is a commonly used and effective tool in some aspects of traffic forecasting. These models include the National Travel Demand Model and the European Travel Demand Model. However, a model is not a substitute for a comprehensive traffic forecasting effort. Before a travel demand model can be used for traffic design, additional details about the project area may be required, and additional traffic analysis areas and road links may need to be created in the model to more closely reflect the conditions of the

project area. The model should also be refined to incorporate future developments in the project area. Traffic volumes obtained directly from the travel demand model should not be used as detailed traffic forecasts for road projects.

- For a major highway project in an urban area, a travel demand model can be used to help estimate growth rates for future forecast conditions. Road improvement projects in rural areas can use a travel demand model to help estimate growth rates for future forecast conditions. Estimated growth rates from travel demand models should, however, be compared to historical traffic volume trends. Any significant discrepancy between estimated growth rates from model volumes and historical growth trends should be documented and appropriately accounted for in future forecasts. Traffic generated is the result of diverted traffic as well as vehicle-induced travel. When an existing route parallels a much more attractive new route, the total traffic on the two routes will be greater than that on the old route before the new route opened. This additional traffic resulting from deviation and normal growth is referred to as “generated traffic” and should be taken into account when determining the future growth rate.
- Traffic generation is typically highest for new interstates and highways. Traffic generation is typically more likely to occur in urban areas. All assumptions regarding traffic generation should be well documented. The estimated future growth rate (normal growth rate without adjustments) can be multiplied by 1.00 (without adjustment) or a higher value (for new interstates) to account for traffic generation based on the traffic study. The traffic generation adjustment should also be considered when determining whether the growth rates used for the Without Project and With Project traffic volumes will be the same or different.
- The design of road geometry is largely based on traffic volume forecasts. Since traffic forecasts are used throughout the project development process, it is important that the definition of the Without Project and With Project scenarios and the Base Year and Design Year remain consistent. It should be noted that the projected traffic forecasts for the 2 scenarios cannot have different traffic growth rates.
- In general, traffic forecasts should not change whether a road or intersection has a conventional or unconventional design. However, when a proposed improvement is expected to increase capacity, it may draw traffic from a parallel route. The traffic forecasting process should take this into account and make adjustments to reflect capacity changes due to an unconventional design, similar to the adjustments made for a conventional design.
- The transport model should be used to determine the traffic volume on a new bypass route. Usually, new roads, including bypasses, are already included in the national model. If this is not the case, the new route should be added to the model in the following year to determine the traffic volume for the design year. If the model is

calibrated, the projected traffic volumes can be obtained directly from the loaded model network. If the model has not been calibrated, traffic studies should consider comparing results from different models to obtain an estimated increase in traffic that is likely to be redirected to the new route.

- Once traffic growth rates have been developed, future traffic volumes for several sections along the project can be calculated and compared with the traffic volume projections from the calibrated national model. As a rule, the two projections should not differ by more than 10% from each other. If not, a traffic study should examine the disparity and propose an explanation for it. It is important to consider whether or not the future road can handle the expected traffic volumes. The traffic study should address this issue in the forecast documentation. Future traffic volumes should be compared with the capacity limits in the regulations. Adjustments may be necessary due to limited road capacity. If adjustments are made due to capacity constraints, these should be documented through traffic studies.
- The national travel demand forecasting model is used to estimate future traffic volumes over a planning period of at least 30 years. The models estimate future traffic volumes on segments of a functionally classified road network (motorways, national roads (European, main and secondary), county roads and municipal roads). It is also a tool that can be used by traffic studies as a secondary source of information to assess the reasonableness of projected future traffic forecasts.
- Accurate counting of truck and freight traffic demand is a top priority. Appropriate data sources should be used to determine the percentage of heavy traffic in the annual daily average. In general, the future percentage of heavy traffic should remain the same as the existing percentage of heavy traffic, unless documented by traffic studies. In addition, traffic studies should examine historical trends in truck traffic based on nearby traffic counters.
- For site-specific traffic forecasting, it is advisable to construct a localized travel demand model. Forecasting the future growth of millions of separate road trips is an impossible task given the enormous range of variables. In addition, it is possible to make reasonable assumptions about the factors that might be expected to change and to test the effects of these changing factors. A number of uncertainties remain in the forecasts, but, if the underlying relationships have been well determined and stable over long periods, probably to a lesser extent than is present in most forecasts. The forecasts are broken down by road type, and by vehicle type. They therefore indicate how traffic on various road categories can be expected to grow. It should be emphasized, however, that the figures do not apply to any particular length of a particular type of road in a particular type of area. Those roads where traffic is closest to capacity should grow more slowly than the national average; those with more nominal capacity available could grow more rapidly, and those subject to diversion from the most congested roads even more rapidly. In addition, areas with population

and economic activity growing faster than the national average will also grow traffic above the national average. Likewise, areas where motorization is currently below the national average can be expected to grow traffic more rapidly.

- All forecasts are inherently uncertain, this uncertainty being determined by the variability of input indicators. The forecast for the period 2020–2050 is more detailed than previous road traffic forecasts, which leads to an improvement in the basis of analysis and a better reflection of real uncertainties, by taking into account a larger number of variables. It is not realistic to adopt high growth assumptions for all variables over the entire forecast period, as the probability of maintaining high growth rates in the long term is low. On the other hand, in the early years there is a higher degree of uncertainty, associated with the positioning of the economy within the business cycle. At the same time, the interaction between the elements of the forecast can lead to a reduction in aggregate uncertainty. Consequently, the forecast has been developed based on the most probable estimates of all components, values close to these estimates being considered more likely to materialize than those located at a greater distance.
- Restricting the projections to the current road network does not cause traffic growth to cease, although it does cause the growth rate to increase at a slower rate than would otherwise be the case and compared to the recent past, especially in the last years of the projection. In response to the decrease in speed and/or reliability, travelers change their travel time, route, origin and/or destination, travel less frequently, combine trips (sometimes with other travelers), and switch modes for all or part of the trip (little influenced by the quality and costs of the other modes); only in a minority of cases do they stop traveling.
- The average daily annual traffic will register significant increases as a result of an increase of the degree of motorization, finding a real solution to shorten the time spent in traffic will become an urgent matter.
- It is estimated that there will also be a trend of increasing motorcycle traffic on the main national road network, but somewhat slower than on European roads.
- There is a continuous decrease in 2-axle truck traffic for the period 1990 - 2015, so for the next period we can expect, at best, a slight increase, as the demand for medium-distance freight transport increases.
- Given that, in the 1990s, there was no diversity of trucks and special vehicles for transporting grain and construction materials, this gap was filled by tractors using trailers. As the truck category diversified, the use of tractors for transportation purposes began to be abandoned.
- It is noted that this is a new category of vehicles with a continuous decrease from 1990 to the present in the average daily annual traffic. Trucks with trailers are heavy and unstable on the road. They were a solution to increase the transport capacity in

the conditions in which trucks did not have MTMA greater than 10 - 15 tons. Consequently, it is expected that their number will also be decreasing for the coming period.

- The category of motor vehicles with MTMA ≤ 3.5t with trailer is newly introduced in the census list and as a result it will be very difficult to estimate the evolution coefficients for the period 2022 - 2050. For this reason, as in the development of the coefficients we will take into account the possibility that this category of motor vehicles had a similar trend to the total number of freight vehicles.

2.1. Personal contributions

My research makes significant original contributions to the field of transport engineering through:

- Methodological contributions

- The development of an integrated methodology that combines, for the first time in the Romanian context, economic analysis with technical traffic modeling, providing a combined approach to road traffic forecasting. This methodology overcomes the limitations of previous models by explicitly integrating socio-economic factors into the forecast equations.

- Applicative contributions

- The determination of the evolution coefficients for different vehicle categories and road types constitutes the main applied contribution of the research. For the category "Articulated vehicles (TIR)" on the European road network, the forecast coefficients evolve from 1.00 in 2022 to 1.93 for the average scenario, 2.30 for the optimistic scenario and 1.86 for the pessimistic scenario in 2050.
- The development of a set of scenarios (optimistic, medium, pessimistic) that reflect economic and social uncertainties provides the necessary tools for flexible planning of infrastructure investments. These scenarios allow for an adaptive approach to development strategies depending on future economic developments.

- Long-term forecast results

  The results of the analysis indicate significant increases in road traffic for all vehicle categories and road types analyzed:

- Developing and justifying an optimistic growth scenario for road traffic by 2050, which projects a potential doubling of volumes based on its correlation with key drivers like sustained GDP growth (annual GDP of 4–5%), the intensification of urbanization and the development of the national road transport sector, as well as the convergence of the degree of motorization towards the European average

- The pessimistic scenario serves as a lower-bound projection, reflecting the impact of decarbonisation targets and a significant modal shift that could limit traffic growth to approximately 40% by 2050.
- Detailed analyses reveal significant differences in traffic evolution by vehicle categories:
  - Heavy commercial vehicles are experiencing the highest growth rates, reflecting the development of international trade and modern logistics. For this category, the growth coefficients on highways reach values above 2.0 in the optimistic scenario by 2050.
  - Passenger cars show a more moderate evolution, influenced by the gradual saturation of the car market and trends towards sustainable mobility. Estimated increases are between 50-80% depending on the scenario and the type of road.
- The research results provide the scientific foundation for strategic planning of the national road infrastructure:
- Prioritizing investments in the expansion and modernization of highways becomes imperative, given the forecasted increases in international transit traffic. The developed coefficients indicate the need to double capacity on the main European corridors by 2050.
- The development of the secondary network requires increased attention, given the redistribution of traffic from national roads to the local and county network. Specific forecasts for this category indicate increases of 40-70%, requiring sustained investments in the modernization of the existing infrastructure.
- Integration into national strategies - The developed coefficients serve as a basis for updating the National Transport Strategy and for substantiating project proposals within European funding programs (TEN-T, Structural Funds).
- Alignment with European standards - The developed methodology complies with UNECE/EUROSTAT recommendations and uses tools compatible with the European TRANS-TOOLS model, ensuring consistency with European-level planning.
- The forecast coefficients for the road network were taken over as part of the update *"Standard for determining the calculation traffic for road design in terms of bearing capacity and circulation capacity (AND 584/2025)"*

Contributions to knowledge in the field

- The research introduces significant methodological innovations in the field of road traffic forecasting:

- The design of a multiple regression model that, together with logarithmic functions to correct for exponential growth trends in the initial phase, as well as the integration of the saturation effects of the road network starting with 2040, provides a more realistic approach than the simple linear models previously used.

- The use of an extensive network of automatic traffic counters to improve data quality and generate a more accurate predictive base, combined with the analysis of historical data from the CESTRIN censuses (1980-2022), creates a database for the analysis of Romanian road traffic.
- The developed methodology can be adapted and applied in other countries with similar socio-economic characteristics to Romania, especially in Central and Eastern European countries in the process of economic convergence towards European standards. The general principles of the model can be transferred by adapting specific local parameters.

2.2. Dissemination of results

The author disseminated the results of the doctoral thesis in the following conferences and scientific articles:

- Sandu Robert Adrian, Răcănel Carmen, Documentary study on establishing global traffic evolution functions, PPCS - Research Report No. 1, 2021;
- Sandu Robert Adrian, Răcănel Carmen, Analysis of traffic evolution on Romanian roads, PPCS - Research Report no. 2, 2021;
- Sandu Robert Adrian, Răcănel Carmen, Traffic evolution functions, PPCS - Research Report no. 3, 2022;
- Sandu Robert Adrian, Răcănel Carmen, Traffic Data Collection Systems: VEKPI – Count, Romanian Journal of Transport Infrastructure 14(2):1-11, February 2026; https://www.researchgate.net/publication/401040921_Traffic_Data_Collection_Systems_VEKPI_-_Count
- Petcu Mihai Dragos, Racanel Carmen, Ioniță Stefan, Sandu Robert Adrian, Correlation of Road Crashes with Road Characteristics, Romanian Journal of Transport Infrastructure 14(2):1-20, February 2026; https://www.researchgate.net/publication/401040638_Correlation_of_Road_Crashes_with_Road_Characteristics
- Sandu Robert Adrian, Anicăi Anca, The impact of the Sars-CoV2 pandemic on road traffic, Conference: ROAD RESEARCH AND ADMINISTRATION "C.A.R.", December 2024; https://www.researchgate.net/publication/400900839_Impactul_pandemiei_Sars-CoV2_asupra_traficului_rutier

- Ioniță Ștefan, Sandu Robert Adrian, Radu Robert Silviu Iacob, BRIDGE MANAGEMENT SYSTEM (BMS) Substantiation tool regarding the prioritization of bridges for carrying out rehabilitation and maintenance works on the D.N. and Motorways network in Romania, based on the analysis of the main technical condition indicators and the level of intervention, Conference: ROAD RESEARCH AND ADMINISTRATION "C.A.R.", 2024; https://www.researchgate.net/publication/400900761_BRIDGE_MANAGEMENT_SYSTSY_BMS_Instrument_de_fundamentare_privind_prioritizarea_podurilor_pentru_efectuaref_lucrarilor_de_reabilitare_si_intretinere_pe_reteaua_de_DN_si_Autostrazi_din_RomanRo_in_baza_an
- Ioniță Ștefan, Sandu Robert Adrian, Niculescu Mariana, Road Management System (PMS/GIS) developed and used by CESTRIN for Prioritizing Current Maintenance and Repair Works on the Highways and National Roads Network in Romania, Conference: ROAD RESEARCH AND ADMINISTRATION "C.A.R.", 2024; https://www.researchgate.net/publication/400900599_Sistemul_de_management_al_drumurilor_PMSGIS_dezvoltat_si_utilizat_de_CESTRIN_in_vederea_Prioritizati_Lucrarilor_de_Intretinere_si_Reparatii_curente_pe_Reteaua_de_Autostrazi_si_Drumuri_Nationale_din_R
- Sandu Robert Adrian, Răcănel Carmen, Key indicators affecting the evolution of road traffic in Romania, Conference: 8th International Conference on Road and Rail Infrastructure, 2024; https://www.researchgate.net/publication/385242844_Key_indicators_affecting_the_evolution_of_road_traffic_in_Romania
- Dan Crăciunescu, Răcănel Carmen, Ioniță Ștefan, Sandu Robert Adrian, George Sicoe, Mariana Niculescu, Advanced Technologies for Detection and Assessment of Road Degradation State. Experimental and Modeling Approaches, Romanian Journal of Transport Infrastructure 12(2):1-17, 2024; https://www.researchgate.net/publication/379216835_Advanced_Technologies_for_Detection_and_Assessment_of_Road_Degradation_State_Experimental_and_Modeling_Approaches
- Hagiescu Corneliu, Hagiescu Mihai, Cristian Păunescu, Sandu Robert Adrian, Ștefan Velicu, Innovative Use of Torcreting (Guniting) for Repairing Wearing Surface of Roads, Advancements in Civil Engineering & Technology 5(2), July 2022; https://www.researchgate.net/publication/361998911_Innovative_Use_of_Torcreting_Guniting_for_Repairing_Wearing_Surface_of_Roads
- Sandu Robert Adrian, Răcănel Carmen, Daniela Ioana Manea, Mihaela Mihai, Possibilities to quantify the road traffic on the national road network and motorways in Romania, Proceedings of the International Conference on Applied Statistics, 2019; https://www.researchgate.net/publication/339266700_Possibilities_to_quantify_the_road_traffic_on_the_national_road_network_and_motorways_in_Romania

- Sandu Robert Adrian, Răcănel Carmen, Considerations regarding the evolution of road traffic on the national road and motorway network in Romania, XV National Congress of Roads and Bridges, Iasi, September 19-22, 2018; https://www.researchgate.net/publication/358676109_CONSIDERATII_PRIVIND_EVOLUTIA_TRAFICULUI_RUTIER_PE_RETEAUA_DE_DRUMURI_NATIONALE_SI_AUTOSTRAZI_DIN_ROMANIA
- Sandu Robert Adrian, Valentin Anton, Mathematical modeling of non-rigid road systems, Student Scientific Session Transport Infrastructure Engineering 8th edition, Bucharest, June 25, 2018.
- Sandu Robert Adrian, Răcănel Carmen, Determining the coefficients of road traffic evolution on the national road network – Methodological substantiation and implications for infrastructure planning, Drumuri Poduri Magazine, March 2026

2.3. Future research directions

The results obtained in this research highlights both the robustness of the proposed methodology for road traffic forecasting and the complexity of the analyzed phenomena. In this context, a series of future research directions are outlined aimed at deepening, extending and refining the developed conceptual and applicative framework.

- Improving road traffic forecasting models

Although the multiple linear regression model used demonstrated a high capacity to explain the variation in road traffic, future research may aim at integrating advanced modeling methods. In this regard, the use of nonlinear models, machine learning techniques and dynamic econometric models can contribute to a more faithful capture of the complex relationships between socio-economic variables and transport demand. Thus, an increase in the accuracy of forecasts can be achieved, especially in conditions of economic volatility and structural changes.

- Integrating the impact of technological change into traffic models

Rapid developments in transport technologies require continuous development of forecasting methodologies. Future research should analyze the impact of electric vehicles, autonomous vehicles and intelligent transport systems on traffic volumes and composition. These technologies can significantly change user behavior and the spatial distribution of traffic flows, requiring the development of predictive models adapted to the new realities.

- Integrating the environmental and sustainability dimension

The growth of road traffic generates significant pressures on the environment, which requires the explicit inclusion of sustainability indicators in forecasting models. Future research directions may aim at correlating traffic volumes with greenhouse gas emissions, resource consumption and impact on air quality. In this context, the

development of sustainable transport scenarios becomes essential for the substantiation of public policies oriented towards decarbonisation.

- Development of traffic models at regional and local level

The research results highlight the limitations of nationally aggregated models in capturing local traffic characteristics. Consequently, an important research direction is the development of regional and local models, capable of reflecting the specifics of urban and peri-urban areas. The integration of fine-scale mobility data and the analysis of generated and redistributed traffic can lead to a better substantiation of infrastructure projects.

- In-depth analysis of freight transport

Given the accelerated dynamics of freight transport, it is necessary to develop models dedicated to this segment. Future research may include the analysis of logistics flows, the impact of e-commerce and the evolution of supply chains on road traffic. Such an approach would allow for a more precise differentiation of forecasts by vehicle categories and transport types.

- Uncertainty modeling and probabilistic scenario development

Traffic forecasts are inherently affected by uncertainties generated by the variability of input factors. In this context, future research may aim at developing probabilistic models that allow quantifying the risks associated with different evolution scenarios. The use of simulations and confidence intervals can contribute to better substantiating decisions regarding infrastructure investments.

- Assessing the impact of public policies on transport demand

A relevant research direction is the analysis of the interdependence between public policies and the evolution of road traffic. Studying the effects of transport taxes, traffic restrictions and urban mobility policies can provide valuable information for optimizing infrastructure development strategies and managing transport demand.

- Extending the methodology to an international context

The methodology developed in this research has potential for application in other countries with similar socio-economic characteristics. Future research may aim at testing and adapting the model in different national contexts, especially in Central and Eastern European countries. This will allow the generalizability of the results to be assessed and any necessary adjustments to be identified.

- Leveraging Big Data in traffic analysis

The development of digital technologies offers significant opportunities for improving the quality of data used in forecasting. The integration of data from sensors, navigation

applications and mobile devices can enable more detailed and real-time analysis of road traffic. Future research can explore ways to use these data sources to increase the accuracy of predictive models.

- Analysis of the relationship between infrastructure and induced demand

The concept of generated traffic highlights that infrastructure development can lead to increased transport demand. In this context, future research can aim to quantify the relationship between infrastructure investments and traffic developments, as well as to assess the long-term effects of road network expansion. Such an analysis is essential to avoid over- or under-dimensioning of infrastructure projects.

In conclusion, the proposed future research directions highlight the need for a multidisciplinary and adaptive approach to road traffic analysis and forecasting. The integration of economic, technological, environmental and social factors into a unified methodological framework is an essential condition for the development of robust predictive models and for the substantiation of efficient long-term transport policies.