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Doctoral Thesis

Doctoral Thesis Summary

STUDIES AND RESEARCH ON THE INFLUENCE OF ROAD TRAFFIC ON FUEL CONSUMPTION AND VEHICLE EMISSIONS

STUDII ŞI CERCETĂRI PRIVIND INFLUENŢA TRAFICULUI RUTIER ASUPRA CONSUMULUI DE COMBUSTIBIL ŞI A EMISIILOR AUTOVEHICULELOR

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Thank you.

Foreword

In the current context of global concerns regarding climate change, deteriorating air quality, and the need to transition towards sustainable mobility, the environmental impact of road transport has become one of the most important areas of research internationally. In recent years, scientific and policy discussions have increasingly focused on the role of motor vehicles in generating greenhouse gas emissions and atmospheric pollutants, leading to an accelerated shift towards vehicle electrification and a gradual reduction in the use of internal combustion engines.

The choice of this research topic was motivated by the need for a rigorous, scientifically grounded, and balanced assessment of the actual influence of road traffic conditions on vehicle fuel consumption and emissions. Although the transport sector is frequently at the forefront of discussions concerning environmental pollution, it is essential that impact assessments be based on reliable experimental data obtained under real-world operating conditions and correlated with numerical simulation scenarios. In this context, the present thesis aims to provide an in-depth investigation involving several types of vehicles, highlighting how traffic conditions influence emission levels and fuel consumption.

Through experimental investigations and simulations developed in the AMESIM environment, this thesis demonstrates that measures aimed at improving traffic flow and maintaining a constant vehicle speed can lead to substantial reductions in pollutant emissions and energy consumption along specific road sections. This finding supports the need to integrate intelligent traffic management measures into modern environmental protection strategies and urban mobility optimization approaches.

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Contents

1. INTRODUCTION.....	6
1.1. Assessment of Pollution Generated by Road Transport and the Environmental Effects of Emissions from Internal Combustion Engines.....	6
1.2. Research Objectives.....	8
2. CURRENT STATE OF RESEARCH ON THE RELATIONSHIP BETWEEN MOTOR VEHICLES, ROAD TRAFFIC, POLLUTANT EMISSIONS, AND FUEL (ENERGY) CONSUMPTION	10
2.1. Current State of Research on the Influence of Road Traffic Parameters on Vehicle Fuel Consumption and Emissions	10
2.2. General Considerations on Vehicle Dynamics in Road Traffic	11
2.3. Basic Elements of the Road Transport System	12
2.4. Vehicle Propulsion Systems.....	12
2.5. Effects of Propulsion System Design Characteristics on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions	13
2.6. Effects of Propulsion System Operating Parameters on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions	14
2.7. Influence of Vehicle Design Parameters on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions.....	14
2.8. Influence of Road Traffic Parameters on Vehicle Emissions and Fuel (Energy) Consumption	15
2.9. Driving Cycles Used for Measuring Emissions and Fuel (Energy) Consumption	16
3. MODELING AND SIMULATION OF REAL-WORLD DRIVING CYCLES IN THE AMESIM ENVIRONMENT.....	18
3.1. Objectives of Driving Cycle Simulation.....	18
3.2. Modeling and Simulation Methodology	18
3.3. Simulation of Driving Cycles Using Real-World Traffic Data	19
4. EXPERIMENTAL RESEARCH AND DATA PROCESSING	23
4.1. Experimental Research Methodology	23
4.1.1. Preparation of Equipment for Experimental Research.....	24
4.1.2. Route Selection Criteria for Experimental Research to Develop Real-World Driving Cycles	25
4.2. Vehicles Used for Testing (Vehicle Specifications)	26
4.3. Specifications of the Equipment Used in the Experimental Research	26
4.3.1. Chassis Dynamometer	26
4.3.2. Gas Analyzer	27
4.3.3. OBD II Diagnostic System – KTS 560	28
4.3.4. Fuel Flow Meter	28
4.3.5. Statistical Analysis of Experimental Data.....	29
5. RESULTS OF THE EXPERIMENTAL RESEARCH	30
5.1. Influence of Urban Traffic Characteristics on Exhaust Emission Concentrations and Fuel Consumption (Test Series I).....	30

5.2. Investigation of Factors Influencing Exhaust Emission Concentrations and Fuel Consumption under Urban Traffic Conditions (Test Series II)	34
5.3. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Suburban Traffic Conditions	37
5.4. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Extra-Urban Traffic Conditions	41
5.5. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Road Traffic Conditions Represented by the WLTC Driving Cycle.....	44
5.6. Comparison of Experimental Results Obtained under WLTC and Real-World Driving Conditions	47
6. CONCLUSIONS AND PERSONAL CONTRIBUTIONS.....	49
6.1. Final Conclusions.....	49
6.2. Personal Contributions.....	50
6.3. Future Research Directions and Developments (Proposals for Future Work).....	50

1. INTRODUCTION

Road transport is an essential component of economic and social development, ensuring the mobility of people and goods and contributing to regional interconnectivity. Like other economic activities involving energy conversion processes, the operation of this sector generates emissions that affect the environment. However, these emissions must be assessed within a broader context, considering the full range of anthropogenic sources and the differing contributions of the energy, industrial, agricultural, and transport sectors. Accordingly, the environmental impact of road transport must be assessed objectively, based on its actual contribution to overall emissions and in relation to technological advances in motor vehicles and the progressive reduction of vehicle-specific emissions [1–3].

Over the past two decades, technological advances in motor vehicles and the successive introduction of European emission standards have led to reductions in vehicle-specific emissions and improvements in energy efficiency. The Euro standards have established progressively stricter limits for nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM), driving the development and implementation of advanced emission control systems. At the same time, the optimization of combustion processes, the use of modern fuel injection systems, turbocharging, exhaust gas recirculation, exhaust aftertreatment systems, partial electrification of propulsion systems, transmission optimization, and vehicle mass reduction have contributed to lower fuel consumption and a reduced environmental impact.

Meanwhile, vehicle evaluation methods have evolved from standardized laboratory driving cycles, such as the New European Driving Cycle (NEDC), towards procedures and testing methods that are more representative of real-world operating conditions, such as the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and Real Driving Emissions (RDE) testing. This development highlights the need to assess vehicle performance not only under standardized conditions but also in relation to the specific characteristics of real-world road traffic [2–5].

The relevance of research in this field is reinforced by European objectives aimed at reducing the environmental impact of transport, improving energy efficiency, and transitioning towards sustainable mobility. In this context, investigating the relationship between traffic conditions, vehicle operating regimes, fuel consumption, and pollutant concentrations is of particular importance. Dynamic driving parameters, such as vehicle speed, acceleration and deceleration, idling periods, traffic intensity, and road infrastructure characteristics, can significantly influence engine operating conditions and, consequently, fuel consumption and exhaust emission concentrations.

The present doctoral thesis addresses this research area by investigating in greater depth the relationship between road traffic conditions and the energy-related performance of motor vehicles. The proposed methodological approach integrates data collected under real-world traffic conditions with experimental investigations conducted under controlled laboratory conditions. Dynamic parameters recorded in real-world traffic are used to develop driving cycles, which are subsequently reproduced on a chassis dynamometer. This methodology enables a controlled and repeatable analysis of vehicle performance and an assessment of the influence of different operating regimes on fuel consumption and exhaust emission concentrations.

1.1. Assessment of Pollution Generated by Road Transport and the Environmental Effects of Emissions from Internal Combustion Engines

Globally, the transport sector accounts for approximately 20–24% of CO_2 emissions associated with energy consumption [5], with road transport representing the largest share within this sector. In the

European Union, the contribution of road transport to overall emissions is determined by both the high volume of passenger and freight transport and its fundamental role in economic activity. At the same time, the continuous growth of the vehicle fleet must be assessed in conjunction with technological advances in motor vehicles and the reduction in vehicle-specific emissions achieved through the introduction of emission standards and the development of modern propulsion and exhaust aftertreatment systems [2, 3, 5–7].

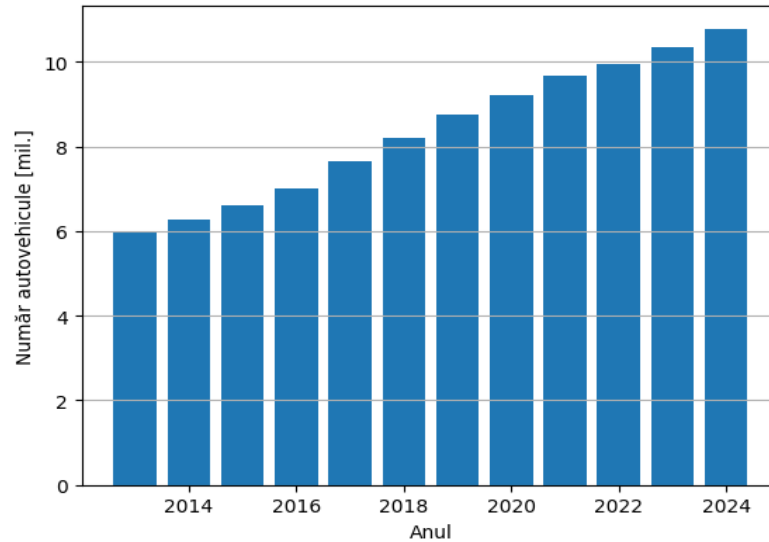


Fig. 1.1 - Evolution of the Vehicle Fleet in Romania, 2013–2024 [8]

The evolution of European emission standards illustrates the progressive tightening of the limits imposed on the main pollutants emitted by motor vehicles. The Euro 6 standard, gradually introduced from 2014 onwards, marked an important milestone by establishing stricter emission limits and extending vehicle emission assessments to real-world driving conditions through Real Driving Emissions (RDE) testing.

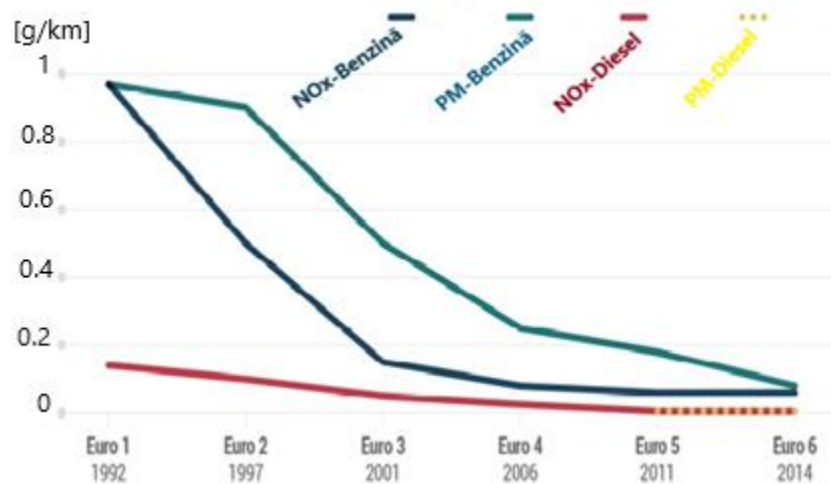


Fig. 1.2 - Influence of Euro Emission Standards on Vehicle Emissions [2]

A new stage is represented by the Euro 7 standard, which extends the assessment of vehicle environmental impacts beyond exhaust emissions. The regulation introduces requirements concerning non-exhaust emissions, including those generated by brake and tyre wear, as well as additional requirements regarding the durability of emission control systems and their monitoring throughout the vehicle's service life. For passenger cars and light-duty vehicles, the emission limits for the main pollutants remain similar to those established under Euro 6. However, the requirements for maintaining the performance of emission control systems are extended to at least 10 years or 200,000

km [9–13]. Thus, the emphasis shifts from assessing emissions generated solely by engine operation towards evaluating the environmental impact of vehicles over an extended period of operation.

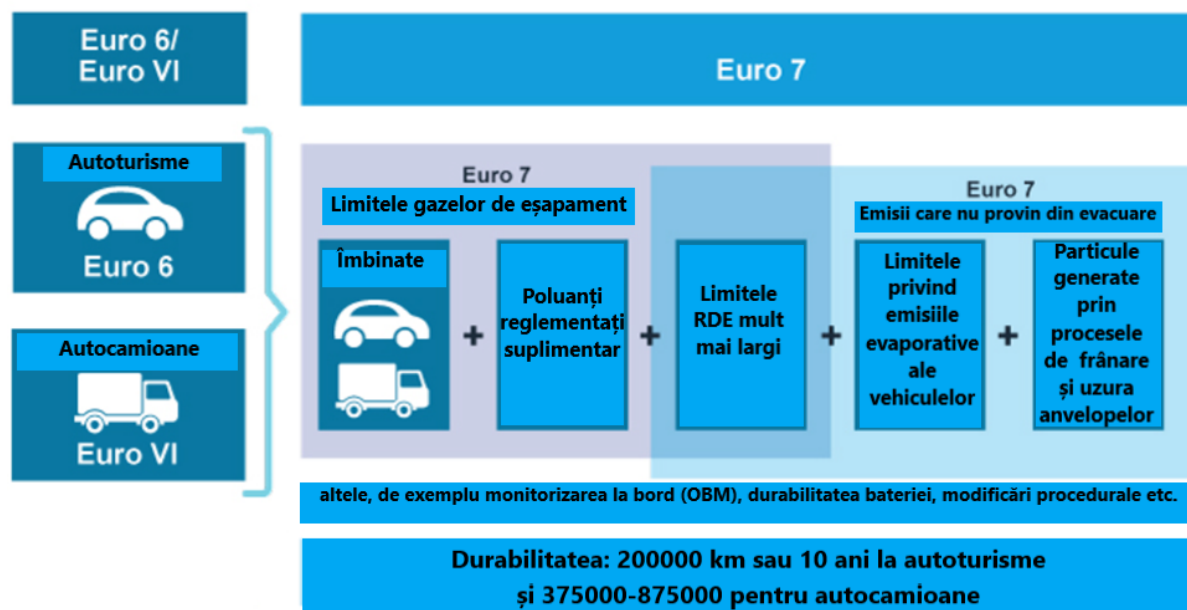


Fig. 1.3 - Evolution of European Emission Standards – Transition from Euro 6 to Euro 7 [9]

Emissions associated with road transport include both greenhouse gases, such as CO₂, CH₄, and N₂O, and atmospheric pollutants, such as nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), and sulfur dioxide (SO₂). Their effects occur both directly and through the formation of secondary pollutants. NO_x has significant adverse effects on the respiratory system and contributes to the formation of ground-level ozone, while CO impairs oxygen transport in the human body. Fine particulate matter, originating from both combustion processes and brake and tyre wear, is associated with respiratory and cardiovascular diseases. Furthermore, atmospheric reactions involving NO_x and VOCs contribute to the formation of ground-level ozone and secondary particulate matter [10–15].

Carbon dioxide (CO₂) is one of the main products of fuel combustion in internal combustion engines and plays an important role in the global climate balance. A proportion of anthropogenic CO₂ emissions is absorbed by vegetation, soils, and oceans, while the remaining fraction accumulates in the atmosphere [3, 16]. Reductions in atmospheric CO₂ concentrations can be supported through both natural carbon sequestration processes, such as afforestation, reforestation, and soil carbon management, and carbon capture and storage technologies [17, 18].

Overall, assessing the environmental impact of road transport highlights the need for an integrated approach. Reducing this impact depends not only on the development of propulsion systems and exhaust gas aftertreatment technologies but also on the actual operating conditions of motor vehicles and the organization of road traffic. From this perspective, identifying vehicle operating regimes associated with high fuel consumption and elevated pollutant concentrations represents a relevant research direction for optimizing road mobility.

1.2. Research Objectives

The main objective of this doctoral thesis is to assess the influence of road traffic conditions on CO, NO_x, and CO₂ concentrations and fuel consumption in vehicles equipped with internal combustion engine-based and hybrid propulsion systems, in the context of current requirements aimed at reducing the environmental impact of transport. The research is based on the hypothesis that exhaust emission concentrations and fuel consumption are influenced by both engine operating conditions and the

dynamic characteristics of road traffic, including vehicle speed, stops, acceleration and deceleration, road infrastructure characteristics, and traffic intensity.

To achieve the main research objective, the following specific objectives were established:

- To review the scientific literature and representative research findings concerning the influence of road traffic on pollutant concentrations and fuel consumption;
- To develop an experimental model for evaluating exhaust emission concentrations as a function of traffic intensity, based on real-world data and statistical analysis of driving cycles;
- To analyze the behavior of exhaust emission concentrations under idling and dynamic operating conditions, in order to identify differences associated with engine operating regimes;
- To determine variations in exhaust emission concentrations and fuel consumption according to road traffic intensity—low, moderate, and high—and urban or extra-urban driving conditions;
- To identify segments of real-world driving cycles characterized by significant increases in exhaust emission concentrations and fuel consumption, as well as segments exhibiting substantially lower values;
- To compare the experimental results obtained on the chassis dynamometer with the manufacturer-declared values determined according to the WLTP, in order to highlight differences between standardized testing conditions and real-world operating conditions;
- To assess the influence of engine management systems on exhaust emission concentrations and energy efficiency;
- To conduct a comparative analysis of urban and extra-urban driving cycles in terms of exhaust emission concentrations and fuel consumption, with the aim of identifying findings applicable to road traffic management;
- To evaluate the potential for reducing pollutant concentrations by optimizing traffic conditions, including traffic signal management, the use of roundabouts, speed control, and congestion reduction, through the modeling and simulation of a real-world driving cycle in the AMESIM environment.

2. CURRENT STATE OF RESEARCH ON THE RELATIONSHIP BETWEEN MOTOR VEHICLES, ROAD TRAFFIC, POLLUTANT EMISSIONS, AND FUEL (ENERGY) CONSUMPTION

The relationship between motor vehicles, road traffic conditions, and energy performance requires an integrated approach that simultaneously considers the characteristics of propulsion systems, vehicle design characteristics, road infrastructure, traffic flow parameters, and real-world operating conditions. Technological advances in the automotive sector have focused on optimizing combustion processes, reducing energy losses, recovering energy, developing exhaust aftertreatment systems, and expanding the use of hybrid and electric propulsion systems. In parallel, the development of intelligent infrastructure and modern traffic management systems offers opportunities to optimize traffic flow and reduce fuel consumption under real-world operating conditions.

Current studies indicate that energy performance and exhaust emission concentrations are not determined exclusively by engine characteristics but result from the interaction between the vehicle, driver, road infrastructure, and traffic conditions. Parameters such as vehicle mass and aerodynamic characteristics, speed, acceleration, traffic density, idling periods, intersection types, traffic signal control, and road longitudinal gradient continuously influence the load on the propulsion system and, consequently, fuel consumption and exhaust emission concentrations. This integrated approach forms the basis for analyzing the vehicle–traffic–emissions–fuel consumption relationship investigated in this doctoral thesis.

2.1. Current State of Research on the Influence of Road Traffic Parameters on Vehicle Fuel Consumption and Emissions

Methods for evaluating fuel consumption and emissions have evolved from testing exclusively under standardized laboratory conditions towards approaches that combine real-world driving measurements with controlled testing on a chassis dynamometer. The use of Portable Emissions Measurement Systems (PEMS), On-Board Diagnostics (OBD) and Global Positioning System (GPS) data, as well as telematics systems, enables the characterization of vehicle behavior under real-world driving conditions, while reproducing driving cycles on a chassis dynamometer provides the control and repeatability required for comparing results [19, 20].

The scientific literature highlights the significant influence of traffic conditions on fuel consumption and emissions. Conditions characterized by low average speeds, frequent stops, and repeated accelerations lead to increased fuel consumption and changes in exhaust emission concentrations, with these effects primarily associated with transient operating conditions following periods of idling [21]. Road gradient and speed variations further influence engine load and NO_x emission behavior [22], while the analysis of telematics data confirms the correlation between average speed, idling duration, number of stops, acceleration profiles, and fuel consumption [23]. Furthermore, urban infrastructure elements, such as unsignalized pedestrian crossings, can lead to repeated stop-and-go driving conditions, affecting fuel consumption and instantaneous exhaust emission concentrations [24].

Driving style is another important factor. Testing the same diesel-powered vehicle along the same route with 30 drivers having different levels of experience revealed significant differences between driving styles. Drivers characterized by more aggressive acceleration and higher average speeds exhibited average NO_x and PM values up to 17% and 29% higher, respectively, compared with those adopting a less aggressive driving style. Other studies confirm increased fuel consumption during aggressive acceleration and the relevance of eco-driving principles, even when following standardized driving cycles [25–27].

Comparative studies of conventional, hybrid, and electric propulsion systems highlight the advantages of electrified powertrains, particularly in urban traffic, where regenerative braking enables the

recovery of part of the kinetic energy that would otherwise be dissipated during braking. Under extra-urban driving conditions, characterized by more stable speeds and fewer stops, the differences compared with conventional propulsion systems become less pronounced [28–30]. In parallel, the development of statistical models, machine learning methods, and the use of large datasets enable the estimation of fuel consumption and emissions based on vehicle speed, acceleration, route characteristics, weather conditions, and traffic characteristics [20, 31–33].

2.2. General Considerations on Vehicle Dynamics in Road Traffic

Vehicle dynamics directly influence the energy required for vehicle movement. The total force opposing vehicle motion results from the combined effects of rolling resistance, aerodynamic drag, gradient resistance, and acceleration resistance. Variations in these components lead to changes in the load on the propulsion system and, consequently, in fuel consumption and exhaust emission concentrations.

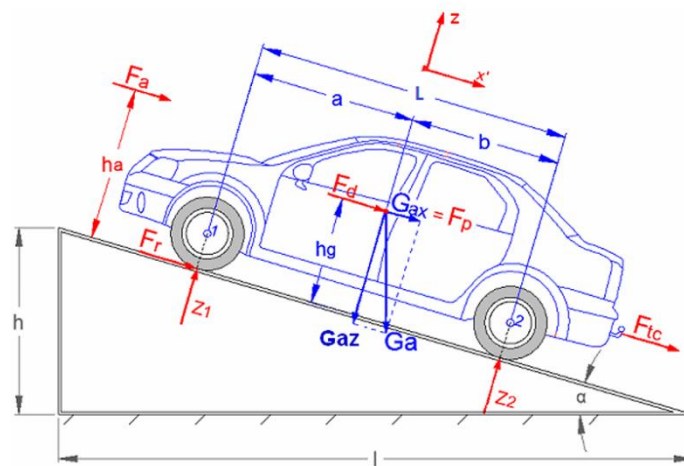


Fig. 2.1 - Forces and Moments Acting on the Vehicle [34]

Rolling resistance is primarily influenced by tyre characteristics, tyre pressure, vertical load, and road surface characteristics. A 10% reduction in the rolling resistance coefficient can result in an approximately 1–2% reduction in fuel consumption [35, 36]. Aerodynamic drag becomes increasingly significant as vehicle speed increases, owing to its dependence on the square of vehicle speed. A 10% reduction in the product of the aerodynamic drag coefficient and frontal area can lead to an approximately 2.5–3% reduction in total fuel consumption [37].

Table 2.1 - Influence of Vehicle Design, Operating, and Usage Parameters on Fuel Consumption.

Factor	Efect asupra consumului de combustibil	Fenomen
Masa vehiculului	crește consumul proporțional cu masa	crește rezistența la rulare și energia necesară la accelerații
Coeficientul de rezistență la înaintare ($C_x \cdot A$)	crește exponențial la viteze mari	rezistența aerodinamică este proporțională cu v^2
Presiunea din anvelope	3–5 % la pneuri cu presiunea sub cea prescrisă [35]	crește rezistența la rulare
Regimul de funcționare al motorului	optim la 70–85 % din sarcina maximă [38, 39]	randament termic maxim
Stilul de conducere și condițiile de trafic	până la +40 % variație	acelerații inutile și agresive și staționări frecvente
Temperatura ambientală	Consumul crește la temperaturi negative (10–20%)	densitatea aerului și vâscozitatea uleiului cresc

Fuel consumption is a fundamental indicator of energy efficiency and depends on the power required for vehicle propulsion, the efficiency of the propulsion system, and operating conditions. At low speeds, typical of urban traffic, frequent stops and repeated accelerations lead to increased fuel consumption per unit distance. At moderate speeds, approximately 50–80 km/h, the propulsion system may operate within a range favorable to energy efficiency, whereas at higher speeds, increased aerodynamic drag leads to greater energy demand.

2.3. Basic Elements of the Road Transport System

From a technical and functional perspective, the road transport system integrates infrastructure, traffic control and safety measures, and traffic flow. Road and intersection geometry, intersection density, access management, and route continuity determine operating speeds and traffic flow distribution, thereby influencing the likelihood of congestion. Traffic control systems—including traffic signals, road signs, road markings, adaptive traffic control systems, and speed management measures—affect stopping and starting patterns and idling duration, thus having direct implications for energy consumption.

From a traffic flow perspective, the relevant parameters include average speed and its distribution, traffic density, traffic flow rate, delays, number of stops, and queue lengths. In urban environments, the frequent succession of acceleration, deceleration, and idling phases results in more variable vehicle operating conditions compared with uninterrupted traffic flow. High traffic density leads to lower average speeds and greater speed fluctuations. Adaptive traffic signal control systems can reduce idling time and the number of complete stops, contributing to improved traffic flow and reduced fuel consumption [40, 41].

2.4. Vehicle Propulsion Systems

The evolution of vehicle propulsion systems is determined by the relationship between the energy density of the energy source, conversion efficiency, dynamic performance, costs, and environmental requirements. The main current propulsion architectures include conventional systems based on internal combustion engines, hybrid systems combining an internal combustion engine with one or more electric motors, and battery electric propulsion systems.

Conventional propulsion systems have undergone significant technological development following the successive introduction of Euro emission standards. The integration of three-way catalytic converters and lambda sensors, the development of direct fuel injection, turbocharging, exhaust gas recirculation, and the subsequent introduction of particulate filters and Selective Catalytic Reduction (SCR) systems have transformed the conventional internal combustion engine into a complex system in which combustion control is closely integrated with exhaust gas management. The evolution from Euro 1 to Euro 6 has been accompanied by improvements in energy efficiency and progressive reductions in regulated emissions.

Hybrid propulsion systems combine the advantages of internal combustion engines with those of electric propulsion, enabling energy recovery during braking, assistance to the internal combustion engine during periods of high power demand, and, depending on the system architecture, operation in fully electric mode. The control unit manages energy distribution between the system components according to load, speed, temperature, and battery state of charge [42–47]. These advantages are more pronounced in urban traffic, where frequent braking enables energy recovery, while additional mass, structural complexity, and dependence on battery condition represent the main limitations.

Electric propulsion systems convert electrical energy stored in the battery into mechanical energy through an electric motor and are characterized by high energy conversion efficiency. Their main components include the traction battery, battery management system, power electronics, electric motor, and control systems. Their advantages include the absence of local combustion-related emissions, regenerative braking, and a simplified transmission system. The main limitations are

associated with battery energy density, vehicle mass, charging time, charging infrastructure, thermal management, and the resources required for battery manufacturing.

Table 2.2 - Comparison of Hybrid Propulsion Architectures: MHEV, HEV, PHEV, and REE

Tip sistem hibrid	Denumire completă	Configurație energetică	Capacitate baterie	Posibilitate rulare electrică	Arhitectură mecanică	Avantaje principale	Limitări principale
MHEV	Mild Hybrid Electric Vehicle	Motor termic + generator electric de 48 V (asistență)	0,5–1 kWh	Nu (doar asistare)	Belt Starter Generator sau ISG	Consum redus 5–10%, cost mic, integrare simplă	Nu permite rulare electrică; câștig limitat în emisii
HEV	Hybrid Electric Vehicle	Motor termic + motor electric + baterie mică	1–2 kWh	Da, la viteze mici (sub 40 km/h, urban)	eCVT, transmisie planetară sau paralelă	Consum redus 15–25%, emisii mai mici, recuperare energie	Complexitate ridicată, masă suplimentară, performanță variabilă
PHEV	Plug-in Hybrid Electric Vehicle	Motor termic + motor electric + baterie mare	10–25 kWh	Da, autonomie 40–80 km	Paralel/serie, încărcare la priză	Rulare electrică extinsă, emisii aproape zero în oraș, cost pe km redus	Masă mare, cost ridicat, eficiență scade dacă bateria e descărcată
REEV (opțional)	Range Extended Electric Vehicle	Tracțiune exclusiv electrică; MAI doar generator	15–40 kWh	Da, tracțiune 100% electrică	Motor termic necuplat la transmisie	Randament optim, emisii reduse, funcționare electrică permanentă	Sistem foarte complex, volum/baterie mare, producție scumpă

2.5. Effects of Propulsion System Design Characteristics on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions

The design characteristics of the engine, fuel supply system, and transmission determine how the propulsion system responds to variations in operating conditions imposed by road traffic. In spark-ignition engines, the evolution of fuel injection systems from Port Fuel Injection/Multi-Point Injection (PFI/MPI) to Gasoline Direct Injection (GDI) has enabled more precise control of mixture formation and supported engine downsizing (strategies aimed at reducing engine displacement) and turbocharging. Increasing injection pressure promotes fuel atomization and the formation of a more homogeneous air–fuel mixture, but also places greater demands on the fuel supply system [48–53].

Table 2.3 - Comparative Overview of Injection Pressure

Sistem	Domeniu tipic de presiune (ordine de mărime)	Efecte dominante asupra consumului/emisiilor
MAS – PFI/MPI	joasă presiune 2,5–4 bar (0,25–0,4 MPa)	amestec stabil, PN/PM mai redus decât GDI, dar control mai limitat la downsizing
MAS – GDI modern	până la ~35 MPa (350 bar)	atomizare mai fină, potențial consum mai mic; risc PN/PM în cazul depunerii combustibilului pe pereții cilindrului (reduc prin presiune ridicată, strategii de injecție și utilizarea filtrului de particule GPF).
MAS – GDI avansat	50 MPa (500+ bar) (tendință)	țintă: reducere particule și îmbunătățire pulverizare/ardere
MAC – Common Rail	~2.000–2.500 bar (modern)	scade soot/PM, permite injecții multiple; posibil compromis NO _x fără EGR/SCR
MAC – CR avansat	până la ~3.000 bar	țintă: eficiență și emisii mai bune, control mai fin al injecției

For compression-ignition engines, the development of Common Rail injection systems has enabled fuel pressure generation to be decoupled from injection timing and facilitated the implementation of multiple injection events. Increasing injection pressures, together with improvements in injector response times and electronic control strategies, have enabled the optimization of the combustion process. Pilot, main, and post-injection events allow the heat release rate to be controlled, combustion noise to be reduced, NO_x and particulate formation to be managed, and diesel particulate filter (DPF) regeneration to be controlled. In modern systems, fuel injection, exhaust gas recirculation (EGR), turbocharging, and diesel oxidation catalyst (DOC), DPF, and selective catalytic reduction (SCR) systems operate in an integrated manner, since optimizing a single parameter in isolation is insufficient to achieve both high energy efficiency and low exhaust emission concentrations [54, 55].

The transmission also plays an important role in energy efficiency, as it determines the engine operating point in relation to the power demand at the wheels. Increasing the number of gear ratios, reducing internal losses, employing torque converter lock-up, implementing coasting strategies, and integrating engine–transmission control enable the engine to operate within higher-efficiency regions. Modern automatic transmissions, dual-clutch transmissions, continuously variable transmissions (CVTs), and transmissions designed for hybrid propulsion systems reduce the dependence of energy efficiency on the driver's gear selection, representing a significant advantage under traffic conditions characterized by frequent variations in vehicle speed and engine load.

2.6. Effects of Propulsion System Operating Parameters on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions

In addition to design-related factors, the behavior of propulsion systems under real-world traffic conditions is influenced by engine speed and load, thermal operating conditions, and the degree of electrification. These parameters determine the engine operating point on its performance map and directly influence fuel consumption and exhaust emission concentrations under urban, extra-urban, and motorway driving conditions [56, 57].

Engine speed influences mechanical and pumping losses, the combustion process, and specific fuel consumption. The highest efficiency is generally achieved at intermediate engine speeds and loads, whereas operation at very low or very high engine speeds leads to increased specific fuel consumption [58]. Engine load has a similar influence, with low-load operation generally associated with conditions outside the maximum-efficiency region, while high loads result in higher combustion temperatures and changes in NO_x and particulate formation.

Thermal operating conditions are particularly important because they influence both the combustion process and the efficiency of exhaust aftertreatment systems, including diesel oxidation catalysts (DOC), three-way catalysts (TWC), diesel and gasoline particulate filters (DPF/GPF), and selective catalytic reduction (SCR) systems. During the warm-up period following a cold start, insufficient operating temperatures limit pollutant conversion efficiency, explaining the elevated exhaust emission concentrations observed during the first few minutes of engine operation [59, 60].

Propulsion system electrification modifies the operating conditions of the internal combustion engine by enabling energy recovery during braking and allowing engine operating points to shift towards regions of higher energy efficiency. The advantages of hybrid propulsion systems are more pronounced under urban and suburban driving conditions, characterized by frequent acceleration, deceleration, and stopping events, whereas at higher vehicle speeds, the contribution of the electric propulsion system may become less significant [57, 58, 61].

2.7. Influence of Vehicle Design Parameters on Emissions and Fuel (Energy) Consumption under Different Traffic Conditions

Under real-world driving conditions, the power required at the wheels is influenced by vehicle mass, aerodynamic characteristics, and rolling resistance. The main vehicle design parameters analyzed

include vehicle mass, frontal area, aerodynamic drag coefficient, and tyre characteristics, with their effects varying according to traffic conditions [62].

Vehicle mass primarily influences the energy required for acceleration and rolling resistance. Its effect is more pronounced in urban stop-and-go traffic, characterized by repeated acceleration and deceleration events, whereas at high constant speeds, the influence of aerodynamic parameters becomes dominant [63–65].

Frontal area and the aerodynamic drag coefficient determine aerodynamic drag. Their influence is relatively limited at low speeds but increases significantly under extra-urban and motorway driving conditions, where aerodynamic drag represents a major component of the total energy demand [66–69].

Tyres influence fuel consumption through rolling resistance, which depends on tyre construction, load, temperature, and inflation pressure. The use of low rolling resistance tyres and the maintenance of appropriate inflation pressure contribute to reducing energy losses and, consequently, fuel consumption [70–72].

2.8. Influence of Road Traffic Parameters on Vehicle Emissions and Fuel (Energy) Consumption

Road traffic parameters influence fuel consumption and exhaust emission concentrations through two main mechanisms: changes in the power demand at the wheels and changes in the thermal operating conditions of the engine and exhaust aftertreatment systems. Consequently, vehicle speed, acceleration, deceleration, stopping frequency, and idling duration are essential parameters for characterizing a real-world driving cycle. Modern models, such as COPERT, Vehicle Specific Power (VSP), and Scaled Tractive Power (STP), use vehicle speed and/or power demand to describe these effects [73–75].

Frequent acceleration and deceleration events cause rapid variations in power demand and shift engine operating points outside regions of optimal energy efficiency. The energy supplied to accelerate the vehicle is subsequently dissipated to a large extent during braking, except in systems capable of regenerative energy recovery. Therefore, reducing speed fluctuations, anticipating traffic conditions, and limiting unnecessary acceleration are important principles of energy-efficient driving [76–78]. The standard deviation of vehicle speed can be used to characterize driving speed variability, with higher values associated with frequent transitions between acceleration, braking, and subsequent acceleration [79].

Idling has an important characteristic, as it involves fuel consumption without any actual vehicle movement. Its impact is more pronounced in urban traffic, characterized by frequent stops [80, 81]. Thermal operating conditions also have a significant influence: at low engine temperatures, the combustion process and exhaust aftertreatment systems have not yet reached their optimal operating ranges, resulting in changes in exhaust emission concentrations [82–84].

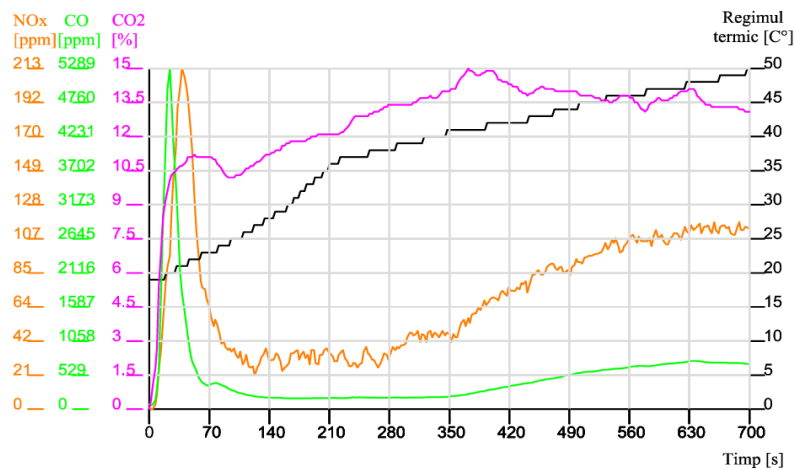


Fig. 2.2 - Variation in NO_x, CO, and CO₂ Exhaust Emission Concentrations as a Function of Engine Thermal Operating Conditions in Spark-Ignition Engines [33]

Start–Stop systems reduce fuel consumption associated with idling by automatically shutting down the engine when the vehicle comes to a stop and restarting it when driving resumes [85–87]. The effectiveness of these systems depends on engine temperature and stop duration, with greater benefits achieved when stops are sufficiently long to offset the energy required for engine restarting [88–90].

Driving style is another determining factor. Aggressive acceleration, frequent braking, and substantial speed fluctuations increase energy demand, whereas maintaining a relatively constant speed and anticipating traffic conditions reduce energy losses associated with transient operating conditions [91]. Driver feedback, eco-coaching, and eco-scoring systems use parameters such as vehicle speed, acceleration, engine speed, and accelerator pedal position to identify energy-inefficient driving maneuvers and provide recommendations to drivers [92–97].

In addition to dynamic driving parameters, ambient conditions and the technical condition of the vehicle influence fuel consumption and exhaust emission concentrations. Low ambient temperatures extend the time required for the engine and exhaust aftertreatment systems to reach their optimal operating temperatures, an effect that is particularly relevant during short urban journeys [83]. Inadequate maintenance, malfunctions of auxiliary systems, or increased intake flow resistance can adversely affect energy efficiency [80, 98]. Fuel composition can influence the combustion process and emission formation [99], while lubricant viscosity affects mechanical friction losses and, consequently, fuel consumption [100, 101].

2.9. Driving Cycles Used for Measuring Emissions and Fuel (Energy) Consumption

The evaluation of modern motor vehicles involves both standardized laboratory testing procedures and tests conducted under real-world driving conditions. Real Driving Emissions (RDE) testing was introduced in the European Union to complement laboratory tests and assess vehicle performance under real-world traffic conditions, characterized by variations in vehicle speed, road topography, and ambient conditions [102, 103].

RDE testing employs Portable Emissions Measurement Systems (PEMS) installed directly on the vehicle, enabling continuous measurement of exhaust emissions while simultaneously recording driving parameters and ambient conditions. An RDE test route includes urban, rural, and motorway driving conditions and is therefore characterized by greater variability than a standardized laboratory driving cycle. Validity criteria, testing conditions, equipment requirements, and data processing methods are established through specific regulations [104–107].

By comparison, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) provides the controlled and repeatable conditions required for vehicle type approval and comparison, whereas RDE testing enables the assessment of vehicle performance under real-world operating conditions. The two methods therefore serve complementary purposes: WLTP provides a standardized reference, while RDE testing allows verification of the extent to which the performance observed under controlled conditions is maintained during real-world vehicle operation.

Table 2.4 - Comparison of RDE and WLTP Testing Procedures

Aspect	RDE (condiții reale)	WLTP (laborator)
Mediu de testare	Drumul public, trafic real	Banc dinamometric, condiții controlate
Variabilitatea profilelor de viteză	Variabil, specific fiecărui traseu	Standardizat, predeterminat
Reprezentativitate pentru utilizare reală	Ridicată	Limitată
Poluanți monitorizați	Poluanți în trafic real (NO _x , PM)	Poluanți reglementați în laborator
Echipament	PEMS portabil	Măsurare fixă, controlată

The review of the current state of research therefore demonstrates that fuel consumption and exhaust emission concentrations cannot be assessed solely on the basis of vehicle design characteristics or values obtained under standardized driving cycle conditions. Vehicle speed and its variations, acceleration and deceleration, idling periods, traffic intensity, road infrastructure, thermal operating conditions, driving style, and propulsion system characteristics interact to determine energy performance and exhaust emission concentrations under real-world operating conditions. These findings highlight the need to use driving cycles derived from real-world traffic data and reproduce them under controlled conditions, thereby enabling the experimental assessment of the influence of traffic parameters on fuel consumption and exhaust emission concentrations under comparable and repeatable conditions.

3. MODELING AND SIMULATION OF REAL-WORLD DRIVING CYCLES IN THE AMESIM ENVIRONMENT

Numerical modeling and simulation enable the assessment of vehicle behavior under controlled conditions and the analysis of the influence of various operating parameters on fuel consumption and exhaust emission concentrations. Numerical models allow the integration of the main vehicle subsystems and the reproduction of real-world driving cycles, defined by variations in vehicle speed over time [108, 109]. By systematically modifying the speed profile, different traffic conditions can be compared, and the effects of smoother driving patterns on energy efficiency and exhaust emission concentrations can be evaluated [110].

3.1. Objectives of Driving Cycle Simulation

As part of this research, a real-world urban driving cycle was simulated for Vehicle 2 (V2), equipped with a spark-ignition engine (SIE), using a numerical model developed in the AMESIM environment. The main objective was to reproduce a real-world driving cycle and assess the influence of smoothing the vehicle speed profile on fuel consumption and CO, CO₂, and NO_x exhaust emission concentrations.

For this purpose, a road section characterized by low speeds and frequent speed fluctuations, representative of congested urban traffic, was selected. The analyzed section is located on 15 Noiembrie Boulevard, between the intersections with Castanilor Street and Mihail Kogălniceanu Street (Fig. 3.1), where the experimentally recorded speed profile exhibits frequent fluctuations within the range of 15–40 km/h. Traffic conditions are also influenced by the use of the available road infrastructure: of the three traffic lanes, one is designated for public transport, while another is affected by parking maneuvers, resulting in traffic flowing predominantly along the central lane.



Fig. 3.1 - Road Infrastructure Layout – 15 Noiembrie Boulevard with Three Traffic Lanes

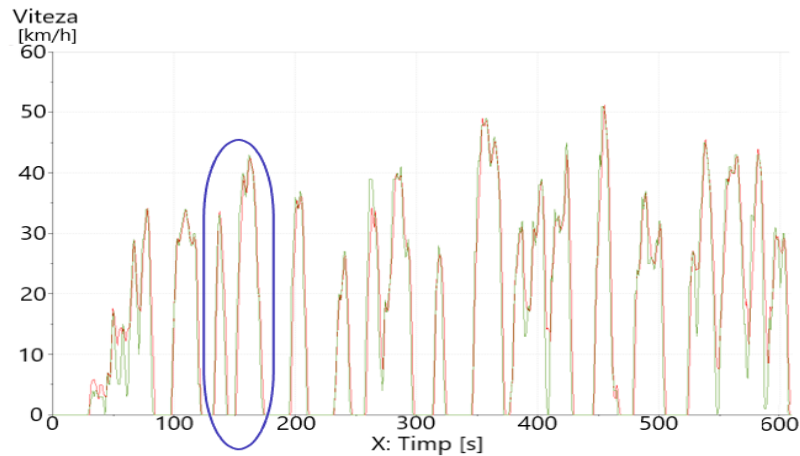
Based on these conditions, a hypothetical optimization scenario was investigated, involving an increase in traffic capacity and the establishment of a more uniform driving pattern. In the numerical model, this intervention was represented by imposing a constant speed of 30 km/h over the selected segment of the driving cycle, in order to assess the effects of reducing transient operating conditions on the parameters under investigation.

3.2. Modeling and Simulation Methodology

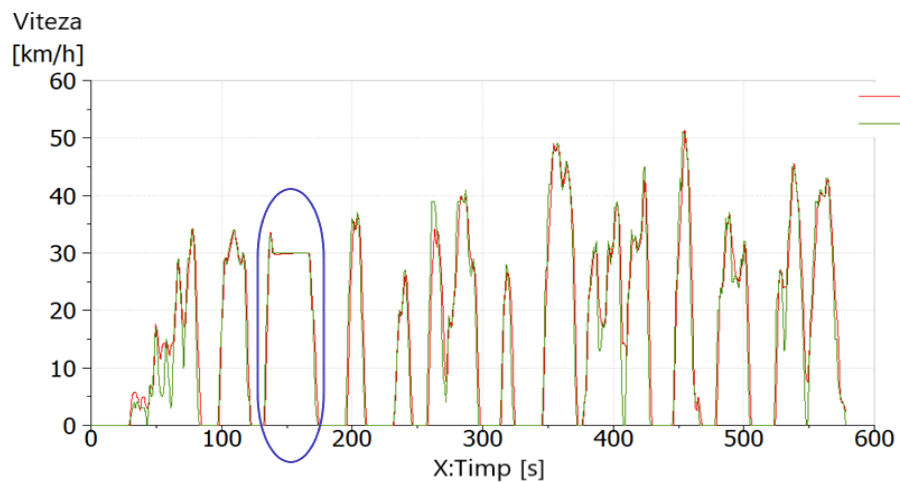
The modeling was performed using a forward-looking approach, in which the dynamic behavior of the vehicle is determined by the imposed driving conditions. The vehicle model was configured using the technical parameters of the engine, transmission, and vehicle, together with the characteristics of the resistive forces opposing vehicle motion and the environmental conditions. The modular structure integrates the driver, Engine Control Unit (ECU), internal combustion engine, transmission, and

vehicle longitudinal dynamics. The engine was characterized using engine speed–load maps, while the transmission was defined by its gear ratios, mechanical efficiencies, and gear-shifting strategy.

The real-world urban driving cycle was introduced into the model as a speed–time profile, based on which the "Driver" block generates the accelerator and brake commands required to reproduce the prescribed speed profile. During the 130–175 s interval, the original driving cycle exhibits repeated speed fluctuations between 0 and 40 km/h, characteristic of congested urban traffic. In the optimized scenario, this driving pattern was replaced by travel at a constant speed of 30 km/h.



a)



b)

Fig. 3.2 - Urban Driving Cycle Simulated in the AMESIM Environment (green line – prescribed speed; red line – actual vehicle speed obtained from the simulation): (a) Reference Driving Cycle; (b) Optimized Driving Cycle.

The comparative analysis of the two scenarios focuses on fuel consumption and exhaust emission concentrations, with the model iteratively calculating the vehicle's dynamic and operating parameters. This methodology enables a direct assessment of the influence of speed profile smoothing on propulsion system operation.

3.3.Simulation of Driving Cycles Using Real-World Traffic Data

Before evaluating the optimization scenario, the AMESIM model was validated by comparing the simulated results with the experimental results obtained on the chassis dynamometer using the same speed profile. This validation was necessary to verify the model's ability to reproduce vehicle behavior under the conditions of the analyzed urban driving cycle and to establish a reliable basis for its subsequent application in evaluating the modified scenario.

The comparison between experimental and simulated results demonstrates good agreement in the trends of the analyzed parameters. For NO_x , CO, and CO_2 exhaust emission concentrations, the model reproduces the trends observed experimentally, including the elevated values during the initial phase of the driving cycle and their subsequent reduction following the stabilization of thermal operating conditions and the attainment of effective operation of the exhaust aftertreatment system. In the case of CO, the maximum simulated values during the first 200 s reach approximately 1.3 g/s, compared with experimental values that do not exceed 1 g/s.

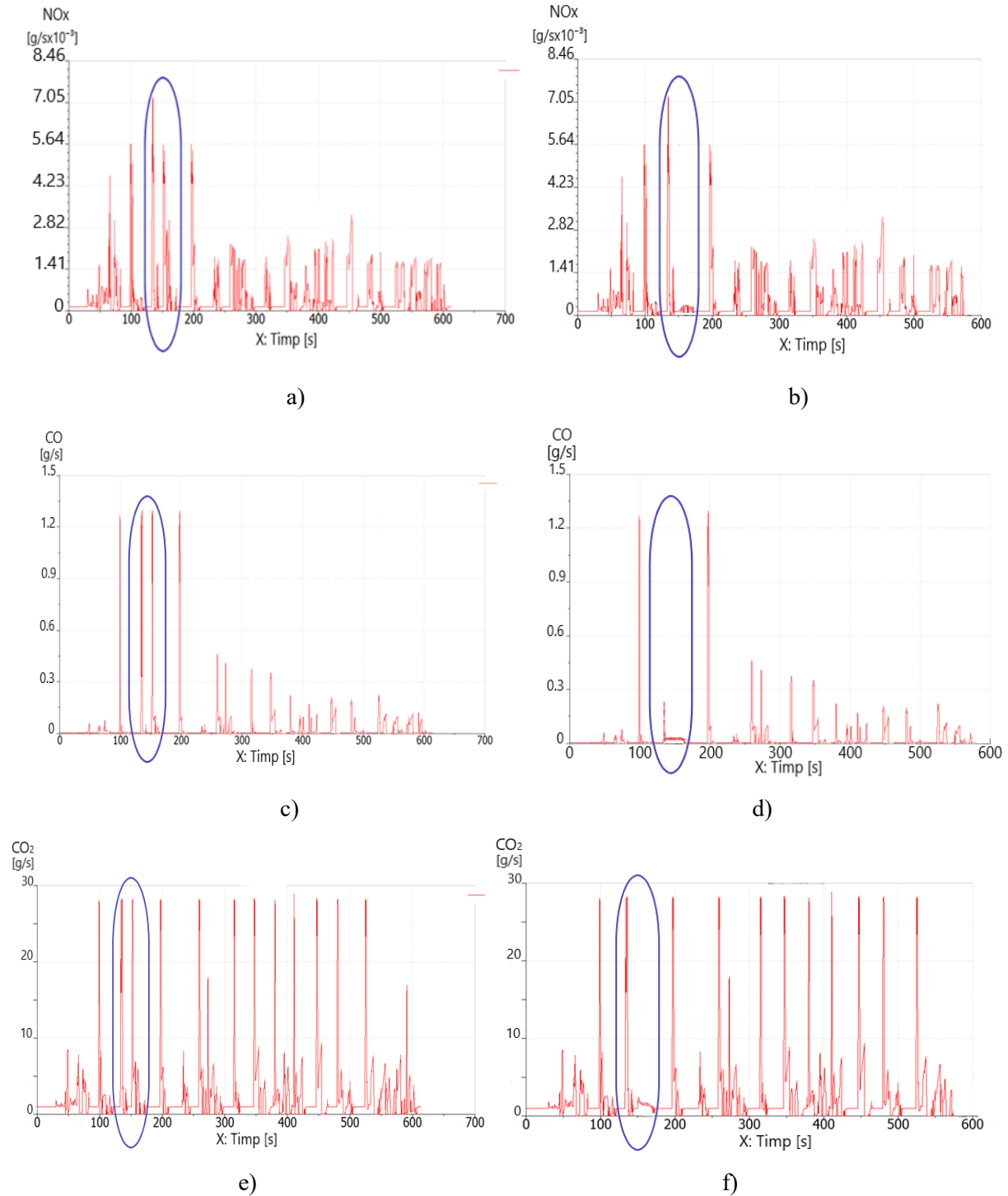


Fig. 3.3 - Instantaneous Emission Rates (V2 – Spark-Ignition Engine with a Three-Way Catalytic Converter): (a), (c), and (e) under Laboratory Conditions; (b), (d), and (f) in the AMESIM Simulation Environment.

Very good agreement was also obtained for fuel consumption. The total fuel consumption determined experimentally was 355 g, equivalent to 10.2 L/100 km, while the AMESIM simulation yielded 362 g, corresponding to 10.4 L/100 km. The small difference between the two results confirms the model's ability to reproduce the vehicle's energy-related performance and supports its application in analyzing the optimization scenario.

The analysis of transient operating conditions reveals a direct correlation between speed variations, engine load, and instantaneous fuel consumption. Fuel consumption peaks occur primarily during acceleration phases, when power demand and the quantity of injected fuel increase. At approximately 153 s, the increase in vehicle speed to around 35–40 km/h results in an approximately 300% increase in fuel consumption compared with the preceding driving segments, accompanied by increases in CO₂ and CO emission values.

To evaluate the effects of improving traffic flow, the speed profile was modified only during the 130–170 s interval, while the remainder of the driving cycle was kept unchanged. Imposing a constant speed of 30 km/h reduced fluctuations in the analyzed parameters by eliminating repeated acceleration and deceleration events and stabilizing engine load.

For CO, the values within the optimized interval tend towards an almost constant level below 0.1 g/s, while CO₂ fluctuations are also reduced. This behavior is associated with reduced transient engine loads and a more uniform fuel flow rate required for vehicle propulsion.

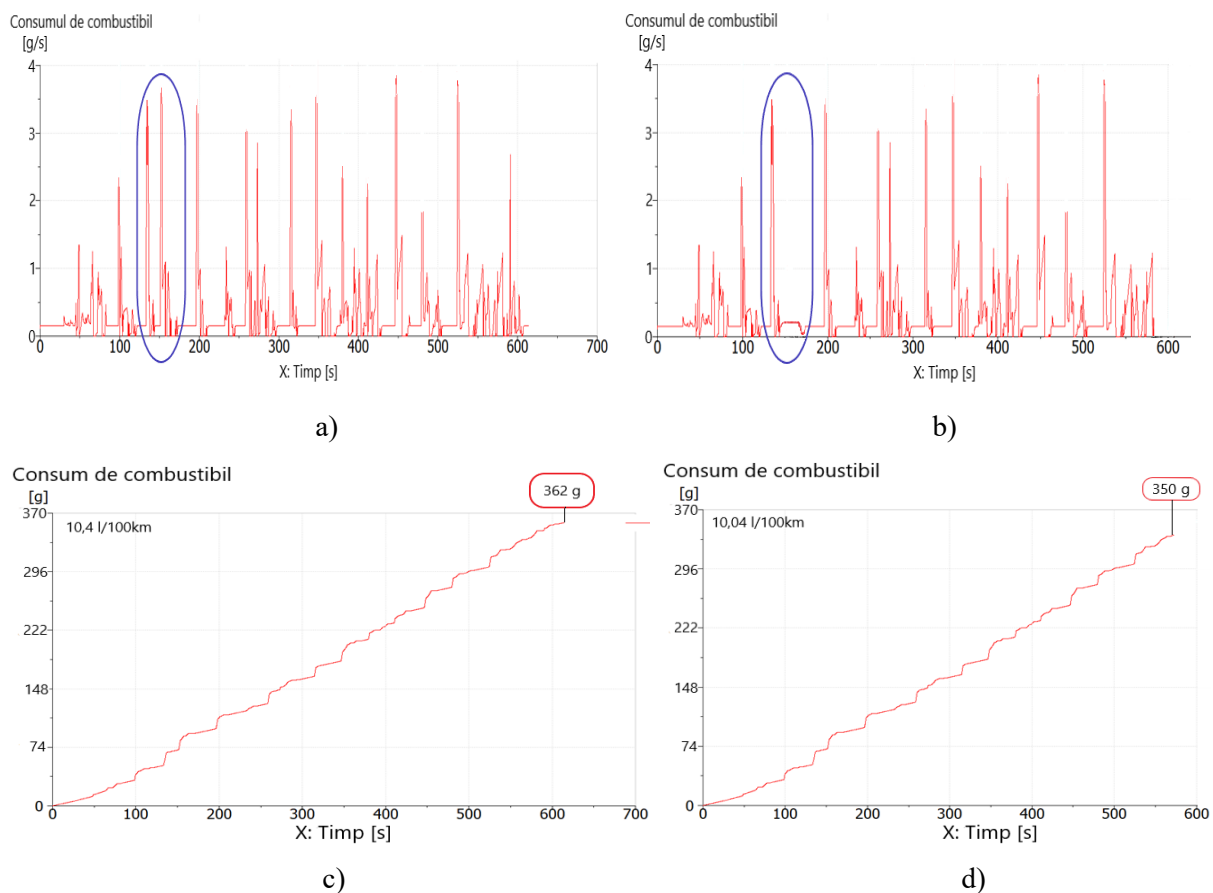


Fig. 3.4 - Fuel Consumption Values (V2 – Spark-Ignition Engine with a Three-Way Catalytic Converter): (a) and (c) under Laboratory Conditions; (b) and (d) in the AMESIM Simulation Environment.

The main quantitative result of the simulation is the reduction in total fuel consumption from 362 g to 350 g per driving cycle, corresponding to a decrease of approximately 3.31%. Fuel consumption per unit distance decreased from 10.4 L/100 km to 10.04 L/100 km, representing a reduction of 0.36 L/100 km. These results demonstrate that smoothing the speed profile over the analyzed segment leads to

lower fuel consumption and reduced fluctuations in NO_x , CO, and CO_2 exhaust emission concentrations within the modified section of the driving cycle.

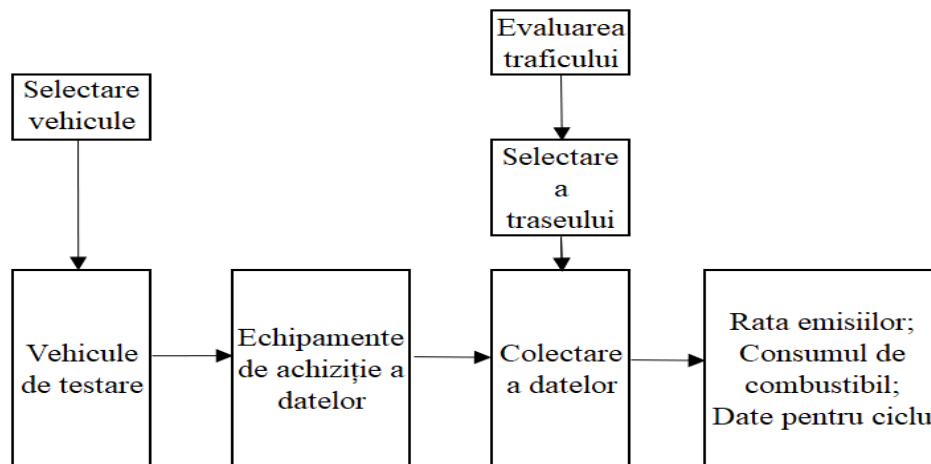
Therefore, numerical modeling confirms the direct influence of traffic conditions on propulsion system operation. Reducing transient operating conditions and maintaining a constant vehicle speed can improve vehicle energy efficiency, with the results providing a basis for evaluating measures aimed at improving urban traffic flow.

4. EXPERIMENTAL RESEARCH AND DATA PROCESSING

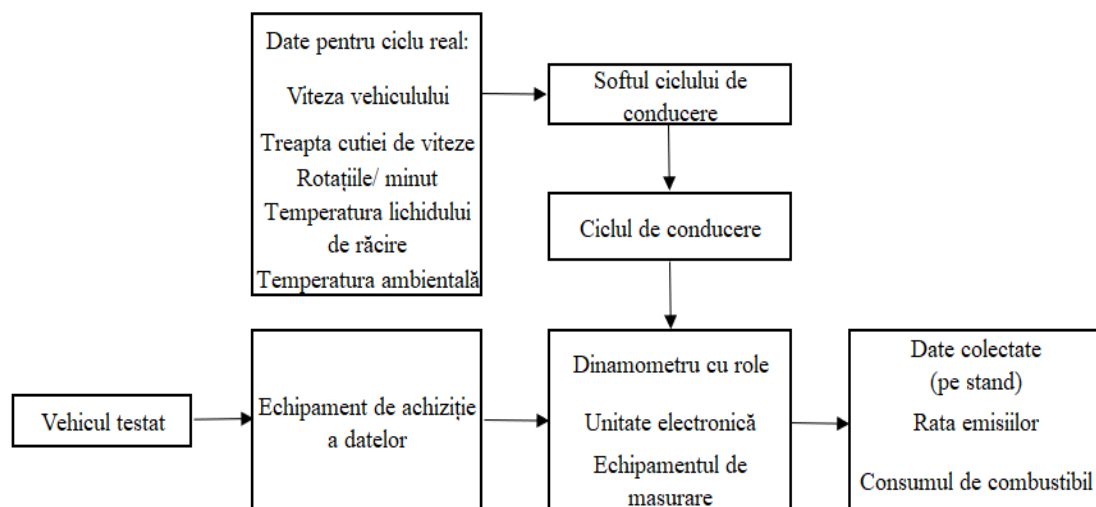
4.1. Experimental Research Methodology

The experimental research was designed to assess the influence of real-world traffic conditions on fuel consumption and exhaust emission concentrations while ensuring the repeatability and comparability of measurements. The adopted methodology aimed to correlate vehicle behavior under real-world traffic conditions with the results obtained under controlled laboratory conditions.

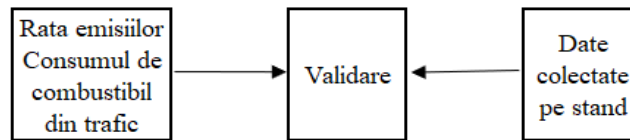
The experimental program was structured into two complementary stages. The first stage involved conducting investigations under real-world traffic conditions along predefined routes representative of urban, suburban, and extra-urban driving conditions. During this stage, dynamic driving parameters were recorded, primarily vehicle speed, acceleration, deceleration, and stopping events. In the second stage, the driving cycles obtained from real-world traffic were reproduced on a chassis dynamometer under controlled and repeatable conditions, while exhaust emission concentrations, fuel consumption, and vehicle operating parameters were recorded.



a)



b)



c)

Fig. 4.1 - General Research Framework: (a) Organization of Experimental Research under Real-World Traffic Conditions; (b) Organization of Experimental Research under Simulated Traffic Conditions in the Laboratory; (c) Results Validation Framework.

4.1.1. Preparation of Equipment for Experimental Research

In the initial stage, each vehicle was tested under real-world traffic conditions along the same predefined route, which was subsequently reproduced on the MAHA LPS 3000 chassis dynamometer. However, the preliminary analysis revealed that the inevitable variations in speed, acceleration, and deceleration between successive runs along the same route prevented rigorous comparisons between vehicles.

To overcome this methodological limitation, the research was expanded to include the recording and analysis of more than 220 real-world driving cycles, covering different urban, extra-urban, and mixed traffic conditions. Representative driving cycles were selected from this dataset and subsequently reproduced in the laboratory under identical conditions. This approach reduced the variability associated with real-world traffic and enabled meaningful comparisons between the vehicles under investigation.

The speed–time data recorded under real-world traffic conditions were imported into the chassis dynamometer software, which generated the driving cycle profile to be followed by the driver during testing. To ensure accurate reproduction of the driving cycles, the permissible deviation from the recorded speed profile was limited to ± 2 km/h. Any deviation beyond this tolerance was visually indicated to the driver, allowing immediate speed correction.

4.1.1.1. Preparation of Vehicles for Experimental Research

Before testing, the vehicles were inspected to eliminate the influence of technical factors that could affect the results. All vehicles were required to be in proper technical condition, free from mechanical or electronic faults and exhaust system leaks. No modifications to the emission control systems, electronic control unit, or fuel injection system were permitted. The braking and steering systems, tyre condition, and tyre inflation pressures recommended by the manufacturer were also checked.

The mass of each vehicle was determined with the driver and the equipment required for testing on board. This value was used to establish the equivalent inertia mass applied on the chassis dynamometer. The tests were conducted with the engine initially cold, at a temperature below 20 °C, while the laboratory temperature was maintained within the range established for the experimental research.

4.1.1.2. Preparation of Experimental Research Equipment

The experimental setup included the MAHA LPS 3000 chassis dynamometer, the Madur GA 21 Plus gas analyzer, the AIC 1200 fuel flow meter, the BC 3329 LOG 20 onboard computer, and the Bosch KTS 560 diagnostic system. The integrated use of these instruments enabled the simultaneous recording of exhaust emission concentrations, fuel consumption, and vehicle operating parameters.

The gas analyzer was periodically calibrated to maintain measurement accuracy.

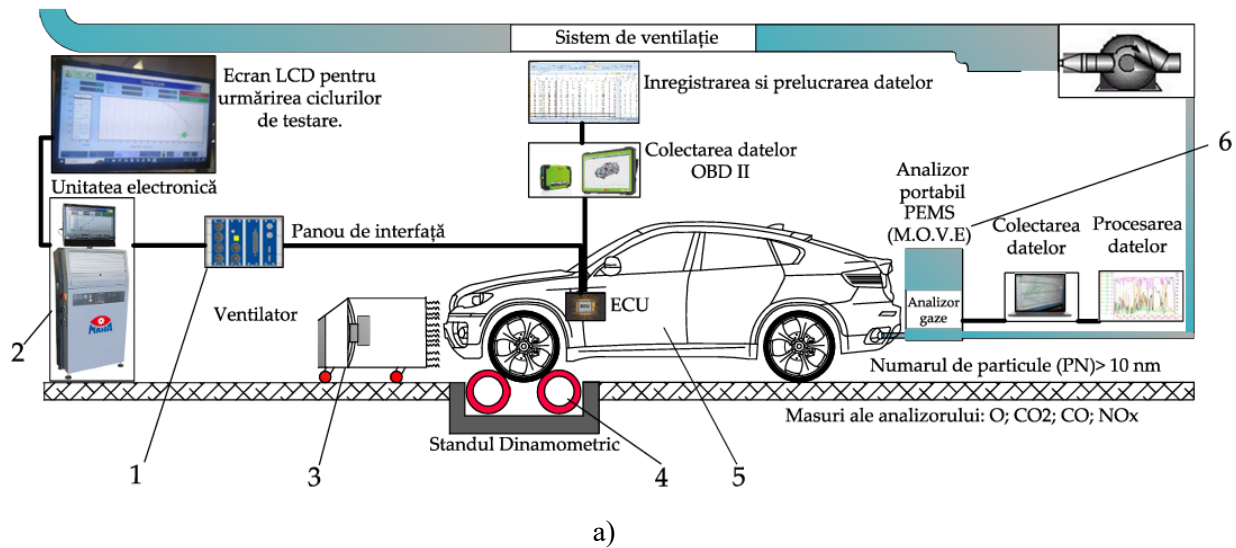


Fig. 4.2 - Experimental Research Laboratory: (a) Schematic Diagram of the Experimental Test Setup; (b) View of the Experimental Test Setup; 1. Connection Interface to the Vehicle's Electronic System (OBD II); 2. Control System; 3. Cooling Fans (2 Units); 4. Dynamometer Rollers Equipped with Eddy-Current Braking Systems; 5. Vehicle Under Test; 6. Exhaust Gas Sampling System for the Gas Analyzer.

Preparation of the chassis dynamometer involved calibrating the equipment, inspecting the rollers and braking system, and entering the parameters specific to each vehicle. In addition, the frontal cooling fan system, exhaust gas extraction system, and laboratory ventilation system were checked. These procedures were intended to minimize the influence of external factors and ensure the accurate reproduction of driving conditions.

4.1.2. Route Selection Criteria for Experimental Research to Develop Real-World Driving Cycles

The routes were selected to be representative of traffic conditions in the city of Braşov and its surrounding areas. Their selection considered both traffic intensity and the complexity of the road infrastructure, characterized by signalized intersections, intersections controlled by traffic signs, roundabouts, pedestrian crossings, and public transport stops.

An important selection criterion was the variation in traffic flow according to the time of day, covering both peak hours and periods characterized by lower traffic volumes. The routes were established to reflect the city's specific mobility patterns and connections to administrative institutions, educational

facilities, hospitals, economic areas, and other major transport routes. A traffic study was conducted to support the route selection process.

4.2. Vehicles Used for Testing (Vehicle Specifications)

The selection of vehicles aimed to highlight the influence of traffic conditions on propulsion systems with different design and operating characteristics. The research was organized into two stages. In the first stage, four vehicles were analyzed: two equipped with spark-ignition (SI) engines and two with compression-ignition (CI) engines. The objective was to evaluate the influence of urban traffic conditions at different times of the day on fuel consumption and exhaust emission concentrations.

In the second stage, five vehicles were included: two equipped with spark-ignition engines, two with compression-ignition engines, and one with a hybrid propulsion system. The tests investigated the influence of engine thermal operating conditions, acceleration and deceleration events, and traffic characteristics on the analyzed parameters. Vehicle selection considered differences in manufacturer, propulsion system type, body type, engine displacement, power output, and mass. The vehicles complied with Euro 6 and Euro 6d-TEMP emission standards.

This diversity enabled a comparative assessment of the response of different propulsion systems under identical driving conditions, allowing the effects of road traffic to be distinguished from those associated with the vehicles' design characteristics.

4.3. Specifications of the Equipment Used in the Experimental Research

The experimental research required the simultaneous measurement of vehicle dynamic parameters, engine operating parameters, exhaust emission concentrations, and fuel consumption. For this purpose, the MAHA LPS 3000 chassis dynamometer, the GA 21 Plus gas analyzer, the Bosch KTS 560 diagnostic system, and a fuel consumption measurement system consisting of the AIC 1200 fuel flow meter and the BC 3329 onboard computer were used. The integration of these instruments enabled the temporal correlation of vehicle operating conditions with exhaust emission concentrations and fuel consumption values.

4.3.1. Chassis Dynamometer

The MAHA LPS 3000 chassis dynamometer was the central component of the experimental setup, as it enables the laboratory reproduction of driving cycles recorded under real-world traffic conditions. The roller system equipped with an eddy-current brake applies a controlled load to the driven wheels, simulating the resistive forces encountered during vehicle operation.

A key advantage for the present research is repeatability: the same speed–time profile can be reproduced for different vehicles under controlled conditions, eliminating the inevitable variations encountered in real-world traffic. The chassis dynamometer also enables the measurement of speed, torque, and power, as well as the integration of data provided by the gas analyzer and the OBD II system. The measurement accuracy of the chassis dynamometer is approximately $\pm 2\%$.

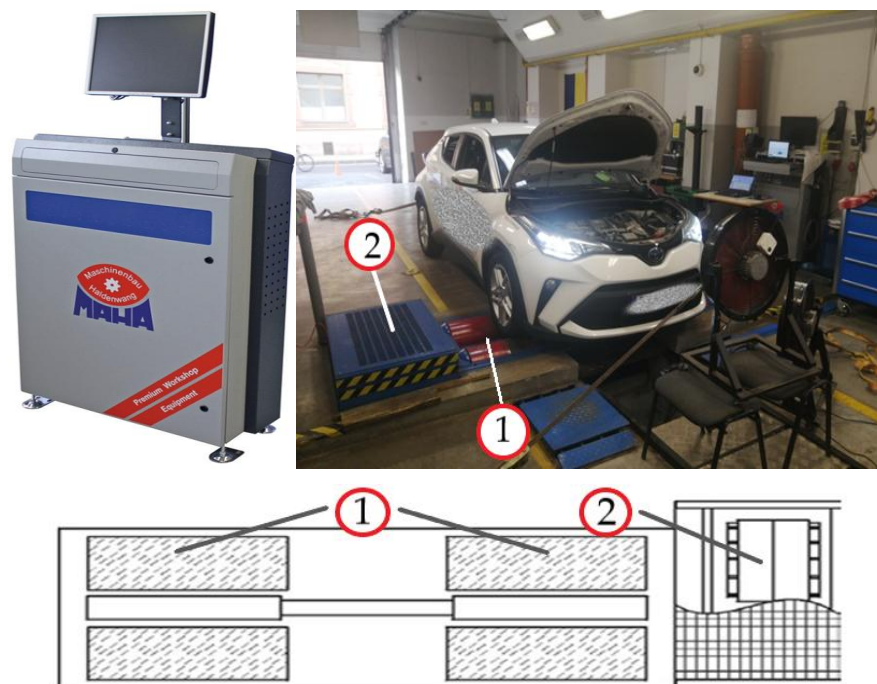


Fig. 4.3 - MAHA LPS 3000 Chassis Dynamometer: 1 – Dynamometer Rollers; 2 – Dynamometer Motor.

To reproduce real-world operating loads, the parameters specific to each vehicle were entered into the chassis dynamometer software. The total resistance to vehicle motion is determined by considering the components associated with rolling resistance, aerodynamic drag, vehicle inertia, and, where applicable, road gradient. The coefficients Cf A, Cf B, and Cf C allow the dynamometer load to be adjusted according to the characteristics of each vehicle. Thus, at each point of the real-world driving cycle, the chassis dynamometer generates the corresponding resistance at the rollers under the simulated driving conditions.

Table 4.1 - Example Calculation of the CfA, CfB, and CfC Coefficients Performed by the MAHA LPS 3000 Chassis Dynamometer Software at a Reference Speed of 90 km/h.

Vehicul	Vehicul 1 (MAS)	Vehicul 2 (MAS)	Vehicul 3 (MAC)	Vehicul 4 (MAC)	Vehicul 5 (Hibrid)
Cf A [KW]	3,46	4,75	5,87	6,95	4,71
Cf B [KW]	0	0	0	0	0
Cf C [KW]	9,8	7,82	12,25	7,44	11,2

4.3.2. Gas Analyzer

The GA 21 Plus gas analyzer was used for the real-time measurement of exhaust emission concentrations. The equipment enables the recording of the parameters required for the research and the transfer of data for subsequent processing. Before each series of tests, the integrity of the sampling system, the operation of the measurement modules, the leak-tightness of the sampling circuit, and the attainment of normal operating temperature were verified.

For real-world traffic tests, the gas analyzer was secured inside the vehicle, and the sampling probe was inserted into the exhaust system. This configuration enabled the continuous recording of exhaust emission concentrations throughout the real-world driving cycles and their subsequent comparison with the values obtained by reproducing the same cycles under laboratory conditions.

4.3.3. OBD II Diagnostic System – KTS 560

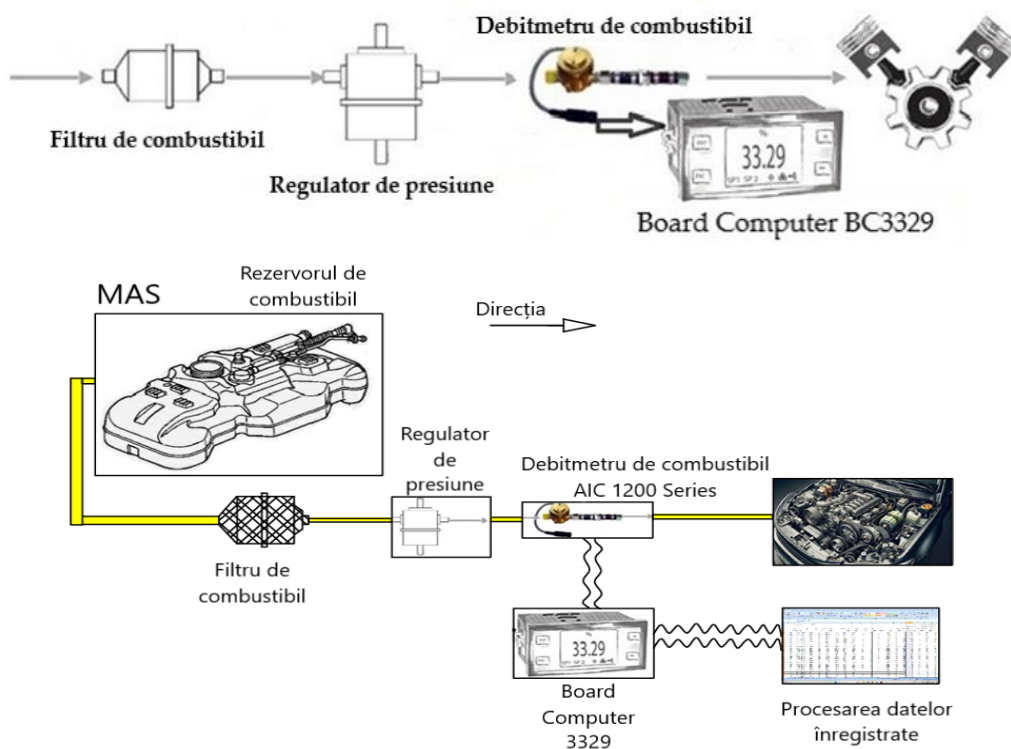
Vehicle operating parameters were acquired through the OBD II interface and the Bosch KTS 560 diagnostic system. Parameters such as engine speed, engine coolant temperature, intake air temperature and pressure, engine load, and other parameters available depending on the specific characteristics of each vehicle were monitored.

Temperature monitoring was particularly important for the research, as it enabled the correlation of engine thermal operating conditions with variations in exhaust emission concentrations and fuel consumption. The data obtained were synchronized with the information recorded by the other measurement instruments.

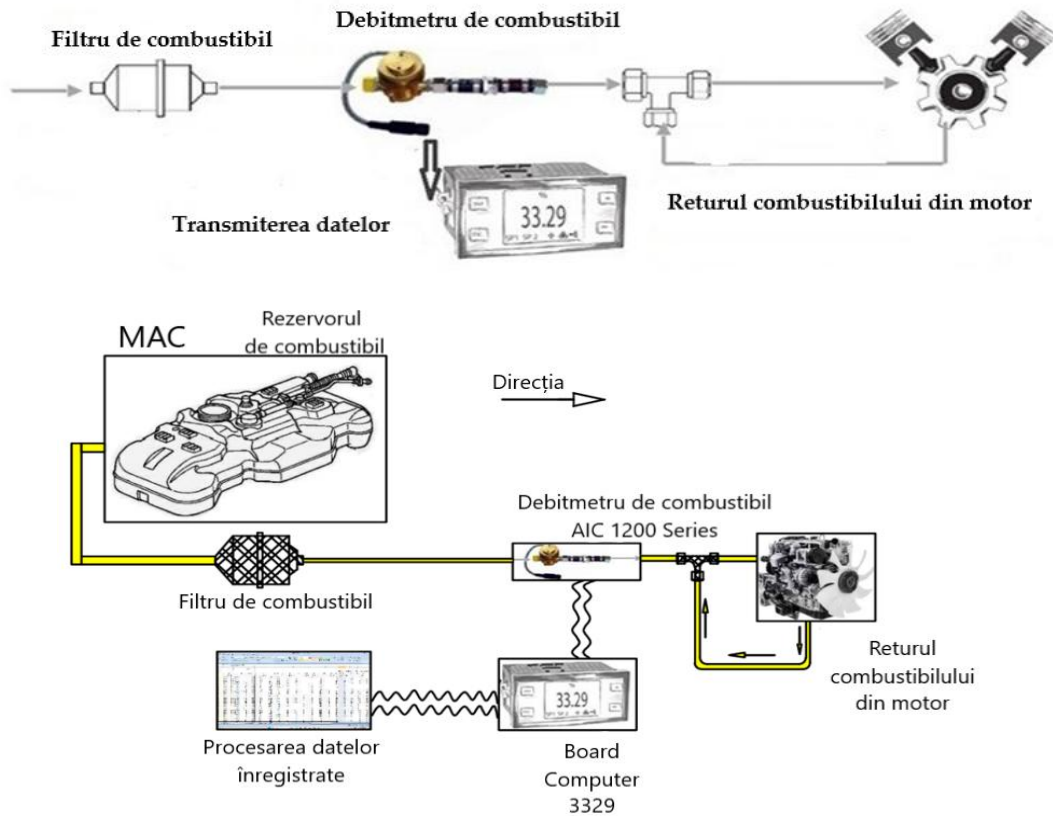
4.3.4. Fuel Flow Meter

Fuel consumption was measured using the AIC 1200 fuel flow meter, connected to the BC 3329 onboard computer and installed in the vehicle's fuel supply circuit.

Proper installation and preparation of the system were necessary to prevent air accumulation in the fuel circuit and maintain measurement accuracy. The recorded data were temporally correlated with vehicle speed, engine operating conditions, and exhaust emission concentrations, enabling the identification of driving cycle segments characterized by high or low fuel consumption.



a)



b)

Fig. 4.4 - Onboard Fuel Consumption Measurement System: (a) Vehicles Equipped with Gasoline Engines (Gasoline Density – 0.74 kg/L); (b) Vehicles Equipped with Diesel Engines (Diesel Fuel Density – 0.84 kg/L).

4.3.5. Statistical Analysis of Experimental Data

The processing of experimental data aimed to transform the recordings obtained from different measurement systems into a unified dataset required to analyze the relationships between driving conditions, traffic conditions, vehicle characteristics, fuel consumption, and exhaust emission concentrations.

Data were recorded continuously at 2-second intervals. The data obtained from the chassis dynamometer, gas analyzer, fuel flow meter, and vehicle systems were synchronized, a necessary procedure because the equipment used had different data acquisition characteristics.

Recordings from different sources were converted and standardized into a common data processing format. This stage enabled the direct correlation of variations in vehicle speed, acceleration, and deceleration with changes in fuel consumption and exhaust emission concentrations. Parameter synchronization made it possible to identify operating conditions associated with maximum or minimum values and to compare these across different driving cycles and vehicles.

5. RESULTS OF THE EXPERIMENTAL RESEARCH

The analysis of experimental results represents the central stage of the research, focusing on evaluating the influence of traffic conditions and propulsion system characteristics on fuel consumption and exhaust emission concentrations. Unlike assessments based exclusively on standardized driving cycles, the methodology adopted enabled the controlled reproduction, on a chassis dynamometer, of driving cycles recorded under real-world traffic conditions, while preserving the dynamic characteristics of vehicle operation: speed variations, acceleration and deceleration events, stops, and idling periods.

The study aimed to obtain and use driving cycles that would highlight the following aspects:

- a) The influence of road traffic characteristics on exhaust emission concentrations and fuel consumption using real-world urban driving cycles (Test Series I);
- b) The influence of propulsion system characteristics on exhaust emission concentrations and fuel consumption under identical traffic conditions, using real-world urban, suburban, and extra-urban driving cycles (Test Series II);
- c) The influence of propulsion system characteristics on exhaust emission concentrations and fuel consumption under identical driving conditions, using a standardized driving cycle (WLTC).

Thus, the real-world driving cycles reproduced in the laboratory provide the basis for the analyses presented in the following chapters.

5.1. Influence of Urban Traffic Characteristics on Exhaust Emission Concentrations and Fuel Consumption (Test Series I)

The first series of tests (Fig. 5.1) aimed to investigate the influence of road traffic conditions on vehicle operation (two vehicles equipped with spark-ignition engines and two with compression-ignition engines) by driving along the same urban route during three periods of the day: morning, afternoon, and evening. The analysis of the recorded driving cycles reveals significant differences in travel duration, number of stops, stationary time, and average speed, resulting from variations in traffic intensity and interactions with road infrastructure elements.

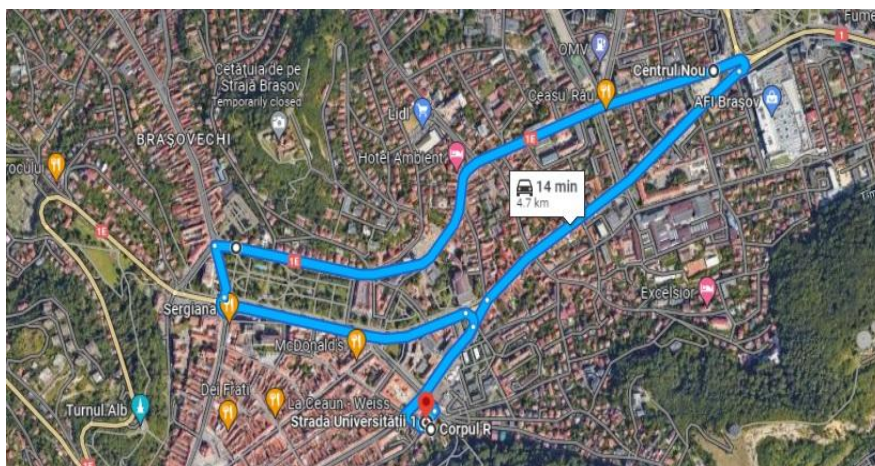


Fig. 5.1 - Selected Urban Route

For all the vehicles analyzed, the same general trend in driving characteristics was observed, confirming the decisive role of traffic conditions. The number of stops decreases from periods of heavy traffic to those characterized by smoother traffic flow. For example, the number of stops decreases from 14 to 7 for V1 and from 16 to 8 for V2. At the same time, stationary time is

considerably reduced. Average speeds, the number of stops, and driving cycle durations demonstrate that the differences between the recorded cycles are primarily determined by traffic conditions and road infrastructure, and to a lesser extent by vehicle-specific characteristics.

Table 5.1 - Urban Driving Cycle Characteristics (Test Series I) for Each Vehicle

Ciclul Urban (CU) - prima serie de teste				
Vehicul	Caracteristicile ciclului	Dimineață	După-amiază	Seară
V1	Etapă de conducere [%]	CU 100 %	CU 100 %	CU 100 %
	Durață [s]	594	760	550
	Distanță [km]	4,7	4,7	4,7
	Nr. opriri	14	10	7
	Faza de staționare [s]	213	115	69
	Viteza max. [km/h]	60	60	60
	Viteza med. cu stop [km/h]	28,4	22,3	30,7
	Viteza medie fara stop [km/h]	44,4	26,2	35,1
	Acceleratia maxima [m/s ²]	1,57	1,52	1,49
V2	Deceleratia maxima [m/s ²]	-1,56	-1,51	-1,5
	Etapă de conducere [%]	CU 100 %	CU 100 %	CU 100 %
	Durață [s]	612	847	700
	Distanță [km]	4,7	4,7	4,7
	Nr. opriri	16	14	8
	Faza de staționare [s]	225	169	106
	Viteza max. [km/h]	50	60	60
	Viteza med. cu stop [km/h]	27,6	19,9	24,1
	Viteza medie fara stop [km/h]	43,7	24,9	28,4
V3	Acceleratia maxima [m/s ²]	1,52	1,5	1,43
	Deceleratia maxima [m/s ²]	-1,51	-1,49	-1,42
	Etapă de conducere [%]	CU 100 %	CU 100 %	CU 100 %
	Durață [s]	680	825	650
	Distanță [km/h]	4,7	4,7	4,7
	Nr. opriri	19	13	8
	Faza de staționare [s]	282	198	102
	Viteza max. [km/h]	52	60	60
	Viteza med. cu stop [km/h]	24,8	20,4	26
V4	Viteza medie fara stop [km/h]	42,5	26,8	30,8
	Acceleratia maximă [m/s ²]	1,56	1,53	1,47
	Deceleratia minimă [m/s ²]	-1,57	-1,52	-1,46
	Etapă de conducere [%]	CU 100 %	CU 100 %	CU 100 %
	Durață [s]	636	860	770
	Distanță [km/h]	4,7	4,7	4,7
	Nr. opriri	19	15	10
	Faza de staționare [s]	225	153	156
	Viteza max. [km/h]	57	60	60
V1;V2 V3;V4	Viteza med. cu stop [km/h]	26,6	19,6	21,9
	Viteza medie fara stop [km/h]	41,1	23,9	27,5
	Acceleratia maximă [m/s ²]	1,61	1,59	1,55
	Deceleratia maximă [m/s ²]	-1,6	-1,58	-1,56
V1;V2	Viteza med. cu stop [km/h]	26,8	20,5	25,6
V3;V4	Viteza medie fara stop [km/h]	42,9	25,4	30,4

V1-Vehicle 1 (SIE); Vehicle 2 (SIE); Vehicle 3 (CIE); Vehicle 4 (CIE)

The analysis of engine operating parameters also reveals differences between vehicles equipped with spark-ignition (SI) and compression-ignition (CI) engines. During the morning driving cycle, V1 and V2 recorded average speeds of 28.4 km/h and 27.6 km/h, respectively. However, the average calculated engine load was 25.7% for V1 and 51% for V2. For V3 and V4, the average calculated engine load values were 29.6% and 27.1%, respectively. Variations in engine speed and load closely follow changes in vehicle speed, demonstrating the relationship between traffic dynamics and propulsion system operating conditions.

An important factor influencing the results is the engine thermal operating condition. The experimental investigations were conducted during the cold season, in February and March, and engine temperatures remained significantly below the nominal operating temperature range of 90–105 °C. For the four vehicles included in the first test series, the recorded temperatures ranged from

approximately 9 to 47 °C, depending on the driving cycle. Under these conditions, mechanical losses are higher, while the combustion process and exhaust aftertreatment systems have not yet reached their optimal operating temperature range. Consequently, fuel consumption and exhaust emission concentrations are affected, particularly during the initial phase of the driving cycle.

Table 5.2 - Comparison of Urban Traffic Parameters: Morning, Afternoon, and Evening.

Ciclu urban (prima serie)									
Vehicule	Dimineață			După-amiază			Seară		
	Vmed [km/h]	V.S.C.med [%]	Media Rot/min	Vmed [km/h]	V.S.C.med [%]	Media Rot/min	Vmed [km/h]	V.S.C.med [%]	Media Rot/min
V 1	28,4	25,7	1272	22,3	22,5	1321	30,7	29,5	1596
V 2	27,6	51	1305	19,9	36,3	1322	24,1	35,7	1401
V 3	24,8	29,6	1066	20,4	24,4	969	26	29,9	1199
V 4	26,6	27,1	1337	19,6	19,6	1491	21,9	20,6	1380

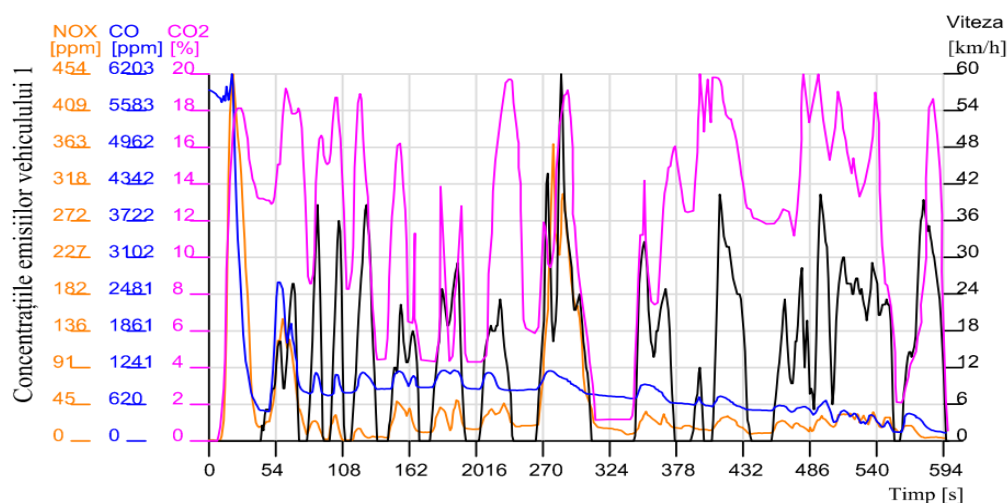
V.S.C.- Valoare sarcină calculată a motorului

Table 5.3 - Engine Thermal Operating Conditions During Testing.

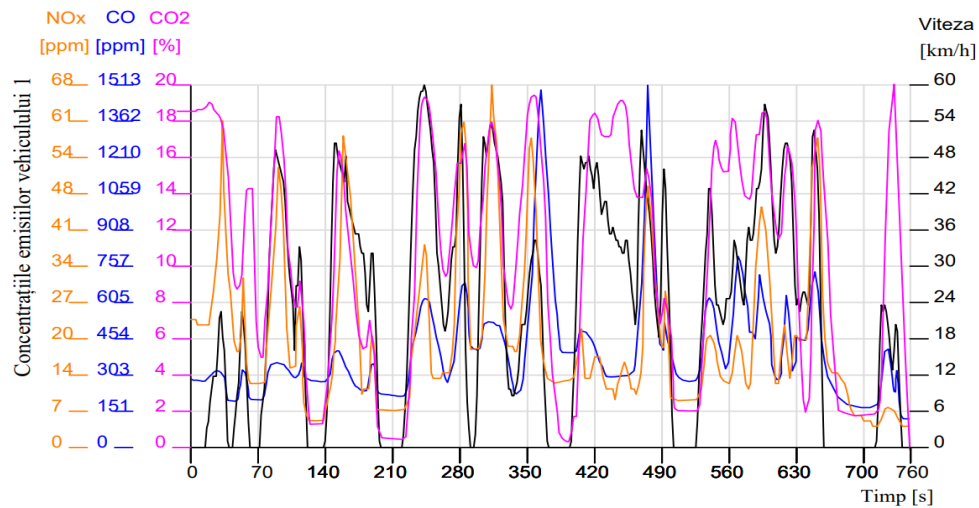
Vehiculul testat	Ciclu		
	Dimineață	După amiază	Seară
Vehicul 1 (°C)	11-42	12-47	10-40
Vehicul 2 (°C)	10-46	11-43	12-43
Vehicul 3 (°C)	12-38	11-39	12-40
Vehicul 4 (°C)	10-36	11-37	9-34

The results concerning exhaust emission concentrations confirm the combined influence of engine thermal operating conditions and the transient nature of urban traffic. For vehicles equipped with spark-ignition (SI) engines, elevated CO concentrations occur predominantly during the initial phase of the driving cycles and during acceleration, being associated with the low temperature of the three-way catalytic converter and temporary mixture enrichment under transient load conditions. As the exhaust aftertreatment system warms up, the concentrations decrease significantly.

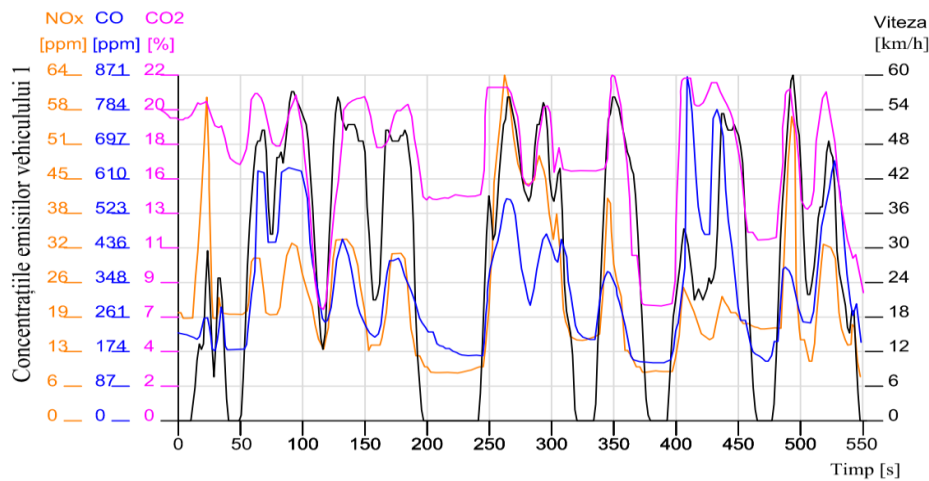
For V1, more than 90% of the recorded NO_x concentrations do not exceed 45 ppm, while occasional increases are associated with acceleration phases, when engine load and combustion temperatures rise. During the afternoon driving cycle, the maximum NO_x concentration was approximately 68 ppm, while the maximum CO concentration reached 1,513 ppm. CO₂ concentrations reached approximately 20%, with their variations closely following the engine's power demand.



a)



b)



c)

Fig. 5.2 - Instantaneous Exhaust Emission Concentrations for Vehicle 1 (V1 – Spark-Ignition Engine with a Three-Way Catalytic Converter) under Dynamic Urban Driving Conditions, Test Series I: (a) Morning Driving Cycle (07:00–08:00); (b) Afternoon Driving Cycle (15:00–16:00); (c) Evening Driving Cycle (18:30–19:30).

For vehicles equipped with compression-ignition (CI) engines, NO_x behavior is more sensitive to increases in engine load and the thermal operating conditions of the SCR system. During the first few minutes of operation, the low exhaust gas temperature limits the efficiency of the aftertreatment system, while acceleration events cause rapid increases in NO_x concentrations. As the engine and exhaust aftertreatment system warm up, the baseline levels of NO_x and CO decrease. This behavior confirms that the results cannot be interpreted solely in relation to vehicle speed; engine load, transient operating conditions, and propulsion system temperature must also be considered simultaneously.

The overall analysis of the first test series demonstrates that urban traffic characterized by repeated stops, idling, and successive acceleration events leads to significant variations in exhaust emission concentrations and fuel consumption. Conversely, improved traffic flow reduces the frequency of transient operating conditions and promotes more stable operation of the engine and exhaust aftertreatment systems.

Regarding fuel consumption, the results reveal a direct correlation with driving dynamics. The most significant instantaneous increases occur during acceleration phases, when power demand and engine load rise. During deceleration, fuel consumption decreases considerably, and under certain conditions,

the fuel injection system may temporarily interrupt fuel delivery. Although idling is characterized by a relatively low instantaneous fuel consumption rate, its contribution becomes significant over the entire driving cycle when the cumulative duration of stationary periods is high.

The results of the first test series therefore confirm that the assessment of fuel consumption and exhaust emission concentrations under urban driving conditions must consider the structure of the entire driving cycle rather than average speed alone. Two driving cycles with similar average speeds may produce different results if they differ in the number of stops, acceleration and deceleration events, or idling periods.

5.2. Investigation of Factors Influencing Exhaust Emission Concentrations and Fuel Consumption under Urban Traffic Conditions (Test Series II)

To distinguish the influence of traffic conditions from that of vehicle characteristics, the five vehicles included in the second test series (two spark-ignition vehicles, V1/V2; two compression-ignition vehicles, V3/V4; and one hybrid vehicle, V5) were subjected to the same driving profile. The selected urban driving cycle has a duration of 612 s (Fig. 5.3), a distance of 4.7 km, a total stationary time of 225 s, a maximum speed of 50 km/h, and an average speed, including stops, of 27.6 km/h. Using the same driving cycle allows the resulting differences to be attributed primarily to propulsion system characteristics, combustion processes, control strategies, and exhaust aftertreatment systems.

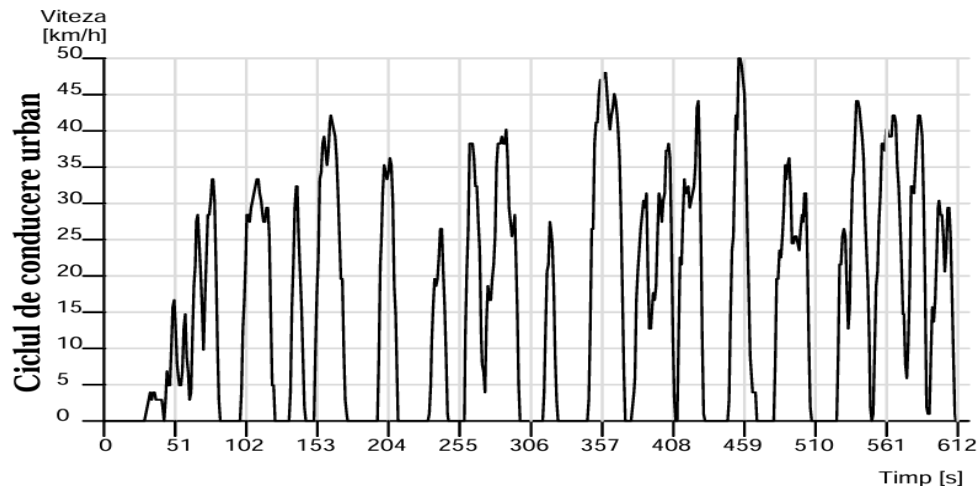


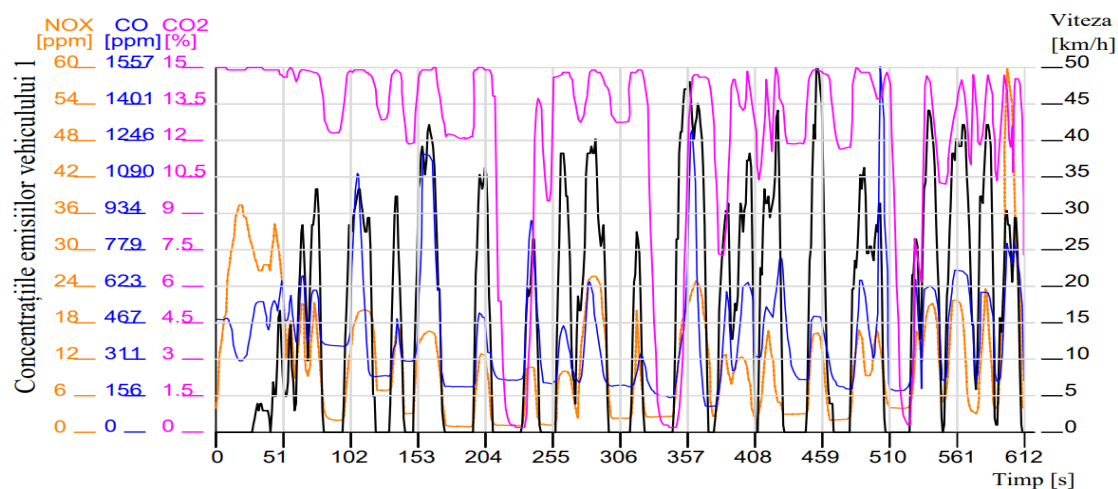
Fig. 5.3 - Real-World Urban Driving Cycle (Test Series II).

Under these conditions, the five vehicles exhibit clear differences in their operating behavior. For V1 and V2, equipped with spark-ignition (SI) engines, NO_x concentrations are relatively low, although increases occur during acceleration phases. CO concentrations are more sensitive to transient operating conditions due to temporary mixture enrichment and the operating conditions of the three-way catalytic converter. V1 reaches CO concentrations of approximately 1,557 ppm, while V2 records values of up to approximately 4,104 ppm during the initial phase of the driving cycle. Following the stabilization of thermal operating conditions, these concentrations decrease considerably (Fig. 5.4).

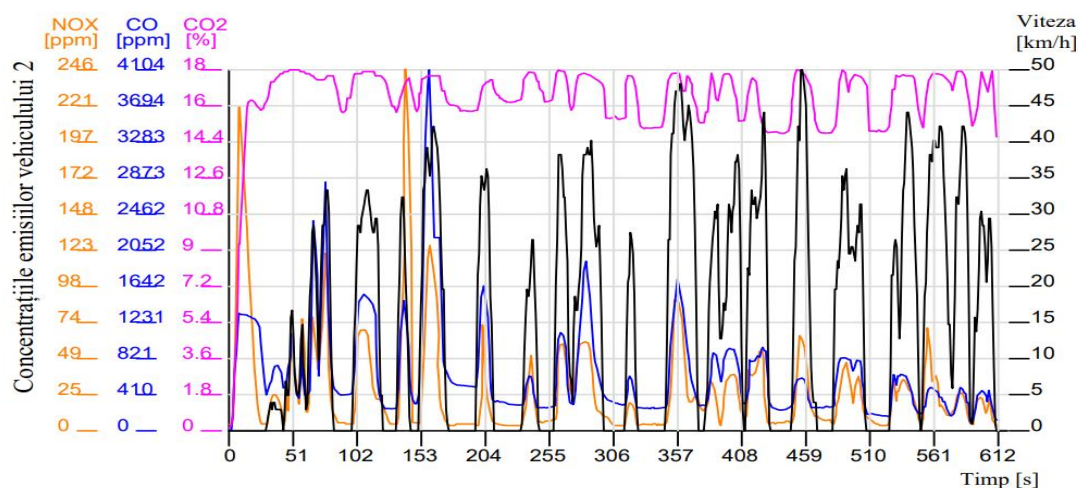
For vehicles equipped with compression-ignition (CI) engines, CO concentrations are considerably lower. V3 records values of approximately 5 ppm, while V4 exhibits a maximum of approximately 718 ppm during the initial phase of the driving cycle, followed by a decrease to approximately 60 ppm once operating conditions stabilize. In contrast, NO_x behavior becomes more significant for these vehicles, depending on engine load, exhaust gas temperature, and SCR system efficiency.

The hybrid vehicle V5 records the lowest NO_x concentrations during the urban driving cycle, generally remaining below 25 ppm. Increases occur primarily between approximately 50 and 120 s, when the internal combustion engine is operating. CO concentrations are also low throughout most of the

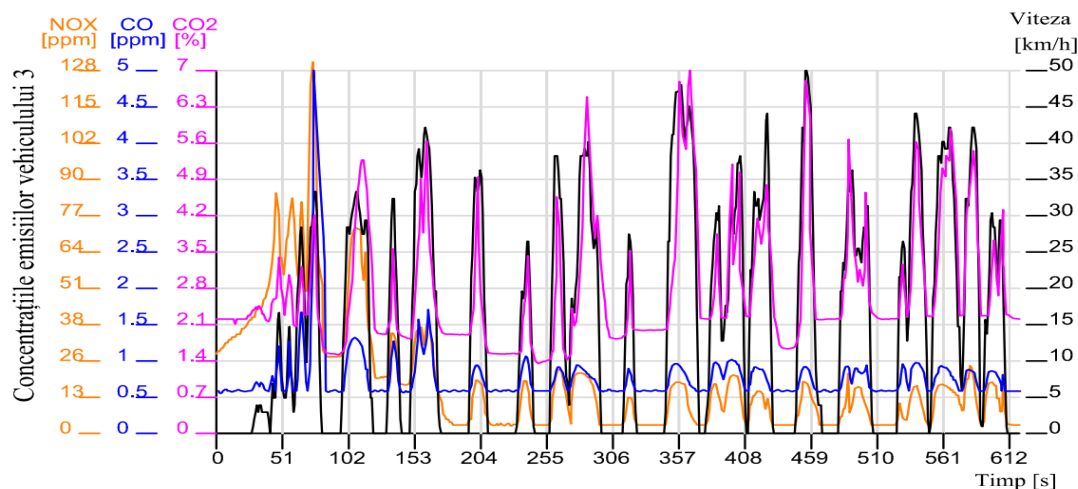
driving cycle, with a maximum of approximately 573 ppm recorded during the initial phase. Subsequently, the values generally remain below 170 ppm.



a)



b)



c)

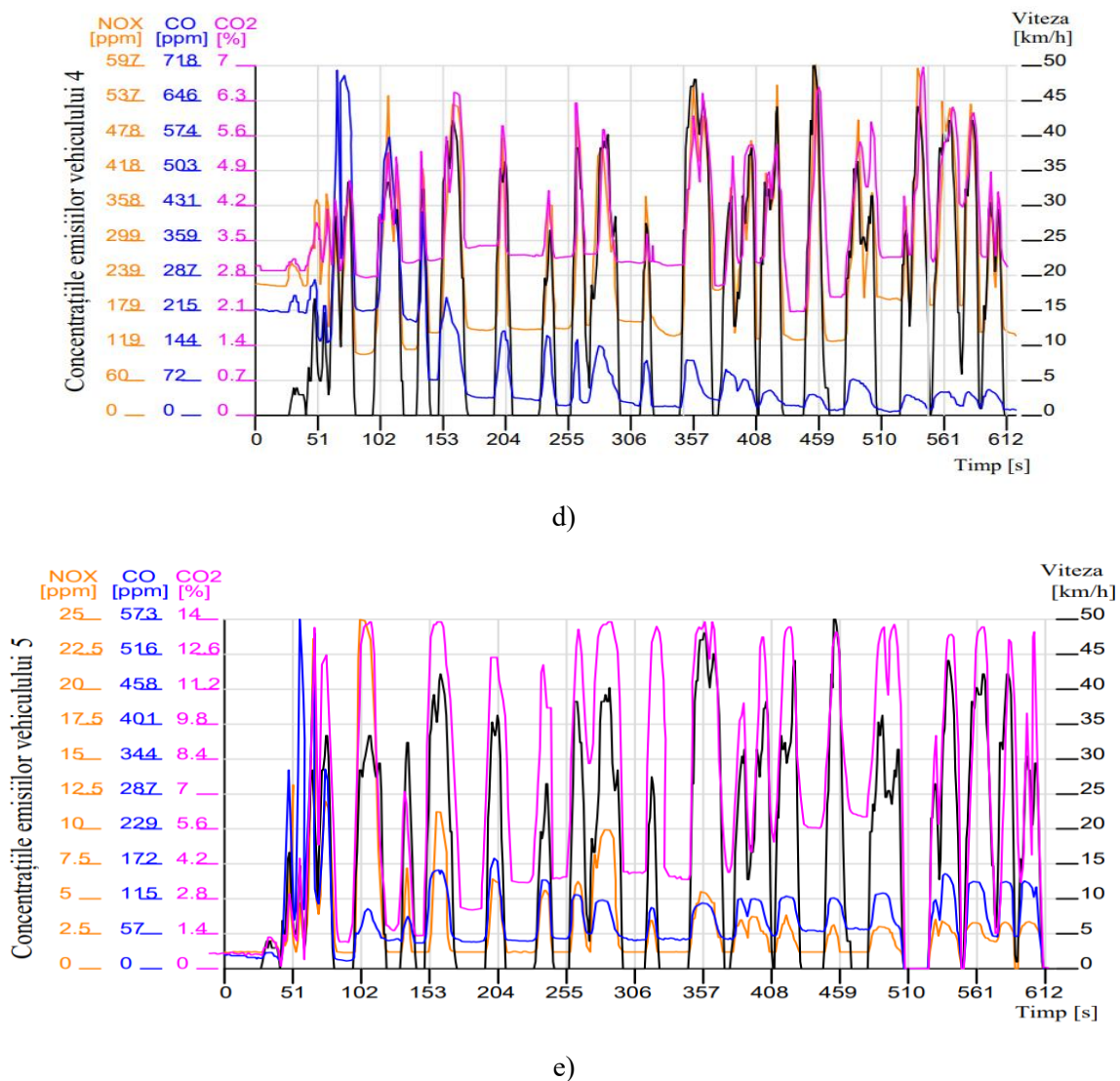


Fig. 5.4 - Effect of Dynamic Driving Conditions During the Real-World Urban Driving Cycle (U-BV Cycle) on NO_x, CO, and CO₂ Concentrations: (a) and (b) Spark-Ignition Engines – Vehicles 1 (Direct Injection, Turbocharged) and 2 (Indirect Injection, Naturally Aspirated); (c) and (d) Compression-Ignition Engines – Vehicles 3 and 4 (Indirect Injection, Turbocharged); (e) Vehicle 5 (Hybrid).

Regarding CO₂, vehicles equipped with spark-ignition (SI) engines generally exhibit concentrations ranging from approximately 12% to 18%, while V5 records values between approximately 5% and 14%. Variations in CO₂ concentrations closely follow changes in engine load and fuel consumption, with values increasing during acceleration and decreasing during deceleration. In this context, CO₂ is analyzed as an indicator associated with the combustion process and fuel consumption, rather than being classified as a conventional air pollutant.

The comparison of the five vehicles under the same driving cycle thus highlights two distinct components. The speed profile determines when dynamic loads occur, while the magnitude of the response depends on the characteristics of the propulsion system and the efficiency of the exhaust aftertreatment systems. This distinction represents one of the key advantages of reproducing the same real-world driving cycle under controlled conditions.

5.3. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Suburban Traffic Conditions

The suburban driving cycle was introduced to evaluate vehicle performance under operating conditions intermediate between urban and extra-urban driving. The cycle has a duration of 640 s and covers a distance of 5.4 km, with a maximum speed of 90 km/h, an average speed including stops of 30.3 km/h, and a total stationary time of 107 s. Compared with the urban driving cycle, the speed profile includes longer periods of steady-speed driving and fewer stops, resulting in more uniform loading of the propulsion system.

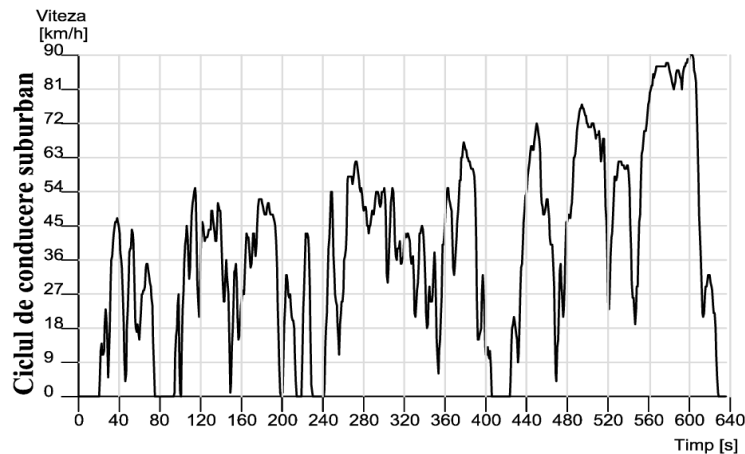
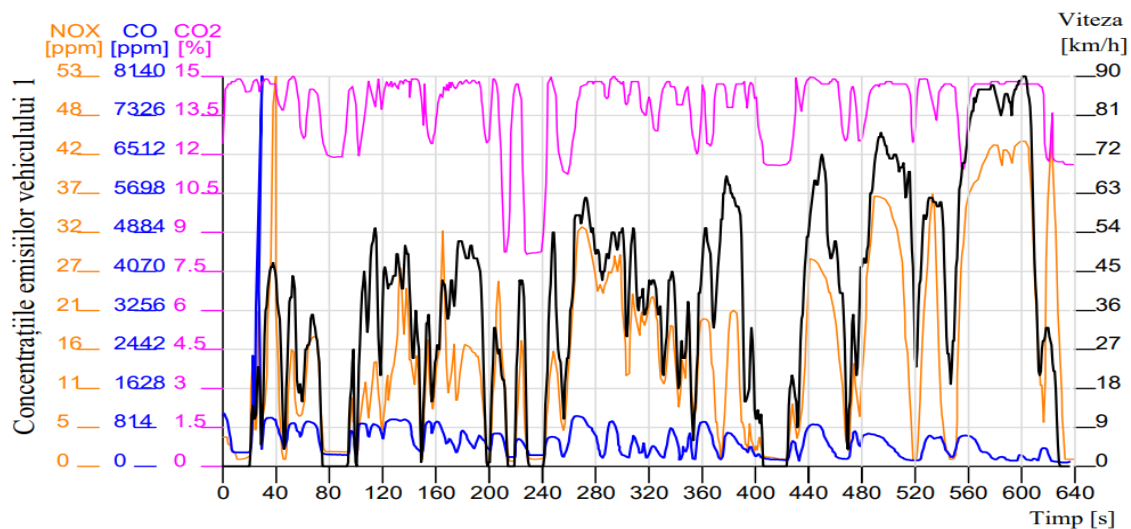


Fig. 5.5 - Suburban Driving Cycle.

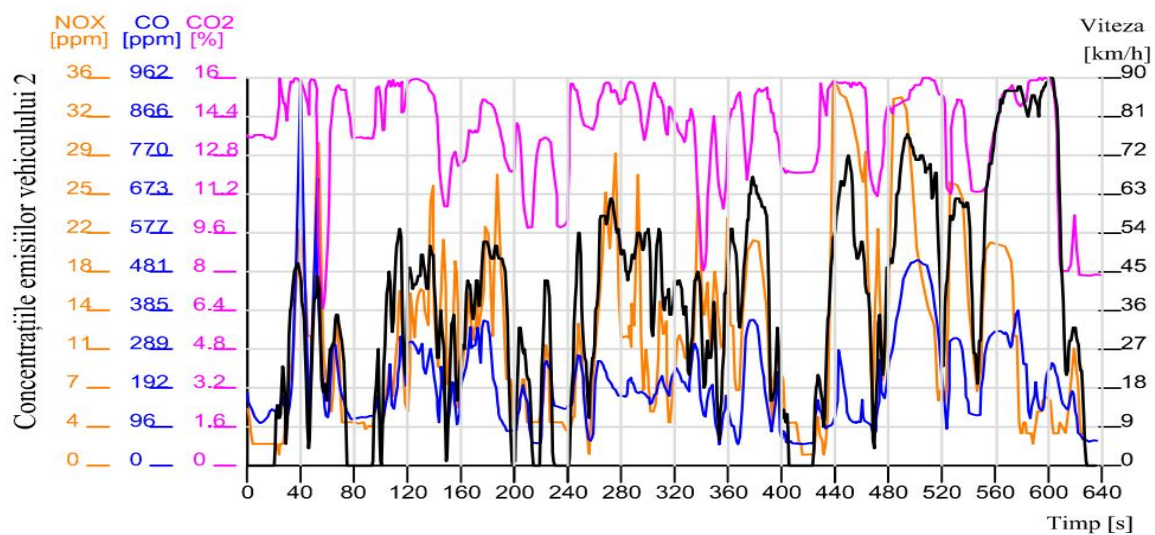
For V1 and V2, NO_x concentrations remain low throughout most of the driving cycle, with maximum values of approximately 50 ppm for V1 and 35 ppm for V2. Increases occur predominantly during acceleration to speeds of 60–80 km/h. After the first few minutes, the concentrations stabilize as the three-way catalytic converter operates within a favorable temperature range. CO concentrations exhibit transient peaks, while CO_2 concentrations range approximately between 12% and 15% (Fig. 5.6).

For V3 and V4, the results highlight the stronger influence of engine load and temperature on NO_x concentrations. V3 records maximum values of approximately 160 ppm during the initial phase of the driving cycle, followed by a decrease after approximately 240 s, as the temperature rises and the SCR system reaches effective operating conditions. V4 exhibits higher values, confirming differences in exhaust aftertreatment efficiency and control strategies between the two vehicles equipped with compression-ignition (CI) engines.

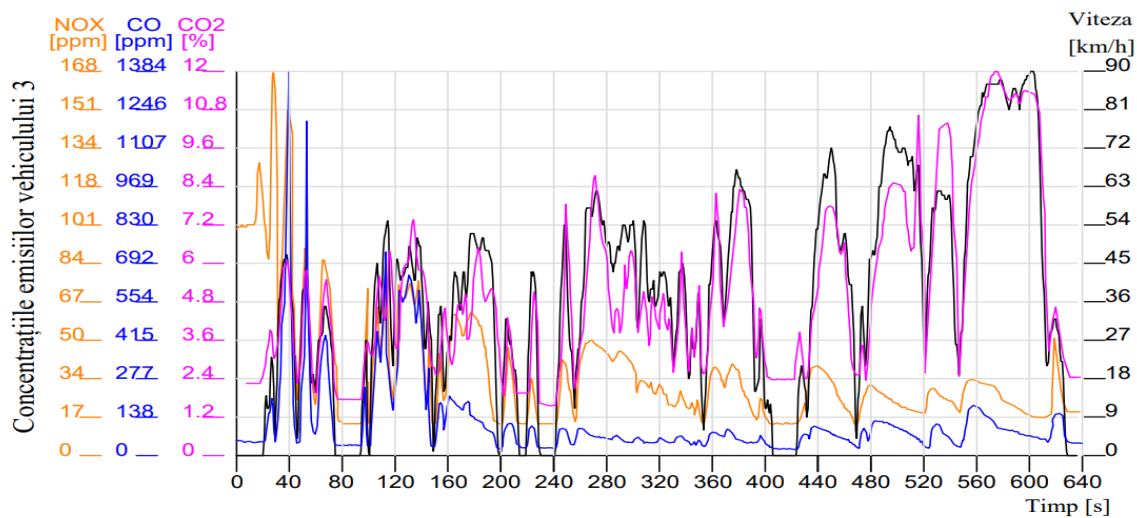
The hybrid vehicle exhibits low NO_x and CO concentrations throughout most of the driving cycle. Following the initial phase, NO_x concentrations remain at or below approximately 50 ppm, while CO concentrations range between 200 and 400 ppm. However, the advantages of the hybrid propulsion system are limited by thermal operating conditions. Under the experimental conditions, the electric motor did not provide propulsion during the driving cycle because the required thermal conditions were not met, and the internal combustion engine remained active. The automatic engine stop function was activated at approximately 400 s, reducing fuel consumption during the stationary period.



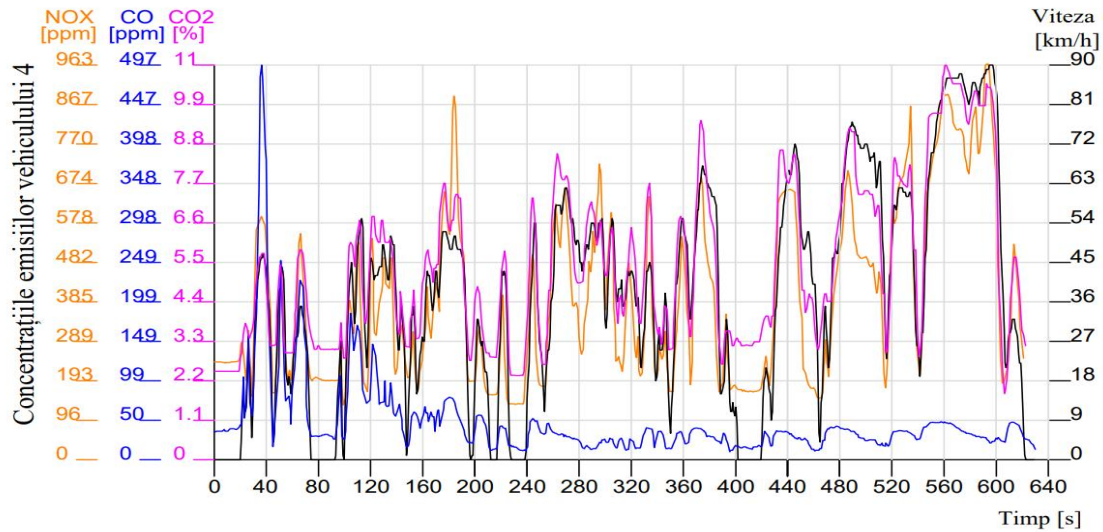
a)



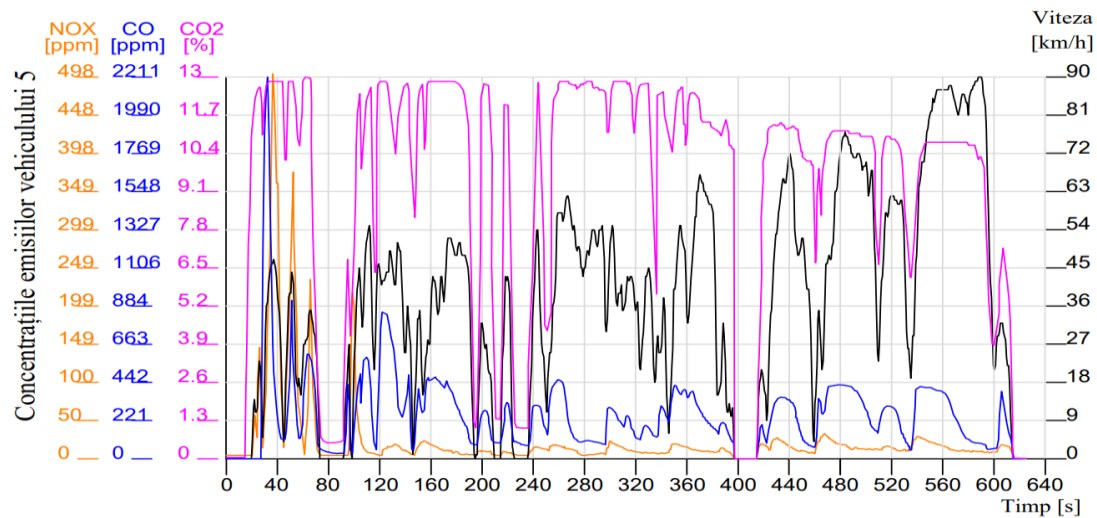
b)



c)



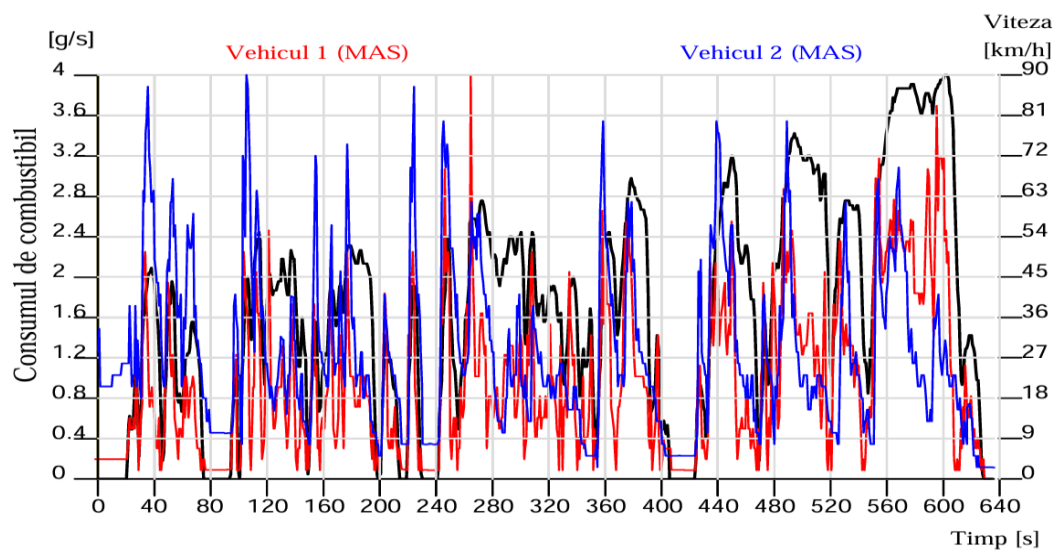
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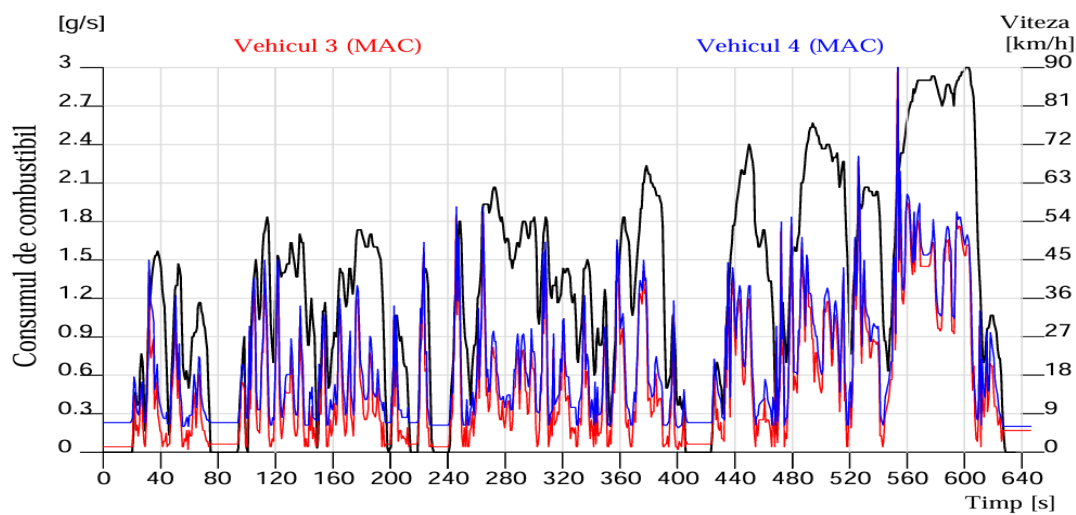
e)

Fig. 5.6 - Effect of Dynamic Driving Conditions During the Real-World Suburban Driving Cycle (S-BV Cycle) on NO_x, CO, and CO₂ Concentrations: (a) and (b) Spark-Ignition Engines – Vehicles 1 (Direct Injection, Turbocharged) and 2 (Indirect Injection, Naturally Aspirated); (c) and (d) Compression-Ignition Engines – Vehicles 3 and 4 (Indirect Injection, Turbocharged); (e) Vehicle 5 (Hybrid).

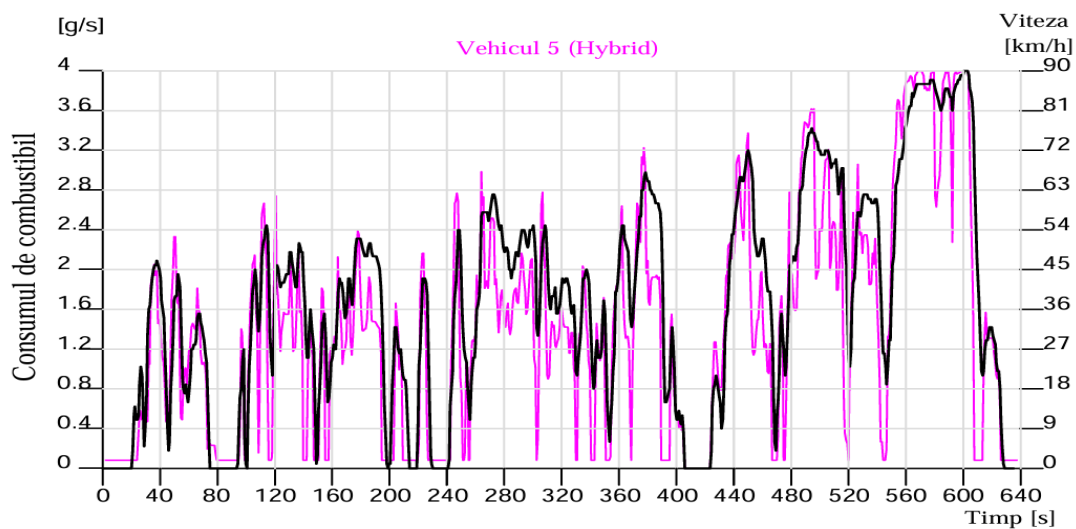
The analysis of fuel consumption confirms the influence of dynamic driving conditions. For all vehicles, instantaneous fuel consumption increases during acceleration and at higher speeds. Vehicles equipped with compression-ignition (CI) engines exhibit lower values than those equipped with spark-ignition (SI) engines: maximum values are approximately 1.6–1.8 g/s for V4 and 0.8–1 g/s for V3. This behavior is associated with the higher thermal efficiency of compression-ignition engines and their operation under excess-air conditions.



a)



b)



c)

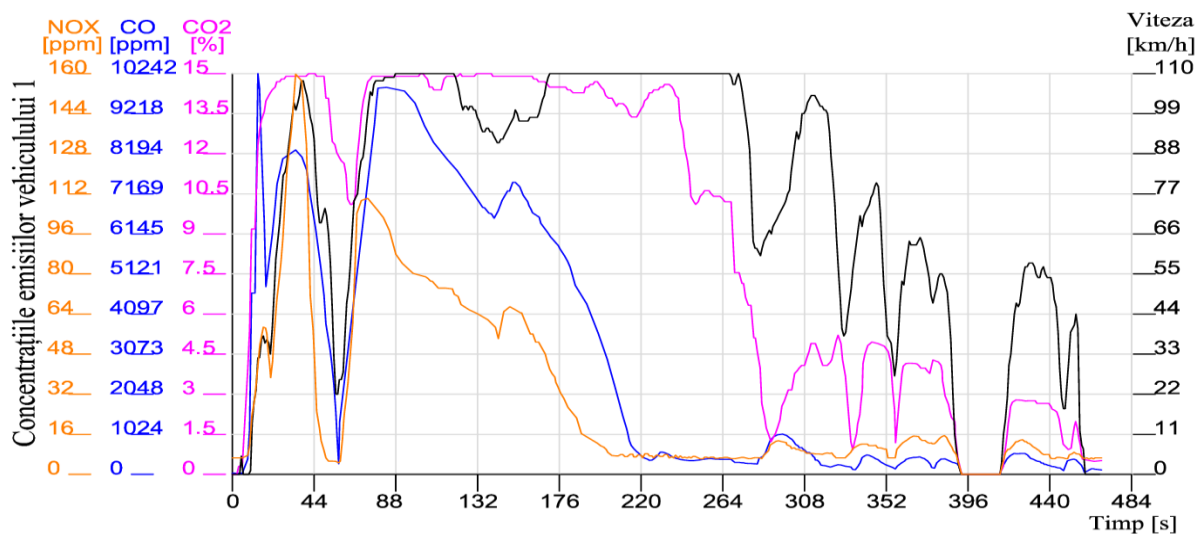
Fig. 5.7 - Instantaneous Fuel Consumption Values During the Suburban Driving Cycle (Test Series II): (a) SIE; (b) CIE; (c) Hybrid Vehicle.

Compared with urban driving conditions, the suburban driving cycle highlights the advantages of more uniform driving: reducing the frequency of acceleration and deceleration limits fluctuations in fuel consumption and allows the exhaust aftertreatment systems to operate for longer periods within a favorable temperature range.

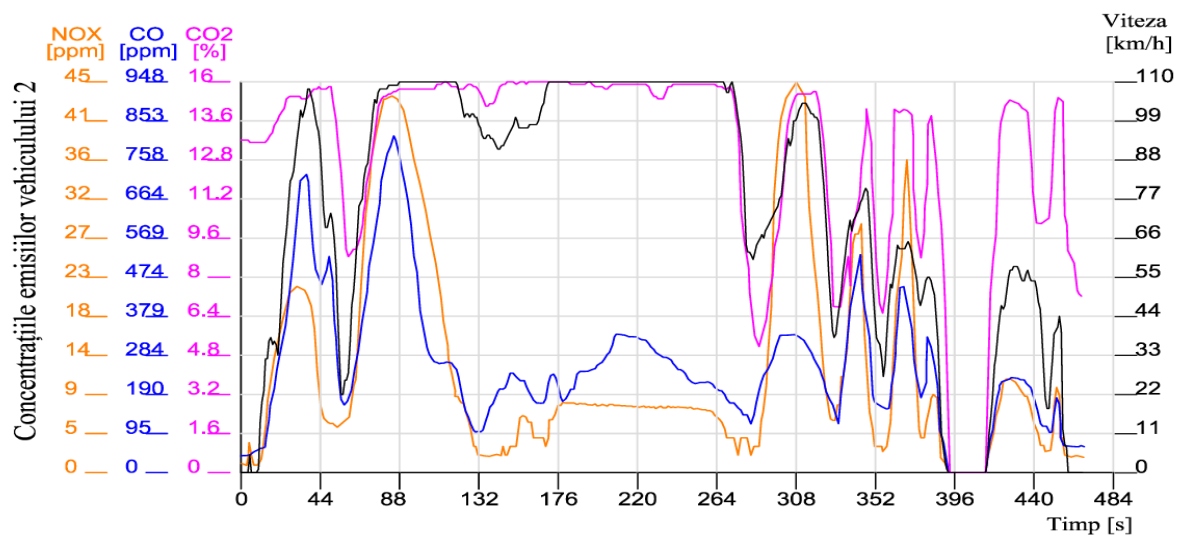
5.4. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Extra-Urban Traffic Conditions

The extra-urban driving cycle extends the analysis by introducing operating conditions characterized by higher speeds and extended periods of steady-speed driving. The maximum speed reaches 110 km/h, while the average speed including stops is 52.8 km/h and the average speed excluding stops is 57.8 km/h. The number of stops is reduced to four, with a total stationary time of 42 s. Under these conditions, the influence of repeated stopping and starting decreases, while engine load and aerodynamic drag become increasingly important.

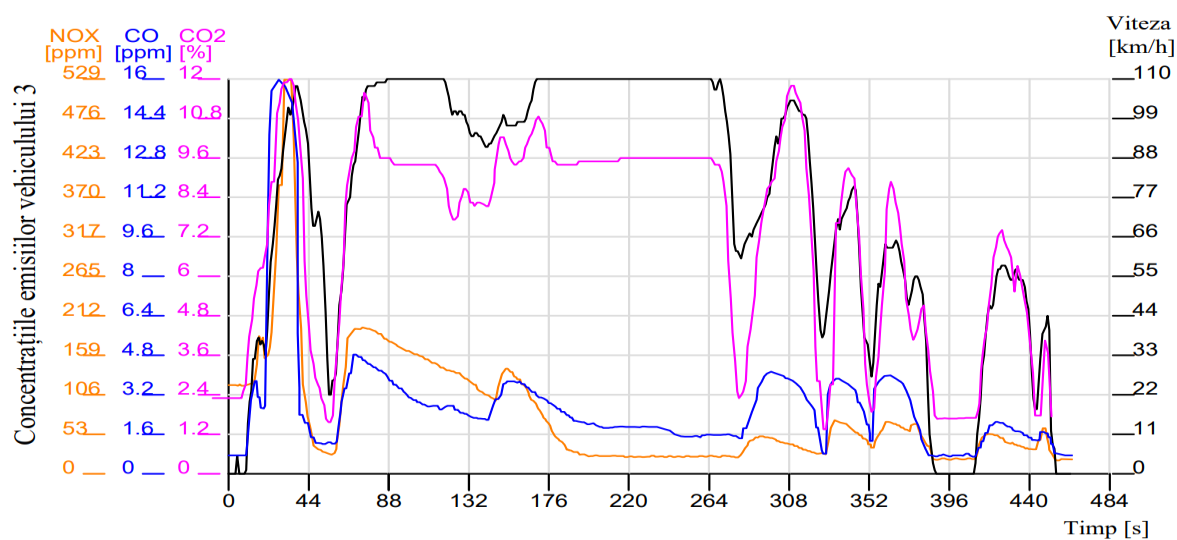
For V1 and V2, NO_x concentrations generally remain low, with maximum values of approximately 160 ppm for V1 and 45 ppm for V2. The increases are associated with the initial acceleration phases, while concentrations decrease after the speed stabilizes at approximately 90–100 km/h, indicating efficient operation of the three-way catalytic converter. CO concentrations also decrease once the thermal operating conditions stabilize, while CO₂ concentrations remain approximately within the range of 14–16%, corresponding to the energy demand required for driving at higher speeds.



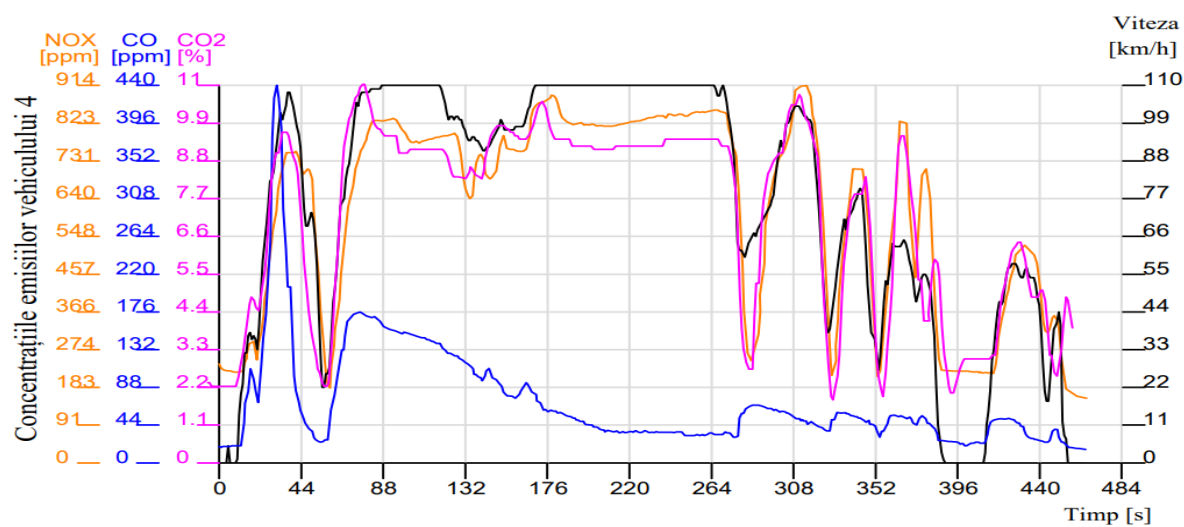
a)



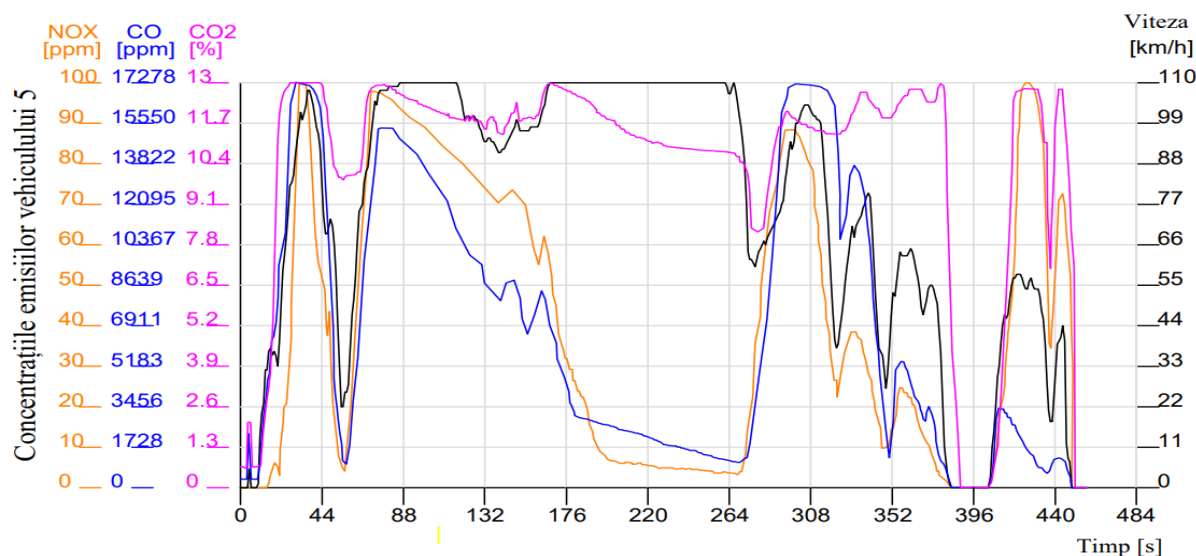
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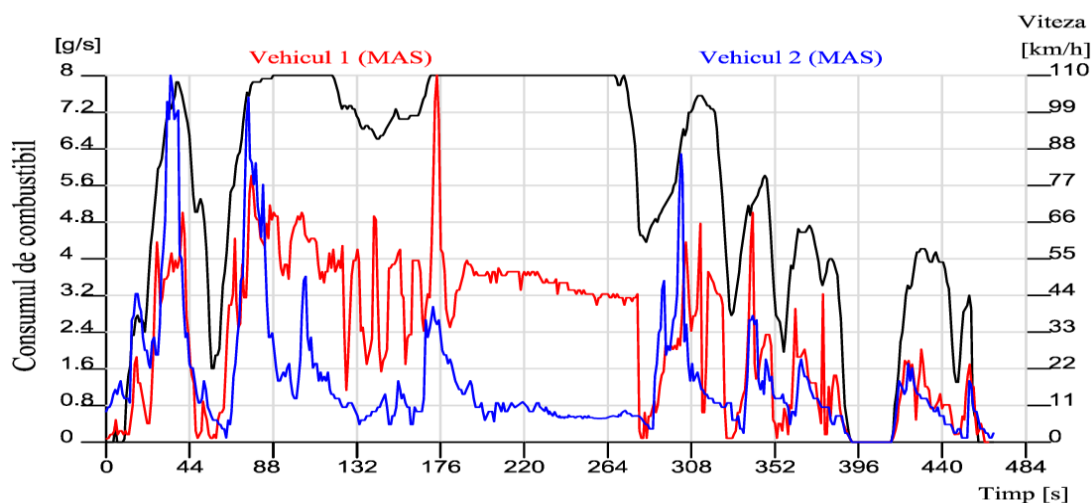


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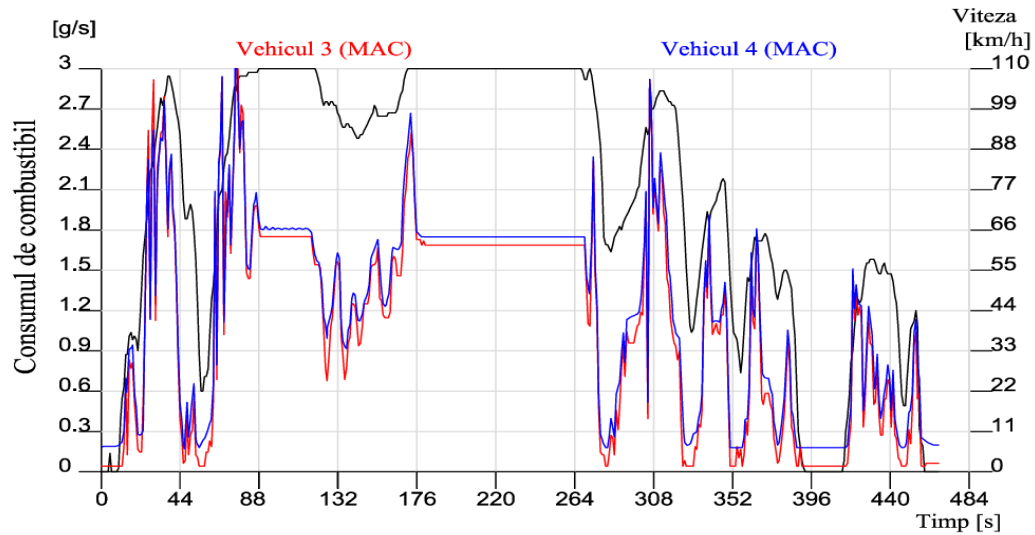
Fig. 5.8 - Effect of Dynamic Driving Conditions During the Real-World Extra-Urban Driving Cycle (E-BV Cycle) on NO_x, CO, and CO₂ Concentrations: (a) and (b) Spark-Ignition Engines – Vehicles 1 (Direct Injection, Turbocharged) and 2 (Indirect Injection, Naturally Aspirated); (c) and (d) Compression-Ignition Engines – Vehicles 3 and 4 (Indirect Injection, Turbocharged); (e) Vehicle 5 (Hybrid).

For vehicles equipped with compression-ignition (CI) engines, the increase in engine load results in a different pattern of NO_x concentrations. V3 exhibits an initial peak of approximately 529 ppm, followed by a decrease to approximately 50 ppm once the SCR system reaches its appropriate operating temperature range. V4 records considerably higher values, reaching approximately 900 ppm during high-load phases at speeds approaching 100 km/h. The difference between V3 and V4 demonstrates the influence of engine design characteristics and exhaust aftertreatment strategies, even among vehicles belonging to the same engine category.

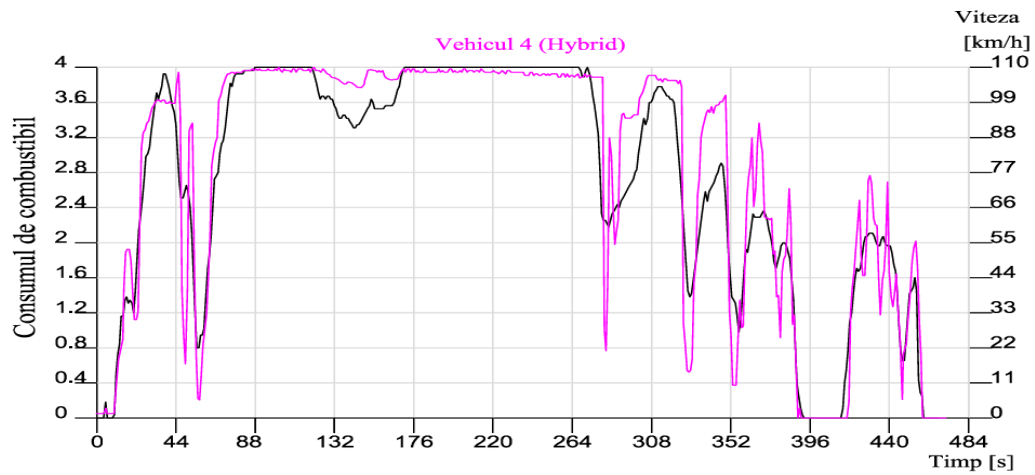
For V5, thermal operating conditions once again limit the use of the electric propulsion system, with the internal combustion engine remaining active throughout almost the entire driving cycle. Consequently, fuel consumption follows the speed profile, reaching values close to 4 g/s in the highest-speed sections (Fig. 5.9). Therefore, under the experimental conditions investigated, the energy consumption characteristics of the hybrid vehicle during extra-urban driving are similar to those of a conventional vehicle equipped with a spark-ignition engine.



a)



b)



c)

Fig. 5.9 - Instantaneous Fuel Consumption Values During the Extra-Urban Driving Cycle (Test Series II): (a) Spark-Ignition Vehicles; (b) Compression-Ignition Vehicles; (c) Hybrid Vehicle.

For all vehicles, fuel consumption increases again at speeds of approximately 90–110 km/h. This finding is important because it demonstrates that reducing fuel consumption by improving traffic flow does not imply an unlimited increase in driving speed. At low speeds, transient operating conditions and frequent stops result in higher fuel consumption; within the intermediate speed range, operating conditions are more favorable, whereas at higher speeds, increasing aerodynamic drag leads to a renewed rise in energy demand.

5.5. Investigation of Exhaust Emission Concentrations and Fuel Consumption under Road Traffic Conditions Represented by the WLTC Driving Cycle

The WLTC driving cycle was used to extend the research by evaluating the five vehicles under a standardized speed profile consisting of successive low-, medium-, high-, and extra-high-speed phases. Unlike the real-world driving cycles, which were performed at ambient temperatures of approximately 9–12 °C, WLTC testing was conducted at a higher ambient temperature (23 °C),

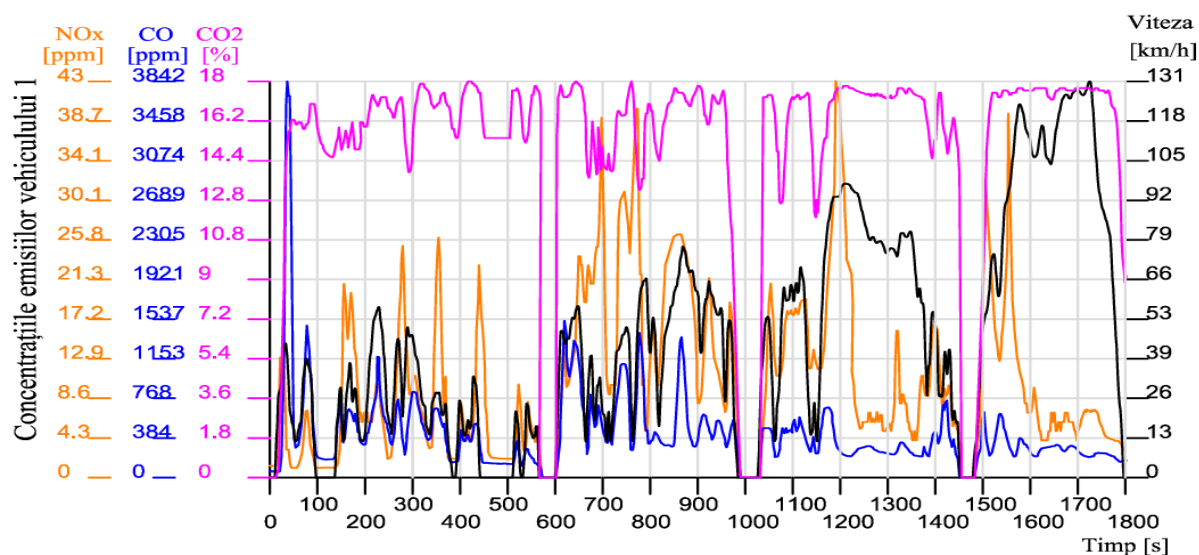
allowing the influence of the driving profile and the progressive warming of the engine and exhaust aftertreatment systems to be more clearly identified.

For V1 and V2, NO_x concentrations remain low throughout most of the driving cycle, with maximum values of approximately 40–45 ppm for V1 and below 30 ppm for V2 (Fig. 5.10). The peaks are associated with acceleration phases, while concentrations decrease during periods of steady-speed driving due to the efficient operation of the three-way catalytic converter. CO concentrations are higher during the initial phases, after which they stabilize at low levels. CO₂ concentrations range approximately between 14% and 18%, particularly during the high-speed phases.

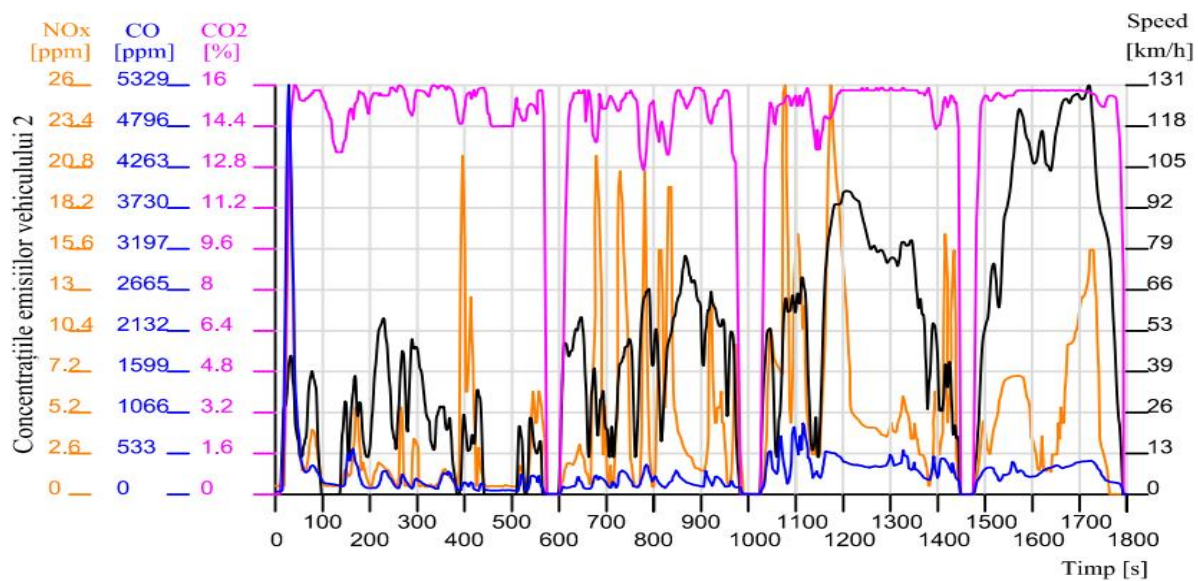
Comparison with the real-world driving cycles highlights the importance of thermal operating conditions. In Test Series I, NO_x peaks exceeding 450 ppm for V1 and reaching approximately 240 ppm for V2 were recorded during certain sections of the urban driving cycle, whereas the maximum values observed during the WLTC are considerably lower. This difference confirms the significant influence of cold starts, ambient temperature, and exhaust aftertreatment system temperatures on the concentrations measured under real-world driving conditions.

For V3, maximum NO_x concentrations reach approximately 220 ppm during the initial phases, after which they progressively decrease as the exhaust gas temperature rises and the efficiency of the SCR system improves. V4 exhibits the highest values among the vehicles investigated, exceeding 1,000 ppm during certain high-speed and high-load phases. For both vehicles equipped with compression-ignition (CI) engines, CO concentrations remain low throughout most of the driving cycle, while CO₂ concentrations generally remain below 12%.

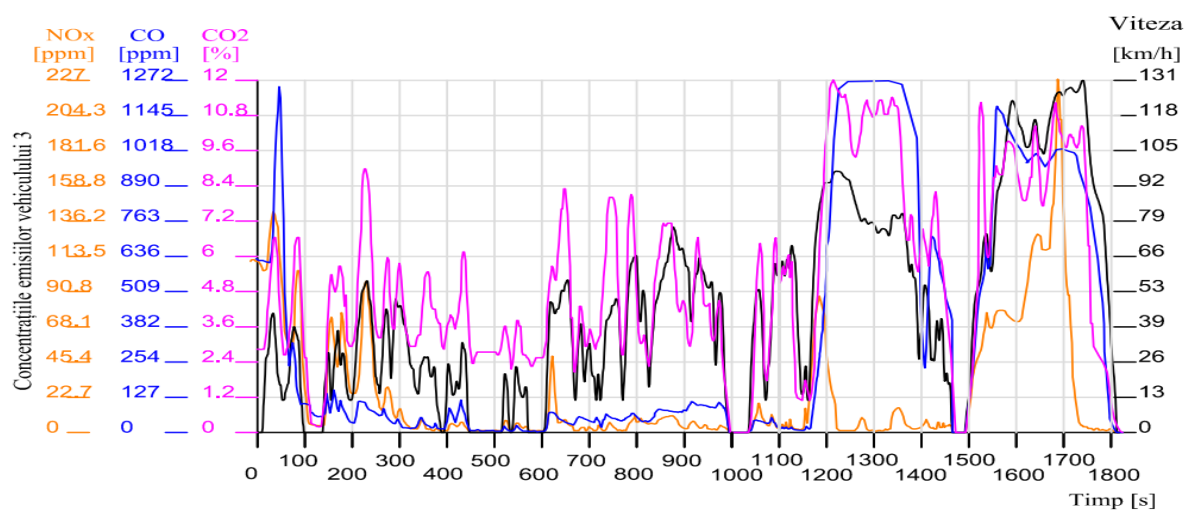
V5 exhibits intermediate behaviour, with NO_x concentrations generally remaining below 90 ppm. CO concentrations decrease once operating conditions stabilize, while CO₂ concentrations range approximately between 8% and 12%. The automatic engine stop function was activated for V1, V2, and V5 at approximately 550 s, and for V3 and V4 after approximately 1,000 s, highlighting the influence of thermal operating conditions and vehicle-specific control strategies on the operation of this system.



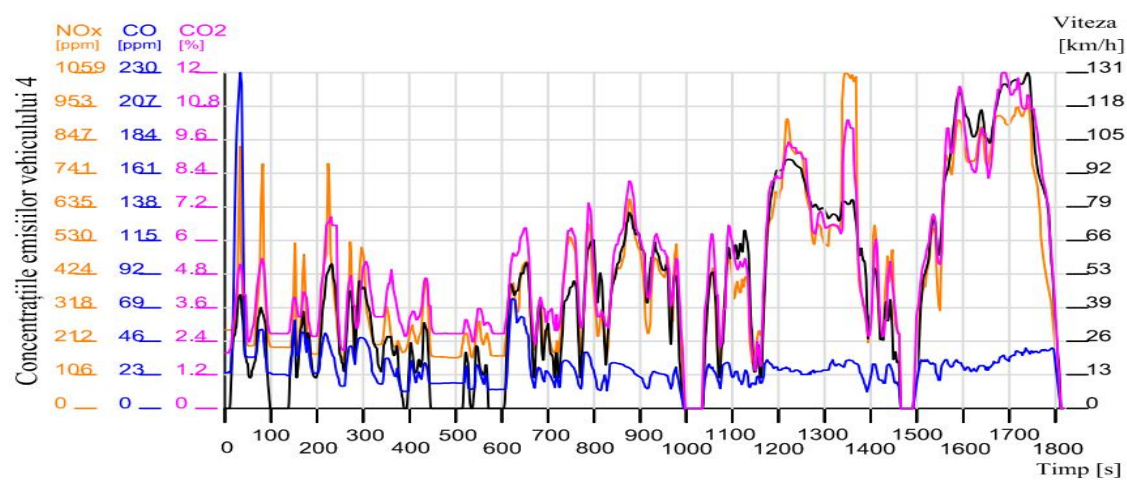
a)



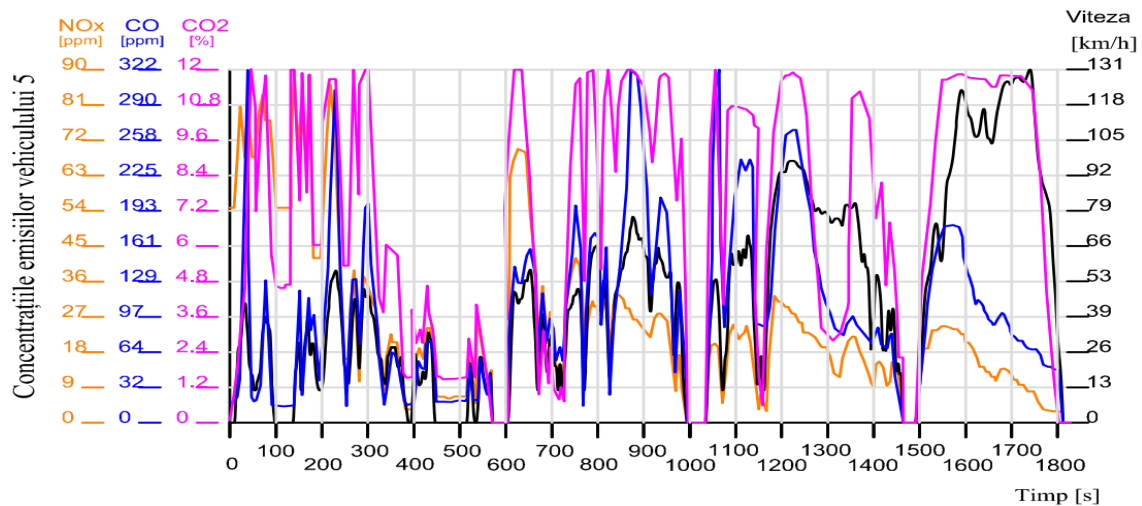
b)



c)



d)



e)

Fig. 5.10 - Effect of Dynamic Driving Conditions During the WLTC Driving Cycle on NO_x , CO, and CO_2 Concentrations: (a) and (b) Spark-Ignition Engines – Vehicles 1 (Direct Injection, Turbocharged) and 2 (Indirect Injection, Naturally Aspirated); (c) and (d) Compression-Ignition Engines – Vehicles 3 and 4 (Indirect Injection, Turbocharged); (e) Vehicle 5 (Hybrid).

The analysis of fuel consumption across the four WLTC phases confirms its dependence on vehicle speed and engine load. During the low-speed phase, successive stops and accelerations result in significant variations in instantaneous fuel consumption. During the medium-speed phases, engine operation becomes more stable, and specific fuel consumption tends towards more favourable values. During the high- and extra-high-speed phases, power demand progressively increases, primarily due to aerodynamic drag, resulting in a renewed increase in fuel consumption.

5.6. Comparison of Experimental Results Obtained under WLTC and Real-World Driving Conditions

The integrated analysis of the real-world driving cycles and the WLTC demonstrates that the influence of traffic conditions on fuel consumption and exhaust emission concentrations cannot be characterized solely by average speed. The number and duration of stops, the frequency of acceleration and deceleration, the magnitude of speed variations, engine load, and thermal operating conditions are determining factors in the behaviour of the propulsion system.

Urban driving conditions are the most sensitive to these factors. Frequent sequences of stopping, starting, and accelerating lead to substantial variations in fuel consumption and exhaust emission concentrations, and these effects are amplified when the engine and exhaust aftertreatment systems operate below their optimal temperatures. Improving traffic flow reduces the frequency of transient operating conditions and allows more stable operation of the propulsion system.

Under suburban driving conditions, higher speeds and fewer stops result in more uniform operation. Exhaust aftertreatment systems benefit from more favourable operating temperatures, while variations in fuel consumption and exhaust emission concentrations are smaller than those observed under urban driving conditions. During the transition to extra-urban driving, the benefits of more stable operation are maintained; however, increasing vehicle speed leads to higher energy demand, particularly due to increased aerodynamic drag.

The results also reveal clear differences between propulsion systems. Vehicles equipped with spark-ignition (SI) engines exhibit low NO_x concentrations once the three-way catalytic converter reaches its appropriate operating temperature, although CO concentration peaks may occur during engine start-up and acceleration. Vehicles equipped with compression-ignition (CI) engines exhibit low CO

concentrations and lower fuel consumption under numerous operating conditions; however, NO_x concentrations are strongly dependent on engine load and SCR system efficiency. The significant differences observed between V3 and V4 demonstrate that classifying vehicles solely according to engine type is insufficient, as exhaust aftertreatment technology and control strategies must also be considered.

For the hybrid vehicle, the advantages of the propulsion system depend on operating conditions. During the urban driving cycle, the vehicle exhibits low exhaust emission concentrations; however, at low temperatures and under suburban and extra-urban driving conditions, the use of electric propulsion is limited. Under these circumstances, the internal combustion engine remains active for extended periods, and the vehicle's energy consumption characteristics become similar to those of a conventional vehicle.

An important finding of the research is the influence of thermal operating conditions. The differences between the real-world driving cycles performed at low ambient temperatures and the WLTC conducted under controlled conditions demonstrate that the efficiency of exhaust aftertreatment systems cannot be considered constant. The time required for the engine, catalytic converter, and SCR system to reach their appropriate operating temperatures directly influences the recorded values, particularly during the first few minutes of driving.

Overall, the experimental results demonstrate a direct relationship between traffic dynamics, propulsion system operating conditions, fuel consumption, and exhaust emission concentrations. The most unfavourable conditions are associated with a combination of low temperatures, frequent stops, and repeated acceleration. Driving conditions characterized by moderate and relatively constant speeds allow the engine to operate within higher-efficiency ranges and reduce the magnitude of variations in the parameters investigated. At higher speeds, fuel consumption increases again due to additional energy demand, particularly as a result of increased aerodynamic drag.

This experimental conclusion supports the approach adopted in the numerical modelling: reducing the number of stops and unnecessary speed variations, without excessively increasing driving speed, represents an effective strategy for reducing fuel consumption and limiting variations in exhaust emission concentrations under road traffic conditions.

6. CONCLUSIONS AND PERSONAL CONTRIBUTIONS

6.1. Final Conclusions

The present doctoral thesis demonstrates, through an integrated experimental approach and numerical validation, that the influence of road traffic on vehicle fuel consumption and exhaust emissions is direct, quantifiable, and strongly dependent on real-world operating conditions. The results confirm the initial research hypothesis that pollutant emission concentrations and fuel consumption cannot be rigorously evaluated solely through standardized driving cycles but must be analysed in relation to traffic dynamics, engine thermal operating conditions, and the characteristics of road infrastructure.

A major scientific contribution of the thesis is the development and validation of a hybrid experimental methodology based on correlating real-world driving cycles recorded under urban, suburban, and extra-urban traffic conditions with their accurate reproduction on a chassis dynamometer. This approach made it possible to eliminate uncontrollable variables associated with real-world traffic and objectively compare the energy and environmental performance of vehicles equipped with different propulsion systems.

The experimental analysis revealed that traffic conditions characterized by low average speeds, frequent stops, and repeated acceleration and deceleration result in the highest fuel consumption and pollutant emission levels. In particular, urban driving was identified as the operating regime with the greatest energy and environmental impact due to the high density of traffic conflict points and the frequent occurrence of transient operating conditions. Conversely, driving cycles characterized by higher speeds and stabilized operating conditions demonstrated the highest energy efficiency, confirming that improving traffic flow represents one of the most effective measures for simultaneously reducing fuel consumption and environmental pollution.

From the perspective of physicochemical mechanisms, the research demonstrated that combustion gas temperature is a key parameter influencing NO_x formation reactions. NO_x formation is strongly determined by the quality of the air–fuel mixture, the fraction of residual or recirculated exhaust gases, and the amount of mixture burned before the piston reaches top dead centre. These factors have different effects depending on the engine type, whether spark-ignition (SI) or compression-ignition (CI). Engine operating parameters, particularly engine speed and instantaneous load, directly influence combustion gas temperature and, consequently, NO_x formation, explaining the considerable variations in exhaust emission concentrations even under apparently identical driving conditions.

An important finding of the thesis is the demonstration that the same vehicle speed can be achieved through different combinations of engine speed and load, each resulting in distinct exhaust emission concentrations. This provides a rigorous explanation of why pollutant emission concentrations may differ at the same vehicle speed. Furthermore, exhaust aftertreatment systems exhibit different conversion efficiencies depending on exhaust gas flow rate and thermal operating conditions, further contributing to the variations in emissions recorded experimentally.

The results demonstrated clear differences between propulsion system types. Vehicles equipped with compression-ignition (CI) engines consistently exhibited lower fuel consumption than those equipped with spark-ignition (SI) engines, particularly under stabilized operating conditions and at medium and high speeds, confirming the higher thermal efficiency of compression-ignition engines. Nevertheless, high NO_x emission levels were recorded for certain diesel vehicles, particularly the vehicle manufactured in 2015, highlighting the limitations of exhaust aftertreatment systems under real-world operating conditions.

A particularly relevant conclusion is that the thermal operating conditions of the engine and exhaust aftertreatment systems have a decisive influence on the emission profile along a driving route. Cold starts and the first few hundred seconds of engine operation generate high CO, HC, and NO_x emission peaks, making areas characterized by frequent engine starts and repeated stops critical locations for urban air quality. This finding has direct implications for traffic management in heavily congested areas and for strategies aimed at controlling emissions under real-world operating conditions.

The results obtained and presented in this thesis also demonstrate the value of numerical modelling and simulation in analysing vehicle energy consumption characteristics. The model developed and validated in the AMESIM environment confirmed the accuracy of real-world driving cycle reproduction and enabled the evaluation of hypothetical traffic optimization scenarios. The simulation results demonstrated that maintaining more uniform speeds and reducing transient operating conditions lead to measurable decreases in fuel consumption rate and cumulative emissions, providing a sound basis for implementing intelligent urban traffic management systems. The small differences between laboratory tests and AMESIM simulations, of approximately 2–3%, confirm the robustness of the methodology and the validity of the results obtained.

From an applied perspective, the conclusions of the thesis support the need to move beyond evaluation based exclusively on standardized driving cycles towards integrated methodologies incorporating real-world driving cycles and experimental validation under controlled conditions. This approach provides a considerably more accurate representation of the actual environmental impact of road transport and can serve as a valuable tool for developing sustainable mobility policies, optimizing urban infrastructure, and supporting future regulations concerning emissions under real-world operating conditions.

Overall, the research confirms that reducing the environmental impact of road transport depends not only on advances in propulsion technologies but also on how traffic is organized, controlled, and adapted to the characteristics of road infrastructure and the urban environment. Through its experimental approach, numerical validation, and the practical relevance of its conclusions, the thesis makes an original, scientifically well-founded contribution with direct applications in automotive engineering and environmental protection.

6.2. Personal Contributions

- Development and validation of an original research methodological framework based on road traffic simulation and the reproduction of real-world operating conditions, aimed at evaluating the influence of dynamic driving conditions on pollutant emissions and fuel consumption through the development of new representative testing cycles.
- Development of representative real-world driving cycles for urban, suburban, and extra-urban conditions, based on dynamic parameters collected in real-world traffic (speed, acceleration, deceleration, stops, and thermal operating conditions), subsequently used for experimental reproduction on a chassis dynamometer.
- Identification and quantification of the influence of traffic intensity on pollutant emission levels through a comparative analysis of driving cycles performed during different time intervals and under varying traffic flow conditions.
- Development and validation of a dedicated software application in the AutoCAD environment, designed to integrate and process experimental data obtained during testing, with automatic generation of graphical representations required for the comparative analysis of pollutant emissions and fuel consumption.
- Demonstration, through numerical simulation and experimental validation, of the beneficial effect of maintaining more uniform vehicle speeds on reducing fuel consumption and pollutant emissions, contributing to the development of intelligent urban traffic management solutions.
- Identification of differences between the values obtained under standardized WLTC testing conditions and those determined under real-world operating conditions, with direct relevance to the assessment of actual vehicle performance.

6.3. Future Research Directions and Developments (Proposals for Future Work)

- Analysis of the individual phases of the WLTC driving cycle (low, medium, high, and extra-high) by correlating fuel consumption, engine speed, engine load, and pollutant emissions to identify critical operating conditions. This approach is frequently used in

the scientific literature to highlight dynamic variations in emissions under transient operating conditions.

- Investigation of the influence of acceleration and dynamic engine load on pollutant emissions, including vehicle launch from a standstill and rapid load variations, in correlation with parameters such as tyre pressure and vehicle mass. Recent studies indicate that these conditions have a significant impact on instantaneous emissions, particularly NO_x and CO.
- Analysis of Real Driving Emissions (RDE) by extending experimental testing beyond the chassis dynamometer to evaluate differences between controlled laboratory conditions and real-world traffic conditions.
- Investigation of the behaviour of exhaust aftertreatment systems (TWC, SCR, and DPF) as a function of temperature, engine load, degradation state (efficiency/inefficiency), and operating conditions, with particular emphasis on pollutant conversion efficiency during transient operation and cold starts.
- Analysis of electric motor activation timing and control strategies in hybrid vehicles by correlating electric motor operation with internal combustion engine load, battery state of charge, and vehicle speed profile. This research direction is essential for optimizing fuel consumption and reducing pollutant emissions.
- Comparative analysis of conventional, hybrid, and electric vehicles in terms of energy consumption and equivalent CO₂ emissions under similar operating conditions.
- Life Cycle Assessment (LCA) of emissions from electric, hybrid, and conventional vehicles, including:
 - Vehicle production (particularly battery manufacturing for electric vehicles);
 - Vehicle operation and use;
 - Recycling and end-of-life management. This approach enables the assessment of total CO₂ emissions throughout the vehicle life cycle, from production to end-of-life disposal, and is extensively investigated in recent scientific research.
- Analysis of energy consumption in electric vehicles as a function of:
 - Driving style;
 - Traffic conditions;
 - Ambient temperature;
 - Use of auxiliary systems (HVAC). Studies indicate significant variations in driving range and energy efficiency depending on these parameters.
- Investigation of performance degradation over time by analysing changes in pollutant emissions and fuel consumption as vehicle mileage increases, including the degradation of catalytic converters and batteries.
- Integration of artificial intelligence and machine learning methods for:
 - Prediction of pollutant emissions based on engine operating parameters;
 - Optimization of engine control strategies;
 - Detection of operational anomalies.

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LIST OF PUBLISHED SCIENTIFIC PAPERS

During the preparation of my doctoral thesis, I authored four scientific papers as first author, which were published in conference proceedings indexed in the Web of Science (ISI Proceedings):

1. Constantin Nitoiu^[0009-0004-5899-9985], Corneliu Cofaru^[0000-0001-5076-0671], Mihaela Virginia Popescu and Cristian Klement, The Study of Vehicle Emissions using a Dynamic Cycle Performed on the Base of Real Urban Traffic, EAEC – CONAT 2024, The International Congress of Automotive and Transport Engineering, Transylvania University Brasov, 6-8 november 2024, <https://www.webofscience.com/wos/woscc/full-record/WOS:001462624600002>; https://doi.org/10.1007/978-3-031-77631-1_2, pp. 15-30.
2. Constantin Nitoiu^[0009-0004-5899-9985], Corneliu Cofaru^[0000-0001-5076-0671], Mihaela Virginia Popescu, Comparative Analysis of the Emissions Obtained on the Dynamometer Stand During Use the WLTP Cycle and the Real Urban Driving Cycle on Two Types of Ve-hicles, EAEC – CONAT 2024, The International Congress of Automotive and Transport Engineering, Transylvania University Brasov, 6-8 november 2024, <https://www.webofscience.com/wos/woscc/full-record/WOS:001462624600003> ; https://doi.org/10.1007/978-3-031-77631-1_3, pp. 31-43,.
3. Pampa V.M., Ispas N., Cofaru C., Nastasoiu M., Ionita D.T., Nitoiu C.: An Estimation of the Energy Consumption of Electric, Hybrid and Classic Road Vehicles Starting from the Equivalent WLTP Driving Cycles, Ingineria Automobilului, No. 72/ September 2024, pp. 5-11, ISSN 1842-4074, <https://www.webofscience.com/wos/woscc/full-record/WOS:001340317100002>; <https://www.peeref.com/works/84377770>.
4. Constantin Nitoiu, Corneliu Cofaru, Mihaela Popescu, Influence of road and traffic conditions on emissions and fuel consumption of light vehicles in a real urban driving cycle, Environmental Science and Pollution Research, 21 May 2024, <https://doi.org/10.1007/s11356-025-36573-3>.
5. Constantin Nitoiu, Corneliu Cofaru, Mihaela Popescu, Modeling real cycles using driving cycle software to analyze the influence of road traffic characteristics on the emission of different types of vehicles, 13.11.2024, doi: 10.20944/preprints202411.1003.v1.

During the preparation of my doctoral thesis, I participated in the following international conferences:

The International Congress of Automotive and Transport Engineering, EAEC – CONAT 2024, Transylvania University Brasov, 6-8 november 2024.