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THE IMPACT OF ROAD INFRASTRUCTURE ON FUEL CONSUMPTION AND EMISSIONS OF A ROAD VEHICLE – A CASE STUDY

Summary. This article addresses an underexplored yet important factor—the influence of road geometry and characteristics on the energy demands and environmental footprint of road vehicle operation. Based on a case study using real-world data from the operation of a petrol-powered passenger car, differences in fuel consumption and CO₂ and NO_x emissions when driving on rural and urban roads are analyzed. The results indicate that factors such as road gradient, traffic flow characteristics, and stop frequency can significantly affect operational efficiency. The study provides evidence that traffic engineering applications have a measurable impact on fuel consumption and pollutant emissions and, as such, should not be overlooked. Based on these findings, the study proposes that road infrastructure characteristics and management should be actively integrated into strategic sustainable transport policy measures, particularly within the framework of the European Union's Green Deal objectives.

1. INTRODUCTION

The issue of road transport emissions is gaining importance in the context of global efforts to reduce the carbon footprint and improve air quality. Among the factors influencing fuel consumption and emissions are the technical parameters of vehicles and the characteristics of the road infrastructure. The present research aims to analyze the impact of road infrastructure and traffic engineering solutions on vehicle fuel consumption and emissions. This article presents a case study based on real-world operational data from a passenger car. Available literature indicates that, so far, research has primarily focused on vehicles themselves, while the influence of road infrastructure has been addressed mainly through restrictive measures (such as low-emission zones).

For example, according to the latest regulations, all vehicles in European Union countries must undergo type-approval tests, including both the laboratory-based Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and real driving emissions (RDE) tests, to verify actual pollutant outputs. Furthermore, the European Union's Green Deal sets an ambitious goal of achieving carbon neutrality by 2050, which includes tightening emission standards for road vehicles.

The upcoming EURO 7 emission standards, expected to come into effect in the near future, introduce even stricter limits for pollutants such as nitrogen oxides (NO_x) and particulate matter. These measures are necessary to reduce the environmental impact of transport, but they also raise questions regarding their feasibility and economic implications.

One of the main arguments of Green Deal advocates is that stricter emission limits will drive innovation in the automotive industry, accelerate the transition to electromobility, and reduce dependence on fossil fuels. Meanwhile, critics warn of potential negative effects on vehicle affordability and risks related to insufficient infrastructure for alternative propulsion systems.

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In this context, it is both necessary and fair to consider other factors and to understand how road characteristics influence real-world fuel consumption and emissions. This is directly related to the effectiveness of policy measures not only within the Green Deal framework; thus, attention should be paid not only to vehicles but also to the road infrastructure itself.

2. LITERATURE REVIEW

Numerous studies have explored vehicle emissions and the impact of road infrastructure on vehicle operation. These studies often focus on optimizing individual aspects of transport, such as fuel consumption, emissions production, or improved traffic flow. The results of some of this research have already been implemented in practice and have influenced both legislation [1] and navigation applications – such as eco-routing [2, 3], a navigation method that aims to select the most fuel-efficient route. Furthermore, advanced systems are being developed that, owing to Dynamic Predictive Systems navigation, can predict terrain and efficiently control the vehicle's drivetrain based on those characteristics [4]. This optimizes vehicle operation and emissions reduction in real-time.

Despite these advances, most attention continues to be directed primarily at the vehicles themselves – whether it concerns their technological development, electrification, or aerodynamic improvements [5–8]. Road infrastructure is often viewed as an immutable element that is difficult to modify or optimize. However, this approach overlooks the fact that roads are largely publicly owned, which opens opportunities for systemic solutions.

Public authorities responsible for implementing the Green Deal, mainly through restrictive measures, can influence not only vehicle regulation but also the design and management of the road network.

Another key factor affecting emissions production is driving style [9]. This factor depends on the driver's behavior, experience, ability to anticipate traffic situations, and skill to drive smoothly without unnecessary acceleration or braking. The question then becomes how effectively road design can be integrated into emissions reduction strategies, and what potential infrastructure optimization has to contribute to achieving carbon neutrality.

Regulatory authorities – particularly those in the European Union – are introducing stricter standards and testing cycles (such as WLTP and RDE) to reduce the environmental impact of transportation. However, standardized laboratory tests do not provide a fully realistic picture of emissions in everyday operation, making real-world measurements crucial [10].

Growing attention to the environmental aspects of transport is driving efforts to reduce exhaust gas emissions and decarbonize mobility. Both international and European regulations have defined limits for individual exhaust gas components and specified methodologies for their measurement [11]. Vehicle exhaust gases contain substances with harmful impacts on human health and the climate. Their quantity is closely related to fuel consumption and the technical condition of the engine. Therefore, reducing fuel consumption represents an effective way to lower the emissions burden.

The key components of vehicular emissions, according to [9], are the following:

- **Carbon monoxide (CO):** A toxic gas formed as a result of incomplete combustion, predominantly in spark-ignition engines. It binds with hemoglobin, reducing the blood's oxygen-carrying capacity.
- **Carbon dioxide (CO₂):** The principal greenhouse gas generated through complete combustion processes. It plays a significant role in anthropogenic climate change.
- **Nitrogen oxides (NO_x):** Produced at elevated combustion temperatures. Particularly prevalent in compression-ignition (diesel) engines, NO_x emissions are difficult to mitigate and are therefore subject to the most stringent environmental regulations.
- **Unburned hydrocarbons (HC):** Remnants of fuel that were not fully combusted. Certain hydrocarbon compounds are toxic or carcinogenic and contribute to the formation of ground-level ozone and photochemical smog.
- **Sulfur oxides (SO_x):** Emissions mainly associated with diesel engines that depend on the sulfur content of the fuel. Elevated concentrations of SO_x contribute to acid rain and have harmful ecological impacts.

- **Particulate matter (PM):** Composed largely of carbonaceous materials. Fine particles smaller than $1\ \mu\text{m}$ (PM_{10}) can penetrate the pulmonary barrier and enter the bloodstream, often carrying carcinogenic substances.

The design of road infrastructure constitutes a complex process that integrates a wide array of technical, operational, safety-related, environmental, and economic factors. A fundamental input parameter is the nature of the traffic flow – specifically its intensity, composition, and design speed – which collectively determine aspects such as cross-sectional layout, pavement structure, and the type of intersection design. Geographical and environmental conditions, including topography, geotechnical properties of the subgrade, and the presence of groundwater or surface water, influence the routing, scope of earthworks, and drainage engineering solutions.

The urban planning context plays a pivotal role in urban environments, encompassing the built-up character of the area, connectivity to the existing transport network, access to public transport, and the need to accommodate pedestrian and bicycle traffic. Safety measures form an integral component of the design, tailored to site-specific conditions – such as ensuring sufficient sight distances, grade-separated pedestrian crossings, the deployment of guardrails, and the incorporation of passive safety elements.

Today, environmental considerations—such as landscape protection, noise and emissions mitigation, and land take minimization – are an essential part of any transportation infrastructure project. However, these aspects are frequently subordinated to cost-cutting pressures in both construction and maintenance, often to the detriment of quality. Economic considerations are also of major importance, as the construction and operation of roads should be efficient in terms of both investment costs and societal benefits, which are typically assessed through cost-benefit analyses.

Current road design standards primarily focus on traffic safety; however, environmental objectives aligned with the European Green Deal strategy appear to be insufficiently prioritized, even though their achievement cannot be assumed to be cost-neutral.

A substantial body of research is devoted to measuring vehicular exhaust emissions. For instance, Cvitanic et al. [12] analyzed the impact of road geometry on fuel consumption and emissions in vehicles operated under free-flow conditions (measured at the 85th percentile speed). A field experiment involving constant-speed and free-flow driving was conducted using a passenger car equipped with a high-performance (10-Hz) Bluetooth GPS device and an onboard diagnostic (OBD) interface. This setup enabled the collection of data on driving trajectory, speed, acceleration, and fuel consumption. Regression analyses were then used to examine the relationships between free-flow speed, fuel consumption, and geometric road characteristics (e.g., curvature, length, longitudinal gradient), resulting in a predictive model that can evaluate alternative roadway design options for a given corridor in terms of efficiency and safety. The most influential geometric factors for fuel consumption were the gradient and the radii of adjacent curves. For constant-speed driving, gradient emerged as the sole geometric parameter with a significant effect on consumption.

Gkyrtis [14] conceptualized roads as three-dimensional linear infrastructures located within either urban or non-urban contexts. While design guidelines are strictly followed to ensure safe and comfortable transport of passengers and goods, they must also align with the terrain configuration and spatial constraints, especially in urban and peri-urban areas. Fuel consumption and emissions during vehicle operation are influenced by both driving behavior and specific roadway design characteristics, including surface condition. Gkyrtis's study focused on the environmental performance of roads from the perspective of fuel consumption in heavy vehicles, which predominantly serve urban freight transport needs. The influence of horizontal and vertical alignment was modeled using speed and longitudinal gradient as key variables. The theoretical results indicate that gradient plays the most critical role in the rate of fuel consumption increase; for instance, an increase in gradient from 2% to 7% corresponds to a 2.5-fold increase in fuel use. This effect was less pronounced at speeds between 25 and 45 km/h. The study highlights the need to consider the environmental impacts of roads during the operational phase to inform more sustainable freight transport practices. It also underscores the need for ad hoc fuel consumption models based on empirical data that adequately reflect local conditions and can be utilized by road engineers and urban planners. However, this initiative stops short of proposing interventions in roadway design itself.

Fan [15] highlighted a widening discrepancy between vehicle fuel consumption under laboratory test conditions and real-world driving, which may undermine the development of policies targeting energy efficiency and emission reductions. His study documented a 42% average discrepancy, based on 0.95 billion traffic records (including speed and acceleration) and fuel consumption data collected from 395 light commercial vehicles in Beijing via OBD devices. Independent assessments were carried out for the contributing factors, including discrepancies in fuel consumption rate (FCR), engine load, and road gradient, between standardized testing cycles and real-world driving. The differences attributable to FCR, engine load, and gradient accounted for 20.7%, 17.0%, and 3.2% of the discrepancy, respectively (only 1.0% remained unexplained). Replacing the New European Driving Cycle (NEDC) with the China Light-Duty Vehicle Test Cycle (CLTC-P) could reduce the engine load-related discrepancy from 17.0% to 6.9%. The study concluded that policies should prioritize the development of localized testing procedures or real-time monitoring of fuel consumption via onboard devices to better reflect actual vehicle efficiency. However, this research treated road infrastructure as a fixed variable.

The influence of traffic conditions and driving style was investigated by De Vlieger [16], who examined the impact of roadway type, driver behavior, and traffic conditions on fuel consumption and emissions using a small test fleet of passenger vehicles. Urban driving was associated with the highest fuel consumption and emission levels—approximately double those observed on suburban bypass routes, which generally exhibited the lowest values. Emission increases were even more pronounced than fuel consumption increases. Depending on road type and vehicle technology, aggressive driving resulted in up to a 40% increase in fuel use compared to normal driving, and even greater differences were observed in emissions. Driver behavior had a greater effect on gasoline vehicles than on diesel-powered vehicles. Traffic conditions also exerted a significant influence, with dense urban traffic increasing fuel consumption by 20–45%. During peak hours, bypass routes experienced the largest increases in consumption (up to 200%) with excess fuel use of up to 5 L per 100 km. De Vlieger concludes that more environmentally friendly routing during peak periods favors the use of highways and bypasses over shorter routes, as these facilitate smoother driving patterns.

3. METHODOLOGY

The data used in this study were obtained through field measurements conducted on a specific road section using a designated vehicle and precise measuring equipment. The measurement design consisted of several stages, including detailed planning of the route and data acquisition process.

The test route was located within the urban area of the city of Žilina, situated in the Slovak Republic. The total length of the measured section was 16 km. The measurement was carried out on March 22, 2022, under stable climatic conditions with an average air temperature of 10 °C (climatic conditions also affect the generation of emissions, but this measurement is a general demonstration of their generation, not their precise expression). The route was designed to represent typical urban traffic conditions, including various types of intersections, stop-and-go traffic, and sections allowing for continuous driving. A schematic representation of the route is provided in Fig. 2.

The same point was designated as the start and end of the route to ensure identical initial and final elevations. Additionally, the total elevation gain of the proposed route was designed not to exceed 100 m. The elevation profile of the route is shown in Fig. 3.

For the measurement, a Fiat 500 vehicle equipped with a mild-hybrid powertrain was selected. The electric motor, which is recharged through regenerative braking during driving, has a power output of 2.07 kW. The vehicle was type-approved on November 7, 2019, which implies that it had to comply with the Euro 6 emission standard during the approval testing process [10]. Details are provided in Table 1.

The geographic positioning of the measuring vehicle was determined using a GPS sensor, which continuously recorded coordinates every second in the WGS 84 system. This method of localization enabled the emission values to be linked to specific segments of the route (also recorded at one-second intervals), which was essential for subsequent spatial analysis of the results.

A MAHA MGT 5 exhaust gas analyzer was used to measure exhaust gas emissions during the real driving emissions (RDE) test cycle. This low-flow emission analyzer features no display and is designed to analyze carbon monoxide (CO), carbon dioxide (CO₂), unburned hydrocarbons (HC), oxygen (O₂), and nitrogen oxides (NO_x) while also calculating the air-fuel equivalence ratio, λ . The resulting emission components are expressed either as percentages or in parts per million (ppm), depending on the substance measured.



Fig. 1. Proposed route for measurement [17]



Fig. 2. Horizontal profile of the route [10]

The analyzer was accompanied by a laptop running a program called MAHA EMISSION VIEWER, which is used to start and operate the emission station and retrieve records of the measured exhaust components. The MAHA MGT 5 was equipped with an active condensed water separator featuring a separate membrane pump. The 8-m-long hose connected to the exhaust probe was cleaned automatically. The measuring unit was operated with a two-point calibration system.

The station's equipment also included a 3-m USB cable for connecting the analyzer to the computer. The analyzer's dimensions were 240 mm in length, 560 mm in width, and 300 mm in height. The warm-up time required to reach operating temperature was 10 minutes. The device weighed 10 kg and operated at a flow rate of 5 L/min under a pressure range of 0.75–1.1 bar. The analyzer is depicted in Fig. 3 below [17].

Table 1

Vehicle's technical specifications [10]

Category	Parameter	Value
Engine and transmission	Engine type and configuration	Petrol inline-three with a 3.6-kW electric motor
	Displacement [cm ³]	999
	Max. power [kW] at rpm	51 at 6000 rpm
	Max. torque [Nm] at rpm	92 at 3500 rpm
	Transmission	6-speed manual gearbox
Dimensions	External dimensions (length/width/height) [mm]	3546/1627/1488
	Wheelbase [mm]	2300
	Luggage capacity [l]	185/550
Weights	Curb weight/payload [kg]	865/365
Performance	Top speed [km/h]	167
	Acceleration 0–100 km/h [s]	13.VIII
	Energy consumption (combined WLTP) [kWh/100 kmg]	5.3–5.7
	CO ₂ emissions [g/kmg - EURO 6]	88–90 (NEDC), 119–127 (WLTP)
Category	Parameter	Value



Fig. 3. Exhaust Gas Analyzer MAHA MGT 5 [17]

The collected data were analyzed based on their spatial positions, as determined via GPS coordinates, and then compared with specific segments of the road infrastructure as defined by relevant traffic engineering applications and cartographic sources. Emission data and fuel consumption were converted into grams per second (g/s). Three representative real-world traffic scenarios were selected to illustrate

how different driving situations (e.g., acceleration, stopping, and uphill driving) influence exhaust emissions production. These scenarios were thoroughly evaluated in terms of the measured values of emission components and the vehicle's operational parameters.

4. RESULTS

After the route was designed, the vehicle was selected, and the appropriate equipment for recording the necessary data was chosen, the measurements were carried out on March 25, 2022, in the city of Žilina. Before the actual measurements could be taken, it was necessary to install the measuring equipment in the vehicle and perform the required methodological and technical procedures. This was essential to ensure that the obtained data would have the required quality, quantity, and frequency. For clarity, the results are presented as an image that illustrates the specific case study section, graphical outputs from the driving cycle, and an overview of the cumulative data.

4.1. Case Study 1 – Driving at an intersection

In this example of a 180-m road segment (shown in Fig. 4), the produced CO₂ emissions amount to 53 g. This implies that to comply with the EURO 6 standard over the remaining 820 m of one such kilometer driven in an urban environment, only 37 g of CO₂ remains allowable under the New European Driving Cycle (NEDC) standard, and 74 g of CO₂ under the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) standard. The graphs show that elevated CO₂ emissions occur roughly from the midpoint, coinciding with the acceleration triggered by passing through the intersection. It is also necessary to consider that the road's terrain profile features a downhill slope, which physically assists during vehicle acceleration – and, combined with a relatively smooth start, likely has a beneficial effect on the amount of CO produced (0.0042 g).

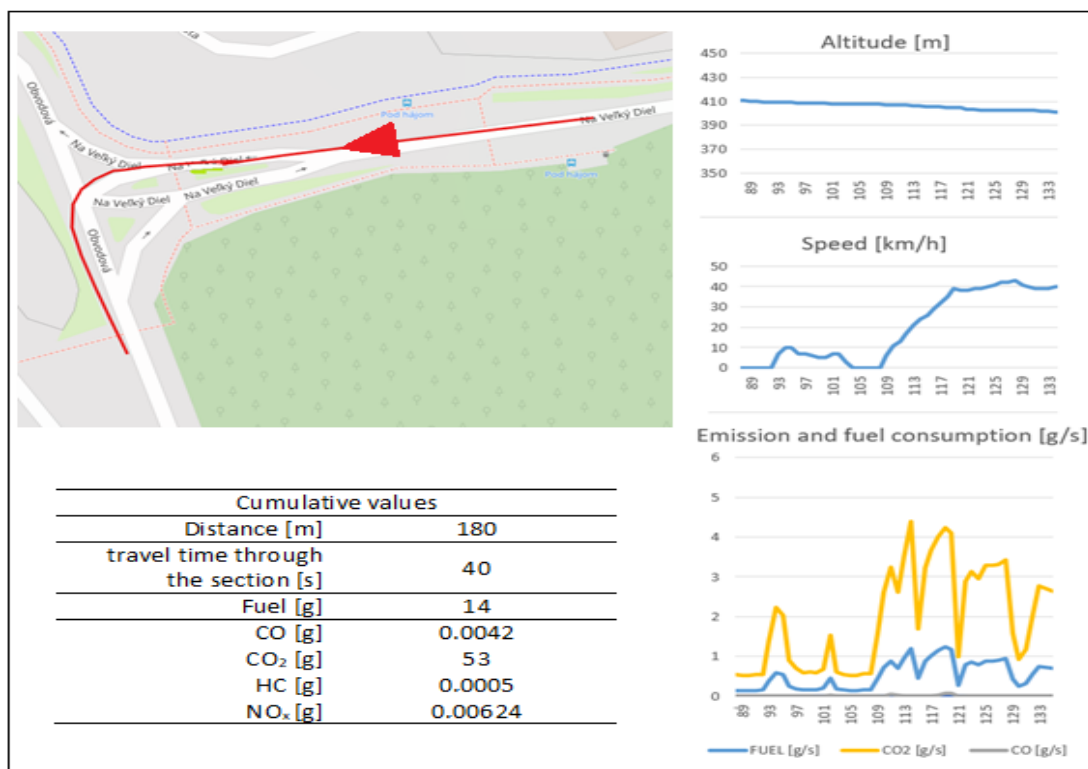


Fig. 4. Overview of measurements at the selected location. The x-axis on all graphs represents seconds from the vehicle's start

4.2. Case Study 2 – Driving in a queue before an intersection

In the analyzed section depicted in Fig. 5, the vehicle traveled in a traffic queue in the immediate vicinity of an intersection, followed by a smooth acceleration to a speed of 39 km/h. The graphs show that during repeated stopping and subsequent creeping forward, there was a sudden and significant increase in CO₂ emissions. This phenomenon is typical for operational modes involving frequent speed changes, where the combustion engine operates outside its optimal range, resulting in reduced combustion efficiency and increased emission load. It is important to note that this effect was caused by a specific traffic engineering design, but it is not sufficiently accounted for or systematically addressed in the current traffic solution design. Creeping in a queue is thus a direct consequence of traffic management and spatial arrangement of the roadway, which has an immediate impact not only on traffic flow smoothness but also on the air quality in the area. This situation represents just one of many model examples where more detailed measurements and analyses can provide more accurate and comprehensive information about real emission outputs in urban traffic conditions.

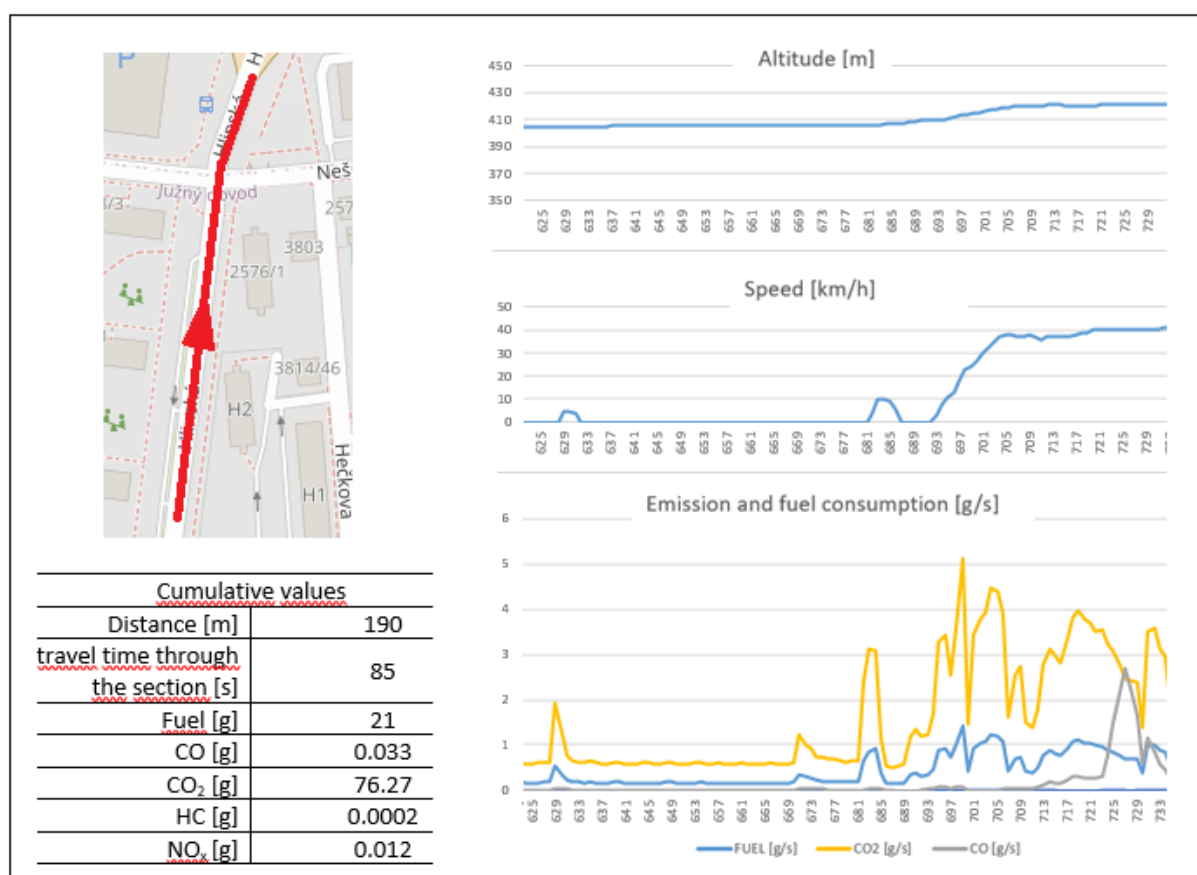


Fig. 5. Overview of measurements in the selected location. The x-axis of all graphs represents the time in seconds from the vehicle's start

4.3. Case Study 3 – Driving in a queue before an intersection

The analysis of this traffic situation (shown in Fig. 6) indicates that the vehicle approached the roundabout by coasting without acceleration (referred to as freewheeling), then lightly decelerated; then, after passing through the roundabout, it significantly accelerated. This driving behavior sequence is confirmed by elevated carbon monoxide (CO) emission levels measured immediately after the vehicle

exited the roundabout. The pronounced increase in emissions, observed in the 1790th second of driving, can be attributed to a high probability of a downshift to a lower gear, accompanied by rapid acceleration.

Regarding roundabouts, it is important to note that their structural design and operational principles necessitate vehicle deceleration and a subsequent restart in almost every case, even when the traffic load is minimal. In contrast to traditional at-grade intersections, which can often be crossed smoothly without significant speed changes during low traffic volumes, roundabouts require a reduction in speed due to the need to merge into the circulating traffic.

While this design element offers certain safety advantages, attention must be drawn to its impact on specific vehicle groups, particularly emergency service vehicles (integrated rescue system; IZS). During emergency interventions, when every second is critical, roundabouts may increase response times, as emergency vehicles must slow down and adapt to traffic flow within the roundabout, which often makes rapid passage impossible.

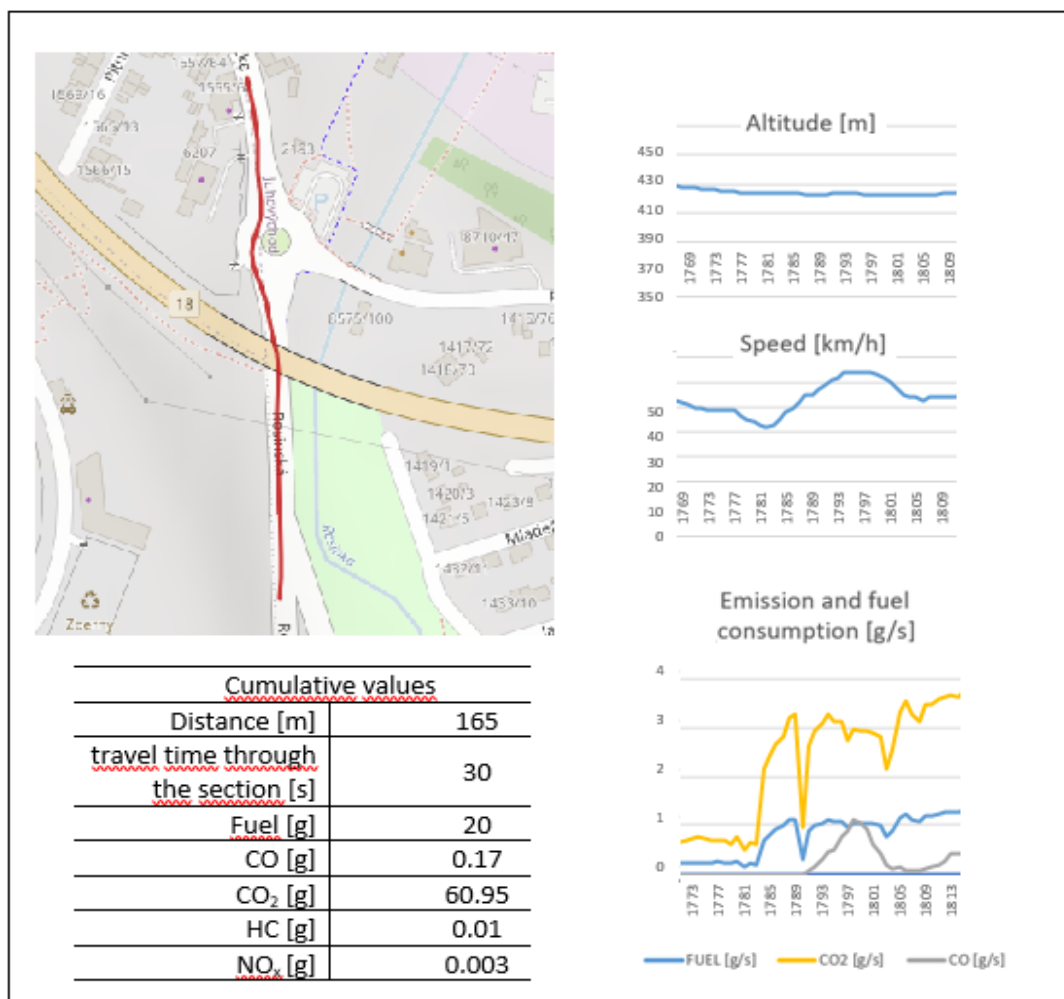


Fig. 6. Overview of measurements in the selected location. The x-axis of all graphs represents the time in seconds from the vehicle's start

5. DISCUSSION

The measurements confirm that fuel consumption and emission levels are influenced by vehicle technology, driving style, and (significantly) by the road environment. Specifically, segments with disrupted traffic flow, which are characterized by frequent stops, slow movement, and abrupt

accelerations, exhibit higher fuel usage and increased emissions. Even a parking lot (and, thus, its design) impacts emissions.

Although the current study was carried out using a single mild-hybrid passenger vehicle, the findings are relevant due to the high volume of daily traffic on the analyzed road segments. Local infrastructure conditions, such as steep gradients or inefficient traffic control, were shown to directly affect the operational efficiency of the vehicle and its emission output. The results highlight the discrepancy between real-world driving conditions and standardized laboratory tests. Urban traffic dynamics, especially stop-and-go movement and interactions at intersections, can substantially alter emission profiles compared to test-bench scenarios.

6. CONCLUSIONS

The presented case study confirms that road infrastructure plays a crucial role in determining vehicle fuel consumption and emissions. While technological improvements in vehicle design are undoubtedly important, they cannot be the only pathway for reducing transport-related environmental burdens. The environment in which vehicles operate – including traffic flow, road gradient, surface condition, and intersection design – has a significant and systemic effect on their real-world performance and emission output. The measurements show that roads with frequent stops, creeping traffic, and abrupt acceleration patterns significantly increase fuel consumption and emissions.

Although the data were obtained using only one vehicle type, the analyzed road segments are used daily by thousands of vehicles. This means that even small inefficiencies caused by poorly designed or managed road infrastructure can cumulatively contribute to a substantial environmental impact. Thus, the influence of infrastructure is not local or isolated but systemic and cumulative. In this context, public authorities, who typically own and manage road infrastructure, have a unique opportunity and responsibility to shape the transport system by regulating vehicles and deliberately designing and managing roads. Road infrastructure should no longer be regarded as a passive asset serving traffic but as an active element in the emissions system that either contributes to or reduces unnecessary emissions. A conceptual shift is needed, such as adopting the notion of an “average kilometer” as a new design benchmark. Each kilometer of a roadway should be planned in a way that encourages vehicle behavior aligned with emissions-reduction targets. This includes minimizing steep gradients, avoiding unnecessary stops, optimizing traffic flow, ensuring effective network connectivity, and integrating intelligent traffic control systems (e.g., adaptive signals, eco-routing).

Vehicular emissions require a more holistic approach that combines technological innovation in vehicles with a strategic transformation of the road infrastructure itself. Only by considering these dimensions can climate goals, such as those set forth in the Green Deal, be achieved. Road design must evolve into an intentional tool for environmental protection, not just a means of mobility.

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