# Metrological greenhouse gas emission assessment of the transport sector in Türkiye: Towards instrumentation, uncertainty and trends

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ABSTRACT
Environmental issues, including global warming, dependence on fossil fuels, deforestation, and rising $CO_2$ emissions, have become major challenges worldwide. In Türkiye, fossil fuel demand has continued to rise over the past two decades, despite policies promoting renewable energy. The effectiveness of these policies on transport-related greenhouse gas (GHG) emissions remains uncertain. To address this gap, this study analyses the long-term evolution of transport emissions over the last 33 years, integrating inventory-based estimates with experimental measurements to provide a metrologically validated dataset. Portable exhaust gas analysers (Horiba PG-350 and Testo 350XL) were used in conjunction with calibrated thermal mass flow meters and thermocouples to quantify $CO_2$, $CH_4$, and $N_2O$ emissions across various vehicle types and load conditions. Calibration traceability and uncertainty estimation were performed in accordance with ISO/IEC 17025 and the GUM guidelines. Experimental results were compared with IPCC Tier 2 estimates, showing close agreement for $CO_2$ (± 3.8 %) and larger variability for $CH_4$ and $N_2O$. These findings highlight the essential role of metrology in improving the reliability of emission data and support the integration of measurement-based validation into national GHG inventory frameworks.

## 1. INTRODUCTION

The global increase in energy demand has led to a sharp rise in the use of fossil fuels, primarily oil, coal, and natural gas, particularly within the transportation sector. This trend is associated with significant greenhouse gas (GHG) emissions, notably carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), which play a central role in global warming and climate change [1], [2]. In addition to $CO_2$, methane ($CH_4$) emissions are increasingly recognized as critical components of GHG inventories, also in the livestock sector; recent works in Acta IMEKO demonstrate IoT-based systems for $CH_4$ emission monitoring from ruminants [3] and quantification of $CH_4$ production from different forages [4]-[6]. As transportation systems remain heavily dependent on internal combustion engines, precise quantification of their environmental impact has become essential [7]. The authors previously applied similar monitoring approaches to assess high-frequency electromagnetic field pollution in urban areas [8].

Accurate and traceable measurement of GHG emissions is fundamental not only for constructing national inventories but also for validating predictive models, such as those outlined by the Intergovernmental Panel on Climate Change (IPCC). In this context, the metrological characterization of emission sources, based on experimental measurements, calibration procedures, and uncertainty analysis, offers an essential tool for both environmental and engineering sciences [9], [10].

This study aligns with recent efforts in the metrology community to establish traceable methods for GHG monitoring, explicitly focusing on the transport sector in Türkiye. It analyses how GHG emissions have evolved over the last three decades. Beyond assessing the impacts of national and international policies, the work integrates experimental measurements using calibrated analysers and defined driving cycles to provide a metrologically robust dataset. These results enable a direct comparison with IPCC Tier 2 emission estimates, providing insight into the accuracy, variability, and reliability of theoretical models when applied to real-world data.

In recent years, more than 70 countries, including Türkiye, have signed international protocols and set targets aligned with the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement [11]. Among these targets, the reduction of GHG emissions in the transport sector stands out as a key objective due to its share in total national emissions. Türkiye, as an Annex-I country, submits its National Inventory Report (NIR) annually to the United Nations Framework Convention on Climate Change (UNFCCC), reporting detailed emission data from all transport modes: road, rail, maritime, aviation, and pipeline.

Despite various efforts to promote renewable energy and improve fuel efficiency, Türkiye's transport sector continues to rely heavily on fossil fuels, with road transport being the dominant contributor [12]. The national policies implemented over the past decades have shown a time-lag effect, with measurable improvements in emission reductions becoming evident approximately ten years after policy changes were introduced [13]. This highlights the need for high-quality, traceable data to evaluate policy effectiveness and to support future strategies.

More than 70 countries signed a joint protocol in 2020 to reduce greenhouse gases and related adverse impacts [9].

In this context, they agreed to commit to achieving net-zero carbon emissions by 2050, thereby achieving carbon neutrality.

According to the Turkish Statistical Institute's (TURKSTAT) 2022 annual report, the transport sector generated 91.87 million tons of $CO_2$ equivalent emissions [14]. Road transportation accounted for 94.1 % of total transport emissions, domestic aviation for 3.7 %, domestic waterborne navigation for 1.2 %, railways for 0.6 %, and pipeline transportation for 0.5 %. Previous studies have mainly focused on G7 and BRICS countries [15] and have rarely applied metrologically rigorous approaches to Türkiye.

This paper, therefore, examines the following:

RQ 1: What are the recent trends in greenhouse gas emissions of the transportation sector?

RQ 2: What is the future status of the driving factors underlying these trends?

By combining a 33-year inventory analysis with a targeted experimental campaign, and by emphasizing instrumentation, standardized protocols, and uncertainty evaluation, the study contributes a measurement-based framework for understanding transport GHG emissions in Türkiye.

## 2. MATERIALS AND METHODS

### 2.1. Data extraction, synthesis, and analysis

All measurements were repeated three times under identical conditions to assess repeatability. The uncertainty budget was calculated in accordance with the ISO GUM guidelines, considering instrumental resolution, calibration drift, and environmental variability. The expanded uncertainty ($k = 2$) was estimated to be:

- $CO_2$: ± 2.5 %
- $CH_4$: ± 4.2 %
- $N_2O$: ± 5.1 %.

The measured values were compared with the IPCC Tier 2 estimations, showing an average deviation of 3.8 % for $CO_2$ and higher variability for $CH_4$ and $N_2O$, due to variations in fuel composition, combustion dynamics, and transient engine operation. The experimental approach is consistent with previous methodological developments by the authors, including modelling and self-organization dynamics in acoustically levitated solutions [16], acoustic standing wave analysis [17], and testing of drying process models [18]. Calibration and uncertainty assessment procedures also draw on methods, such as those developed for high-frequency measurements, extreme impedance calibrations, and the use of ultrasonic flow meters as a reference [19], [20].

### 2.2. Calibration and drift verification procedures

Before each measurement session, the portable gas analysers (Horiba PG-350 and Testo 350XL) were calibrated using certified span gases ($CO_2$ and $CH_4$) and a zero gas ($N_2$), according to a two-point procedure. Calibration was performed at the beginning and end of each test day, and repeated every 4 hours of continuous operation, to minimize drift effects.

Drift verification was carried out by re-injecting the span gas after each measurement sequence: deviations larger than ± 2 % of the span value triggered a full re-calibration.

The thermal mass flow meter (Bronkhorst) was verified once per test day against a reference flow standard. Thermocouples were checked at the start and end of the campaign in a thermostatic bath.

Calibration intervals were selected in accordance with manufacturer recommendations and the ISO/IEC 17025 guidelines, ensuring traceability to national standards.

### 2.3. Emission inventory methodology

The Intergovernmental Panel on Climate Change (IPCC) guidelines are used for calculating emissions. Türkiye implements Tier 1 and Tier 2 methodologies to estimate GHG emissions of mobile sources for the time period 1990–2022, as shown in equation (1) below:

$$Emissions = \sum_a [Fuel_a \cdot EF_a], \qquad (1)$$

where *Emissions* represents emissions of $CO_2$ (kg), $Fuel_a$ is fuel sold (TJ), $EF_a$ is the emission factor (kg/TJ), $a$ is the type of fuel (e.g., petrol, diesel, natural gas, LPG), and this is equal to the carbon content of the fuel multiplied by 44/12.

All EFs were taken from the 2006 IPCC Guidelines. DHMI provides air traffic data. Emissions were estimated using the IPCC T2 methodology, as explained in the IPCC Guidelines for National GHG Inventories (IPCC, 2006). The calculation methodology is based on national energy consumption data and air traffic data for each airport, categorized by aircraft type. For the activities, default EFs were used. Air traffic data, which includes landing and take-off (LTO) and cruise cycles, is processed for all airports in Türkiye. All activities below 914 m were included in the LTO cycle; movements over 914 m altitude were covered in the cruise cycle. Domestic flights for all aircraft types have been accounted for, considering estimated individual fuel consumption values. The necessary EFs for LTO and cruise for each type of aircraft have been chosen from the IPCC reference manual.
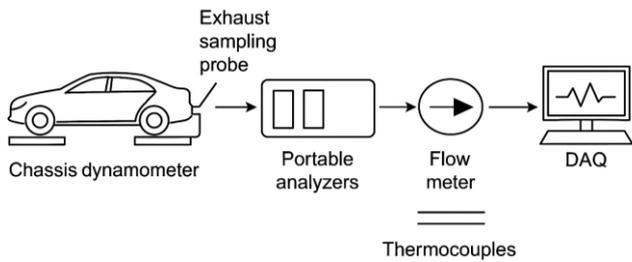
Figure 1. Schematic of the measurement chain and sampling points.

## 2.4. Measurement chain and instrument specifications

A schematic of the measurement chain (chassis dynamometer, exhaust sampling probe, analysers, flow meter, thermocouples, DAQ) is provided in Figure 1. Table 1 lists instruments and declared specifications (principle, typical range, declared accuracy/uncertainty, response time). The emphasis on traceability and robust instrumentation recalls previous campaigns where advanced generators were developed for biophysical and electronic applications [21].

## 3. RESULTS AND DISCUSSION

### 3.1. Vehicle fleet and EV projections

The number of road motor vehicles is presented in Figure 2 by category (car, minibus, bus, small truck, truck, motorcycle, special purpose vehicle, road construction and work vehicles, tractor). Electric vehicle (EV) and charging infrastructure projections have been reported by the Energy Market Regulatory Authority (EMRA) (Figure 3a). According to these reports, three scenarios (low, medium, and high) were studied to project the adoption of electric vehicles (EVs). Another study conducted by the Ministry of Transport and Infrastructure (MoTI), as part of the 'Determination of Location of the Electric Vehicle Charging Stations' project, also analysed three scenarios (National Transport Masterplan, Global Trend, and Climate Change Net Zero) (Figure 3b). Based on these estimations, EV numbers were projected using a spline regression method (Figure 3c). In this scenario (Figure 3d), statistics from the International Energy Agency (IEA), surveys, and expert opinions from various stakeholders and non-governmental organizations were utilized. In scenario 3 (Climate Change Net Zero), it is assumed that from a given year, fossil fuel car sales start to decrease, while only electric vehicle sales occur.

Given these studies,

i)   it is possible to assume a ratio for EVs at the end of the projection year (2035) and the increase from the starting year;

ii)  hydrogen vehicle introduction could start from 2030 to 2035, with 1 % increase per year mostly for heavy-duty vehicles;

iii) emission reduction potential of motor vehicle technology (Euro 7–8) and energy efficiency could be determined as 5 % and 10 % for 2030 and 2035, respectively.
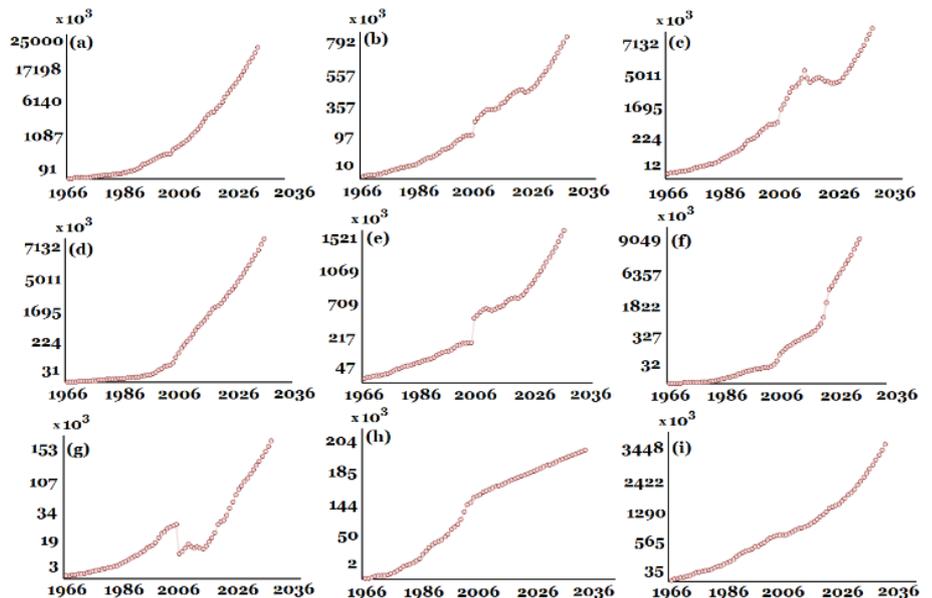


Figure 2. Number of road motor vehicles by category: (a) car; (b) minibus; (c) bus; (d) small truck; (e) truck; (f) motorcycle; (g) special purpose vehicle; (h) road construction and work vehicles; and (i) tractor.

Table 1. List of instruments and declared specifications: principle, typical range, declared accuracy/uncertainty, and response time.

| Instrument | Model | Principle | Typical range | Declared accuracy uncertainty | Calibration reference | Traceability | Typical response time |
|---|---|---|---|---|---|---|---|
| Portable gas analyzer | Horiba PG-350 | NDIR ($CO_2$), FID ($CH_4$), CLD ($NO_x$) | $CO_2$: 0–20 % vol CH₄: 0–5000 ppm | $CO_2$: ± 2 % FS $CH_4$: ± 3 % FS | Certified $CO_2$, $CH_4$ gas mixtures (NIST-traceable) | ISO/IEC 17025 accredited laboratory | < 3 s |
| Portable gas analyzer | Testo 350XL | NDIR ($CO_2$), FID ($CH_4$) | $CO_2$: 0–50,000 ppm $CH_4$: 0–10,000 ppm | $CO_2$: ± 2 % FS $CH_4$: ± 3 % FS | Certified gas mixtures; two-point calibration | Manufacturer certificate + lab calibration | < 3 s |
| Thermocouple | Type K | Thermoelectric voltage | −200 to 1250 °C | ± 1.1 °C (typ.) | Fixed-point cells / calibrated temperature bath | ISO/IEC 17025 calibration laboratory | < 1 s |
| Thermal mass flow meter | Bronkhorst | Thermal mass flow | 0–500 SLPM | ± 1.5 % of reading | Gravimetric or master flow standard | Traceable to national flow standards | < 100 ms |
| Calibration gases & gas dilution system | --- | Primary standard gas mixtures | Depends on the mixture | ± 1 % of concentration (cylinder certificate) | NIST / CEN / EURAMET certified gases | National metrology institutes | --- |
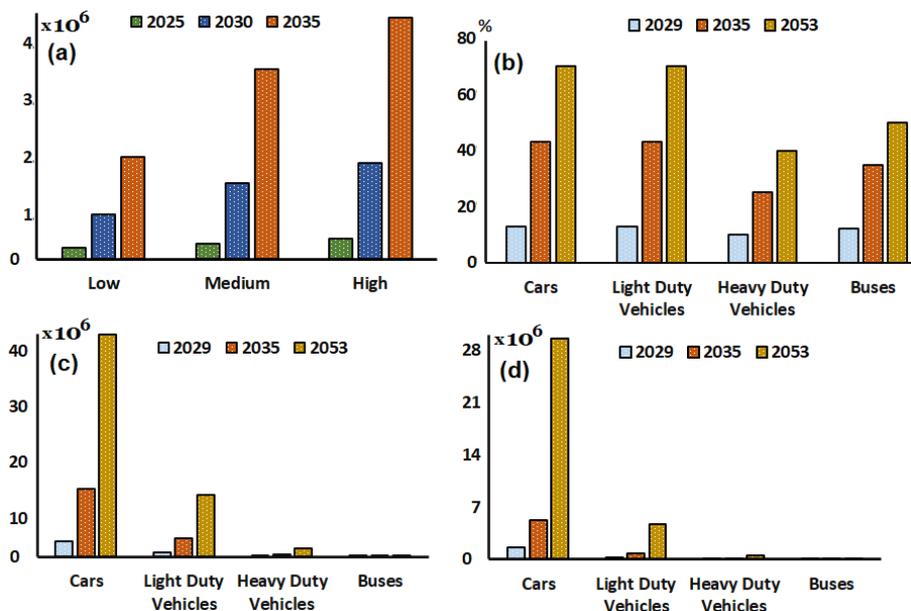
Figure 3. EV scenarios: (a) EMRA report for electric vehicles and charging infrastructure; (b) MoTI National Transport Masterplan; (c) spline regression projection; (d) IEA statistics and stakeholders.

## 3.2. Trends in transport GHG emissions

Greenhouse gas emissions of Türkiye from transportation between 1990 and 2023 are presented in Figure 4. The European Commission has successfully reduced its emissions through the development of effective policies. Taking steps that contribute to the reduction of global harmful emissions, the goal of continuously lowering emission reduction criteria, and efforts to reverse the trend in total regional greenhouse gas emissions, as well as consumption-based $CO_2$ emissions, collectively demonstrate that the country has achieved consistent reductions in these areas.

However, peak years vary depending on the measurement. Due to the consumption of food and similar products in economically developed countries, many studies indicate that the largest share of $CO_2$ emissions in the road freight transport
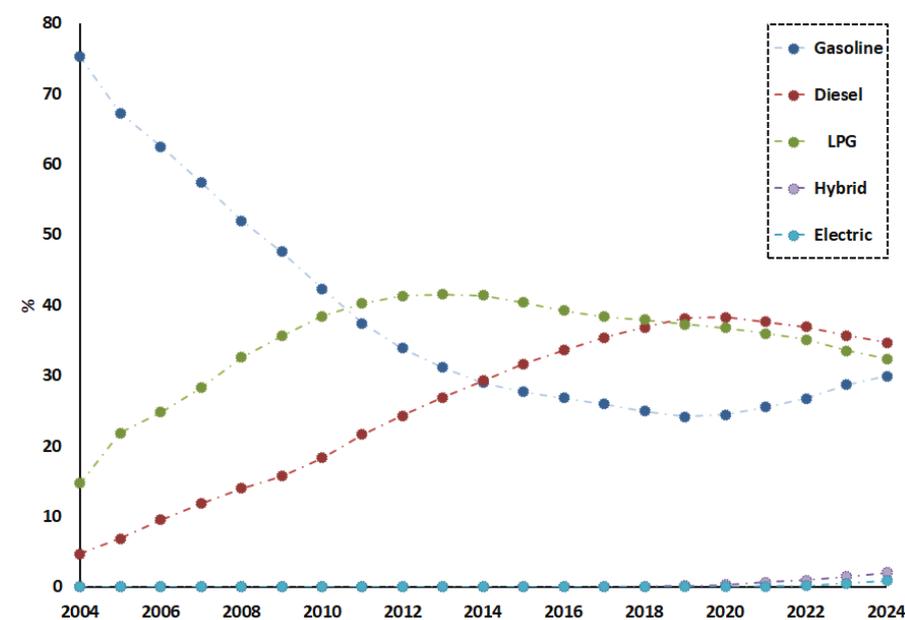
sector is attributed to heavy cargo trucks in countries with high supply and demand intensity [22]. In addition, GHG emissions can increase CO2 emissions in cities where the widespread rollout of private vehicles replaced public transport [23], [24].

## 3.3. Sectoral contributions and mitigation measures

The declining trends in GHG emissions, which are necessary to reach the climate goals laid out at the Paris Climate Conference, are also account for urban experiments. The contribution of key sectors to lower GHG emissions has been at various levels, as shown in Figure 5. These changes reveal a striking pattern of sector-based changes in the country. Continuous emission reductions have been identified with the widespread adoption of electric-powered engines, which are responsible for the vast majority of GHG emission reductions from transportation. Nevertheless, these reports are limited to the actual experiences of the specific region of Türkiye in which the research is conducted. Cities of Türkiye have shown a downward trend in fossil fuel use for urban transport due to the potential of cleaner transportation systems to reduce GHG emissions and expand renewable or zero-carbon energy (such as solar PV, nuclear, or wind energy), including transitions to cleaner fuels (e.g., coal to gas). Lin et al. [25] investigated high-speed rail in the transport sector and reported that overall GHG emissions decreased by 11.183 million tons of $CO_2$ equivalent ($CO_2e$) in China.

## 3.4. Literature context and comparative analysis

Gaseous emissions resulting from vehicles have been largely overlooked when examining the pathways and behaviour of hybrid electric vehicles worldwide. Also, climate change, mainly affected by transportation emissions, is a critical issue that necessitates urgent policy interventions to mitigate its impact on the environment and public health [26], [27]. To achieve meaningful progress, it is essential to implement comprehensive strategies that address both emission reductions and the promotion of sustainable transportation practices. Implementing these strategies will not only help in achieving carbon neutrality goals but also contribute to improved air quality and public health outcomes [28], [29]. This need for reliable detection aligns with recent advances in hydrogen-sensing composites, where metrological protocols have ensured reproducible results [30]. The existing literature on reducing transportation emissions has considered that vehicle electrification can reduce GHG emissions by 11–26 %. However, the potential reductions may
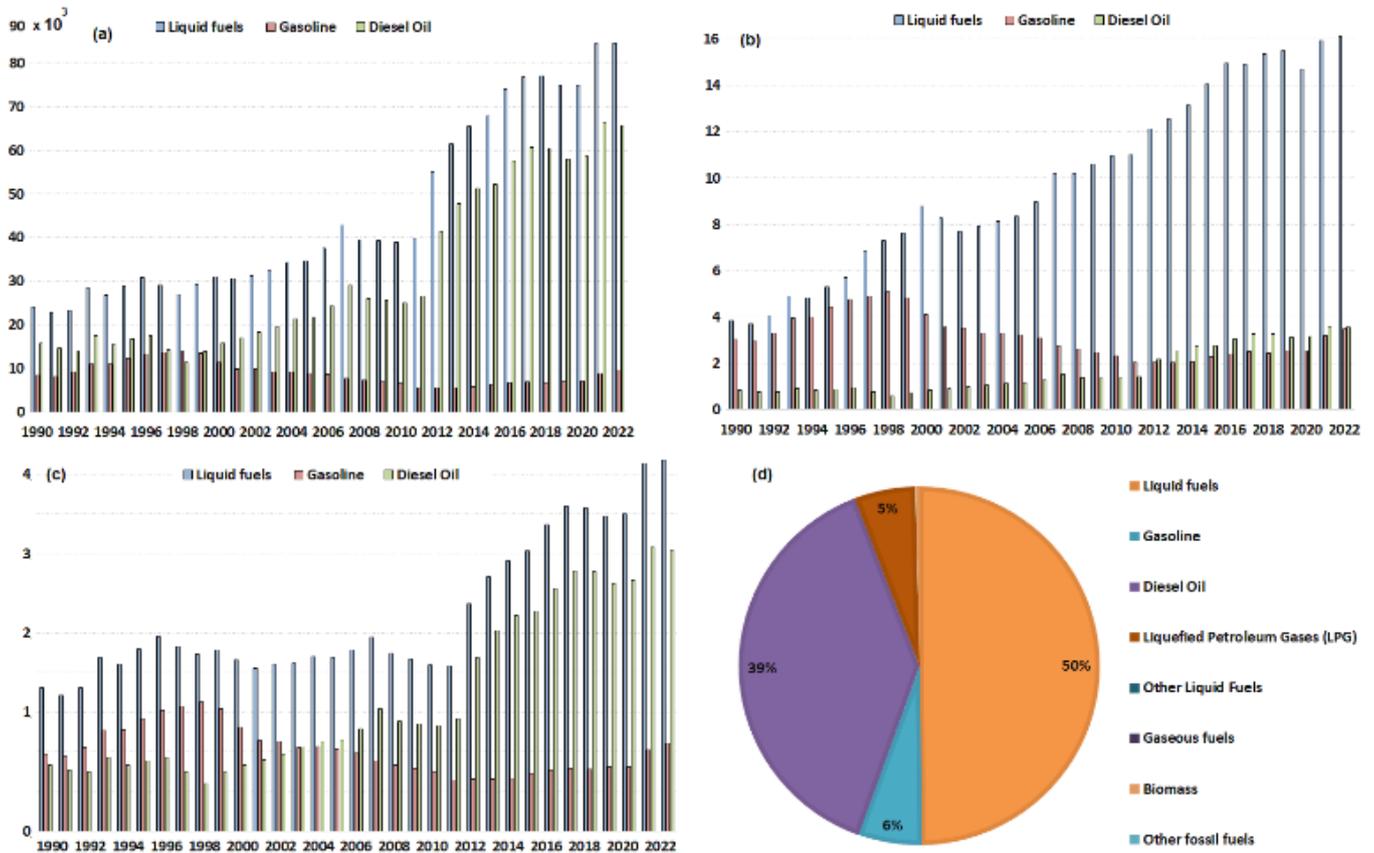


Figure 4. Distribution of registered cars according to fuel type.

Figure 5. (a) CO$_2$; (b) CH$_4$; (c) N$_2$O emissions derived from several fuels between 1990 and 2022; (d) type of fossil fuels.

vary significantly based on factors such as vehicle type, usage patterns, and the carbon intensity of the electricity used for charging. Massar et al. [31] examined the status of GHG emissions in autonomous vehicles. They reported fewer emissions per vehicle-km trip in an environmentally friendly manner.

A study proposed by Wei et al. [32] also suggested that high GHG emissions in 167 global urban areas from 2020 to 2050, as classified by the UN, will result in a net calculation of GHG emissions across eight urban sectors. A growing number of cities are also proposing carbon neutrality targets by 2050, although European and North American cities that are rapidly implementing green policies plan to achieve this goal by 2030. Türkiye-level GHG emission inventories have been developed in the transportation sector, as well as in other sectors, such as the metal, chemical, machinery, and cement sectors, with GHG reductions, improved production efficiency, fuel switching between different raw materials, and absolute reductions in industrial output at the national level. In this context, the thermos-kinetic characterization of novel adsorbent materials has been recently reported, showing the relevance of metrological validation for pollutant removal [33], [34]. Methane produced by motor vehicles used in transportation has been detected at varying levels. The long-term decline and changes in emissions are similar to the situation in other countries, with no significant trends. As road transportation in Türkiye remains the largest sector, it is also the source of the highest CO$_2$ emissions. While CO$_2$ emissions were high in 2000, by 2020, there had been a significant decrease, primarily due to the decrease in the number of vehicles on the road. Although N$_2$O emissions are relatively small compared to CO$_2$ and CH$_4$, there is no significant

decrease. As a result of our studies, we observe that although various countries had CO$_2$ reduction rates in 1990, very few have consistently achieved the required decarbonization rates. Studies conducted by Kawajiri et al. [35] have shown that lower emissions are driven by climate policies in developed countries and sectors that address annual emission reductions. However, studies conducted in developing countries have demonstrated that GHG emission growth is at higher levels and climate policies are not working well. Such deviations, even if within expanded uncertainties, highlight the importance of traceability and comparability in national inventories, as also demonstrated in recent works on CH$_4$ monitoring [3].

### 3.5. Current challenges and policy implications

The lack of significant progress in reducing transport emissions, which are the second largest source of emissions, has been cited as an area where these countries have a role in mitigating climate change, both for technological reasons (i.e. the realization of affordable low-carbon energy vectors to replace liquid fossil fuels) and for the continuity and direction of political and economic drivers (such as car consumption cultures and the influence of the automotive industry on transport planning). The policies implemented to reduce and monitor GHG emissions must be much more aggressive and comprehensive, which is crucial for GHG emission reduction efforts to reach their limits.

### 4. CONCLUSIONS

This study analysed the evolution of greenhouse gas (GHG) emissions from the transport sector in Türkiye since 1990, combining long-term inventory data with targeted experimental

measurements. By integrating national energy consumption and activity data with direct measurements of $CO_2$, $CH_4$, and $N_2O$, using calibrated portable analysers, the research provides a metrologically robust dataset for evaluating emission factors and validating IPCC Tier 2 estimates.

The results confirm that:

- $CO_2$ emissions from road transport remain the dominant contributor to total transport-sector GHG emissions but show a measurable decrease in recent years when normalized to vehicle numbers;
- $CH_2$ and $N_2O$ emissions display greater variability, reflecting differences in fuel composition, combustion conditions, and catalyst performance;
- experimental measurements show good agreement with inventory-based estimates for $CO_2$ ($\pm$ 3.8 %), while highlighting the need for updated emission factors for $CH_2$ and $N_2O$.

This dual approach demonstrates the added value of combining measurement science with traditional inventory methods. Portable exhaust analysers, traceable calibration gases, and uncertainty budgets, as outlined in the GUM, enhance the credibility of emission data and provide a robust technical basis for refining national inventories submitted to the UNFCCC.

From a policy perspective, the findings underline the importance of:

- maintaining regular measurement campaigns to update emission factors;
- expanding testing to on-road Portable Emission Measurement Systems (PEMS) and hybrid/electric vehicle fleets;
- incorporating uncertainty analysis systematically into transport-sector GHG reporting.

Such measures can help accelerate Türkiye's progress towards emission reduction targets, while ensuring that its national inventories are consistent with international standards. The approach presented here can serve as a reference framework for future IMEKO initiatives in environmental metrology, ensuring harmonized and traceable assessments of GHG emissions.

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