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# Assessing the Impact of Road Infrastructure on Air Pollution: Evidence from Türkiye

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**Abstract**

Traffic-related air pollutants have significant impacts on urban air quality. Given the critical role of transportation infrastructure in shaping traffic congestion and vehicle emissions, understanding how road networks affect these air pollutants is particularly important in Türkiye, where rapid road expansion is a key component of transportation policy. This study examines the environmental implications of road infrastructure development in Türkiye by analyzing its impact on $NO_x$ emissions and $PM_{10}$ concentrations at the provincial level from 2012 to 2022. The dynamic panel results indicate that an increase in road length—including total roads, divided roads, and asphalt roads—significantly reduces $NO_x$ emissions, suggesting that expanded road networks may help alleviate air pollution by mitigating congestion and improving traffic flow. In contrast, no statistically significant relationship is found between road length and $PM_{10}$ concentrations, suggesting that particulate pollution is more strongly influenced by non-traffic sources such as industry, residential heating, or natural factors. By examining provincial road networks and differentiating between road types, this study provides novel evidence on the heterogeneous effects of road infrastructure on air quality, thereby addressing a significant gap in the existing literature and offering insights into how road infrastructure development influences environmental outcomes.

**Keywords:** greenhouse gases; air pollutants; traffic-related emissions; nitrogen oxides ($NO_x$); particulate matter ($PM_{10}$); road infrastructure; system GMM

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## 1. Introduction

Greenhouse gas emissions constitute a significant threat to environmental sustainability. In the context of the Kyoto Protocol, incentive-based policies such as emissions trading and the Clean Development Mechanism are extensively discussed as strategies for reducing greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report, has indicated that mitigation efforts should aim to reduce emissions to at least 50% of 2000 levels by 2050 [1]. More recent IPCC reports, however, emphasize the necessity of achieving global net-zero emissions by approximately 2050 to limit global warming to 1.5 °C above pre-industrial levels [2]. Within this framework, the Green Deal refers to a policy and action plan designed to promote economic growth, employment, and social welfare, while concurrently advancing environmental sustainability [3]. The Green Deal seeks to establish a foundation for sustainable economic development. It represents

a crucial step toward understanding the gravity of global warming and formulating effective solutions to address this critical issue. In addition to these efforts, the European Union adopted the Directive (EU) 2024/2881 on ambient air quality and cleaner air for Europe (AAQD) with the target of achieving zero pollution by 2050. Through this directive, parameters such as limit values, target values, and critical levels for air pollutants are updated, and ambient air quality targets aligned with the World Health Organization (WHO) are determined. This directive also emphasizes the international harmonization of air quality policies and provides a broader policy context for evaluating national air quality standards [4].

Türkiye's rapidly expanding economy and population have increased the significance of road transportation. Data from the Turkish Statistical Institute (TurkStat) indicate that the population density has progressively risen from 98.27 persons per square kilometer in 2012 to 110.93 persons per square kilometer in 2023 [5]. The length of roads, transportation volume, and vehicle numbers in Türkiye are continuously growing. Consequently, Türkiye has undertaken substantial investments in projects to expand road infrastructure and modernize existing roads, thereby enhancing traffic flow through increased network capacity. In this study, road infrastructure refers to the physical part of the road transport system. These include the total road length, divided highways, and asphalt road and together indicate the capacity and quality of the transportation network. As of 2022, according to data from the General Directorate of Highways of the Republic of Türkiye, the total length of roads has reached 65,056 km, with divided highways accounting for 23,725.21 km [6]. Additionally, the proportion of asphalt roads has gradually increased, and the number of motor vehicles reached 28,951,792 in 2024 [7]. This trend indicates a shift towards greater road usage and higher vehicle capacity. Such developments directly influence roadway utilization levels, traffic conditions, and the overall transportation infrastructure. The expansion of road infrastructure necessitates an assessment of its environmental implications, particularly concerning pollutant emissions such as $NO_x$ and $PM_{10}$. In this context, Figure 1, prepared by the authors using QGIS software, illustrates the main roads and highways in Türkiye along with air quality monitoring stations. The figure is constructed by importing spatial data, assigning geographic coordinates, and overlaying the layers to accurately represent the national road network. In the map, pink lines indicate highways, blue lines represent main roads, and the monitoring stations are color-coded based on $PM_{10}$ air quality: green for good, yellow for moderate, orange for sensitive, red for unhealthy, and gray for no data.

Currently, roadways have gained importance as the cornerstone of transportation; however, the environmental impacts of these infrastructures have not received adequate attention. The transportation sector, particularly road transport, is highly energy-intensive and represents a significant source of both air pollution and greenhouse gas emissions. Emissions from motor vehicles considerably contribute to urban air pollution, thereby exacerbating environmental degradation [8–10]. Automobiles emit pollutants such as nitrogen oxides ($NO_x$), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter ($PM_{10}$ and $PM_{2.5}$) [8,11]. Critical factors, including fossil fuel consumption and traffic congestion within transportation activities, play a vital role in influencing these emissions [12]. Under congested traffic conditions, decreased vehicle speeds result in less efficient fuel combustion, thereby increasing emission levels. Furthermore, extended travel durations caused by slow-moving traffic further amplify the release of harmful pollutants into the urban environment [8,13,14]. Data published by TurkStat indicate that the transportation sector accounts for a substantial proportion of Türkiye's total greenhouse gas emissions [15]. According to TurkStat's greenhouse gas inventory data, in 2020, transportation contributed to 80,680 kilotons of the total 523.9 million tons of greenhouse

gases expressed in $CO_2$ equivalent. Of these transportation-related emissions, 94.9% are attributable to road transport [15].

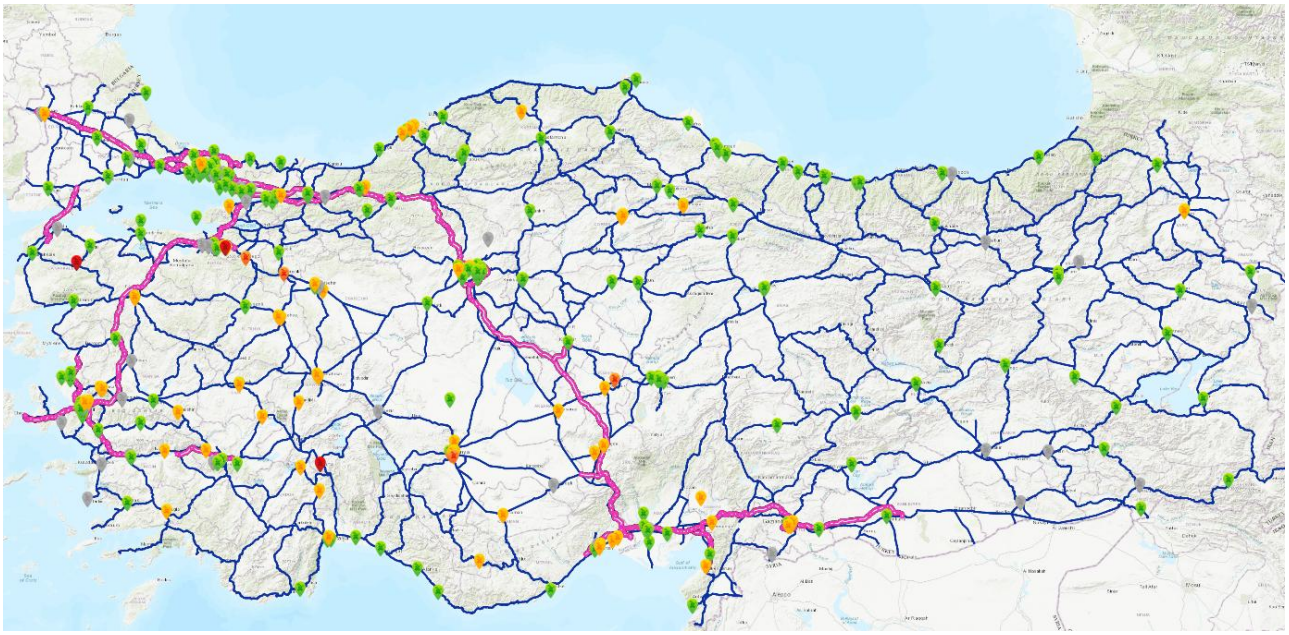


**Figure 1.** Map of the Main Roads, Highways, and Air Quality Monitoring Stations in Türkiye. **Source:** Authors' own elaboration using data from the Republic of Türkiye General Directorate of Highways (KGM) and OpenStreetMap, processed and visualized in QGIS 3.34. Available online: https://www.kgm.gov.tr (accessed on 10 February 2025).

The Air Quality Assessment and Management Regulation of the Republic of Türkiye, published in the Official Gazette in 2008, established national air quality limit values with the aim of gradually harmonizing them with the EU limit values. According to this regulation, the target annual limit value for nitrogen oxides ($NO_x$) in Türkiye is 30 $\mu g/m^3$. Figure 2, which illustrates the spatial distribution of $NO_x$ intensity levels across Türkiye for 2023, is generated using an interpolation method within QGIS 3.34 software, employing annual average $NO_x$ values obtained from air quality monitoring stations. The Inverse Distance Weighting (IDW) method is used as the interpolation technique because it offers more fast and reliable estimates for irregularly distributed air quality monitoring station data and has been widely applied in environmental studies [16–18]. Different colors denote varying levels of $NO_x$ concentrations on the map; for example, red indicates a zone where $NO_x$ levels exceed 77.2 $\mu g/m^3$. To facilitate a more detailed spatial analysis, twenty color classes are implemented with automatically defined, narrow level intervals. This visualization aids in identifying high-concentration regions and analyzing regional disparities in air pollution. The areas of highest $NO_x$ density observed on the map appear to correspond with zones exhibiting high transportation activity. Although these regions also typically feature significant industrial operations, the spatial pattern suggests that road transportation significantly contributes to elevated $NO_x$ concentrations. This increase, particularly evident in areas with traffic congestion and extensive road infrastructure utilization, highlights the spatial impact of transportation-related emissions. The levels observed in Figure 2 indicate that most regions in Türkiye exceed the 30 $\mu g/m^3$ limit, underscoring the need for more intensive monitoring and effective emission reduction strategies.

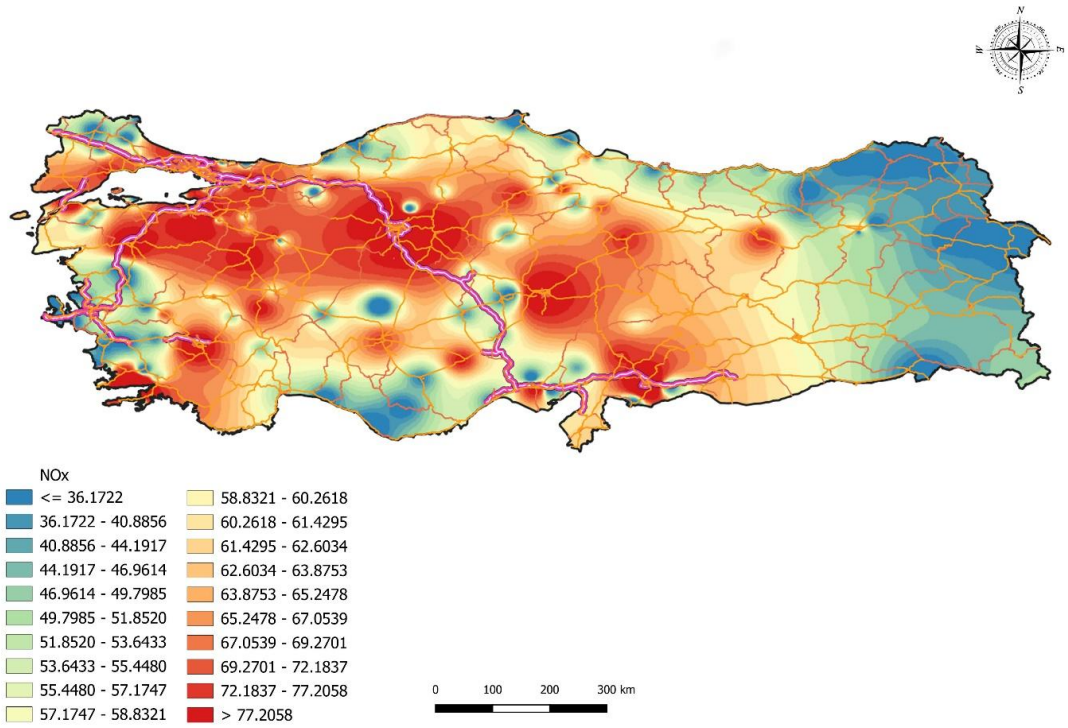



**Figure 2.** Interpolated Spatial Distribution of $NO_x$ Concentrations Across Türkiye in 2023. **Source:** Authors' own elaboration using air quality data from the Ministry of Environment, Urbanization, and Climate Change of Türkiye. Available online: https://sim.csb.gov.tr (accessed on 1 October 2024).

This study investigates the relationship between the development of physical roadway infrastructure and air pollution levels in Türkiye. The dynamic panel data estimates demonstrate that an increase in road length of any type significantly associates with lower $NO_x$ emissions, a principal traffic-related air pollutant. Conversely, no statistically significant association is observed between road infrastructure and $PM_{10}$ concentrations, implying that the influence of road length expansion may be more pollutant-specific, particularly for those closely associated with vehicular activity.

This study makes several contributions to the existing literature. First, instead of relying on a single road type, it incorporates three distinct categories of road infrastructure—total road length, divided highways, and asphalt roads—to provide a more nuanced understanding of how different road types relate to $NO_x$ emissions. Second, while many previous studies construct pollution indicators themselves [19,20], this research utilizes officially collected $NO_x$ data from the Ministry of Environment, Urbanization, and Climate Change of Türkiye, thereby enhancing data reliability and transparency. Third, although a substantial portion of prior research has primarily focused on carbon dioxide ($CO_2$) emissions [21–23], this study centers on nitrogen oxides ($NO_x$)—a group of pollutants more directly linked to road traffic and known for their significant adverse effects on human health and environmental quality. Lastly, the use of the System Generalized Method of Moments (System GMM) estimation technique helps address potential endogeneity and dynamic panel bias, improving the robustness of the empirical results.

This paper is organized as follows: Section 2 presents a review of existing literature regarding the impacts of road infrastructure development on air pollution. Section 3 delineates the methodology employed in the study, details the data utilized in the analysis, and introduces the econometric model. In Section 4, the results of the regression analysis are articulated and examined. Finally, Section 5 summarizes the conclusions derived from the study.

## 2. Literature Review

As the global emphasis on sustainability intensifies, policies aimed at reducing emissions have assumed increasing significance. Concurrently, the determinants of emissions and air pollution have garnered expanding scholarly attention. Despite this heightened interest, research specifically examining the impact of road infrastructure on air pollution remains relatively limited.

Cassady et al. [24] note that, based on 1999 data from 314 U.S. metropolitan areas, the expansion of the road network facilitated additional driving, resulting in increased vehicle usage and elevated emissions of $NO_x$ and VOCs. Ye and Li [25] investigate the influence of road traffic infrastructure development on the air pollution index and $PM_{2.5}$ levels through the application of a spatial panel regression model to data from 273 cities between 2008 and 2021. Their findings indicate that such infrastructure not only aids in reducing local air pollution but also engenders positive spillover effects, particularly benefiting adjacent urban regions.

Consistent with prior research, Xie et al. [19], utilizing the STIRPAT model and a panel dataset encompassing 283 Chinese cities over the period 2003–2013, conclude that while transportation infrastructure elevates carbon emissions and intensity in large and medium-sized cities, this relationship is statistically insignificant in smaller cities. Churchill et al. [21] employ a panel dataset spanning 150 years, from 1870 to 2014, and the STIRPAT model to demonstrate that a 1% increase in transportation infrastructure correlates with approximately a 0.4% rise in $CO_2$ emissions across 17 OECD countries.

Han et al. [20] offer a somewhat divergent perspective by analyzing data from 29 Chinese provinces over the period 1995–2013. They discover that increases in infrastructure material stocks per residential area—including 13 types of infrastructure such as highways, roads, and railways—exert a negative impact on $CO_2$ emissions. Their empirical approach, predicated on the STIRPAT model, facilitates a nuanced assessment of environmental impacts driven by socioeconomic factors.

Further extending this line of inquiry, Luo et al. [26], through analysis of China's road infrastructure during 2006–2010 employing a fixed effects model, identify a negative correlation between $PM_{10}$ levels and both the road density index—defined as the ratio of road surface area to total urban area—and road width. Their study reveals that a 1% expansion in road width results in a reduction of 0.084 $\mu g/m^3$ in $PM_{10}$ concentrations.

Building on previous studies, Sun et al. [27] empirically examine the relationship between urban traffic infrastructure investments and air quality across 83 cities from 2000 to 2012, utilizing fixed effects and system GMM models. They find that such investments contribute to long-term improvements in air quality. Expanding this research, Sun et al. [28] employ similar econometric techniques on panel data from the same cities to explore the differential impacts of various road construction types on the air pollution index (API). Their findings suggest that road lengthening is more effective in eastern regions, whereas road widening provides greater benefits in central and western areas.

Furthermore, Peng et al. [22] analyze Chinese data from 1978 to 2021 using an ARDL model, concluding that strengthening railway infrastructure relative to roads can mitigate per capita $CO_2$ emissions in both the short and long terms. Their estimations also support the Environmental Kuznets Curve hypothesis by revealing an inverted U-shaped relationship between economic growth and per capita carbon emissions from the transport sector. Wang et al. [23], employing the CS-ARDL approach for the period 1990–2021 across five populous countries—namely China, India, the United States, Brazil, and Indonesia—find that investments in transportation infrastructure and agricultural value addition significantly increase per capita $CO_2$ emissions.

This study differentiates itself from prior research in several notable aspects. Firstly, earlier studies predominantly focus on carbon dioxide ($CO_2$) and $PM_{10}$ as primary pollutants in air quality assessments. In contrast, this study incorporates nitrogen oxides ($NO_x$) and $PM_{10}$ to more accurately represent traffic-related air pollution. These pollutants serve as more sensitive indicators due to their direct emission from motor vehicles and their pivotal role in urban air quality. As such, their inclusion aligns with methodologies employed by Tezel-Oguz [29] and Schultz [30]. Secondly, while some existing studies concentrate on localized city impacts, their findings lack sufficient generalizability for national conclusions. This research offers a comprehensive analysis utilizing data from 2012 to 2022 across 81 provinces, encompassing regions with diverse levels of industrialization, vehicle usage, and population.

## 3. Data and Methodology

### *3.1. Data and Variables*

In order to investigate the relationship between road infrastructure and traffic-related air pollution in Türkiye, a set of variables has been constructed based on annual province-level panel data spanning the period from 2012 to 2022. The dependent variable in this study is air pollution, measured by two distinct pollutants: nitrogen oxides ($NO_x$) and particulate matter with a diameter of 10 μm or less ($PM_{10}$). Separate analyses are conducted for each pollutant to capture their individual dynamics and potential spatial variations. Air pollution data are collected daily and provided by the Republic of Türkiye's Ministry of Environment, Urbanization and Climate Change. Although these data are initially recorded daily at monitoring stations, they are aggregated into annual averages to align with the control variables, which are available only on an annual basis. This temporal harmonization ensures consistency within the dataset, facilitating reliable panel data analysis at the provincial level over the specified period.

Regarding road infrastructure, the independent variables are categorized into three segments reflecting their functional roles: total road length, divided highways, and asphalt roads. The total road length serves as the primary variable representing overall road infrastructure across provinces. Additionally, the lengths of divided and asphalt roads are utilized to assess the robustness of the results and to explore whether different types of roads produce varying environmental impacts across different model specifications. Total road length provides a general indicator of connectivity and infrastructure extent, while divided roads are associated with higher capacity and speed, primarily supporting freight transport and intercity mobility. Asphalt roads, in turn, reflect surface quality and modernization, which may influence vehicular efficiency and emissions. All data on road infrastructure is obtained from the Republic of Türkiye's General Directorate of Highways on an annual provincial basis.

A set of control variables is incorporated to account for other factors that may influence air pollution levels. Specifically, the impact of road infrastructure on $NO_x$ is analyzed more accurately by controlling factors such as regional economic activity, settlement density, and the natural absorption capacity of pollutants. Data on gross domestic product per capita and population density, which serve as indicators of urbanization and industrialization across provinces, are obtained from the TurkStat [5]. Higher income levels are considered to potentially increase $NO_x$ emissions due to greater car ownership and motor vehicle usage. Population density is included to reflect traffic volume, particularly in urbanized areas where increased transportation activity can elevate traffic-related air pollutant concentrations. Higher population density represents a higher level of urban concentration, often reflecting traffic congestion and higher energy consumption, which can negatively impact air quality. The forest variable, sourced from the General Directorate of Agriculture and

Forestry of the Republic of Türkiye, quantifies forest area by province and functions as an environmental indicator that may influence regional ecological conditions.

All data are compiled at the provincial level for Türkiye's 81 provinces, covering the period from 2012 to 2022. To normalize distributions, mitigate the influence of outliers, and enhance the assumption of linearity, all variables in the model have been transformed using their base-10 logarithms (log) prior to analysis. Table 1 provides a summary of the descriptive statistics for all variables.

**Table 1.** Summary Statistics.

| Variable | Obs. | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| $NO_x$ ($\mu g/m^3$) | 530 | 426.918 | 290.511 | 0.739 | 2046.794 |
| $PM_{10}$ ($\mu g/m^3$) | 945 | 52.223 | 18.671 | 11.721 | 136.388 |
| Total Road Length(km) | 891 | 796.710 | 465.698 | 131 | 3159 |
| Divided Highways (km) | 891 | 267.535 | 178.416 | 28.8 | 1234.486 |
| Asphalt Roads (km) | 891 | 752.324 | 441.648 | 121 | 3030 |
| GDP per capita (USD/person) | 891 | 8079.472 | 2999.435 | 2870.524 | 20,883 |
| Population Density (persons/$km^2$) | 972 | 128.758 | 321.208 | 11.06 | 3061.58 |
| Forest Area (hectare) | 971 | 282,506.2 | 235,220.1 | 8 | 1,303,773 |

An analysis of the minimum and maximum values within the summary statistics demonstrates significant interprovincial variability across all datasets. For example, the maximum $NO_x$ concentration is 2046.794 $\mu g/m^3$, whereas the minimum is 0.739 $\mu g/m^3$, with an average of 426.918 $\mu g/m^3$. Similarly, $PM_{10}$ concentration levels range from 11.721 $\mu g/m^3$ to 136.388 $\mu g/m^3$ among provinces, with a mean of 52.223 $\mu g/m^3$. These data elucidate the spatial variation and the potential severity of traffic-related air pollution in Türkiye. Such heterogeneity is both plausible and anticipated in province-specific analyses, reflecting the diverse structural characteristics of provinces—including economic development, infrastructure, and demographic dynamics.

### *3.2. Methodological Framework*

To establish the general analytical framework of this study, and following literature —particularly the modeling approach of Luo et al. [26]—air pollution can be modeled as a function of road infrastructure and other factors, as follows:

$$Pollution = f\,(Road,\ GDP\ per\ Capita,\ Population\ Density,\ Forest\ Area)$$

where *Road* denotes road infrastructure, which is the key explanatory variable of this study, and the other notations are self-explanatory.

**Hypothesis 1:** *Developments in road infrastructure reduce emissions by alleviating traffic congestion and improving traffic flow efficiency.*

Road infrastructure affects emissions through multiple interrelated factors. Well-developed road networks can alleviate traffic congestion, reduce vehicle idling time, and increase average vehicle travel speeds. Improved traffic efficiency can also increase fuel combustion efficiency and thereby reduces emissions per kilometer [25,31].

**Hypothesis 2:** *The impact of road infrastructure on air pollutant emissions remains consistent across different road types.*

Given that concentrations of air pollutants such as $NO_x$ and $PM_{10}$ may be influenced by cumulative emissions over time, they may not solely represent the immediate effects of current pollution levels but also encapsulate delayed impacts attributable to previous emissions, thereby indicating the existence of time-lag effects. Consequently, it is essential to consider the lagged variables of air pollutants ($pollution_{it-1}$) in order to evaluate these time-lag effects accurately. This research employs a dynamic panel data model utilizing the System Generalized Method of Moments (System GMM) to analyze the influence of road infrastructure development on air pollution over temporal scales, integrating lagged pollutant indicators into the analytical framework.

We specify our econometric model as follows:

$$pollution_{it} = \alpha_0 + \beta_1\, pollution_{i(t-1)} + \beta_2\, infrastructure_{it} + \beta_3\, pgdp_{it} + \beta_4\, popdens_{it} + \beta_5\, forest_{it} + \lambda_t + \varepsilon_{it} \quad (1)$$

where $pollution_{it}$ denotes the annual average concentrations of nitrogen oxide or particulate matter with a diameter of 10 μm or less in province $i$ at time $t$; $pollution_{i(t-1)}$ is its one-year lag of the dependent variable; $infrastructure_{it}$ represents road infrastructure, proxied by total road length, divided road length, and asphalt length across different model specifications; $pgdp_{it}$ is the GDP per capita; $popdens_{it}$ is the population density, $forest_{it}$ denotes forest area, $\lambda_t$ denotes a set of time dummies, $t$ denotes time and $i$ denotes province.

The Generalized Method of Moments (GMM), initially introduced by Hansen [32], encompasses two primary methodologies, with the most prevalent in empirical research being Difference GMM and System GMM. Although Difference GMM has traditionally been utilized in the analysis of dynamic panels, it may suffer from issues related to weak instruments. The development of System GMM by Blundell and Bond [33] addressed these limitations by combining moment conditions in both first differences and levels. Consequently, the System GMM is extensively adopted within the empirical literature. Considering the potential simultaneity between road infrastructure development and regional dynamics, endogeneity emerges as a critical concern in our analysis. While expanded road networks can influence air pollution levels, variables such as economic activity, demographic factors, and mobility demand—which are associated with air pollution—may also impact infrastructure investment decisions. Additionally, explanatory variables including GDP per capita, population density, and forest area are likely endogenous, as they can be jointly determined with pollution levels or influenced by shared factors such as economic development or regional policy priorities. Our research employs the System GMM estimation, appropriate for the dynamic panel data structure and the potential presence of endogeneity and autocorrelation. For example, increased pollution levels may prompt the construction of new roads to mitigate pollution, exemplifying a case of simultaneity bias.

This method alleviates endogeneity issues by employing lagged levels and first differences of potentially endogenous variables. Consistent with this rationale, Arellano and Bond [34] assert that endogeneity in dynamic panel models may originate from omitted valid instruments, and they highlight that utilizing all valid lagged levels of the endogenous variables as instruments can effectively mitigate this concern. Furthermore, Baum et al. [35] indicated that heteroskedasticity frequently constitutes one of the primary challenges in empirical analysis, and that the application of GMM offers a robust estimation technique to address this issue. The system GMM methodology employed in this study accounts for heteroskedasticity and autocorrelation within the error terms, thereby ensuring more reliable and robust estimations in the context of both cross-sectional and temporal variations.

## 4. Empirical Results

Drawing on provincial-level data from Türkiye for the period 2012–2022, this study empirically examines the effects of road infrastructure—distinguished by total length, divided roads, and asphalt roads—on air pollution indicators. Separate estimations are conducted for $NO_x$ and $PM_{10}$ pollutants, employing System GMM models to mitigate the problem of endogeneity in our independent variables and to obtain consistent estimation.

Table 2 presents the results of the System GMM estimation for each specification concerning air pollutant indicators and road type variables. The first three columns report the estimated coefficients for $NO_x$, and the last three columns provide the corresponding results for $PM_{10}$. The findings demonstrate that road infrastructure exerts a statistically significant and negative impact on $NO_x$ emissions across all three types of roads. The estimation results reveal that a 1% increase in total road length correlates with approximately a 1.083% decrease in $NO_x$ emissions. This outcome indicates a considerable inverse relationship, suggesting that the expansion of road infrastructure may aid in alleviating traffic congestion and enhancing traffic flow, thereby reducing pollutant concentrations within the provinces. The observed negative and significant association between road infrastructure and $NO_x$ emissions can be attributed to several interconnected mechanisms. Enhanced road infrastructure can mitigate traffic congestion, facilitating more efficient traffic movement and diminishing the prevalence of stop-and-go driving, which is typically associated with elevated $NO_x$ emissions. Additionally, improved traffic conditions can lead to reduced fuel consumption, as vehicles operate more steadily at optimal speeds. Furthermore, by minimizing travel delays, well-developed road networks can help reduce excessive vehicle usage in densely populated urban areas, consequently contributing to lower emission levels.

**Table 2.** Impact of road infrastructure on air pollution: The System GMM Estimates.

| Independent Variables | Coefficients and Standard Errors | | | | | |
|---|---|---|---|---|---|---|
| | **$NO_x$** | **$NO_x$** | **$NO_x$** | **$PM_{10}$** | **$PM_{10}$** | **$PM_{10}$** |
| lagged DV | 0.413 *** | 0.372 ** | 0.408 *** | 0.805 *** | 0.755 *** | 0.783 *** |
| | (3.413) | (2.499) | (3.571) | (11.780) | (10.636) | (13.653) |
| log road length | −1.083 ** | | | 0.080 | | |
| | (−2.096) | | | (0.352) | | |
| log divided road | | −1.589 ** | | | 0.377 | |
| | | (−2.306) | | | (1.047) | |
| log asphalt road | | | −1.032 ** | | | −0.009 |
| | | | (−2.295) | | | (−0.057) |
| log GDP per capita | −0.394 | −0.801 | −0.291 | −0.133 | 0.108 | −0.171 |
| | (−0.847) | (−1.074) | (−0.632) | (−0.767) | (0.412) | (−1.134) |
| log population density | −0.022 | 0.258 | −0.067 | 0.068 | −0.015 | 0.055 |
| | (−0.137) | (0.861) | (−0.390) | (1.050) | (−0.152) | (0.871) |
| log forest area | 0.510 | 0.753 | 0.479 | 0.027 | 0.073 | −0.002 |
| | (1.511) | (1.554) | (1.473) | (0.920) | (1.443) | (−0.066) |
| Number of Observations | 396 | 396 | 396 | 784 | 784 | 784 |
| Number of Instruments | 64 | 64 | 64 | 64 | 64 | 64 |
| Number of Provinces | 66 | 66 | 66 | 80 | 80 | 80 |
| AR (2) | 0.195 | 0.314 | 0.163 | 0.932 | 0.880 | 0.939 |
| Hansen Test | 0.387 | 0.350 | 0.364 | 0.214 | 0.258 | 0.244 |

Notes: 1%, 5%, and 10% significance levels are denoted as ***, ** and *, respectively. t-statistics are in parentheses. All estimates include the individual year dummies. Our analysis covers the 2012–2022 period at the provincial level.

Furthermore, according to the analysis results, there is a negative and statistically significant relationship for all three road types: total road length, divided roads and asphalt roads. Divided roads contribute to safer and smoother traffic flow, while asphalt roads enhance driving stability and vehicle efficiency, both of which can help reduce fuel consumption and pollutant emissions. Thus, the results show that improving road infrastructure has a significant impact on reducing $NO_x$ emissions, and this effect is not limited to a particular road type.

The analysis reveals no significant impact of road length on $PM_{10}$ concentrations across provinces. This finding is consistent with previous studies, such as Luo et al. [22], who also found no statistically significant impact of road length on $PM_{10}$. The results suggest that, unlike $NO_x$ emissions, which are more directly associated with traffic-related activities, $PM_{10}$ may be affected predominantly by other sources. In particular, various industrial activities, construction and residential heating during colder seasons are recognized as significant sources of particulate matter concentrations. Additionally, natural factors such as dust transport and seasonal weather conditions can significantly influence $PM_{10}$ levels. Therefore, the absence of a statistically significant relationship between road length and $PM_{10}$ concentrations implies that the particulate pollution in Türkiye may be shaped more strongly by these alternative factors, rather than by transportation infrastructure alone. Supporting this view, Mutlu [36] emphasized that primary $PM_{10}$ concentrations may mostly originate from industrial processes, such as material handling, combustion, and operational movement within industrial facilities. In addition, several studies have provided evidence that the consumption of coal and natural gas for residential heating plays a crucial role in determining $PM_{10}$ levels [37–39]. Similarly, previous studies have emphasized that dust transport, especially during the summer, substantially contributes to elevated $PM_{10}$ concentration levels [40–42].

As demonstrated in Table 2, the lagged dependent variable consistently maintains strong significance across all specifications for both $NO_x$ and $PM_{10}$, thereby affirming a high degree of temporal persistence in air pollution levels. Conversely, the control variables—specifically GDP per capita, population density, and forest area—do not display any statistically significant correlation with either $NO_x$ or $PM_{10}$ within any of the models.

Due to data limitations, the number of observations for $NO_x$ is restricted to 396, while the $PM_{10}$ dataset includes 784 observations. To ensure consistency in comparison, an additional estimation was performed using the restricted sample of 396 observations, which corresponds to the subset available for $NO_x$ analysis. The results of this analysis are reported in Table 3. Even within this matched sample, the results for $PM_{10}$ remain statistically insignificant across all model specifications. This result reinforces the conclusion that road length has no measurable impact on $PM_{10}$, regardless of the sample size or composition.

As a robustness check, we exclude the three largest metropolitan provinces (İstanbul, Ankara, and İzmir) from the estimation sample to verify the consistency of the results. Table 4 presents the results of the regional subgroup. The first three columns report the estimated coefficients for $NO_x$ and the last three columns provide the corresponding results for $PM_{10}$. According to Table 4, even when the largest metropolitan cities such as İstanbul, Ankara and İzmir are excluded, the impact of road infrastructure on $NO_x$ is statistically significant and negative for all three road types, and its effect on $PM_{10}$ is statistically insignificant. In other words, the findings show that the subgroup analysis results are consistent with the main analysis, indicating that the findings are robust.

**Table 3.** Robustness Check Using the Restricted $PM_{10}$.

| Independent Variables | Coefficients and Standard Errors | | |
|---|---|---|---|
| | **$PM_{10}$** | **$PM_{10}$** | **$PM_{10}$** |
| lagged DV | 0.486 *** | 0.532 *** | 0.465 *** |
| | (6.586) | (6.769) | (6.572) |
| log road length | −0.226 | | |
| | (−1.362) | | |
| log divided road | | −0.101 | |
| | | (−1.061) | |
| log asphalt road | | | −0.181 |
| | | | (−1.173) |
| log GDP per capita | −0.251 * | −0.253 | −0.247 * |
| | (−1.755) | (−1.597) | (−1.687) |
| log population density | 0.023 | 0.070 | 0.029 |
| | (0.424) | (1.215) | (0.569) |
| log forest area | 0.088 | 0.043 | 0.067 |
| | (1.116) | (0.484) | (0.879) |
| Number of Observations | 394 | 394 | 394 |
| Number of Instruments | 64 | 64 | 64 |
| Number of Provinces | 65 | 65 | 65 |
| AR (2) | 0.746 | 0.745 | 0.758 |
| Hansen Test | 0.274 | 0.260 | 0.233 |

Notes: 1%, 5%, and 10% significance levels are denoted as ***, ** and *, respectively. *t*-statistics are in parentheses. All estimates include the individual year dummies. Our analysis covers the 2012–2022 period at the provincial level.

**Table 4.** Regional Subgroup Analysis of the Impact of Road Infrastructure on Air Pollution (Excluding İstanbul, Ankara, and İzmir).

| Independent Variables | Coefficients and Standard Errors | | | | | |
|---|---|---|---|---|---|---|
| | **$NO_x$** | **$NO_x$** | **$NO_x$** | **$PM_{10}$** | **$PM_{10}$** | **$PM_{10}$** |
| lagged DV | 0.534 *** | 0.434 ** | 0.519 *** | 0.784 *** | 0.756 *** | 0.759 *** |
| | (4.857) | (3.932) | (4.804) | (12.823) | (10.665) | (13.589) |
| log road length | −1.025 ** | | | −0.088 | | |
| | (−2.106) | | | (−0.496) | | |
| log divided road | | −1.328 ** | | | 0.357 | |
| | | (−2.501) | | | (1.015) | |
| log asphalt road | | | −1.033 ** | | | −0.064 |
| | | | (−2.137) | | | (−0.379) |
| log GDP per capita | −0.474 | −0.779 | −0.386 | −0.197 | 0.106 | −0.246 |
| | (−1.060) | (−1.018) | (−0.837) | (−1.199) | (0.416) | (−1.570) |
| log population density | 0.012 | 0.219 | −0.049 | 0.053 | −0.021 | 0.078 |
| | (0.068) | (0.786) | (−0.254) | (0.773) | (−0.192) | (1.016) |
| log forest area | 0.475 * | 0.730 * | 0.451 | 0.022 | 0.062 | −0.004 |
| | (1.876) | (1.823) | (1.637) | (0.867) | (1.263) | (−0.153) |
| Number of Observations | 367 | 367 | 367 | 755 | 755 | 755 |
| Number of Instruments | 64 | 64 | 64 | 64 | 64 | 64 |
| Number of Provinces | 63 | 63 | 63 | 77 | 77 | 77 |
| AR (2) | 0.330 | 0.501 | 0.307 | 0.955 | 0.868 | 0.945 |
| Hansen Test | 0.301 | 0.610 | 0.344 | 0.192 | 0.256 | 0.186 |

Notes: 1%, 5%, and 10% significance levels are denoted as ***, ** and *, respectively. t-statistics are in parentheses. All estimates include the individual year dummies. Our analysis covers the 2012–2022 period at the provincial level.

## 5. Conclusions

This study provides empirical evidence on the environmental impacts of road infrastructure in Türkiye by examining its effects on provincial $NO_x$ and $PM_{10}$ concentrations at the provincial level. Using a System GMM approach applied to a dynamic panel dataset

from 2012 to 2022, the findings reveal that different types of road infrastructure—total road length, divided roads, and asphalt roads—have varying effects on air pollution levels. These results, based on pollution data collected from official monitoring stations, indicate a statistically significant and negative relationship between road infrastructure and $NO_x$ emissions, even after controlling for key socioeconomic and environmental factors, including per capita GDP, population density, and forest area. The negative and significant relationship identified between road length and $NO_x$ emissions demonstrates that extended road networks may facilitate the mitigation of air pollution by reducing traffic congestion and improving traffic flow. This contributes to the reduction in fuel consumption per vehicle and therefore to the reduction in $NO_x$ emissions. In Türkiye, the vehicle fleet is largely composed of diesel-powered and aging vehicles, which contributes to higher emission levels. However, developments in road infrastructure and traffic flow, particularly in urban areas where such vehicles are concentrated, can enhance fuel combustion efficiency and thereby help reduce $NO_x$ emissions. However, no significant association is found between road length and $PM_{10}$ concentrations. In many provinces in Türkiye, industrial combustion processes and residential heating provided by solid fuel consumption significantly affect particulate matter concentrations and can outweigh the contribution of road infrastructure developments. Both $NO_x$ emissions and $PM_{10}$ concentrations are affected by factors such as fuel type, vehicle age, and engine technology, but $PM_{10}$ is more affected by non-exhaust sources such as road dust, brake, and tire wear. The non-significant impact of road length on $PM_{10}$ concentrations suggests that other sources, such as industrial activity, residential heating, or natural factors, may play a more dominant role in particulate pollution in Türkiye.

Some limitations of this study should be considered. Although there are 81 provinces in Türkiye, the analyses are limited to 66 provinces due to a lack of $NO_x$ data. While this situation may restrict the generalizability of the results across the country, the provinces for which data are available are representative of Türkiye in terms of geographic and economic diversity. Additionally, the $NO_x$ data are obtained from fixed air quality monitoring stations, which may limit spatial representativeness to some extent. Nevertheless, the model attempts to isolate traffic-related impacts as much as possible by controlling for variables such as GDP per capita, population density, and forest area.

Despite these limitations, this study makes a significant contribution to the literature as one of the few empirical analyses assessing the relationship between the extent of road infrastructure and air pollutant concentrations in Türkiye. The case of Türkiye provides a valuable perspective for evaluating the relationship between rapid infrastructure development and its environmental effects in developing countries. Overall, the findings of this study enhance the evaluation of infrastructure and environmental quality at the national level and provide new evidence for global discussions on the environmental sustainability of large-scale roadway infrastructure investments. In this context, the study also provides a comparative framework for evaluating both the current analysis results and projections of traffic-related $NO_x$ emissions in Türkiye presented in the literature. According to the study by [43], traffic-related $NO_x$ emissions in Türkiye increased by approximately 19.9% between 2010 and 2020, and are projected to increase by 138.95% by 2050 under the current trend scenario. Although such long-term projection modeling was not conducted in the present study, these estimates highlight the need to extend the modeling framework in future research. In further studies, if the data are aligned temporally, more dynamic analyses can be enabled by taking into account short-term fluctuations and seasonal effects. Future studies may also extend this research by investigating the influence of vehicle types, technical attributes, and fuel compositions on traffic-related air pollutants, and by developing policy recommendations for emissions reduction strategies.

Given the worsening air pollution crisis in urban areas, the findings of this study have a number of practical implications in terms of environmental and transportation policy. These results support the view that investments in road infrastructure, when guided by environmental considerations, can play a complementary role in air quality management strategies by helping to mitigate nitrogen-based pollutants. First, the observed decreased $NO_x$ emissions in areas surrounding newly developed road infrastructure necessitate closer monitoring of the environmental effects of these projects. Strengthening measurement and monitoring systems, particularly in areas with traffic congestion, can improve the accuracy of air quality assessments and benefit policy development. Moreover, integrating emission data from air quality monitoring stations into regional planning processes may play a role in the development of more sustainable and environmentally transportation networks. Finally, the expansion of road networks should be planned to reduce traffic congestion and facilitate more efficient vehicle movement in densely populated areas. Implementing strategies to optimize traffic flow within urban transportation planning can enhance the environmental benefits of road infrastructure investments. As a result of reduced traffic density, exhaust gas emissions would be limited, and fuel consumption would decrease. Consequently, overall energy demand would also decline, contributing to environmental sustainability.

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