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Initial Insights into Teleworking's Effect on Air Quality in Madrid City

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Abstract: Commuting to work by private vehicle is one of the main sources of air pollution in cities, mainly from NO_2 and particulate matter ($PM_{2.5}$ and PM_{10}). With the spread of telework, traffic congestion during peak hours is reduced on certain days of the week, improving air quality. This study analyzes the relationship between the improvement of air quality and urban traffic resulting from teleworking activities after the COVID-19 pandemic in Madrid, Spain. This article considers road traffic and teleworking before the COVID-19 pandemic (2018 and 2019), during the pandemic (2020 and 2021) and in the period after (2022 and 2023) in the city center and the influence on certain environmental factors. Daily NO_2, $PM_{2.5}$, PM_{10}, and O_3 concentration data were collected at air quality stations in Madrid municipality, and traffic data and some meteorological variables such as wind speed, precipitation and temperature were considered. When conducting correlation and regression analysis among the variables, there is a clear association between NO_2 and traffic before the pandemic, which is lower for both PM and O_3. This correlation was maintained during the pandemic, except for O_3, the association of which increased during this period and then decreased in the later period due to various motives. These results seem to indicate the existence of a relevant relationship between urban mobility and air quality and an especially relevant relationship with telework, suggesting the need for policies aimed at promoting sustainable mobility in the future.

Keywords: air quality; telework; urban mobility; COVID-19 pandemic

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1. Introduction

Large cities, usually densely populated, pose a major air pollution problem [1,2]. Urban mobility stands out among reasons for this phenomenon, although meteorology and natural or artificial conditions (e.g., dust intrusions from the Sahara Desert [3]) or industrial activities [4,5]), among others, should not be overlooked.

Mobility in the urban environment can be divided into two large groups: (a) mobility using the so-called soft modes, such as public transport modes, buses or metro, or active modes like walking or cycling, which are less polluting; and (b) mobility using private modes, mainly private cars, which are more polluting [6]. In any case, daily obligatory activities such as commuting to work emit a large amount of pollutants [7].

Of air pollutants found in urban environments, those directly derived from road traffic are a major concern, mainly nitrogen oxides (NO_x and NO_2) [8] and particulate matter. The latter has a double origin in the atmosphere, natural (Saharan dust intrusions [5]) and anthropogenic (mineral extraction activities, road traffic, home heating, etc. [9]). Finally, another pollutant that is often studied when assessing the impact of traffic on air quality is ozone (O_3) [10]. This is a secondary pollutant whose presence on the atmosphere can be linked to NO_2 emissions of road traffic and is only considered as such when it appears in the troposphere, but has vital benefits in higher layers of the atmosphere, such as the stratosphere ("ozone layer" [11]).

These polluting gases cause a handful of problems in cities [12]. On the one hand, they are capable of causing or aggravating many health problems in citizens, including respiratory and cardiovascular problems [13–15]. On the other hand, these air pollutants can also degrade the urban environment by interacting with meteorological variables such as wind or rain [16], causing the accumulation or dispersion of pollutants [17] in certain areas and other problems such as acid rain [18].

In order to solve the problems caused by the pollutants mentioned above, both public institutions and private companies are implementing different actions [17]. Regarding the public institutions, different initiatives have been implemented, such as introducing environmental labels for vehicles, low emission zones (LEZ), traffic speed limitations, fostering public transport, and active mobility. [19]. On the other hand, private companies have implemented sustainable mobility plans for work that include measures such as promoting the use of public transport by subsidizing part of the cost of the public transport card, providing private collective transport to the work site, encouraging carpooling, or measures related to trip reduction such as teleworking encouragement [20].

Although there is no formal definition of telework, it has been commonly defined as working outside the employer's premises, using the Information and Communication Technologies (ICT) [21] from multiple locations such as home office, shared coworking spaces and other places. It was first recorded in the 1970s [20], and became widespread in the aftermath of the COVID-19 pandemic, a period in which personal mobility was severely limited except for emergencies in the spring of 2020, when governments around the world declared nationwide lockdowns, in particular the Spanish Government [22]. This limitation of mobility in Spain led to a significant increase in telematic activities. For instance, e-commerce or e-learning [23] activities increased from 40% of use before the pandemic to 80% after the pandemic [24]. After the lifting of mobility restrictions, especially during the years 2021 and 2022, a return to pre-pandemic normality occurred in all productive sectors [25]. However, despite the return to normality, telework remained a widely accepted option, although no longer as in the previous period [25], regulated in Spain by the 2021 Teleworking Act [26].

Among the reasons cited by most teleworkers as a reason for working remotely, the savings in travel time in the commuting from home to work or study [27] stands out in particular. In addition to saving time, teleworking avoids the commute itself, so the emissions that would be produced do not, thus improving air quality [28].

The relationship between air pollution and traffic is a well-studied topic in the scientific literature [29,30]. Reviews such as those conducted by Shrivastava et al. in 2013 [31] and Forehead et al. in 2018 [32] show the existence of a clear link of traffic with the emission of air pollutants. However, these reviews are before the COVID-19 pandemic and did not consider the effects of changes in mobility patterns on air pollution. During the pandemic and in the period immediately following, air pollution levels experienced a massive decrease [33,34], due to the implementation of prevention measures against the spread of COVID-19, mainly lockdowns and telework and consequently traffic reductions, which led to a decrease in exposure to air pollutants, mainly NO_2, thus improving respiratory health and life expectancy of citizens [34,35]. Querol et al. (2021) [35] mention many studies related to the impact of COVID-19-associated emission reductions on air quality.

Regarding the different methodological approaches used to study the relationship between telework and air quality, there are traditional approaches that combine surveys with air quality indicators or modern approaches that use information from applications or ICTs [36]. Among these methodologies, most of the analyses include direct comparisons of air pollutant between certain periods (mainly before the COVID-19 pandemic and after the pandemic) [37–42]; another popular analysis is the correlation analysis between air pollutant concentrations, traffic flows and, in some cases, meteorological variables [43–45]. Regression analysis is also a common approach when studying this topic. Regarding this specific methodology, linear regression [46,47], linear generalized models (GLM) [48], additive generalize models [42,49] and time series [50] are commonly used to analyze the potential effects of traffic flows and meteorological variables on air quality [50]. In particular, Giovannis in 2018 in Switzerland [16] used a fixed random-effects model in order to analyze the effect that telework has on O_3, NO_2, PM_{10} and CO, among other pollutants. Outside Europe, Kharvi et al. in 2021 in Canada [51] carried out a three-scenario analysis of the impacts of telework in energy consumption and GHG of transport, among other sectors. These scenarios are based on the savings in greenhouse gas (GHG) emissions according to the average commute time in each scenario.

However, the development of teleworking and its effects on traffic and air quality have not been studied as much in the context of the COVID-19 pandemic crisis, since its use has become more widespread only recently. In particular, the COVID-19 crisis led to changes at work, including an increase in the number of employees working from home in some sectors. In 2019, approximately 1 in 20 (5.5%) employed people aged 20 to 64 in the UE regularly worked from home. Due to the COVID-19 crisis, this proportion more than doubled in 2020 to 12.3% (+6.8%). Additionally, there was a further increase in the percentage of people who regularly work from home in 2021, reaching 13.5% (+1.2%) [52].

The effect of telework on air quality has been studied before the pandemic [53,54] in many cases. Kitou et al. in 2006 [55] found that telecommuting (another term to describe telework) 1 day per week reduced both NO_2 and NO_x concentrations for all means of transportation except light rail, but increased PM_{10} emissions, due to heating settings in the homes. As it avoids the need for the worker to commute, the miles per vehicle travelled decreased, thus improving air quality [56,57], at least −69% for NO_x and −78% for particulate matter [58] in the United States, while a 4%, 8%, and 10% reduction for NO_2 when the worker teleworks 2, 3 or 4 days a week [59]. However, it is noted that teleworkers make more trips per day than in-person workers [60], as they can go shopping during working hours while an in-person employee cannot leave the office. This may be potentially disadvantageous in terms of reducing emissions.

Studies, such as Choo et al. published in 2005 [56], found that a reduction in vehicles miles per travel (VMT) of 0.8% is produced when teleworking is in place, when technology was not as advanced as it is today [61].

Anik et al. in 2023 [62] carried out a review of the available literature that concluded that the current spread of telework among commuters during the pandemic and its maintenance over time once the way of life before the imposition of lockdown has been recovered can reshape the urban space, thus irreversibly altering mobility [63]. In the Madrid Region, Akioui et al. found in 2023 that urban areas like Madrid city experienced a 30% increase in teleworking during the pandemic, and a 27% reduction in the trips per day [64].

Therefore, understanding the extent to which the effects of teleworking impact road traffic and thus improve air quality is an important objective for the design of public policies to improve urban living conditions and public health. Unfortunately, this topic has not been studied in depth in Spain, so a research gap has been identified in which this article hopes to provide a first view of the subject.

This article is structured as follows: after the Introduction in Section 1, Section 2 describes the case study of the city of Madrid, the data collection, and the statistical analysis. Section 3 presents the main results of this study. These main findings are discussed in Section 4. Finally, Section 5 contains some conclusions, including remarks, limitations and recommendations for further research.

2. Materials and Methods

2.1. Study Area: The City of Madrid

Madrid City is located in the center of the Madrid Region and the Iberian Peninsula and serves as both the regional and national capital. It was inhabited by 3,332,035 people in 2023 [65], making the city the most densely populated city in Spain, representing population of the 48.5% of the Madrid Region during that year.

Regarding the economic distribution, Madrid City is predominantly a service city, with the third sector, mainly the tourism industry, being the main source of income for the city compared with the rest of the economic sectors.

Madrid City has a very developed public transport network [66]. It has numerous public bus lines (both urban and interurban), rail (metro, which also connects to municipalities outside of Madrid, and commuter trains, "Cercanías") and shared mobility services such as BiciMad (public electric bike sharing initiative, initiated in 2014) and other private enterprises. According to the last report of the Spanish Metropolitan Mobility Observatory 2021, 34.4% of the travels were made using public transport options, while 25.4% were made by private vehicle [67].

In terms of air pollution, the city of Madrid is one of the most polluted cities in the country. At least 42% of air pollutant emissions can be attributed to road traffic [68,69]. The characterization of the vehicle fleet is an important factor when estimating air pollution due to traffic. In Madrid city, at least 25% of vehicles are more than 20 years old; however, the fleet is in a process of renewal, as 20% of the vehicles are less than 4 years old [70]. Since before the pandemic, the average fleet distribution by sector (i.e., passenger car, light duty vehicle, buses, etc.) has not varied substantially between years, but the distribution by fuel has shown an appreciable shift towards hybrid technologies and alternative fuels [71]. To fight against emissions, in Madrid, many measures have been taken over the years. For example, low-emission zones (LEZs) stand out due to the limitations on entering certain parts of the city depending on the environmental label assigned to each vehicle. The implementation of LEZ began to cover the center of the area of the city (including the Escuelas Aguirre Air Quality Station that we used for the study) and progressively expanded its scope of application to cover the entire municipality of Madrid [72].

Figure 1 shows the evolution of the average annual concentration of air pollutants studied in the years 2018, 2019, 2020, 2021, 2022 and 2023 at the Escuelas Aguirre Air Quality Station. As can be seen, 2018 and 2019 recorded a higher average concentration of NO_2 than O_3. When in 2020 lockdown was enforced for the first time, NO_2 concentration drops sharply, while O_3 concentration increases, a trend that is maintained throughout the studied period. This phenomenon may be due to the intertwined relationship between NO_2 and O_3 concentrations, as NO_2 acts as a "precursor" of ozone formation in the lowest layer of the atmosphere [73]. There is also a notable growth in the concentration of particulate matter in 2022, due to the influence of much stronger dust intrusion phenomena [74].

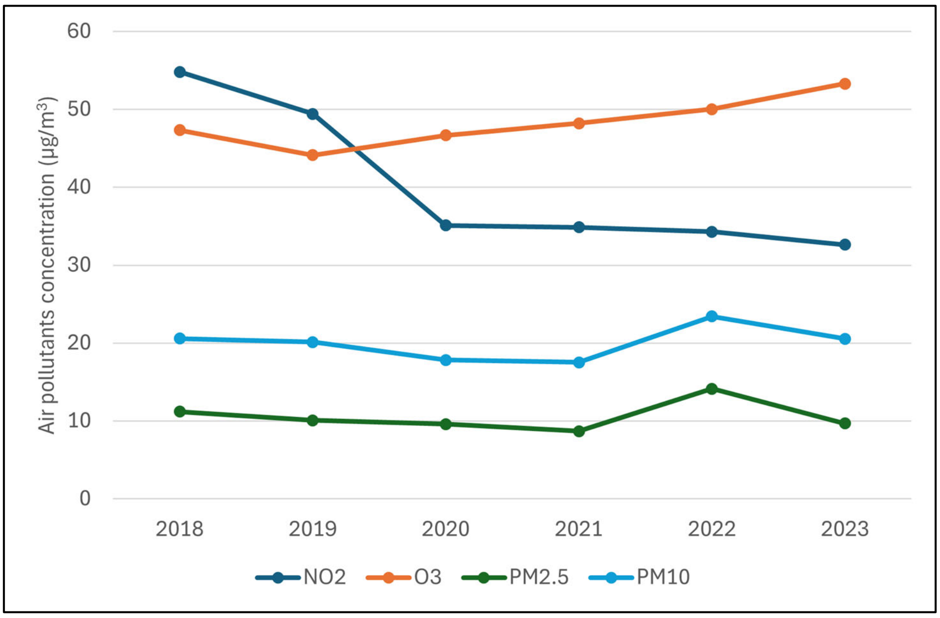

Figure 1. Evolution of the average annual daily air pollutant concentrations in the 2018–2023 period. Source: Own elaboration using data from *Escuelas Aguirre* Air Quality Station.

2.2. Who Teleworks in the Madrid Region? A Teleworker Profile

Telework became a widespread option in the early years of the 2020 decade, especially during and after the COVID-19 pandemic. With the imposition of home and perimetral lockdowns during the years 2020 and 2021, it generated enough momentum to stay as a reliable option for certain workers after the pandemic.

In the Madrid Region, the E.MORES-CM Project studied the mobility habits, preference for telematic activities, e-commerce, among others, and their relationship with the COVID-19 pandemic [59]. A survey was designed and carried out between October and December 2022 in the Madrid Region. For this survey, the Madrid Region was divided into 16 zones, according to the distribution of the population and other variables such as income and socioeconomic level. The participants were those over 16 years of age and who resided in the region. The survey obtained 15,666 valid responses. Among many other issues, participants were asked about the frequency with which they were engaged in telematic activities, including telework. The results of the survey on telework are summarized in Table 1.

Table 1. The teleworker profile in the Madrid Region according to the E.MORES-CM Project Survey in the pre-pandemic period (years 2018 and 2019), during the pandemic period (years 2020 and 2021) and in the post-pandemic period (years 2022 and 2023) [75].

	Pre-Pandemic	During the Pandemic	Post-Pandemic
Percentage * (%)	26.41%	48.47%	39.07%
Age (mean, years)	44.57	43.16	42.36
Gender	Mostly male M: 54.23% F: 45.77%	Mostly female M: 48.33% F: 51.67%	Equal distribution M: 49.75% F: 50.25%
Income	Medium 1500–3000 EUR	Medium 1500–3000 EUR	Medium 1500–3000 EUR
Employment	Employee	Employee	Employee
House type	Apartment	Apartment	Apartment

* The percentage have been calculated based on the number of workers who have the possibility of teleworking.

As can be seen in Figure 2, according to the E.MORES-CM Project survey, the frequency had greatly changed between before the pandemic (left), during the pandemic (center) and after the pandemic (right) [25] for the questioned persons. Before the pandemic, telework was not very common in the Madrid Region, except in the central area of the city and the Madrid metropolitan area. During the pandemic, after the lockdown was enforced, all non-emergency mobility stopped, which meant that no daily commutes were allowed. This increased the frequency of telework in the whole Madrid Region. After the pandemic, when mobility restrictions were lifted, commuters had the possibility of returning to the office, but teleworking remained a habitual option for employees, (39%, according to the Spanish Survey on Equipment and Use of Information and Communication Technologies in Households of 2021 [76]), although reduced compared to the pandemic period.

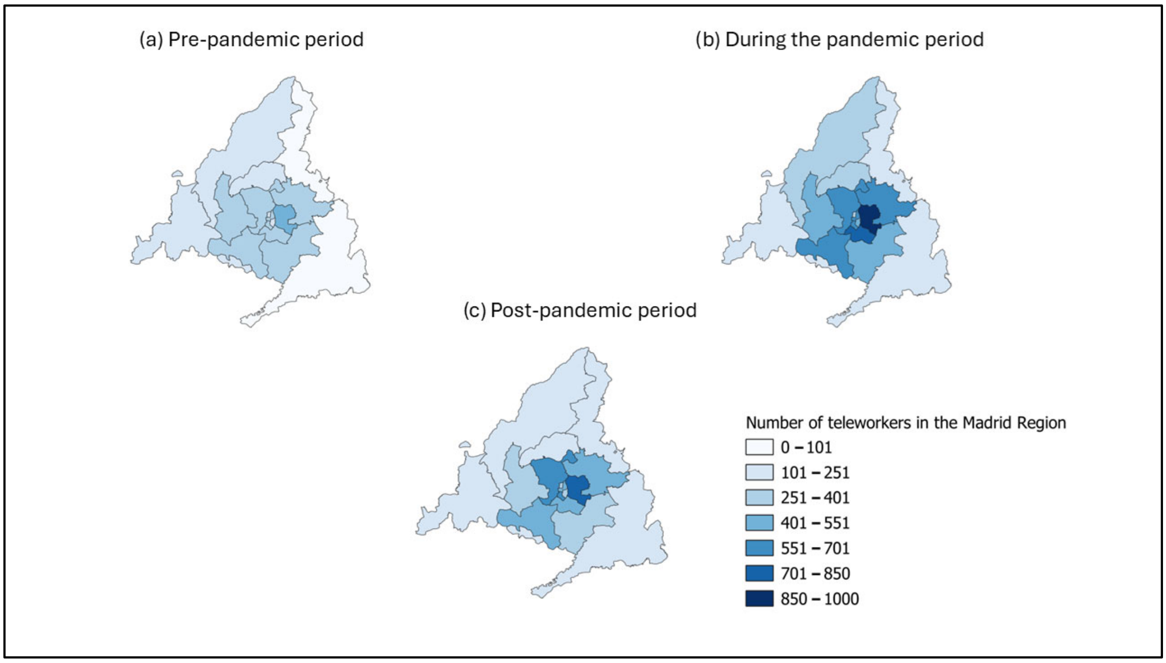

Figure 2. Number of teleworkers before, during, and after the COVID-19 pandemic in the different areas of Madrid Region according to the survey of the E.MORES-CM Project.

2.3. Methods

The relationship between traffic, air pollution, meteorological variables, and telework in the central area of the city of Madrid is studied in this article. Figure 3 shows the methodological framework including the research questions. On the one hand, a correlation analysis was performed between air pollutants, road traffic and meteorological variables to establish whether there is a linear relationship between these variables. On the other hand, a linear regression analysis was carried out to determine the potential effects of telework, traffic flows and meteorology on air pollution. For the analysis, telework is included as a categorical variable, with six categories (daily, 3–4 times per week, 1–2 times per week, once a month and never, the latter being the reference category) to analyze the exact terms of the relationship between air quality and telework. Both correlation and regression analysis were performed for three scenarios: a pre-pandemic scenario (years 2018 and 2019), during the pandemic (years 2020 and 2021), and in post-pandemic scenario (years 2022 and 2023). For the statistical analysis, the Stata 15.1 program [77] was used. To adequately prepare the dataset used in this article, the Excel program from the Office suit was used. Datasets used in this article were collected from two sources: air pollution and traffic data were obtained from the Madrid City Council Open Data Portal [78,79] while the meteorological data were obtained from the States Meteorological Agency (Agencia Estatal de Meteorología, AEMET, in Spanish) Open Data Portal [80].

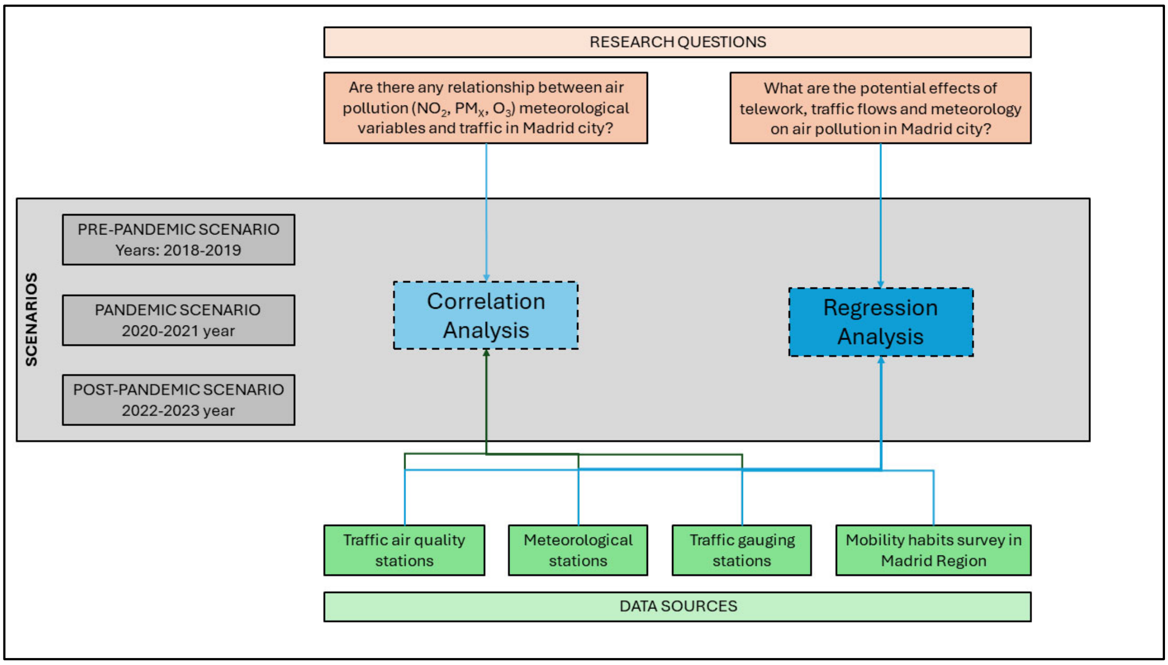

Figure 3. Methodological framework [75,78–80].

2.4. Data Collection

The study area contains the Escuelas Aguirre Air Quality Station of Madrid City. This station is located in a central area of the city of Madrid (see Figure 4). For air pollution data, annual average daily NO_2, $PM_{2.5}$, PM_{10}, and O_3 concentrations for the pre-pandemic period (years 2018 and 2019), during the pandemic period (years 2020 and the 2021) and in the post-pandemic period (years 2022 and 2023). As traffic data, the average daily number of vehicles recorded in the four gauging stations located in the vicinity of the Escuelas Aguirre station was selected for the same time periods as the pollution data. Meteorological variables (temperature, rainfall, and wind speed) were collected from the Retiro meteorological station of the State Meteorological Agency (AEMET) for the same periods as the air pollution and traffic data. As can be seen in Figure 4, all the aforementioned stations are included in a 1 km radius from the Escuelas Aguirre Air Quality Station.

Figure 4. Location of the air quality, traffic, and meteorological stations selected for this study in the city of Madrid.

3. Results

3.1. Descriptive Statistics

The descriptive statistics of the variables used in this article are shown in Table 2. For traffic variables, the daily average number of vehicles circulating in the years of the periods selected detected by the sensors of the gauging stations located in a 1 km radius of the Escuelas Aguirre Air Quality Station.

Table 2. Descriptive statistics of the variables selected for this study in the time periods studied: before the pandemic (2018–2019), during the pandemic (2020–2021), and after the pandemic (2022–2023).

Variable	Period	Daily Mean	Std. Deviation	Min.	Max.
Traffic (per thousand of vehicles)	Pre-Pandemic	17.60	2.91	10	23
	During the Pandemic	13.76	3.08	6	19
	After the Pandemic	16.33	2.49	8	20
NO_2 (μg/m^3)	Pre-Pandemic	52.12	14.74	15	99
	During the Pandemic	34.99	12.56	10	78.5
	After the Pandemic	33.45	10.82	14.5	71
$PM_{2.5}$ (μg/m^3)	Pre-Pandemic	10.64	4.3	3.5	25
	During the Pandemic	9.13	4.0	1.5	27.5
	After the Pandemic	11.92	8.9	2.5	74
PM_{10} (μg/m^3)	Pre-Pandemic	20.36	8.2	7	49.5
	During the Pandemic	17.69	8.2	3	53.5
	After the Pandemic	22.00	14.35	5	125.5
O_3 (μg/m^3)	Pre-Pandemic	45.73	19.6	4.5	92
	During the Pandemic	47.43	18.73	4.5	88.5
	After the Pandemic	51.66	19.68	6.29	90.08
Temperature (°C)	Pre-Pandemic	15.9	7.51	4	31
	During the Pandemic	15.8	7.17	0	30
	After the Pandemic	16.8	7.67	5	32

Table 2. *Cont.*

Variable	Period	Daily Mean	Std. Deviation	Min.	Max.
Rainfall (L/m^2)	Pre-Pandemic	1.3	2.81	0	19
	During the Pandemic	1.5	3.86	0	34
	After the Pandemic	0.98	2.49	0	19
Wind Speed (m/s)	Pre-Pandemic	2.00	0.75	0	4
	During the Pandemic	1.98	0.89	0	6
	After the Pandemic	2.12	0.97	1	6

3.2. Correlation Analysis

Tables 3–5 show the correlation matrices calculated between the road traffic, air pollutants, and meteorological variables for the pre-pandemic period (years 2018–2019), during the pandemic period (years 2020 and 2021) and in post-pandemic period (2022–2023), respectively. For the purposes of correlation analysis, correlation is considered perfect if the coefficient R is 1, strong if it is between 1 and 0.5, moderate between 0.49 and 0.30, weak between 0.29 and 0, while if the coefficient is equal to 0 there is no correlation [81].

Table 3. Correlation matrix for the pre-pandemic period (years 2018–2019).

	Traffic	NO_2	$PM_{2.5}$	PM_{10}	O_3	Temperature	Rainfall
Traffic	1.0000						
NO_2	0.4500	1.0000					
$PM_{2.5}$	−0.1997	0.2563	1.0000				
PM_{10}	−0.0804	0.2153	0.8478	1.0000			
O_3	−0.2588	−0.6031	−0.0166	0.0857	1.0000		
Temperature	−0.3199	−0.5424	0.2618	0.4692	0.6951	1.0000	
Rainfall	0.0632	0.0668	−0.0926	−0.1796	−0.1222	−0.1932	1.0000
Wind speed	0.0981	−0.3361	−0.3516	−0.3470	0.2139	−0.0592	0.1269

Table 4. Correlation matrix for the period during the pandemic (years 2020–2021).

	Traffic	NO_2	$PM_{2.5}$	PM_{10}	O_3	Temperature	Rainfall
Traffic	1.0000						
NO_2	0.5410	1.0000					
$PM_{2.5}$	0.1150	0.3078	1.0000				
PM_{10}	0.2017	0.3381	0.7928	1.0000			
O_3	−0.4633	−0.7163	−0.2152	−0.1041	1.0000		
Temperature	−0.1338	−0.4438	0.0430	0.1153	0.7392	1.0000	
Rainfall	−0.0511	−0.0701	0.2006	0.0747	−0.0615	−0.0703	1.0000
Wind speed	−0.0728	−0.2378	−0.1381	−0.0446	0.2323	0.1121	−0.0185

Table 5. Correlation matrix for the post-pandemic period (years 2022–2023).

	Traffic	NO_2	$PM_{2.5}$	PM_{10}	O_3	Temperature	Rainfall
Traffic	1.0000						
NO_2	0.3888	1.0000					
$PM_{2.5}$	−0.1824	−0.0575	1.0000				
PM_{10}	−0.0944	−0.0050	0.9134	1.0000			
O_3	−0.2560	−0.7390	0.2781	0.3111	1.0000		
Temperature	−0.2545	−0.5082	0.5107	0.5454	0.7496	1.0000	
Rainfall	0.0686	0.0032	−0.1214	0.1343	−0.1392	−0.1302	1.0000
Wind speed	−0.0104	−0.3295	−0.0686	−0.0931	0.2368	0.0276	−0.1154

For the pre-pandemic period (Table 3), a moderate positive correlation is observed between traffic and NO_2 concentration. On the one hand, a negative weak correlation is found between the traffic and particulate matter variables, $PM_{2.5}$ and PM_{10}. Collinearity is observed between NO_2 and O_3, and it is observed in the three periods studied in this article. On the other hand, a moderate negative correlation occurs between temperature and traffic, while a weak correlation is found for the rest of the meteorological variables and traffic in this period.

For the period during the pandemic (Table 4), a strong positive correlation is found between traffic and NO_2, which, on the other hand, is slightly higher than before the pandemic. A weak positive correlation is found between traffic and particulate matter. O_3, in contrast, has a negative moderate correlation with traffic. For meteorological variables, we found that in all variables a negative weak correlation is produced. Temperature is found to have a strong correlation with O_3 concentration, since this pollutant is produced when a high temperature is reached. Likewise, the accumulation of particulate matter produced an increase in the temperature [82].

Lastly, in the post-pandemic period (Table 5), the correlation between NO_2 and traffic decreased from strong to a moderate correlation. Particulate matter shows a weak negative correlation with traffic, while O_3 shows a weak negative correlation. The meteorological variables follow the same trend as the previous periods, reporting a weak correlation with traffic. Temperature was also found to have a linear correlation with O_3, strong and moderate with the particulate matter in the post-pandemic period as well.

3.3. Regression Analysis

Table 6 shows the coefficients obtained from the regression models performed for each air pollutant using traffic, teleworking, temperature, rainfall and wind speed variables, in the three periods studied. The telework variable is introduced as a categorial variable with six categories. The categories refer to the frequency of telework, and are daily, 3–4 times per week, 1–2 times per week, once a month and never, the baseline being the “never telework” option, not shown in the table.

Table 6. Coefficient values obtained from the regression models for each air pollutant in the three periods studied.

Variable		NO_2			$PM_{2.5}$		
		Pre–Pandemic	**During the Pandemic**	**Post–Pandemic**	**Pre–Pandemic**	**During the Pandemic**	**Post–Pandemic**
Traffic		1.72 ***	1.93 ***	1.19 ***	0.16 **	0.18 **	−0.15 *
Telework	*Ocasionally*	−1.88 *	2.51 *	2.82 *	−0.53 *	0.03 *	−2.02 *
Telework	*Once a month*	2.45 *	0.99 *	−0.52 *	1.12 *	0.45 *	5.01 **
Telework	*1–2 times per week*	−1.09 *	−2.97 *	0.50 *	0.59 *	0.32 *	−1.37 *
Telework	*3–4 times per week*	0.61 *	−1.94 *	−0.01 *	0.005 *	−0.79 *	−0.73 *
Telework	*Daily*	−1.42 *	−1.21 *	−1.81 *	0.52 *	0.63 *	0.25 *
Temperature		−0.89 ***	−0.65 ***	−0.62 ***	0.12 ***	0.05 *	0.58 ***
Rainfall		0.03 *	−0.25 *	−0.50 **	−0.04 *	0.22 **	−0.24 *
Wind Speed		−7.72 ***	−2.29 ***	−3.58 ***	−1.88 *	−0.64 **	−0.94 **
		PM_{10}			O_3		
		Pre–Pandemic	**During the Pandemic**	**Post–Pandemic**	**Pre–Pandemic**	**During the Pandemic**	**Post–Pandemic**
Traffic		0.28 **	0.61 ***	0.37 *	−0.40 *	−2.21 ***	−0.55 **
Telework	*Ocasionally*	−2.54+	−0.38 *	−2.79 *	1.73 *	0.45 *	−1.01 *
Telework	*Once a month*	2.38 *	−1.10 *	5.26 *	−4.71 *	−3.87 *	1.83 *
Telework	*1–2 times per week*	1.41 *	−0.02 *	−2.35 *	−0.20 *	3.65 *	1.73 *
Telework	*3–4 times per week*	−0.11 *	−0.79 *	−1.47 *	−6.76 **	1.82 *	3.84 *
Telework	*Daily*	0.68 *	0.69 *	1.28 *	1.02 *	−0.05 *	5.80 **
Temperature		0.51 ***	0.18 **	1.04 ***	1.82 ***	1.77 ***	1.83 ***
Rainfall		−0.16 *	0.21 *	−0.47 *	−0.12 *	−0.14 *	−0.09 *
Wind Speed		−3.43 ***	0.47 *	−1.89 **	6.88 ***	2.82 ***	4.24 ***

*: p-value > 0.05 (non significant); **: 0.01 < p-value < 0.05; ***: p-value < 0.01; +: p-value = 0.051.

NO_2 shows the expected behavior in the three periods studied for the traffic association, as it is strongly associated with road traffic, since, according to the evidence available in the scientific literature, this is the main source of NO_2 in the atmosphere of large cities [83]. For meteorological variables, rainfall shows an association with NO_2 only in the post-pandemic period. Temperature and wind speed are significantly associated with NO_2 in the three periods studied. For telework, no significant association is found before, during, and after the pandemic.

$PM_{2.5}$ was found to have an association with traffic in the pre-pandemic and during the pandemic periods, but not for the post-pandemic period. The temperature is associated with the $PM_{2.5}$ concentration, apart from the during the pandemic period. Wind speed is found to have a significant association in the three periods studied, while rainfall is only associated in the during the pandemic period. Telework was only found to be associated after the pandemic.

PM_{10} was found to have a significant association with traffic for the pre-pandemic and during the pandemic periods, but not for the post-pandemic period. Temperature follows the same trend as traffic. Rainfall is not associated with traffic before the pandemic, showing a significant association during and after the pandemic. Wind speed was associated with PM_{10} concentration before and after the pandemic. Telework was found to have no association with PM_{10} concentration in the three periods studied, although the *p*-value in the pre-pandemic period (0.051) is near the contrast level.

Lastly, ozone had a significant association with traffic for the during the pandemic and post-pandemic periods. Temperature showed a great association with ozone concentration in the three periods considered, the same for the wind speed. Rainfall, on the other hand, does not show an association in any of the periods studied. Telework shown an association with the ozone concentration in the category 3–4 times per week teleworking in the pre-pandemic period, and in the daily category in the post-pandemic period.

4. Discussion

This article analyzes, preliminarily, the possible influence of telework on air quality in the city center of Madrid in three clearly differentiated time periods: before the pandemic, corresponding to the years 2018 and 2019, when teleworking was not a popular option; during the pandemic, corresponding to the years 2020 and 2021, when mobility restrictions were in force and teleworking became the most prevalent way of doing the job; and post-pandemic, corresponding to the years 2022 and 2023, when the situation allowed recovering the pre-pandemic normality and workers started to return to the office.

The air quality monitoring station Escuelas Aguirre is located in the vicinity of Retiro Park and Alcalá Street, in the central Retiro district of the city of Madrid. The traffic gauge stations were selected among those located within a radius of 1 km from the air quality station, and are located on Alcalá, Serrano, Velázquez and Menéndez Pelayo avenues. The meteorological station selected was the closest to the study area, in this case, the Retiro station of the State Meteorological Agency.

In terms of air pollution, the association with traffic is statistically significant for each of the periods studied, which is consistent with other studies [12,29–31]. By pollutant, the one with the strongest association to road traffic is NO_2, as traffic is one of the main sources of this gas in the atmosphere in densely populated urban environments [2,12,14,31,84]. As mentioned in the previous section, a moderate correlation coefficient was obtained between traffic and NO_2 concentration in the pre-pandemic period. However, a strong correlation between these variables was found in the during the pandemic period, while a moderate one is found in the post-pandemic period. As stated above, the main source for NO_2 in the atmosphere in large urban environments is road traffic [2,16]. When the lockdown started, the number of vehicles circulating the streets dropped, as did NO_2 concentration [85]. Fewer vehicles on the road means fewer NO_2 emissions and can be related to a much stronger correlation, as the rest of the possible NO_2 sources such as commercial manufacturing [86] were not emitting during pandemic period.

However, for the concentration of particulate matter, no significant association with traffic was detected, which is due to the fact that traffic, although it has some influence on the accumulation of these compounds [5], is not the main source, this being home heating, industrial activities, or meteorological phenomena, such as dust intrusions [87]. Finally, the relationship of ozone with traffic is widely discussed in the literature. Ozone is considered a pollutant only when it is found in the lowest layer of the atmosphere, called the troposphere [88]. In this circumstance, it is not found naturally, as it is a secondary pollutant, it is produced from nitrogen oxides by photochemical reactions [11,88], which occur mainly in summer, due to the high solar radiation existing in that period [89].

The relationship that teleworking can have with air quality was also studied. Before the pandemic, telematic activities were not particularly well known to the general public, except Internet shopping (e-commerce) [90]. With the outbreak of the pandemic, which led to the limitation of all non-essential mobility, telematic activities spread to virtually the entire population, with teleworking or telematics education standing out. In the period immediately after the pandemic, when mobility had recovered some normality, teleworking was still considered a widespread option for work [64]. In the Madrid Region, at least 26% of workers practiced telework at least once a month before the declaration of the COVID-19 pandemic, compared to 39% who did so in the post-pandemic period. At the national level, according to data from the National Statistics Institute and the Spanish Economy Ministry [25,76], the same trend is observed.

The influence that teleworking can have on air quality is controversial and is still widely discussed in the scientific community. Some studies consider that this phenomenon has beneficial effects on society [63] and the environment [60,91], since it generally avoids the need to commute from the worker's residence to the workplace and vice versa [58]. However, other studies such as the one conducted by Kitou et al. in 2002 in the United States [92] found that, although commuting to work is avoided, the total number of trips does not only does not decrease, but increases, since teleworkers may take advantage of this time to carry out household chores (shopping, picking up packages, etc.) [58] and, since they spend more time in the house, more heating is needed [9]. The mode that the commuter choses to use to arrive to the workplace is also an important factor that influence the air quality [55]. However, we found no significant differences between the periods, so we did not take into account this phenomenon in this research.

The results we obtained in this research showed that the association between teleworking, categorized in six categories, depending on the frequency with which this type of employment is practiced: daily, 3–4 times a week, 1–2 times a week, once a month or never, the latter being considered as the reference category; and air quality can be considered spurious, if not nonexistent, with statistically significant associations occurring in an apparently random manner. Meteorological variables have also been found to have no association with telework, although a small increase in traffic can be observed when it rains or gets cold [93]. This is consistent with Hernandez-Tamurejo et al. in 2023 [94] analysis. They found that telework, when implemented independently, does not have a positive effect on traffic, so air quality does not improve as a result, so other measures are needed to decrease the air pollution emissions. The same results are found in this article, since no significant association (except for some pollutants) is found, thus confirming that teleworking by itself does not help improve traffic by reducing the number of vehicles on the road, as non-work-related trips (shopping, picking up packages, groceries [23]) can occur during work time, so that the distribution of traffic congestion may have changed since the outbreak of the COVID-19 pandemic.

5. Conclusions

Air pollution is one of the main problems we face in large cities like Madrid. As millions of people travel every day to work or study, a considerable number of pollutants are emitted. A variety of measures have been enforced over the years such as implementing low emission zones (LEZ) and parking limitations, but teleworking stands out.

Telework is defined as working outside the usual workplace. Before the COVID-19 pandemic, teleworking was not known amongst the workforce. As the lockdown started, telework became a widespread phenomenon and remained in this state after the pandemic. In this article, we analyzed the possible effects that telework has on air quality. We found that telework alone does not have an effect on air quality as strong as we expected. In addition to the promotion of telework by both public institutions and private enterprises, road traffic regulations are needed in order to reduce air pollutants concentrations in large urban environments such as Madrid City and the rest of Spain.

The preliminary findings obtained in this study are helpful for policymakers interested in promoting livable cities. As a preliminary study, there are certain limitations that are worth analyzing in the future. Future studies can deeply analyze such effects of teleworking considering such teleworkers that use road-based modes for commuting, the effects of rush hours on air pollution, the impacts of implementing LEZ zones or the vehicle fleet characterization. Additionally, a broader analysis including more areas of the city and a comparison with different cities could be also interesting to address. These would contribute to improve accuracy in analyzing and interpreting the results, which could lead to more coherent policy implications.

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Data Availability Statement: The datasets generated during and analyzed during the current study are not publicly available due to internal work but are available from the corresponding author on reasonable request.

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