Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Brazilian truckers' strike and particulate matter (PM_{10}) concentration: Temporal trend and time series models

Greve de caminhoneiros brasileiros e concentração de material particulado (MP_{10}) : tendência temporal e modelos de séries temporais

Danilo Covaes Nogarotto[1], *Felippe Benavente Canteras*[1], *Simone Andrea Pozza*[1]

ABSTRACT

High particulate matter (PM) emissions from vehicular traffic impact air quality in urban areas. In 2018, a truckers' strike interrupted some of the services in Brazil, leading to a fuel outage in several cities that significantly reduced the flow of vehicles. This study evaluated air quality during the strike in two cities (Limeira and Campinas) in Southeastern Brazil. PM_{10} concentration was analyzed in the periods before (BTS — 05/01/2018 to 05/22/2018), during (DTS — 05/23/2018 to 05/30/2018), and after (ATS — 05/31/2018 to 06/30/2018) the strike using the Theil-Sen method and the Autoregressive Integrated Moving Average model with Exogenous Variables (ARIMAX). A reduction in the PM daily mean concentration in both cities occurred during the strike. Considering the daily peak time of vehicular flow (6:00 p.m.), the PM_{10} concentration was 20% higher in the BTS period compared to the DTS period for both cities. In comparison, the ATS period showed concentrations 17% (Limeira) and 7% (Campinas) higher when compared with the DTS period. The variations were statistically significant based on the time series models, and the influences of wind speed, rainfall on the sampling day and the day before sampling, and weekends were also evaluated. It was also possible to verify the contribution of the truckers' strike to the PM_{10} concentration in the two cities evaluated. In Limeira, truck traffic had a greater influence on the concentration of PM_{10}, while in Campinas, the contribution of trucks was like that of light vehicles. Based on the variation of the PM_{10} concentration, the influence of changes in vehicle emission dynamics, one of the main sources of emission in the regions studied, was observed. The results indicate that restricting vehicular traffic had an immediate impact on improving air quality. Therefore, public investment in other types of transport and traffic control policies are suggested.

Keywords: air pollution; trend analysis; road transport; strike impact; ARIMAX models.

RESUMO

As altas emissões de material particulado (MP) do tráfego de veículos impactam a qualidade do ar em áreas urbanas. Em 2018, uma greve de caminhoneiros interrompeu alguns serviços no Brasil, levando à falta de combustível em várias cidades, o que reduziu significativamente o fluxo de veículos. Este estudo avaliou a qualidade do ar durante essa greve, em duas cidades (Limeira e Campinas) no Sudeste do Brasil. A concentração de MP_{10} foi analisada nos períodos antes da greve (BTS — 1º a 22 de maio 2018), durante a greve (DTS — 23 a 30 de maio de 2018) e depois dela (ATS — 31 de maio de 2018 a 30 de junho de 2018), usando o método Theil-Sen e o modelo ARIMAX. Durante a greve ocorreu redução na concentração média diária de MP_{10} nas duas cidades. Considerando-se o horário de pico diário do fluxo veicular (18h), a concentração de MP_{10} foi 20% maior no período BTS do que no DTS, para ambas as cidades. Em comparação, o período ATS apresentou concentrações de 17% (Limeira) e 7% (Campinas) maiores, quando comparado com o DTS. As variações foram estatisticamente significativas com base nos modelos de séries temporais, e foram avaliadas as influências da velocidade do vento, da chuva no dia da amostragem e na véspera da amostragem e nos fins de semana. Também foi possível verificar a contribuição da greve na concentração de MP_{10} nas duas cidades. Em Limeira, o tráfego de caminhões teve maior influência na concentração de MP_{10}, enquanto em Campinas essa contribuição foi similar entre caminhões e veículos leves. Com base na variação da concentração de MP_{10}, observou-se a influência de mudanças na dinâmica de emissão veicular, que é uma das principais fontes emissoras nas regiões analisadas. Os resultados mostram que a restrição do tráfego veicular teve impacto imediato na melhoria da qualidade do ar e, então, são sugeridos investimentos públicos em outros tipos de transporte e políticas de controle de tráfego.

Palavras-chave: poluição do ar; análise de tendência; transporte rodoviário; impacto da greve; modelos ARIMAX.

[1]Universidade Estadual de Campinas – Campinas (SP), Brazil.
Correspondence address: Simone Andrea Pozza – Rua Paschoal Marmo, 1888 – Jardim Nova Itália – CEP: 13484-332 – Limeira (SP), Brazil.
E-mail: spozza@unicamp.br
Conflicts of interest: the authors declare that there are no conflicts of interest.
Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.
Received on: 06/10/2022. Accepted on: 08/29/2022.
https://doi.org/10.5327/Z2176-94781386

Introduction

Policies for planning and investing in transport infrastructure, in strategic areas of the Brazilian territory, have attracted industrial, agricultural, agroindustrial, and commercial activities. As part of economic modernization, the automobile industry was a symbol of international capital expansion in Brazil, influencing Brazilian transport policies by focusing its investments on road transport as compared to other means of transport (Pereira and Lessa, 2011). In this way, the transportation of goods and products in the country is mainly done through highways using trucks (Borba et al., 2017).

Most of the trucks and buses in Brazil run on diesel, one of the most polluting fuels (Leirião and Miraglia, 2019). Some policies address a gradual shift from diesel to other less polluting alternatives. Some studies indicate that the energy demanded by the road transport modal is higher when compared to other types of transport (Franzin et al., 2020).

The use of fuels such as diesel and gasoline has been worsening the quality of urban air due to the emission of gaseous and particulate pollutants (Borba et al., 2017; Malvestio et al., 2018). Particles are emitted not only because of fuel burning but also because of the abrasion of vehicle parts (Winther and Slentø, 2010; Földi et al., 2018). In addition, moving vehicles may cause the resuspension of soil particles and other particles that have already been deposited (Pozza et al., 2006; Cui et al., 2016).

Atmospheric aerosols are important to evaluate air quality. The dynamic of aerosols (transport and deposition) is influenced by the mass and particle size variation (Kopanakis et al., 2012). The PM is a complex mixture of small particles and PM_{10} is considered the inhalable fraction, with an aerodynamic diameter (d_a) less than or equal to 10 µm. Other important fractions of study are Total Suspended Particles (TSP) ($d_a \leq 50$ µm), $PM_{2.5\text{-}10}$ which is considered the coarse inhalable fraction ($d_a \leq 10$ µm), $PM_{2.5}$ which is the fine inhalable fraction, also classified as the respirable fraction. Usually, particles up to 10 µm can cause health problems. However, the larger ones, called TSP, may interfere with the aesthetics of the environment (Hinds, 1999; Juda-Rezler et al., 2011).

Some sporadic events can increase (Basagaña et al., 2018) or reduce (Zheng et al., 2019) the amount of pollutants, especially particles suspended in the atmosphere. These events can include public transport strikes (Carvalho-Oliveira et al., 2005; Silva et al., 2012; Basagaña et al., 2018), which affect the means of locomotion used by the population and, therefore, the quality of the air, increasing the number of vehicles on the streets and the emission of air pollutants.

An increase in PM_{10} may be associated with urban dynamics and meteorological variables (Ramírez et al., 2018; Nogarotto and Pozza, 2020). It can include the reduction of the boundary layer height (Singh et al., 2020), variability in humidity conditions (Singh et al., 2020), and the horizontal movement of air masses (Nogarotto et al., 2021).

Brazilian truckers went on a strike from May 21st to 30th, 2018, affecting the population's routine, mainly because of the lack of fuel in most cities, drastically reducing the number of vehicles in circulation. The main cause of the strike was the price policy practiced by Petróleo Brasileiro S.A. (Petrobras), with daily increases in the prices of diesel, which accounted for more than a 50% increase in the twelve months preceding the strike, directly affecting truck drivers. The strike began on 05/21/2018, after its announcement on 05/18/2018. However, the most significant changes felt by the population began to appear from 05/23/2018 onward. The most critical period was from May 23rd to 30th, considering the shortages of products in drugstores and supermarkets, the cancellations of classes in universities and schools, the interruption in the operation of manufacturing facilities, and cancelations of flights due to the shortage of fuel. On May 26th, there were more than 500 roadblocks on highways over the country. In the city of Limeira, the bus fleet did not work on May 27th, and the Campinas metropolitan transport was reduced by 60% (BBC, 2018; CNN, 2018; G1, 2018).

After a price reduction proposed by the federal government and the use of the armed forces to guarantee the supply of priority goods, gas station supplies were coming back to normality on May 30th. However, fueling cars was still a difficult task, with long queues at the gas stations. Many people were still saving fuel by avoiding using their cars as they had been doing on the previous days until everything got back to normal on May 31st (BBC, 2018; CNN, 2018; G1, 2018).

The strike directly influenced air quality mainly due to the scarcity of fuel in the gas stations and the consequent reduction of the fleet of vehicles on the streets, as demonstrated by the studies of Dantas et al. (2019), Debone et al. (2020), and Leirião et al. (2020). The truck drivers' strike became an opportunity to evaluate the behavior of atmospheric pollutants, especially those coming from vehicular emissions. In this context, we evaluated air quality using data on atmospheric aerosols during the period of the strike in two cities in the Southeast region of Brazil. This study aimed to assess the impact of reduced vehicle flow on PM_{10} levels during the strike period and to develop time series models to assess PM_{10} levels in the periods before, during, and after the truckers' strike. Thus, it was possible to elucidate the influence of road transport on the air quality of the regions studied.

Methodology

Areas of study

For this study, we selected the cities of Campinas and Limeira, which are in the Southeast region of Brazil, at 50 km from each other. Despite being of different sizes in terms of population and territorial area, both are prominent cities of the state of São Paulo as they host diversified activities in the industrial, agricultural, and service fields.

Campinas

The city of Campinas is located about 100 km from the city of São Paulo, the capital of the state of São Paulo (South latitude 22°53'20" and West longitude 47°04'40"). It had an estimated population of 1,194,094 inhabitants over 794.57 km^2 by 2018, making it the third most populous city in the state of São Paulo. The estimated fleet of the city was 864,782 vehicles by 2016 (IBGE, 2019a). Among the main highways that provide access to Campinas, Anhanguera (SP330) and Bandeirantes (SP348) stand out and form the main economic corridor of the country (Figure 1) (Canteras et al., 2019). Considering the segments closer to the city of Campinas, Anhanguera and Bandeirantes have, respectively, average daily traffic of 36,422 and 120,140 vehicles, considering both directions (DER, 2019).

It is also possible to highlight its proximity to the city of Paulínia, which has emissions from industrial activities, especially oil refinery. In any case, it is understood that vehicular emissions are priority sources for the city, as confirmed by the São Paulo State Environmental Agency (CETESB, 2020).

Fires, generally coming from sugarcane cultivation, are another significant source of PM_{10} emissions for Campinas and Limeira. It is worth mentioning that for the periods studied, only a few fires were identified in the city of Campinas (one in the BTS period, one in the DTS period, and 12 in the ATS period), representing less than 4% of the fires in the State of São Paulo, suggesting a low influence on the results obtained in this work (INPE, 2022). These fires occurred mainly in July and August, under drier climatic conditions.

Campinas has a humid subtropical climate (Cfa) according to Köppen's classification (Alvares et al., 2013), being January the wettest month (269.1 mm average) and August the driest month (average of 27 mm), showing an average annual rainfall of 1,397.8 mm (CIIAGRO, 2019). Considering its historical average, February stands out as the hottest month (25.3°C) and June as the coldest month (18.1°C) of the year (CEPAGRI, 2019).

Limeira

The city of Limeira is located 154 km from the capital of the state (South latitude 22°33'53" and West longitude 47°24'06"), with a population of approximately 303,682 inhabitants (2018 estimate) and a 204,092-vehicle fleet (by 2016), distributed over 580.71 km² (IBGE, 2019b). Just like Campinas, the location of Limeira is quite strategic (Figure 1), as it has close access to Anhanguera (SP 330), Bandeirantes (SP 348), and Washington Luís (SP 310) highways, which are three of the major highways of the state. For the Anhanguera highway segment closest to Limeira, the daily flow is approximately 37.686 vehicles per day, in both directions. Bandeirantes has an average of 18.382 vehicles per day considering both directions. On the other side, Washington Luís has daily traffic of approximately 25,940 vehicles (DER, 2019). Besides, Limeira is close to an important pole of industrial ceramic production, especially in the city of Santa Gertrudes. The activities of extraction, processing, and transport of raw materials are important sources of PM in the city of Santa Gertrudes, causing significant impacts on air quality (CETESB, 2020; Nogarotto et al., 2021).

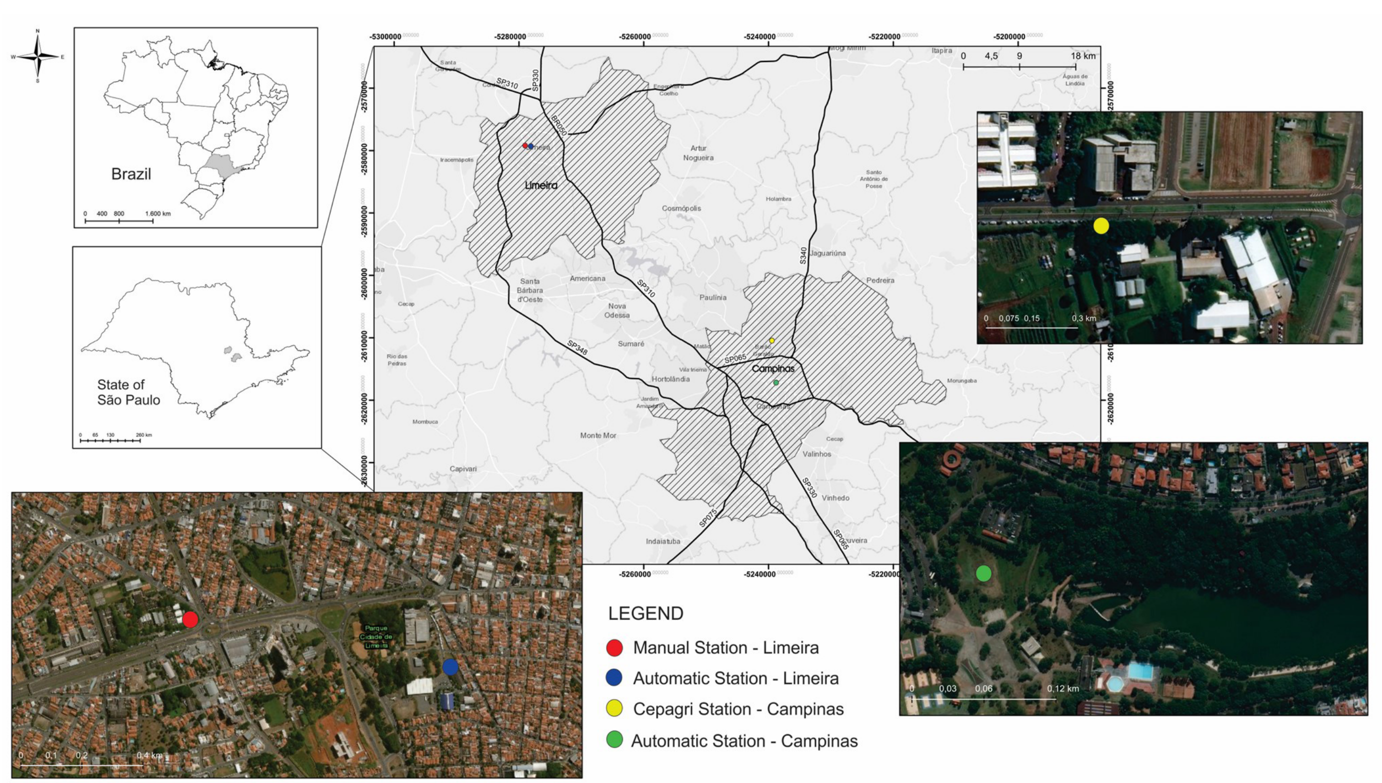

Figure 1 – Location of the stations in the cities of Limeira and Campinas.

Thus, both vehicular emissions and industrial emissions are relevant sources of air pollution in this city (Gonçalves et al., 2022).

For the city of Limeira, the number of fires in the period studied was even lower, with only four fires recorded in the ATS period. The other periods did not record any fires.

According to the Köppen's climate classification, Limeira has a Monsoon-influenced humid subtropical climate (Cwa) (Alvares et al., 2013), with temperatures below 18°C in the winter and over 22°C during the summer. January is the wettest month (average of 242.7 mm) and July is the driest month (average of 24.6 mm), totaling an average of 1263.5 mm of rainfall per year (CIIAGRO, 2019).

Sampling and data acquisition

Data on inhalable PM_{10} were taken from the online platform "Air Quality" (QUALAR), available on CETESB website (QUALAR, 2018). PM_{10} concentrations were obtained from the hourly measurements, totaling 24 measurements per day, made by automatic stations in the cities of Campinas (Figure 1 — green dot) and Limeira (Figure 1 — blue dot) between May 1st and June 30th, 2018. The automatic station of the city of Campinas is located within the Taquaral Park (South latitude 22°52'28" and West longitude 47°03'3"); while in Limeira, it is located next to the City Park, the main park of Limeira (South latitude 22°33'49" and West longitude 47°24'51") (Nogarotto et al., 2021).

Rainfall data

Rainfall data in Campinas were obtained from the automatic station (Figure 1 — yellow dot) of the Center for Meteorological and Climate Research Applied to Agriculture (CEPAGRI/Unicamp) (South latitude 22°48'56"and West longitude 47°03'28"), which is the closest to the CETESB's automatic station (5.5 km from one another).

In Limeira, rainfall data were obtained from an automatic station located at the School of Technology of Unicamp, where PM_{10} and TSP samples were collected (Figure 1 — red dot). The distance between the automatic station of CETESB and the School of Technology is approximately 850 m.

Table 1 shows the total rainfall (in mm) that occurred in the cities of Limeira and Campinas during the study period, which was below the rainfall climatology in both cities (Climate-Data.Org, 2022a; 2022b). It is worth mentioning that rainfall data can directly influence the levels of PM via the process of removal (Olszowski and Ziembik, 2018).

Delimitation of the study period

Three different periods of the truckers' strike were considered and divided as follows: Before the Truckers' Strike (BTS), from 05/01/2018 to 05/22/2018; During the Truckers' Strike (DTS), from 05/23/2018 to 05/30/2018; and After the Truckers' Strike (ATS), from 06/01/2018 to 06/30/2018 (Table 2). The truckers' strike began on 05/21/2018, but its effects on the population were only seen on 05/23/2018. This way, we considered the DTS period as the period from the day 05/23/2018 onward. The day of 05/31/2018 was an atypical day for two reasons: first, because it was the National holiday of Corpus Christi, and second because it was the first day after the beginning of the strike. Thus, our trend analysis considered it to be part of the ATS. However, the weekly cycle analysis considered it separately. Some studies present holidays as a different temporal component regarding the atmospheric pollutant concentration behavior, for example, Basagaña et al. (2018) and Zhao et al. (2018) studies.

At the end of the BTS period, on 05/21/2018 (Monday) and 05/22/2018 (Tuesday), truck drivers started the strike. At first, only trucks stopped, without interfering immediately with other means of transport and production.

Table 1 – Days with rainfall (mm) in both cities.

City	Month	Day	Period	Total Rain	Total for the month	Total for the city
Limeira	May	05/15/2018	BTS	10.9	22.3	26.7
		05/19/2018	BTS	11.4		
	June	06/03/2018	ATS	0.3	4.4	
		06/05/2018	ATS	2.3		
		06/07/2018	ATS	1.5		
		06/13/2018	ATS	0.3		
Campinas	May	05/16/2018	BTS	0.3	8.7	18.9
		05/19/2018	BTS	8.4		
	June	06/07/2018	ATS	7.9	10.2	
		06/08/2018	ATS	0.3		
		06/13/2018	ATS	2.0		

Table 2 – Delimitation of the study period. Days in red correspond to the BTS period, in green to the DTS period, and in yellow to the ATS period.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
May			1	2	3	4	5
	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31*	1	2
June	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30

*National holiday.

To assess the contribution of trucks to the concentration of PM_{10} in the cities studied, we compared the averages over these two days (called "Without Truck" or "WT") with the concentrations found on Mondays and Tuesdays in the other periods. Besides, we compared the average concentration in the WT and DTS periods with the average concentrations in the BTS and ATS periods. The variation in concentration between WT with BTS and ATS indicates an estimate of the percentage reduction in the contribution of trucks to the concentration of PM_{10}. The variation between DTS with BTS and ATS indicates the percentage of reduction in the contribution of all motor vehicles (in general) to the concentration of PM_{10}, considering all the impacts caused by the strike.

Trend analysis

The trend analyses for the daily average, median, and minimum and maximum concentration of PM_{10} were performed using the statistical software R 3.5.1 (R Core Team, 2018), and the TheilSen function of the Openair package (Carslaw and Ropkins, 2012; Carslaw, 2019) for the BTS, DTS, and ATS periods.

The non-parametric method of Theil-Sen (Theil, 1950; Sen, 1968) has its advantages, such as resistance to outliers, besides also being used in non-normal and heteroscedastic data series (Ancelet et al., 2015; Mateus and Gioda, 2017). Bootstrap sampling was used to get the 95% confidence intervals and p-values (Mateus and Gioda, 2017). Data were deseasonalized using loess (Carslaw and Ropkins, 2012; Carslaw, 2019), because of the strong effect that the seasonal cycles can have on trend analyses (Ancelet et al., 2015; Mateus and Gioda, 2017). Seasonal cycles affect the results of the trend analysis because the weather can also have significant influences on the local concentrations of pollutants (Ancelet et al., 2015).

This study aimed to use the trend analysis of daily data (average daily concentration of PM_{10}), different from the one used in several previous studies, where the monthly average (Ancelet et al., 2015; Mateus and Gioda, 2017; Fenech and Aquilina, 2020) or the annual average (Munir et al., 2013; 2016) was used. This methodology adaptation is due to the period of the strike, which lasted only a few days.

Time series model

In this study, Autoregressive Integrated Moving Average (ARIMA) models were combined with regression models to assess the PM_{10} concentration levels in the cities of Limeira and Campinas. These models are called ARIMAX and have been used in different studies to predict the concentration of air pollutants (Catalano et al., 2016; Wongsathan and Chankham, 2016; Ahani et al., 2019). Formally, the ARIMA process is based on the orders p and q, which are the orders of the autoregressive process (p) and moving averages (q), considered by taking the d^{th} differences of the time series variables. In this way, the process is abbreviated as ARIMA (p, d, q), and when exogenous variables (regression model) are incorporated, the model is known as ARIMAX (p, d, q). Further details are presented in Catalano et al. (2016) and Ahani et al. (2019). The ARIMAX model (p, d, q) can be described as 1.

$$\Delta^d Y_t = c + \sum_{i=1}^{p} \varphi_i Y_{t-i} + \varepsilon_t + \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} + \sum_{k=1}^{n} \lambda_k X(t,k) \quad (1)$$

Where:

$\varphi_1, \varphi_2, \ldots, \varphi_p$: coefficients of the autoregressive process;

$\theta_1, \theta_2, \ldots, \theta_q$: coefficients of the moving averages process;

λ: the coefficient vector associated with the n regression variables;

ε_t: the term of the independent errors and identically distributed with zero average (white noise);

c: a constant.

The time series of the natural logarithm of the PM_{10} concentration observed at 6 p.m. (local time) was considered the dependent variable in the ARIMAX model. The choice was based on the time of greatest vehicular flow during one day, according to the National Department of Transport Infrastructure (Brazil, 2006) and the study by Karacasu et al. (2011).

The following regressive variables were considered: the daily average of wind speed, a dummy variable for the occurrence of rain on the current day, a dummy variable for the occurrence of rain on the previous day, a dummy variable for the weekend, a dummy variable for the BTS period, a dummy variable for the ATS period, and finally the natural logarithm of the hourly concentration of PM_{10} at 5 p.m.

The choice of p, d, and q orders of the ARIMAX process was based on the Box-Jenkins methodology (Box et al., 2015; Ahani et al., 2019). The autocorrelation (ACF) and partial autocorrelation (PACF) functions, in addition to the Akaike information criterion (AIC), were analyzed to determine the values of p, d, and q.

The performance of the model was validated based on the values obtained for the Pearson Correlation Coefficient (PCC), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Akaike Information Criterion (AIC) (Ahani et al., 2019). In addition, an residual analysis was performed to check the normality and non-autocorrelation.

The autocorrelation (ACF) and partial autocorrelation (PACF) functions of the residuals were analyzed, as well as the plot of residuals over time and the residuals plot versus the percentiles of the normal distribution (qq-plot), all used to evaluate the statistical assumptions of the ARIMAX model (Catalano et al., 2016; Wongsathan and Chankham, 2016). To assess the normality of the residuals, Anderson-Darling and Shapiro-Wilks tests were performed (Moeeni and Bonakdari, 2018), as well as the Ljung-Box and Box-Pierce tests, to assess the autocorrelation of the residuals (Pinto et al., 2018). The time series analysis was performed using the statistical software R 3.5.1 (R Core Team, 2018).

Results and Discussion

This study was performed with air quality monitoring data and was carried out by two automatic monitoring stations operated by the CETESB (QUALAR, 2018) in the cities of Limeira and Campinas. The sampling period was from May 1st to June 30th, 2018.

Weekly cycle

Table 3 presents the minimum (Min), maximum (Max), and average (Mean) concentrations, as well as the standard deviation (SD), on each of the days of the week, considering the BTS, DTS, and ATS periods. Table 4 shows the percentage of variation (Δ%) of the average concentration during the DTS period compared to the average concentration for the other periods for each day of the week. The DTS column features the day of the DTS period, whose average concentration of PM_{10} was compared with the average concentrations obtained on the same days of the week during BTS and ATS.

Table 3 – Descriptive measures of PM_{10} concentration (μg/m³) in Limeira and Campinas in 2018.

Day of the week	Period	Limeira				Campinas			
		Min	Max	Mean	SD	Min	Max	Mean	SD
Sun	BTS	1.00	78.00	31.78	19.77	1.00	66.00	20.56	14.23
	DTS	13.00	49.00	30.42	11.25	7.00	43.00	21.13	9.41
	ATS	10.00	427.00	43.71	47.95	2.00	54.00	22.43	11.05
Mon	BTS	11.00	100.00	34.72	16.59	1.00	75.00	23.07	12.97
	DTS	16.00	41.00	31.17	8.16	12.00	33.00	20.58	5.45
	ATS	6.00	96.00	37.44	17.20	2.00	74.00	23.59	15.21
Tue	BTS	15.00	84.00	40.01	15.62	3.00	71.00	28.33	13.01
	DTS	10.00	49.00	28.08	12.43	6.00	32.00	17.46	5.94
	ATS	22.00	91.00	47.05	18.06	5.00	56.00	26.74	11.61
Wed	BTS	8.00	105.00	36.79	18.78	1.00	52.00	24.71	12.22
	05/23	33.00	82.00	52.04	11.18	23.00	58.00	36.83	9.19
	05/30	10.00	58.00	29.83	14.24	9.00	28.00	16.00	6.00
	ATS	17.00	100.00	42.07	19.93	8.00	73.00	33.31	13.24
Thu	BTS	13.00	93.00	40.01	17.34	9.00	49.00	24.33	9.02
	DTS	31.00	69.00	42.75	10.26	13.00	50.00	27.50	9.98
	05/31	11.00	61.00	34.71	14.32	16.00	39.00	23.50	6.37
	ATS	9.00	122.00	47.91	25.46	3.00	71.00	29.36	12.95
Fri	BTS	24.00	90.00	44.15	13.77	17.00	55.00	31.58	9.38
	DTS	27.00	66.00	39.25	9.99	13.00	41.00	25.04	7.56
	ATS	9.00	109.00	38.96	21.10	1.00	52.00	25.51	12.47
Sat	BTS	2.00	145.00	47.08	27.00	3.00	68.00	31.56	15.06
	DTS	28.00	66.00	42.21	11.79	18.00	39.00	25.17	6.31
	ATS	10.00	252.00	42.74	26.26	1.00	48.00	25.32	11.98

Source: QUALAR (2018).

In this study, each day of the week was compared separately, considering the BTS, DTS, and ATS periods. The results for each day of the week were shown in an individualized way since the sources and emissions characteristics can be different for each day of the week, being an individualized data evaluation more reliable (Perrone et al., 2019; Huang et al., 2021). In addition, there were two Wednesdays in the DTS period (05/23 and 05/30) and, based on the history described, the strike was responsible for behavioral changes on these two days. In this way, a separate analysis was performed for this specific period.

On Wednesday, 05/23/2018, the PM_{10} concentration in Limeira reached 52.04 μg/m³, the highest observed in the periods studied (Table 3). At the Taquaral station (city of Campinas), the concentration on this day was almost 50% above the average concentration of May (BTS) (Table 4). On this day and Thursday (05/24), the population began to feel the first effects of the strike and started looking for gas stations, mainly in the afternoon and evening, forming huge lines and probably increasing vehicular traffic and, consequently, PM emissions (BBC, 2018; G1, 2018).

The behavior observed on Friday (05/25/2018) and Saturday (05/26) was similar in the two cities. When comparing the average concentration in the BTS period, the average PM_{10} concentration in Limeira was reduced by approximately 10%, while in Campinas it was reduced by approximately 20% (Table 4). Regarding the ATS period, the variation was not so significant, probably due to a natural oscillation of the data, because we did not notice any specific factor.

The average concentration on Sunday (05/27) barely changed in Campinas, not highlighting significant differences between the three periods. On the other hand, in Limeira, the average PM_{10} concentration obtained on Sunday was 30.41% lower than the data registered in the ATS period (Table 4). However, the ATS period average was strongly influenced by the maximum concentration obtained for the periods evaluated (427 μg/m³), which probably indicates equipment failure (Table 3).

It is possible to state that air quality was most impacted by the strike on Monday (05/28), Tuesday (05/29), and Wednesday (05/30), with reductions in PM_{10} levels, in both the BTS and ATS periods, and in both Limeira and Campinas (Table 4).

Table 4 – Percentage variation (Δ%) of PM_{10} average concentrations during the DTS period compared to the BTS and ATS periods.

Day of the week	DTS	Limeira		Campinas	
		BTS	ATS	BTS	ATS
Wed	05/23	41.45	23.69	49.07	10.57
Thu	05/24	6.84	-10.76	13.01	-6.35
Fri	05/25	-11.10	0.73	-20.71	-1.83
Sat	05/26	-10.35	-1.24	-20.25	-0.59
Sun	05/27	-4.28	-30.41	2.77	-5.81
Mon	05/28	-10.24	-16.75	-10.78	-12.76
Tue	05/29	-29.81	-40.31	-38.38	-34.71
Wed	05/30	-18.91	-29.09	-35.24	-51.97

The day of 05/31/2018 was both a national holiday and the first day after the truckers' strike (Table 2), being treated separately from the ATS period because the weekly cycle analysis considered it an atypical day. Note that the average concentrations for both cities were lower if compared with the BTS, DTS, and ATS periods (Table 3). Probably, both the strike and the holiday reduced the level of PM_{10} on this day, possibly due to the lower circulation of motor vehicles in the two cities (Policarpo et al., 2018).

In the city of Limeira, the reduction in the concentration of PM_{10} associated with the halt of the truck fleet occurred in the WT period (32.29 μg/m³) was 19.1 and 23.6% concerning Mondays and Tuesdays in the BTS (39.93 μg/m³) and ATS (42.24 μg/m³) periods, respectively. In Campinas (22.94 μg/m³), the reduction in the WT period was between 16.1 and 8.9% concerning the same periods (Mondays and Tuesdays in BTS — 27.33 μg/m³, and Mondays and Tuesdays in ATS 25.17 μg/m³). The reduction in the average concentration of PM_{10} on Mondays and Tuesdays in the DTS period, about the same days in the BTS and ATS periods, was close in both cities (Limeira — 29.63 μg/m³ and Campinas — 19.02 μg/m³), varying from 25.8 to 30.4%.

Thus, it is possible to affirm that the concentration of PM_{10} in Limeira has a greater contribution from truck emissions, while Campinas has a more balanced contribution from trucks and smaller vehicles.

This difference may be correlated with the size of the cities evaluated, as well as their economic activities. Considering that Campinas is bigger than Limeira in population and urban terms, smaller vehicles may be present in a greater proportion, contributing more significantly to the concentration of PM_{10}.

Trend analysis

Table 5 shows the estimates for the trend analysis of the average, median, minimum, and maximum daily concentrations of PM_{10}, based on the Theil-Sen method. Besides, Figures 2 and 3 present a trend analysis based on the Theil-Sen method for the daily average data of the city of Limeira and the city of Campinas (respectively) according to the BTS, DTS, and ATS periods.

In the city of Limeira, the BTS period showed a downward trend in all the PM_{10} concentrations assessed, with the average and maximum concentrations indicating a reduction at a significance level of 5%, and the minimum and median concentrations showed a downward trend at a significance level of 10%, as shown in Table 5. Considering the average concentrations of PM_{10}, in this period there was a reduction trend of 1.11 μg/m³ per day (Table 5). The rainfall that occurred on the days 05/15/2018 and 05/19/2018 (Table 1) helps to justify the reduction in PM_{10} concentrations in this period. In Figure 2A, it is possible to verify that after the rainy days there was always a reduction in the average concentrations and the lowest occurred just after May 19th.

During the DTS period, it was possible to verify a decreasing trend in the average, minimum, and median concentrations of PM_{10}, all at a significance level of 5%. It is possible to explain the reduction of

3.08 µg/m³ per day in the average concentration of PM_{10} considering a reduced fleet of vehicles due to lack of fuel. The day 05/23/2018 was an atypical day because the first effects of the strike appeared, and the population started to search for fuel at gas stations, which led to a high daily concentration on this day, 52.04 µg/m³ (Table 3). However, as the strike continued, the fleet of vehicles circulating decreased, as well as the concentration of PM_{10} (Figure 2B). The median and minimum concentrations showed a reduction trend of 3.1 and 3.58 µg/m³ per day, during the DTS period (Table 5). Although the maximum concentrations show a decrease of 4.79 µg/m³ per day, this variation did not show a statistically significant difference, probably due to the variability of the data. As DTS was a period in which there were no rain scenarios, an accumulation of PM_{10} would be expected, due to the drier soil, especially if the wind favors the resuspension of PM. However, there was a reduction in the PM_{10} concentration, which may be due to a decreased circulation of people and vehicles, reducing the resuspension of particles from the soil.

Considering the ATS period in the city of Limeira, the average and median concentrations of PM_{10} showed an upward trend (significant at the 10% level) of 0.95 and 1 µg/m³ per day, respectively. June was a typical winter month, dry and without rain (Table 1), which led to increased PM_{10} concentration with the end of the strike and the re-establishment of normal vehicle traffic in the city. In contrast, the minimum and maximum concentrations showed no significant statistical differences, although the analysis pointed to an increase of 0.43 and 1.55 µg/m³ per day, respectively.

In the city of Campinas, BTS and ATS trends were not statistically significant, showing a constant average throughout the days (Figures 3A and 3C) for all concentrations assessed (average, minimum, median, and maximum). However, in the DTS period, the trend was for PM_{10} concentration to decrease, showing a reduction of 2.21 µg/m³ ($p < 0.05$) per day in the average concentration in this period (Figure 3B), reducing from 36.85 to 16 µg/m³ (Table 3).

Table 5 – Trends estimate (before brackets) and 95% Confidence Interval (CI) (between brackets) of the BTS, DTS, and ATS periods.

City	Statistics	Period	Estimate (µg/m³) [95%CI]
Limeira	Average	BTS	-1.11 [-2.62, -0.05] *
		DTS	-3.08 [-5.40, -0.27] *
		ATS	0.95 [-0.33, 2.37] +
	Minimum	BTS	-0.69 [-1.75, 0.00] +
		DTS	-3.58 [-5.99, -1.50] *
		ATS	0.43 [-0.10, 1.00]
	Median	BTS	-1.00 [-2.50, 0.00] +
		DTS	-3.10 [-4.87, -1.06] *
		ATS	1.00 [-0.25, 2.36] +
	Maximum	BTS	-1.92 [-4.75, -0.58] *
		DTS	-4.79 [-8.24, 5.49]
		ATS	1.55 [-0.83, 3.93]
Campinas	Average	BTS	-0.59 [-1.44, 0.56]
		DTS	-2.21 [-3.89, -1.61] **
		ATS	0.33 [-0.57, 1.31]
	Minimum	BTS	-0.50 [-1.33, 0.50]
		DTS	-1.71 [-4.00, 0.67] +
		ATS	0.36 [-0.50, 1.03]
	Median	BTS	-0.64 [-1.55, 0.46]
		DTS	-1.90 [-3.00, -1.00] **
		ATS	0.42 [-0.65, 1.33]
	Maximum	BTS	-0.60 [-2.08, 0.75]
		DTS	-3.71 [-8.00, -2.00] *
		ATS	0.31 [-0.55, 1.33]

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; +$p < 0.10$.

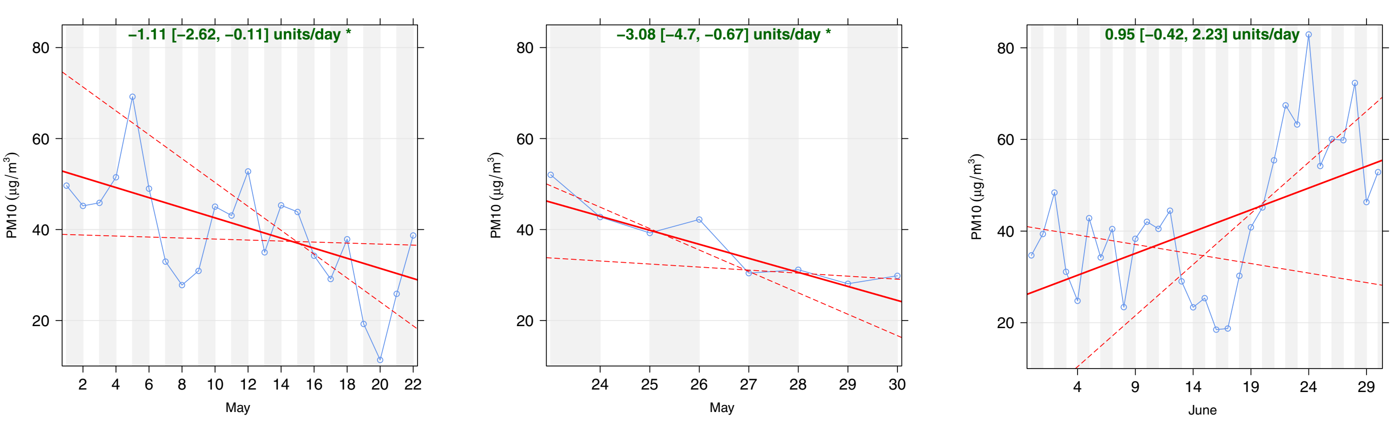

Figure 2 – Trend analysis of the average PM_{10} concentrations (µg/m³) in the city of Limeira for the (A) BTS, (B) DTS, and (C) ATS periods. The solid red line shows the trend estimate and the dashed lines show the 95% CI based on resampling methods.
*$p < 0.05$; +$p < 0.10$.

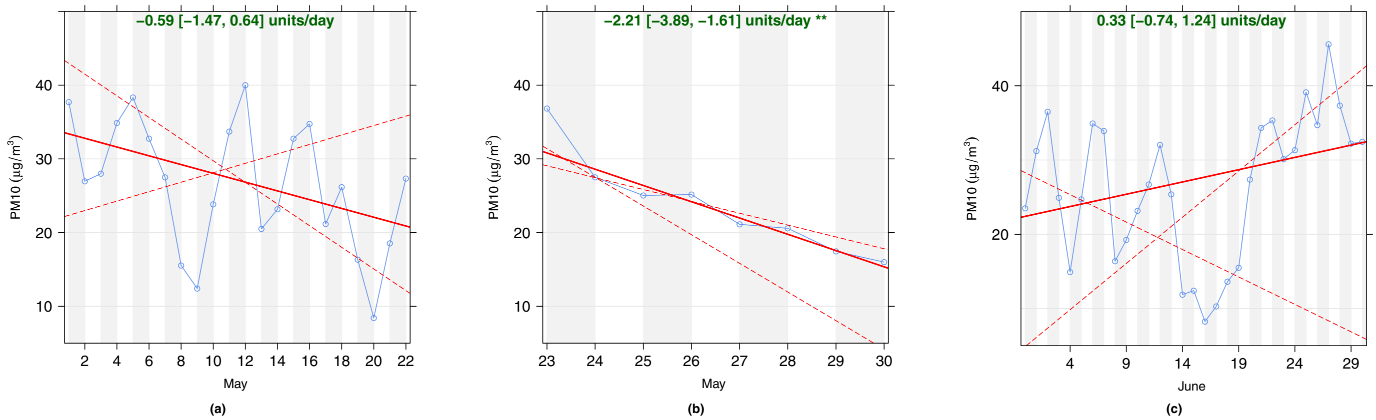

Figure 3 – Trend analysis of the average PM10 concentrations (μg/m3) in the city of Campinas for the (A) BTS, (B) DTS, and (C) ATS periods. The solid red line shows the trend estimate and the dashed lines show the 95%CI based on resampling methods.
**$p < 0.01$.

The minimum, median, and maximum PM_{10} concentrations also showed significant reductions for this period of 1.71 ($p < 0.10$), 1.90 ($p < 0.01$), and 3.71 μg/m³ ($p < 0.05$) per day (Table 5), respectively.

Time series analysis

From the time series of PM_{10} concentrations obtained at 6 p.m., several models were adjusted considering some combinations of p, d, and q values for the ARIMAX model.

The ACF and the PACF were also analyzed. For the time series of the PM_{10} concentrations at 6:00 p.m. in the city of Limeira, the order of the ARIMAX model chosen was p = 1, d = 0, and q = 0, while for the time series for the city of Campinas, the order chosen was p = 2, d = 0, and q = 2. In both cities, the order of the chosen ARIMAX model presented the lowest AIC value.

The assumptions of non-autocorrelation and normality of the residuals were evaluated to verify the adequacy of the proposed models. Autocorrelation and partial autocorrelation functions were plotted. Besides, diagnostic charts were obtained with a chart of residuals over time, residuals versus Normal percentiles, the autocorrelation function, and a chart with the p-values of the Ljung-Box statistic. All of these charts indicate that the residuals are uncorrelated and normally distributed, confirming the adequacy of the proposed models.

The residuals show no evidence of autocorrelation, indicating that the orders chosen in the ARIMAX models in the two cities appear to be adequate. The assumptions of normality and non-autocorrelation of the residuals were evaluated by the Anderson-Darling and Shapiro-Wilks tests (normality) and the Ljung-Box and Box-Pierce tests (non-autocorrelation). The residuals indicated normality in the two tests for the PM_{10} time series in the city of Campinas but, in the city of Limeira, only the Anderson-Darling test indicated normality of the residuals (Table 6). On the other hand, in the tests of non-autocorrelation of residuals, for both cities, there is evidence of non-autocorrelation (Table 6).

Also, to validate the chosen models, the values of the PCC, RSME, and MAE were also calculated among the observed and estimated values, presented in Table 6. It is important to note that the correlation (PCC) was close to 1 in both models, indicating a high correlation between observed and predicted values.

The complete series of PM_{10} concentrations at 6 p.m. in the two cities were compared with the concentration estimated by the ARIMAX(1,0,0) model in Limeira (Figure 4) and by the ARIMAX(2,0,2) model in Campinas (Figure 5). In general, the series predicted by the model can adequately follow the observed series. The exception is three days in Limeira, which had extremely high concentrations, and consequently, the predicted values were underestimated (Figure 4).

Table 7 presents the estimates of the percentage changes and the 95%CI, obtained in the ARIMAX models for the cities of Limeira and Campinas. In addition, the p-value of the t-test for each regressive variable is also presented.

For the city of Limeira, the PM_{10} concentrations at 6:00 p.m. in the BTS period are about 20.8% higher than the concentrations at the same time observed in the DTS period ($p < 0.05$), while in the ATS period, it is 17.2% higher than in the DTS period ($p < 0.10$). Rainfall ($p < 0.01$) and wind ($p < 0.10$) have an influence, reducing the concentration at 6 p.m. by 23.1 and 12.9%, respectively (Table 7).

In the city of Campinas, the variables Rain, BTS, ATS, and the PM_{10} concentration at 5:00 p.m. were statistically significant at the level of 1%. There is a 26.7% reduction in the PM_{10} concentration at 6 p.m. in case of rain. During the BTS period, the concentration at 6 p.m. was about 21.9% higher, and during the ATS period, it was 7.1% higher than the concentration at 6 p.m. in the DTS period (Table 7).

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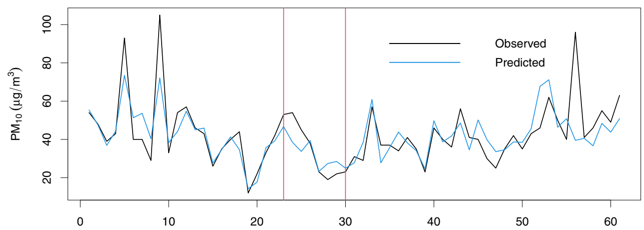

Figure 4 – Observed and Predicted PM_{10} concentrations in Limeira, during sample days at 6 p.m. The red lines delimit the DTS period.

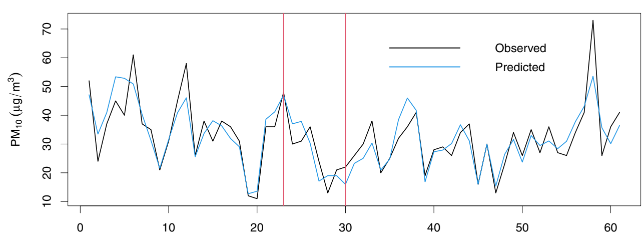

Figure 5 – Observed and Predicted PM_{10} concentrations in Campinas, during sample days at 6 p.m. The red lines delimit the DTS period.

Table 6 – Validation of models and residual analysis.

	Limeira: ARIMAX(1,0,0)	Campinas: ARIMAX(2,0,2)
PCC	0.842	0.923
RSME	0.215	0.164
MAE	0.159	0.134
AIC	5.554	-11.498
p-value (Anderson Darling test)	0.176	0.853
p-value (Shapiro-Wilk test)	0.004	0.828
p-value (Ljung-Box test)	0.960	0.827
p-value (Box-Pierce test)	0.961	0.831

In both cities, the estimated effect of rainfall has a greater influence on reducing the PM_{10} concentration at 6 p.m. On the other hand, the greatest increase effects in the PM_{10} concentration at 6 p.m. was due to the BTS and ATS periods (Table 7). In other words, considering the time of greatest vehicle flow throughout the day, at 6 p.m., PM_{10} concentrations were lower during the strike period (DTS) when compared to the periods before (BTS) and after (ATS) the strike. The results obtained indicate that reduced vehicle flow on the days of the truckers' strike led to reduced vehicle emissions, which caused a decrease in PM_{10} concentrations.

Transport-related events and air quality

Table 8 presents some of the events that affected air quality described in the literature. The events were: public transportation strikes (Carvalho-Oliveira et al., 2005; Silva et al., 2012; Ding et al., 2014; Basagaña et al., 2018), the opening of a subway line (Zheng et al., 2019), and a trucker's strike (this study; Dantas et al., 2019; Debone et al., 2020).

In the cities where a public transportation strike occurred, in general, an increase in the concentration of air pollutants is observed. This is because, with the lack of public means of transportation, the population has no option but to use private cars, thus increasing the flow of vehicles, and consequently, increasing the level of air pollutants. Traffic caused by the increase in vehicles also contributed to worsening air quality (Silva et al., 2012; Ding et al., 2014). On the other hand, investments in public transportation are associated with improvements in air quality, considering that its expansion reduces the need for private cars (Zheng et al., 2019).

This study addresses a specific trucker's strike, which led to fuel shortages in gas stations, reducing traffic flow, including the circulation of public means of transportation. This fact resulted in a significant drop in PM_{10} concentrations during the trucker's strike period, as already shown. It is worth mentioning that the study developed by Dantas et al. (2019) confirms the reductions in the concentrations of other air pollutants such as NO_2, PM_{10}, and NMHC (non-methane hydrocarbons), while Leirião et al. (2020) found a reduction in the concentration of NO_x and PM_{10} during the trucker's strike period.

Table 7 – Parameters estimates, Confidence Interval (CI), and p-value of time series model for Limeira and Campinas cities. These parameters represent the percentual change in PM_{10} concentrations. Analyses were conducted with time series models using the concentration at 6 p.m.

Independent variable	Limeira			Campinas		
	Percentual change	95%CI	p-value	Percentual change	95%CI	p-value
Wind speed	-12.9	(-25.6–1,91)	0.085+	-2.1	(-6.3–2.2)	0.331
Rain	-23.1	(-36.4–-7.03)	0.007**	-26.7	(-37.2–-14.6)	<0.001***
Rain on the previous day	-16.7	(-31.3–0.09)	0.061+	-8.8	(-23.3–8.5)	0.298
Weekend	10.5	(-2.5–25.3)	0.117	2.1	(-12.8–19.5)	0.799
BTS	20.8	(1.2–44.3)	0.037*	21.9	(18.2–25.8)	< 0.001***
ATS	17.2	(-1.9–40.2)	0.081+	7.1	(4.6–9.7)	< 0.001***
Log (PM_{10} at 5:00 p.m.)	0.6	(0.5–0.7)	<0.001***	0.7	(0.6–0.8)	< 0.001***

***p < 0.001; **p < 0.01; *p < 0.05; +p < 0.10.

Table 8 – Comparison of studies involving events that affect air pollution.

Location	Event	Period	n (days)	Air Pollutant	Occurrence during events associated with PM
Cities of Campinas and Limeira, Brazil[a]	Truckers' strike	05/2018 – 06/2018	10	PM_{10} PTS	Reduction of concentration
São Paulo, Brazil[b]	Bus strike	04/06/2003 – 04/08/2003	2	$PM_{2.5}$	Increase in concentration
São Paulo, Brazil[c]	Subway strike	06/2003 and 08/2006	2	PM_{10}	Increase in concentration
Barcelona, Spain[d]	Public Transport strike	2005–2016	208	NOx, PM_{10}, $PM_{2.5}$, PM_1, BC, CO	Increase in concentration
Ottawa, Canada[e]	Public Transport Strike	12/2008 – 02/2009	61	$PM_{2.5}$	Increase in concentration
Changsha, China[f]	Opening of a subway	01/2013 – 04/2015	730	$PM_{2.5}$, CO, O_3	Reduction of the concentration of CO
Rio de Janeiro, Brazil[g]	Truckers' strike	05/2018 – 06/2018	10	CO, SO_2, O_3, NO_2, NMHC, and PM_{10}	Reduction of the concentration of NO_2, PM_{10}, and NMHC
São Paulo, Brazil[h]	Truckers' strike	05/2018	6	NO_x, PM_{10}, and O_3	Reduction of the concentration of NO_x and PM_{10}
Carapicuíba, Osasco, Santos, Cubatão, Guarulhos and São José dos Campos, Brazil[i]	Truckers' strike	05/2018	NA	NO_2 and PM_{10}	Reduction of the concentration of NO_2 and PM_{10}

[a]This study; [b]Carvalho-Oliveira et al. (2005); [c]Silva et al. (2012); [d]Basagaña et al. (2018); [e]Ding et al. (2014); [f]Zheng et al. (2019); [g]Dantas et al. (2019); [h]Leirião et al. (2020); [i]Debone et al. (2020); NA: Not Avaliable.

Also, Debone et al. (2020) found a reduction in NO_2 and PM_{10} in several cities in São Paulo State.

Conclusions

Based on the evolution of air quality (in PM_{10} concentration), this study contextualized the influence of changes in the dynamics of vehicular emission, which is the most important source in the regions studied. The truckers' strike occurred in May 2018 and provide an opportunity to evaluate the behavior of the PM in a period of low circulation of motor vehicles in the cities of Limeira and Campinas. In general, the low circulation of vehicles improved air quality immediately, as it reduced PM levels over the days of the strike. Both the Theil-Sen method and the ARIMAX model, even in this short period of the strike (only 10 days, as its main limiting factor), indicated improvement in air quality due to a reduced vehicular fleet.

The PM_{10} concentration was 20% higher in the BTS period than in the DTS period for both cities, while the ATS period showed concentrations 17% (Limeira) and 7% (Campinas) higher when compared with the DTS period, in the daily peak time of vehicular flow (6 p.m.).

In Limeira, it was possible to identify that trucks had greater influence than light vehicles on the concentration of PM_{10}, while in Campinas this influence was balanced. The results obtained confirm the dependence of Brazil on the road transport system, and how this fact impacts air quality. Thus, it is possible to affirm that the diversification of Brazilian means of transport could lead to an improvement in the quality of ambient air, since it would be possible to reduce the flow of trucks and small vehicles, directly impacting atmospheric emissions. Hence, authorities should evaluate options for more efficient public transportation systems to reduce the number of vehicles in circulation and traffic restrictions policies, which would certainly reduce PM emissions and improve air quality.

Much of the air pollution comes from vehicle emissions, and the truckers' strike was a great opportunity to evaluate that. Thus, investments in public policy for sustainable transport are our main suggestion to improve air quality (Silva et al., 2012; Basagaña et al., 2018; Zheng et al., 2019).

Acknowledgments

The authors thank the students Katherly Tainá Grego Lira, Gabriela de Paula, and Lucas Veloso Marinho for helping us with the samplings held at the School of Technology/Unicamp, and Priscilla Bassi

Penteado for organizing Figure 1. Finally, the authors also thank the Companhia Ambiental do Estado de São Paulo (CETESB) for enabling us to consult the QUALAR database and Espaço da Escrita – Pró-Reitoria de Pesquisa – UNICAMP, for the language services provided. We acknowledge the critical comments from anonymous reviewers and the editor.

Contribution of authors:

NOGAROTTO, D. C.: Methodology; Software; Formal analysis; Data Curation; Investigation; Resources; Writing — Original Draft; Writing — Review and Editing. CANTERAS, F. B.: Conceptualization; Methodology; Writing — Original Draft; Writing — Review and Editing; Supervision; Project Administration. POZZA, S. A.: Conceptualization; Methodology; Writing — Original Draft; Writing — Review and Editing; Supervision; Project Administration.

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