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Analysis of the potential of nighttime light data for monitoring intercity road traffic in the Metropolitan Region of the Paraíba Valley and North Coast (RMVPLN) of São Paulo, Brazil, in the COVID-19 context.

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Abstract

Background

The Corona Virus Disease 2019 (COVID-19) pandemic has forced the implementation of social distancing measures and the so-called lockdowns. The occasion resulted in a series of efforts to develop tools and methods for tracking people's mobility. Remote sensed nighttime data and *in situ* traffic radars are a viable option since they can provide spatially explicitly scientific data in near-real-time.

Objective

To evaluate the potential of nighttime remotely sensed data and traffic radar data on the provision of information about mobility patterns in the Metropolitan Region of the Paraíba Valley and North Coast of São Paulo (RMVPLN).

Methods

The study area is limited to the boundaries of the 39 municipalities of the RMVPLN. Remote sensed Nighttime Light (NTL) data for the period between 2013 and 2019 and traffic radar data from 2018 to 2020 were acquired. At the city level, Auto Regressive Integrated Moving Average was implemented to compare the expected trends in NTL levels based on precedent observations and the actual levels registered in the first months of the pandemic. At the roadway level, the monthly average NTL of roadways and control samples were compared to deepen the discussion on the use of NTL data to estimate the average volume of vehicles in a roadway at a certain period. At the roadway level still, traffic control data from 2018, 2019, and 2020 were analyzed to investigate the changes in the mobility driven by the sanitary measurements in the first epidemiological weeks.

Results

At the city level, there is a significant drop in the average NTL levels from the pandemic on. At the roadway level, the results indicate that comparing control samples radiance levels with the levels of an actual region of interest, is strongly recommended in greater scales, mainly in roadways with lesser infrastructure. Still, at the roadway level, it’s evident the reduction of vehicle flow because of the quarantine’s restrictions in all of the RMVPLN’s highways. This reduction was more incipient than another previous reduction caused by trucker's strike.

Final Remarks

At the city level, the monthly nighttime products are sensitive to changes in socioeconomic activities. To capture the observed changes in the traffic regime on a higher scale, monthly composites must first provide additional information regarding the quality and generation parameters of the monthly composites of nighttime lights.

1. Background

The first case of COVID-19 in Brazil was confirmed on 02/26/2020. Two weeks later, the Brazilian Ministry of Health started to guide the adoption of non-pharmacological measures (MS, 2020), largely dependent on the cooperation of the population. It is noteworthy that the crowding of people is a key factor for the spreading of the virus, which aggravates the pandemic in Brazil since 58% of its population (~ 123 million people) live in metropolitan regions (IBGE, 2019).

São Paulo is the most populous state in Brazil. Among the metropolitan regions of the State of São Paulo, it is found the Paraíba Valley and North Coast (RMVPLN). This region is intercepted by the Presidente Dutra Highway (BR116), which lay across the Metropolitan Regions of São Paulo (RMSP) and Rio de Janeiro (RMRJ). RMVPLN is an important route for the circulation of people and goods, although internally there are substantial socio-spatial heterogeneity of its 2.5 million inhabitants (GOMES et al., 2018). Due to the dispersion of COVID-19, the State of São Paulo enacted the general quarantine on 03/21/2020 to reduce the circulation of people. Characterizing and monitoring regional mobility patterns is fundamental to understand the spreading possibilities of COVID-19, to assess the impact of social distancing policies in the territory, and the definition of joint policies with a rapid response in coping with the disease. Despite the importance of this type of information, the availability of up-to-date data is a limiting factor, and it is necessary to explore new forms of mediation to characterize it.

Nightlight data have been used for showing how the pandemic impacted people daily lives and their activities in a broad variety of human settlements across the world (ANANDI & KIM, 2021; ELVIDGE et al., 2020; BEYER, FRANCO-BEDOYA, and GALDO, 2020). In such studies, the response in the territory to the lockdown or general quarantine measures adopted in different places is observed and has the potential to discuss aspects related to interregional mobility. In recent years, some studies have shown advances in the use of night light data as a basis for vehicle flow and traffic estimates (JECHOW & HÖLKER, 2020; CHANG et al., 2020; SHI et al., 2015). Despite efforts, monitoring road flows is still a major challenge (CHANG et al., 2020), especially with regard to the Brazilian reality. The regional particularities associated with urbanization and spatial organization of the territory are factors that hinder the replicability of such studies and increase the challenges in defining appropriate methodologies to capture regional diversity.

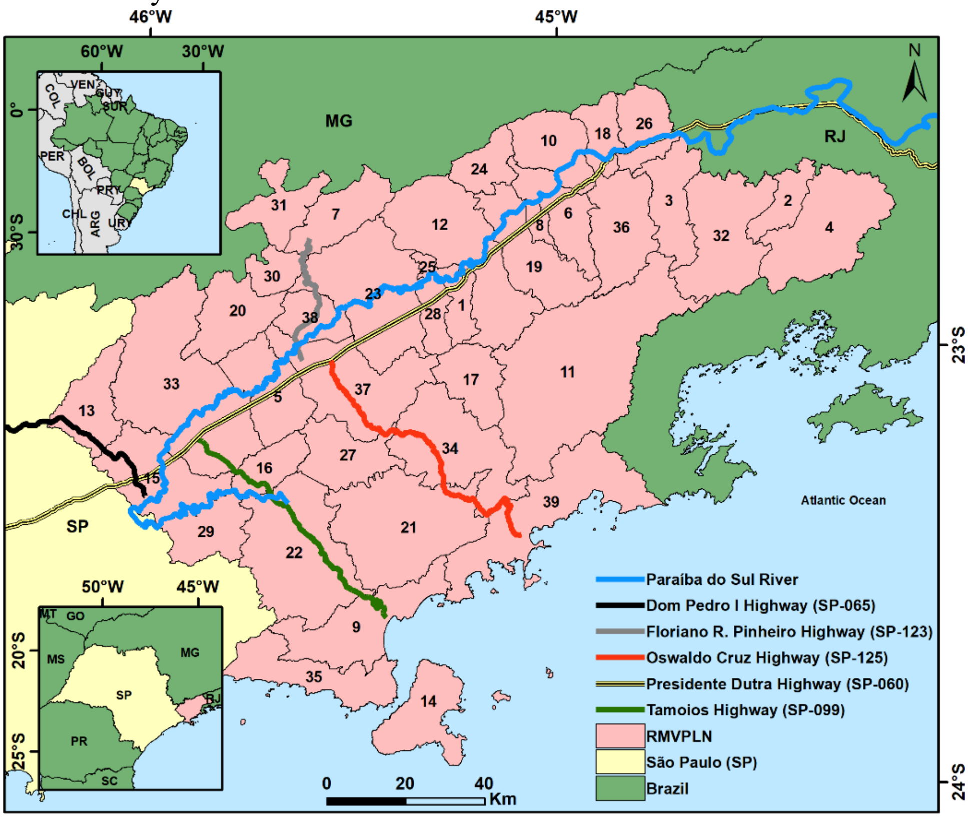
Primary or auxiliary data have been used as a way to build and/or evaluate methodologies based on data from night lights adapted to the regional reality, as discussed in Santos (2019) and Doria (2015). Information on the volume of road traffic, such as that available at the Department of Roads and Highways (DER –

Departamento de Estradas de Rodagem) of the State of São Paulo, can be useful to propose models for monitoring highways and analyzing the impact the mobility restrictions measurements from the COVID-19 pandemic on local and regional traffic patterns.

1.1 Area of study

The RMVPLN is located in the state of São Paulo, Brazil (Figure 1.1). The region is settled between the Metropolitan Region of São Paulo (RMSP) and Rio de Janeiro (RMRJ). Its geographical circumstances led to the expectation for a development system towards the exploitation of the distinct local advantages of its 39 municipalities. In reality, the lack of population, society, and political engagement resulted in sub-regional inequalities, without the consideration for the urban-regional needs as well (GOMES, RESCHILIAN, and UEHARA, 2018).

Figure 1.1 - Metropolitan Region of the Paraiba Valley and North Coast (RMVPLN) and main roadways' location.



1-Aparecida; 2-Arapeí; 3-Areias; 4-Bananal; 5-Caçapava; 6-Cachoeira Paulista; 7-Campos do Jordão; 8-Canas; 9-Caraguatatuba; 10-Cruzeiro; 11-Cunha; 12-Guaratinguetá; 13-Igaratá; 14-Ilhabela; 15-Jacareí; 16-Jambeiro; 17-Lagoinha; 18-Lavrinhas; 19-Lorena; 20-Monteiro Lobato; 21-Natividade da Serra; 22-Paraibuna; 23-Pindamonhangaba; 24-Piquete; 25-Potim; 26-Queluz; 27-Redenção da Serra; 28-Roseira; 29-Santa-Branca; 30-Santo Antônio do Pinhal; 31-São Bento do Sapucaí; 32-São José do Barreiro; 33-São José dos Campos; 34-São Luís do Paraitinga; 35-São Sebastião; 36-Silveiras; 37-Taubaté; 38-Tremembé; 39-Ubatuba.
Source: Produced by the authors.

Highways are the main source of inputs and production outlets in Brazil (CNT, 2019). Besides, the highways promote regional integration, as they are accessed by the inhabitants of the RMVPLN to achieve different purposes in different municipalities in which they reside, such as to work, and access to education and health services. Thus, RMVPLN comprises a highly connected system of municipalities.

In 2020 the population density of the RMVPLN was estimated as 181 person/km², or 2.928.345 inhabitants (IBGE, 2020), living in 39 municipalities with an average of approximately 415 km², over 16.178 km². Two major mobility patterns take place in the RMVPLN: the interregional displacements to work and study on a daily basis; and the intraregional fluxes, associated with daily commercial load transport and seasonal tourist movements, more intense on weekends, holidays, and vacations. From March 2020 onwards, the COVID-19 pandemic, along with its containment and control measures, changed this general mobility pattern in the RMVPLN. We hypothesize that NTL data can be useful as ancillary data to observe and monitor these changes.

1.2 Objectives

The general objective of this research activity is to assess the NTL monthly composite potential to register variations on the human mobility patterns caused by the 2020 COVID-19 pandemic. This objective unfolds in the following specific objectives:

a) Investigate the effects of the COVID-19 pandemic's mobility restrictions measurements over the nighttime lights time series (NTTS) at the municipal level;

b) Propose an adequate procedure to process and analyze VIIRS/DNB monthly composites when investigating mobility issues at the roadway level, considering standard pre-processing techniques;

c) Typify the different profiles of NTTS at the roadway level, accordingly to their nominal average radiance level, roadway basic infrastructure, and surrounding areas;

d) Identify regional mobility patterns and their differences induced by the COVID-19 pandemic based on field and ancillary measures. Road traffic data will compose a reference geographical database for this analysis.

2. METHODS ON NIGHTTIME DATA ACQUISITION AND PRE-PROCESSING PROCEDURE

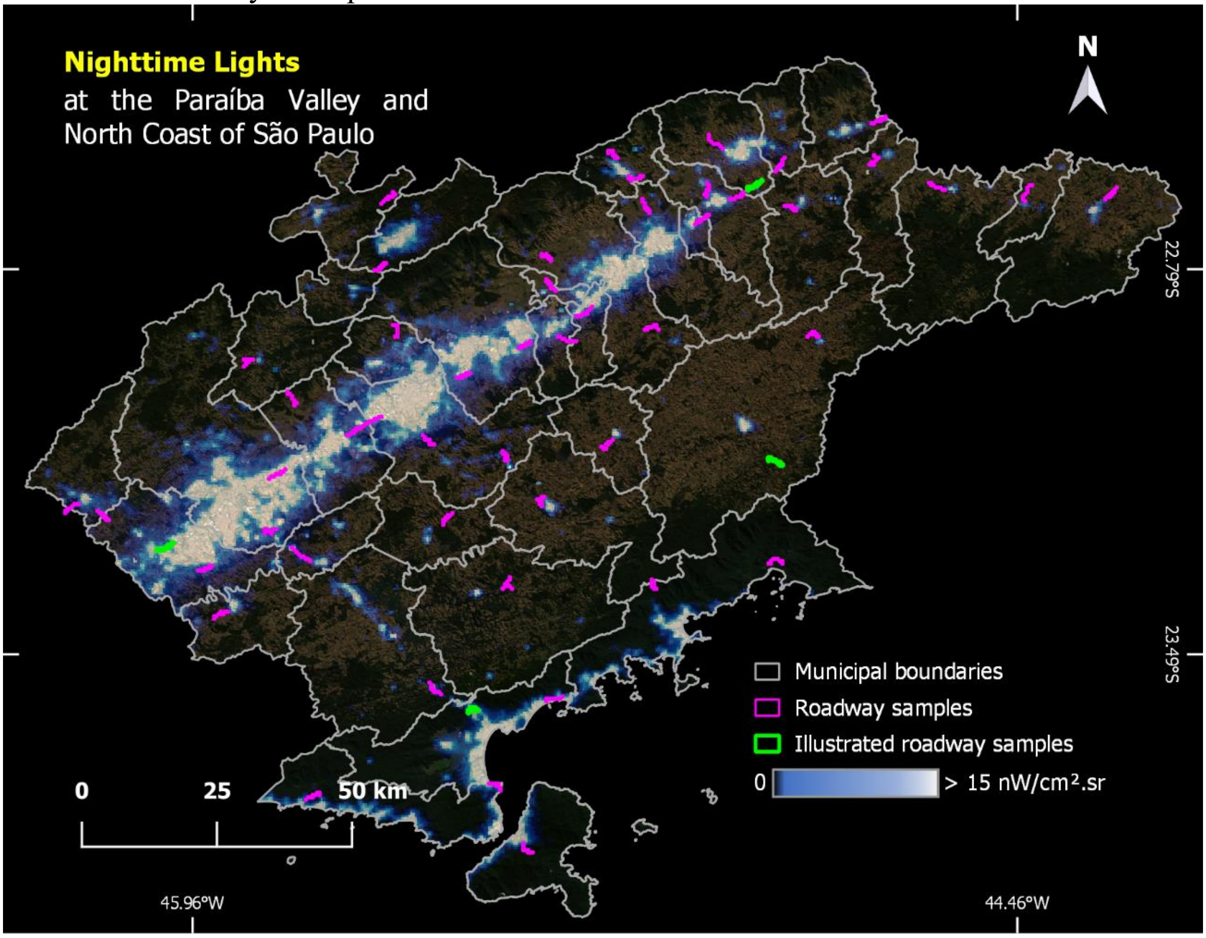
The geopolitical importance, geographical extension, and economic dynamics of the RMVPLN require spatial and temporal resolution as provided by VIIRS/DNB monthly composites. Daily images, besides cloud cover limitation, would require intense image pre-processing efforts, and generate excessive amounts of data. On the other hand, annual NTL composites would overcome these constraints, but also suppress the NTL variance associated with the eventual changes of seasonal mobility. Monthly composites can provide more detailed NTL information than their annual counterpart while still generalized enough to virtually guarantee their availability

The hypothesis under the analysis of the radiance values associated with roadways is that there should be a certain degree of correlation between the radiance level registered by the DNB sensors and the number of vehicles at a particular instant of time. Sample roadways samples were selected and characterized accordingly to the visual interpretation of high-resolution images from the BING Maps and Google Earth repositories. To reduce the contribution of the local background from roadways sections on the monthly average radiance from the monthly composites, an algorithm able to mine for spectrally unbiased background control samples is under development. Bragion et al. (2020) present details on the current status of this tool.

Monthly composites of NTL were made available by the Earth Observation Group, at https://eogdata.mines.edu/products/vnl. Although the monthly composites have advantages regarding their availability and temporal resolution, there are still issues that must be addressed. The monthly composite processing procedure favors the selection of pixels under low lunar radiance conditions and screens out pixels covered by clouds, stray light, and lighting. In this sense, high outliers caused by biomass burning and low radiance values associated with the local background radiance levels or power outages are still present in this product.

In the RMVPLN (Figure 2.1), high outliers can be observed due to occasional biomass burning and gas flares from industrial facilities. High outliers were suppressed through an upper threshold, estimated by using the average radiance value from the city center of the São Paulo city, the most populous city in the country (100 ηW/cm2.sr). For the analysis at the municipal level, the local background radiance level was empirically estimated as 1.5 ηW/cm2.sr, a value low enough to retain pixels associated with the city central area from the smaller towns in the region.

Figure 2.1 - Monthly Average Nighttime Lights from the Day-Night Band sensor (DNB/vcmcfg - Oct., 2019) at the Paraíba Valley and Noth Coast of São Paulo and location of the roadway's samples.



Illustrated roadways samples refer to samples which time series were illustrated in Section 3. At the background, Landsat 8 OLI RGB (Oct. 2020) true color composition, 0.636 - 0.673 µm (red), 0.533 - 0.590 µm (green) and 0.452 - 0.512 µm (blue).
Source: Produced by the authors.

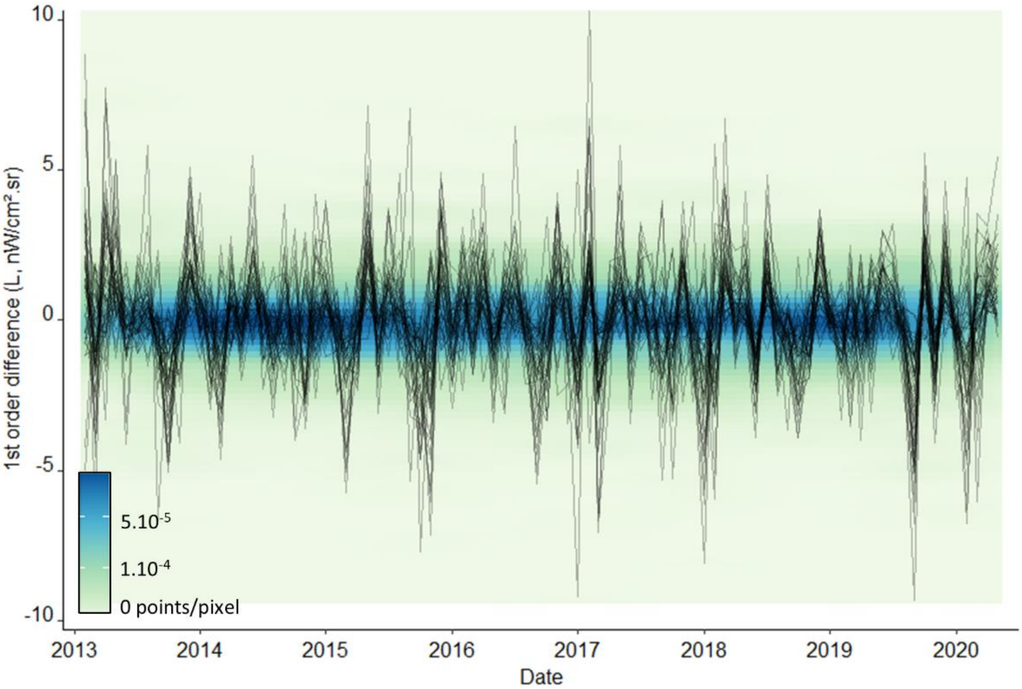
3. NIGHTTIME LIGHT DATA ANALYSIS

3.1 City level averaged radiance time series

An initial exploratory analysis assessed the potential of VIIRS/DNB time series to describe patterns and identify changes in NTL levels from the RMVPLN. We obtained NTL time series (NTTS) for all 39 RMVPLN municipalities (average radiance) from VIIRS/DNB monthly mosaic images, January 2013 to May 2020, taking as lit areas those pixels with radiance value higher than 1.5 ηW/cm².sr.

After removing the time series trend to observe seasonality, by calculating the first-order differences (Figure 3.1), the NTL time series showed to be highly correlated between RMVPLN municipalities (Table 3.1). Generally, the correlation values suggested four patterns of NTL time series in the RMVPLN, that can be associated with the geographical regions and spatial settlement arrangements. Taking a municipality as an example, the patterns are: 1) São José dos Campos (SJC) - intense industry activities and conurbations of cities centers; 2) São Sebastião (SSB) – coastal towns (North Coast); 3) Guaratinguetá (GUA) – along BR-101, in the circuit of religious tourism; 4) Monteiro Lobato (MLB) – agricultural and tourist municipalities in the mountain region of Serra da Mantiqueira.

Figure 3.1 - First-order differences of VIIRS/DNB monthly average radiance for the 39 municipalities of the RMVPLN.



Each black line represents a municipality time series of the average radiance 1st order difference.
Source: Produced by the authors.

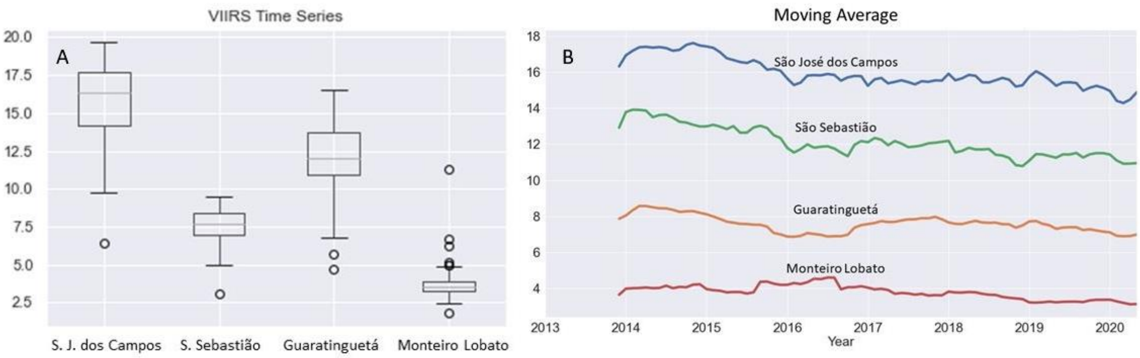
Table 3.1 - VIIRS/DNB monthly time series correlation between the average radiance at night for the 39 municipalities of the Metropolitan Region of Paraíba Valley and North Coast of São Paulo.

	APA	ARA	ARE	BAN	CAC	CPT	CDJ	CAN	CRG	CRU	CUN	GUA	IGA	IBL	JAC	JAM	LAG	LAV	LOR	MLB	NDS	PAR	PIN	PIQ	POT	QUE	RDS	ROS	STB	SAP	SBS	SJB	SJC	SLP	SSB	SIL	TAU	TER	UBA
APA	1.00	0.01	0.13	0.44	0.63	0.57	0.57	0.61	0.63	0.51	0.51	0.78	0.41	0.47	0.55	0.46	0.38	0.21	0.62	0.17	0.22	0.46	0.61	0.23	0.67	0.29	0.20	0.64	0.25	0.26	0.45	0.15	0.56	0.25	0.48	0.46	0.57	0.38	0.56
ARA	0.01	1.00	0.11	0.14	0.05	0.24	0.01	-0.10	0.07	0.32	0.13	0.12	-0.01	0.04	0.01	0.24	-0.03	0.43	0.19	-0.01	0.07	0.15	-0.01	0.41	0.01	0.32	0.18	0.06	0.10	0.09	0.14	0.27	0.11	0.11	0.14	0.29	0.09	0.21	0.19
ARE	0.13	0.11	1.00	0.12	0.24	0.28	0.00	0.01	0.07	0.13	0.15	0.20	0.28	0.09	0.42	0.08	0.15	0.28	0.11	0.06	0.06	0.08	0.04	0.40	0.24	0.34	0.00	0.15	0.25	0.11	0.03	0.18	0.25	0.23	0.06	0.21	0.26	0.13	0.02
BAN	0.44	0.14	0.12	1.00	0.37	0.20	0.27	0.35	0.44	0.41	0.50	0.35	0.27	0.46	0.33	0.34	0.45	0.30	0.26	0.28	0.33	0.43	0.30	0.06	0.23	0.28	0.04	0.25	0.08	0.18	0.22	0.25	0.27	0.15	0.36	0.23	0.30	0.27	0.35
CAC	0.63	0.05	0.24	0.37	1.00	0.51	0.56	0.50	0.71	0.49	0.70	0.65	0.60	0.59	0.74	0.71	0.28	0.22	0.54	0.17	0.29	0.57	0.77	0.28	0.67	0.39	0.35	0.75	0.44	0.26	0.37	0.16	0.85	0.54	0.62	0.29	0.80	0.65	0.63
CPT	0.57	0.24	0.28	0.20	0.51	1.00	0.25	0.50	0.45	0.64	0.36	0.71	0.33	0.38	0.42	0.52	0.16	0.52	0.60	0.00	0.21	0.40	0.46	0.47	0.38	0.53	0.43	0.51	0.34	0.43	0.47	0.19	0.51	0.47	0.43	0.41	0.51	0.33	0.51
CDJ	0.57	0.01	0.00	0.27	0.56	0.25	1.00	0.54	0.37	0.45	0.46	0.54	0.27	0.22	0.39	0.39	0.32	0.33	0.57	0.19	0.22	0.26	0.59	0.17	0.52	0.40	0.06	0.61	0.17	0.28	0.29	0.03	0.48	0.33	0.42	0.32	0.49	0.44	0.40
CAN	0.61	-0.10	0.01	0.35	0.50	0.50	0.54	1.00	0.48	0.63	0.48	0.73	0.47	0.42	0.53	0.48	0.28	0.34	0.70	0.19	0.19	0.38	0.51	0.28	0.48	0.44	0.27	0.55	0.27	0.26	0.43	0.07	0.51	0.38	0.43	0.33	0.46	0.27	0.42
CRG	0.63	0.07	0.07	0.44	0.71	0.45	0.37	0.48	1.00	0.40	0.67	0.63	0.53	0.76	0.68	0.62	0.37	0.13	0.41	0.09	0.27	0.70	0.68	0.19	0.54	0.23	0.23	0.57	0.46	0.20	0.42	0.15	0.65	0.29	0.80	0.36	0.66	0.48	0.79
CRU	0.51	0.32	0.13	0.41	0.49	0.64	0.45	0.63	0.40	1.00	0.47	0.70	0.39	0.37	0.31	0.60	0.13	0.65	0.69	0.16	0.25	0.34	0.43	0.47	0.31	0.72	0.46	0.52	0.29	0.37	0.53	0.27	0.47	0.35	0.45	0.48	0.44	0.40	0.42
CUN	0.51	0.13	0.15	0.50	0.70	0.36	0.46	0.48	0.67	0.47	1.00	0.57	0.55	0.60	0.62	0.61	0.40	0.24	0.50	0.27	0.32	0.41	0.61	0.20	0.54	0.29	0.27	0.62	0.37	0.25	0.35	0.22	0.69	0.33	0.59	0.32	0.58	0.36	0.59
GUA	0.78	0.12	0.20	0.35	0.65	0.71	0.54	0.73	0.63	0.70	0.57	1.00	0.55	0.46	0.61	0.61	0.30	0.41	0.83	0.14	0.21	0.40	0.65	0.41	0.64	0.47	0.38	0.67	0.48	0.31	0.55	0.21	0.70	0.46	0.57	0.46	0.63	0.44	0.60
IGA	0.41	-0.01	0.28	0.27	0.60	0.33	0.27	0.47	0.53	0.39	0.55	0.55	1.00	0.40	0.65	0.58	0.18	0.19	0.37	0.16	0.21	0.34	0.46	0.15	0.49	0.28	0.32	0.45	0.45	0.10	0.36	0.17	0.66	0.45	0.46	0.12	0.50	0.33	0.41
IBL	0.47	0.04	0.09	0.46	0.59	0.38	0.22	0.42	0.76	0.37	0.60	0.46	0.40	1.00	0.58	0.50	0.37	0.12	0.27	0.11	0.28	0.59	0.61	0.28	0.46	0.27	0.25	0.49	0.49	0.33	0.32	0.25	0.55	0.35	0.78	0.16	0.52	0.36	0.76
JAC	0.55	0.01	0.42	0.33	0.74	0.42	0.39	0.53	0.68	0.31	0.62	0.61	0.65	0.58	1.00	0.57	0.41	0.17	0.52	0.18	0.26	0.47	0.59	0.33	0.58	0.34	0.14	0.59	0.54	0.11	0.36	0.26	0.76	0.53	0.57	0.19	0.65	0.41	0.55
JAM	0.46	0.24	0.08	0.34	0.71	0.52	0.39	0.48	0.62	0.60	0.61	0.61	0.58	0.50	0.57	1.00	0.03	0.40	0.46	0.12	0.28	0.47	0.57	0.20	0.40	0.37	0.42	0.53	0.48	0.19	0.45	0.17	0.69	0.53	0.58	0.26	0.64	0.42	0.58
LAG	0.38	-0.03	0.15	0.45	0.28	0.16	0.32	0.28	0.37	0.13	0.40	0.30	0.18	0.37	0.41	0.03	1.00	0.14	0.25	0.00	0.02	0.35	0.37	0.11	0.30	0.09	-0.16	0.25	0.03	0.12	0.22	0.04	0.13	0.27	0.30	0.13	0.28	0.30	0.28
LAV	0.21	0.43	0.28	0.30	0.22	0.52	0.33	0.34	0.13	0.65	0.24	0.41	0.19	0.12	0.17	0.40	0.14	1.00	0.48	0.14	0.22	0.19	0.17	0.40	0.04	0.65	0.24	0.27	0.16	0.38	0.36	0.17	0.16	0.32	0.26	0.36	0.26	0.31	0.28
LOR	0.62	0.19	0.11	0.26	0.54	0.60	0.57	0.70	0.41	0.69	0.50	0.83	0.37	0.27	0.52	0.46	0.25	0.48	1.00	0.22	0.30	0.31	0.56	0.40	0.57	0.54	0.33	0.69	0.39	0.33	0.42	0.20	0.55	0.41	0.41	0.37	0.54	0.48	0.47
MLB	0.17	-0.01	0.06	0.28	0.17	0.00	0.19	0.19	0.09	0.16	0.27	0.14	0.16	0.11	0.18	0.12	0.00	0.14	0.22	1.00	0.47	0.00	0.10	0.09	0.14	0.18	0.04	0.16	0.16	0.12	0.18	-0.03	0.22	0.11	0.14	0.04	0.19	0.20	0.10
NDS	0.22	0.07	0.06	0.33	0.29	0.21	0.22	0.19	0.27	0.25	0.32	0.21	0.21	0.28	0.26	0.28	0.02	0.22	0.30	0.47	1.00	0.35	0.30	0.19	0.21	0.19	0.37	0.24	0.20	0.23	0.13	-0.05	0.27	0.18	0.22	0.18	0.23	0.35	0.43
PAR	0.46	0.15	0.08	0.43	0.57	0.40	0.26	0.38	0.70	0.34	0.41	0.40	0.34	0.59	0.47	0.47	0.35	0.19	0.31	0.00	0.35	1.00	0.52	0.22	0.45	0.23	0.21	0.41	0.38	0.39	0.37	0.05	0.42	0.32	0.61	0.42	0.56	0.52	0.63
PIN	0.61	-0.01	0.04	0.30	0.77	0.46	0.59	0.51	0.68	0.43	0.61	0.65	0.46	0.61	0.59	0.57	0.37	0.17	0.56	0.10	0.30	0.52	1.00	0.28	0.72	0.29	0.24	0.80	0.51	0.32	0.28	0.15	0.71	0.54	0.60	0.17	0.81	0.70	0.69
PIQ	0.23	0.41	0.40	0.06	0.28	0.47	0.17	0.28	0.19	0.47	0.20	0.41	0.15	0.28	0.33	0.20	0.11	0.40	0.40	0.09	0.19	0.22	0.28	1.00	0.34	0.58	0.23	0.36	0.36	0.20	0.15	0.26	0.32	0.33	0.31	0.36	0.27	0.36	0.26
POT	0.67	0.01	0.24	0.23	0.67	0.38	0.52	0.48	0.54	0.31	0.54	0.64	0.49	0.46	0.58	0.40	0.30	0.04	0.57	0.14	0.21	0.45	0.72	0.34	1.00	0.18	0.14	0.72	0.39	0.22	0.17	0.02	0.67	0.39	0.41	0.26	0.62	0.49	0.49
QUE	0.29	0.32	0.34	0.28	0.39	0.53	0.40	0.44	0.23	0.72	0.29	0.47	0.28	0.27	0.34	0.37	0.09	0.65	0.54	0.18	0.19	0.23	0.29	0.58	0.18	1.00	0.18	0.38	0.32	0.42	0.37	0.33	0.37	0.33	0.40	0.34	0.39	0.43	0.35
RDS	0.20	0.18	0.00	0.04	0.35	0.43	0.06	0.27	0.23	0.46	0.27	0.38	0.32	0.25	0.14	0.42	-0.16	0.24	0.33	0.04	0.37	0.21	0.24	0.23	0.14	0.18	1.00	0.29	0.24	0.09	0.32	0.05	0.42	0.19	0.19	0.27	0.24	0.18	0.31
ROS	0.64	0.06	0.15	0.25	0.75	0.51	0.61	0.55	0.57	0.52	0.62	0.67	0.45	0.49	0.59	0.53	0.25	0.27	0.69	0.16	0.24	0.41	0.80	0.36	0.72	0.38	0.29	1.00	0.45	0.28	0.30	0.19	0.72	0.36	0.47	0.29	0.70	0.56	0.55
STB	0.25	0.10	0.25	0.08	0.44	0.34	0.17	0.27	0.46	0.29	0.37	0.48	0.45	0.49	0.54	0.48	0.03	0.16	0.39	0.16	0.20	0.38	0.51	0.36	0.39	0.32	0.24	0.45	1.00	0.30	0.41	0.31	0.57	0.34	0.56	0.16	0.58	0.39	0.42
SAP	0.26	0.09	0.11	0.18	0.26	0.43	0.28	0.26	0.20	0.37	0.25	0.31	0.10	0.33	0.11	0.19	0.12	0.38	0.33	0.12	0.23	0.39	0.32	0.20	0.22	0.42	0.09	0.28	0.30	1.00	0.33	0.22	0.23	0.21	0.35	0.26	0.33	0.34	0.35
SBS	0.45	0.14	0.03	0.22	0.37	0.47	0.29	0.43	0.42	0.53	0.35	0.55	0.36	0.32	0.36	0.45	0.22	0.36	0.42	0.18	0.13	0.37	0.28	0.15	0.17	0.37	0.32	0.30	0.41	0.33	1.00	0.22	0.38	0.16	0.48	0.31	0.44	0.18	0.35
SJB	0.15	0.27	0.18	0.25	0.16	0.19	0.03	0.07	0.15	0.27	0.22	0.21	0.17	0.25	0.26	0.17	0.04	0.17	0.20	-0.03	-0.05	0.05	0.15	0.26	0.02	0.33	0.05	0.19	0.31	0.22	0.22	1.00	0.24	0.19	0.17	0.05	0.05	0.05	0.13
SJC	0.56	0.11	0.25	0.27	0.85	0.51	0.48	0.51	0.65	0.47	0.69	0.70	0.66	0.55	0.76	0.69	0.13	0.16	0.55	0.22	0.27	0.42	0.71	0.32	0.67	0.37	0.42	0.72	0.57	0.23	0.38	0.24	1.00	0.52	0.56	0.27	0.72	0.49	0.55
SLP	0.25	0.11	0.23	0.15	0.54	0.47	0.33	0.38	0.29	0.35	0.33	0.46	0.45	0.35	0.53	0.53	0.27	0.32	0.41	0.11	0.18	0.32	0.54	0.33	0.39	0.33	0.19	0.36	0.34	0.21	0.16	0.19	0.52	1.00	0.39	-0.02	0.50	0.47	0.42
SSB	0.48	0.14	0.06	0.36	0.62	0.43	0.42	0.43	0.80	0.45	0.59	0.57	0.46	0.78	0.57	0.58	0.30	0.26	0.41	0.14	0.22	0.61	0.60	0.31	0.41	0.40	0.19	0.47	0.56	0.35	0.48	0.17	0.56	0.39	1.00	0.25	0.65	0.47	0.76
SIL	0.46	0.29	0.21	0.23	0.29	0.41	0.32	0.33	0.36	0.48	0.32	0.46	0.12	0.16	0.19	0.26	0.13	0.36	0.37	0.04	0.18	0.42	0.17	0.36	0.26	0.34	0.27	0.29	0.16	0.26	0.31	0.05	0.27	-0.02	0.25	1.00	0.26	0.19	0.29
TAU	0.57	0.09	0.26	0.30	0.80	0.51	0.49	0.46	0.66	0.44	0.58	0.63	0.50	0.52	0.65	0.64	0.28	0.26	0.54	0.19	0.23	0.56	0.81	0.27	0.62	0.39	0.24	0.70	0.58	0.33	0.44	0.05	0.72	0.50	0.65	0.26	1.00	0.74	0.62
TER	0.38	0.21	0.13	0.27	0.65	0.33	0.44	0.27	0.48	0.40	0.36	0.44	0.33	0.36	0.41	0.42	0.30	0.31	0.48	0.20	0.35	0.52	0.70	0.36	0.49	0.43	0.18	0.56	0.39	0.34	0.18	0.05	0.49	0.47	0.47	0.19	0.74	1.00	0.49
UBA	0.56	0.19	0.02	0.35	0.63	0.51	0.40	0.42	0.79	0.42	0.59	0.60	0.41	0.76	0.55	0.58	0.28	0.28	0.47	0.10	0.43	0.63	0.69	0.26	0.49	0.35	0.31	0.55	0.42	0.35	0.35	0.13	0.55	0.42	0.76	0.29	0.62	0.49	1.00

Source: Produced by the authors.

The box plots of the original values of NTL time series, and the moving average plot (Figure 3.2) describes these four regional patterns. There are evident differences in the distribution of NTL average values in the time series, both in the statistic description of its median and quartile values, and in the moving average intensity values and evolution. In other words, further and detailed researches about NTL time series in the RMVPLN needs to take into account not only the local correlation but the regional differences as well.

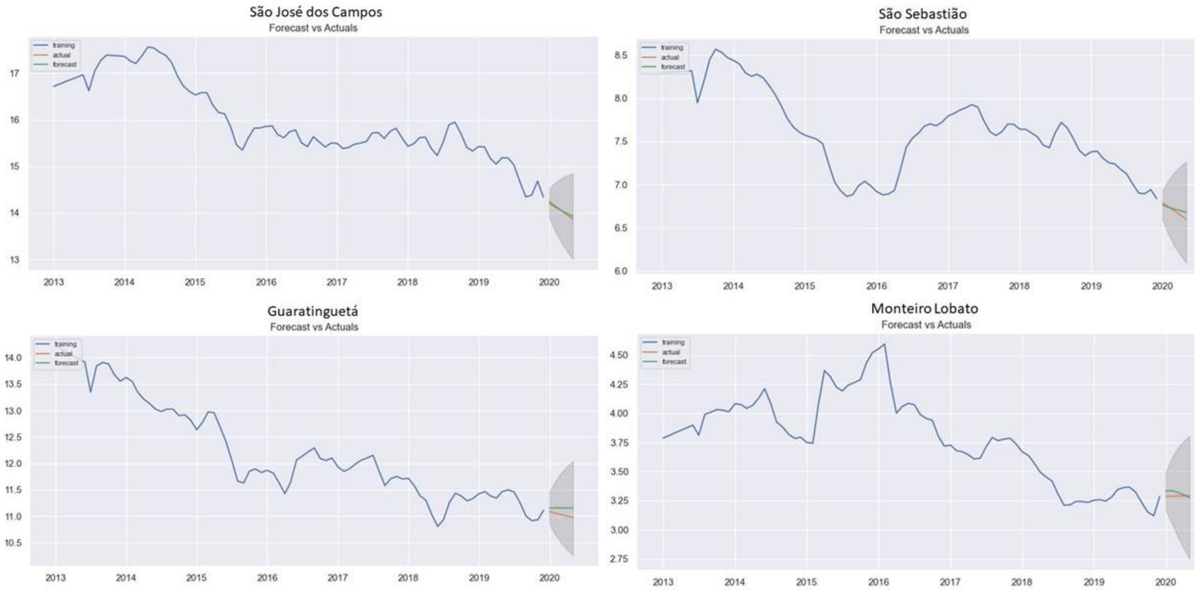
Figure 3.2 - General patterns of NTL time series in the Metropolitan Region of Paraiba Valley and North Coast of São Paulo.



A) Box plot of VIIRS/DNB monthly average radiance, and B) Moving average for representative municipalities - São José dos Campos, São Sebastião, Guaratinguetá, and Monteiro Lobato.
Source: Produced by the authors.

To investigate if the lockdown strategy for the COVID-19 could reflect in changes in NTL patterns by the reduction of human activity and traffic, we procedure a modeling exercise to forecast NTL radiance values for 2020 months. The exercise was based on the time series modeling by the Auto Regressive Integrated Moving Average – ARIMA, from 2013 to 2019 (Figure 3.3). The results showed that the actual NTL values (orange lines in Figure 3.3) for 2020 months (January to May) were lower than the forecasted values (green lines in Figure 3.3), with 95% of confidence, based on the time series modeling (blue lines in Figure 3.3), for the same previous four municipalities that represent the NTL patterns in the RMVPLN. Even though more specific modeling and analysis are necessary, there are evidences that time series are useful to identify changes in the NTL patterns, and it could be useful to better explore NTL emission as a proxy of human activity in the RMVPLN.

Figure 3.3 - Actual (orange) and forecasted (green) VIIRS/DNB monthly average radiance 2020 values based on ARIMA model trained with 2013 to 2019 monthly time series: A) São José dos Campos; B) São Sebastião; C) Guaratinguetá; and D) Monteiro Lobato.



Source: produced by the Authors.

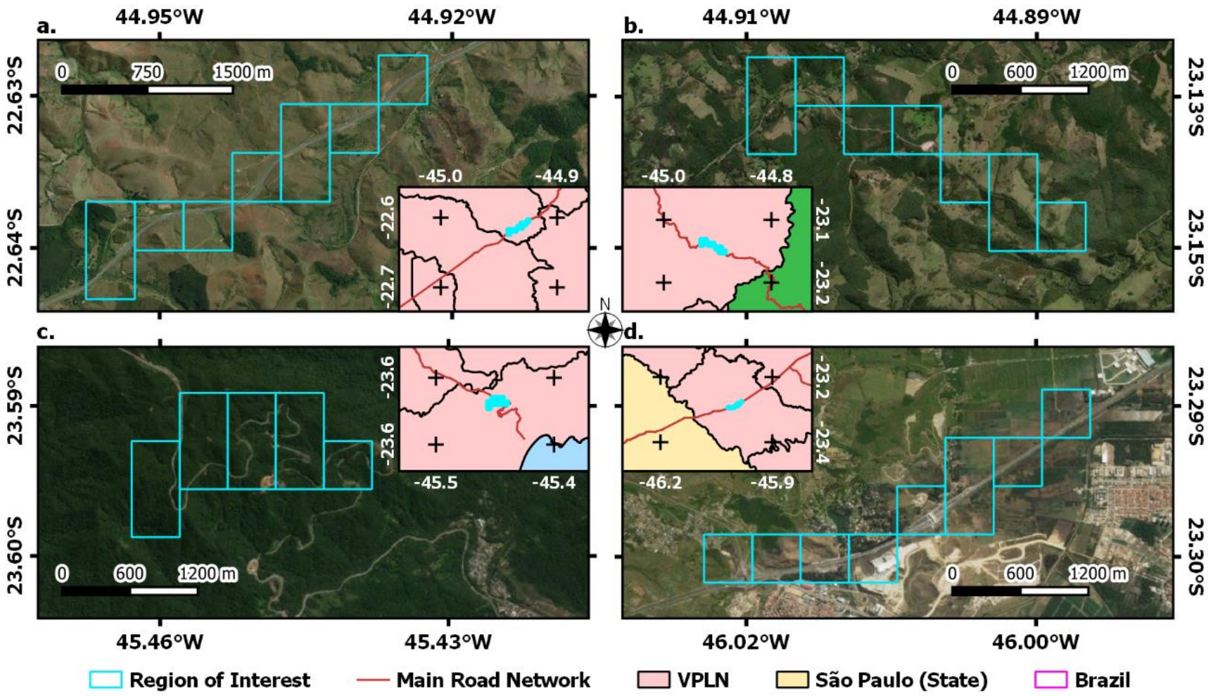
3.2 Roadway level averaged radiance times series

The identification of control samples allows the estimation of a nominal background radiance value accordingly to the reflectance values from the DNB's range and the period of the year (BRAGION et al., 2020). The method potentially reduces the contribution of seasonal changes of the albedo and hardly predictable changes in land cover characteristics to the radiance values registered by the DNB. Thus, by assessing the expected radiance in pseudo-unlit areas, variations of the

NTTS profile and trend shifts should be more confidentially approached. The profile of NTTS from roadways and their respective control samples provides some insights into the role of NTL to estimate traffic regime changes and its limitations.

At the roadway level, the specificities of each roadway have a higher influence on the NTTS general profile and trend. Before concluding the NTTS themselves, we first attempted to proceed with an intercomparison of the control samples' and roadways' NTTS. An initial exploratory analysis suggests that it is possible to distinguish between four different types of NTTS: a) NTTS of roadways with similar low radiance values and profile of the control samples (Figure 3.4b. and Figure 3.5a.); b) NTTS of roadways that are sufficiently high to be distinguishable from the control samples and, when their control sample radiance value is subtracted, there is a major shift on the NTTS aspect (Figure 3.4a. and Figure 3.5b.); c) NTTS of roadways that are high enough to not be influenced by the subtraction of the control sample's NTTS (Figure 3.4d. and Figure 3.5c.) and; d) NTTS of roadways that have major changes in their baselines, very likely due to improvements to the roadways' infrastructure (Figure 3.4c and Figure 3.5d).

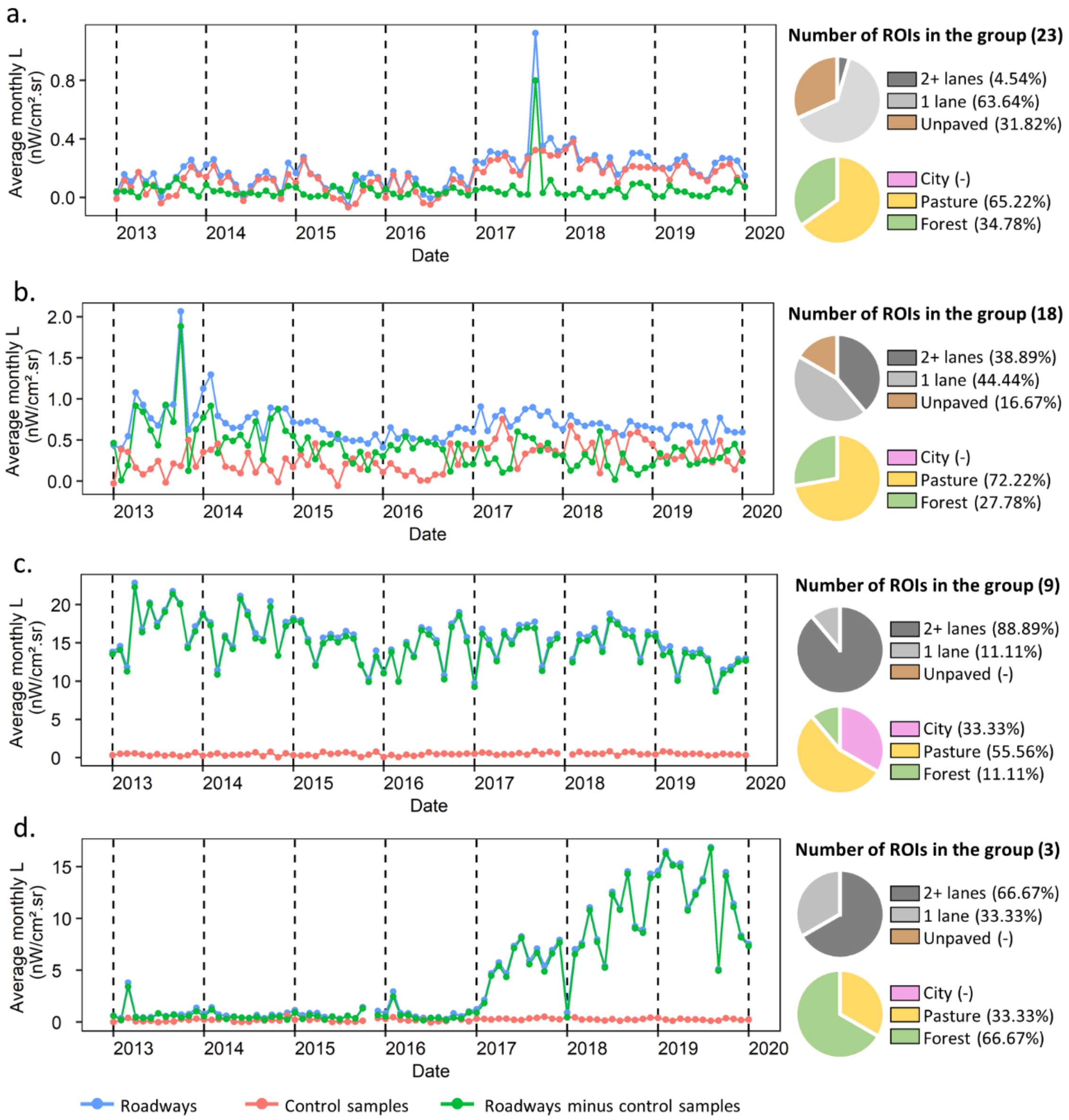
Figure 3.4 - Location of the samples of roadways (namely regions of interest - ROIs) described in the text. The exemplified samples represent the four proposed patterns of NTTS in the RMVPLN, regarding the relation of the control samples and the ROIs time series.



Source: Produced by the authors.

Roadways with NTTS low baselines, somewhere between 0 and 1.5 $\eta W/cm^2.sr$, are found exclusively in rural areas, either in forest or pasture surroundings (Figure 3.4b. and Figure 3.5a.). Although most of them are one-lane paved roads (65%), this type of NTTS is frequently associated with unpaved roads as well (35%). In this case, the similar profile and baseline of the NTTS from control samples and roadways are likely due to a low traffic regime and the lack of roadhouses at the roads' margins.

Figure 3.5 - Time series of nighttime light data (Average monthly Radiance - L) from roadways samples, namely ROIs (blue lines), control samples (red lines) and their difference (green lines); and distribution of the roadway samples, accordingly to their time series profiles, characteristics, and surroundings characteristics.



Source: produced by the authors.

A few roadways presented a similar average radiance baseline of the aforementioned NTTS, although their profile and trends are distinguishable from their control samples (Figure 3.4a. and Figure 3.5b.). In these cases, it is possible that other factors are contributing to the radiance levels detected by the DNB sensors and the subtraction of the control samples average radiance levels from the ROI's average radiance levels plays a major role in the analysis of the NTTS. Monthly average radiance levels from those NTTS ranges from 0 to 6 ηW/cm².sr. The roadways are mostly paved (89%), roughly equally divided in one-lane roadways (44%) and two-lane or more roadways (39%). Like the Roadways with NTTS low baselines, they are all found in rural surroundings, either forest (28%) or pasture (72%).

Another common NTTS profile corresponds to the ones with monthly radiance values high enough to suffer a minor influence from the subtraction of the average radiance values from control samples since there are no changes on the overall trend of the NTTS after the operation (Figure 3.4d. and Figure 3.5c.). Still, the comparison of the control samples' NTTS and the roadways' NTTS is useful to better judge if the variations of monthly average radiance values are higher than expected by chance or due to environmental seasonality. In this case, roadways are exclusively paved, mainly two-lanes or more (89% of the NTTS). All the roadways in the urban perimeter are found in this profile, something to be considered when analyzing the NTTS, since roadways' NTTS in urban perimeters are more subject to being influenced by nightlight infrastructure of nearby settlements. A greater slice of the NTTS is also found in pasture environments (56%) followed by forest (11%).

Finally, three NTTS of roadways noticeable by a very specific characteristic: low radiance values before the period between 2016 and 2017, followed by a sudden increase of the monthly average radiance (Figure 3.4c and Figure 3.5d). Those roadways are all paved, mostly one-lane (2/3), and can be found in forest surroundings (2/3). A close inspection revealed that they are all associated with the Tamoios Highway (SP-099), which has undergone improvements on its infrastructure during this period. In all three cases, the NTTS of the roadways has an average radiance baseline between 0 and 2 ηW/cm².sr. After the improvements, their nominal average radiance ranges from 3 to 9 ηW/cm².sr. Giving that the roadways were preferred selected in sites with a low contribution of light sources on the surroundings areas, it is safe to assume that the increase of the monthly average radiance values occurred due to the intensification of the local traffic patterns.

After comparing the NTTS from control samples and roadways, there is enough evidence to be optimistic about the use of NTL data to acquire traffic flow information. Firstly, monthly radiance levels of roadways are generally lower in unpaved or one-lane paved roadways, and higher in two-lane roadways. Secondly, roadways in urban surroundings are the ones with greater monthly average radiance, while roadways in forest or pasture surroundings are expected to have lower values. Thirdly, it is clear that improvements in the roadway system, such as roadways duplication, can change drastically the monthly averaged radiance levels. In both second and third cases, it is not possible yet to conclude if this is a result of a higher traffic regime or the higher number of exogenous sources of light.

These observations result in further questions, such as at what level the presence of exterior light infrastructure can interfere in the detection and estimation of the number of vehicles in a certain road section; and what levels of changes are sufficiently high to determine if there was a significant change in the traffic regime, accordingly to the NTL data. A more complex task that must be addressed in the future is the image/light sources acquisition geometry, which might play a crucial role in the sensibility of the DNB to vehicle lights. In this report, we mostly approached issues related to methods on how to better distinguish completely unlit roadways (radiance levels not different from spectrally similar unlit areas) from roadways that are lit by anthropogenic light sources.

It is reasonable to assume that, in order to evaluate the association of NTL with traffic data, one must first compare the correlation of traffic-driven metrics and the NTL data itself. Comparing the average number of vehicles in a roadway section at a given instant with its average radiance levels at night could help to understand the aforementioned questions. Nevertheless, the analysis of traffic data also requires a certain amount of effort, mainly due to its granularity and sensibility to local factors, namely a dynamic process.

4. METHODS ON ANALYZING TRAFFIC CONTROL DATA

At the same time, a second database from the DER of the State of São Paulo, was explored to assess the response in the local circulation of social distance measures. The number of vehicles was daily count by equipment installed on different highways of the RMVPLN. We analyzed data for the years 2018, 2019, and 2020. The data were aggregated by type of vehicle (passenger car, commercial, motorcycle, and total) totaling daily vehicles circulating at a given point on each highway. For the equipment that records daily the passage of vehicles in two directions, the original data were divided by two, composing a single daily observation. For the equipment that registered the passage in only one direction, there were no changes. These procedures were necessary for data comparability.

We worked with epidemiological weeks (Table 2) to enable data comparison with COVID-19 occurrence. The State of São Paulo enacted the general quarantine on 03/21/2020, at the end of week 12. From daily records, the weekly averages of vehicles registered by each equipment were calculated (from here on - average of vehicles). Some considerations about this database: only days with data available were considered; we excluded outliers - the highest and the lowest 1% daily values; and the first three weeks of 2018 and 2019 were disregarded because of the lack of data for this period in 2020.

Table 4.1 - Reference dates for epidemiological.

Year	Epidemiological week 4	Epidemiological week 24
2020	01/19 to 01/25	06/07 to 06/13
2019	01/20 to 01/26	06/09 to 06/15
2018	01/21 to 01/27	06/10 to 06/16

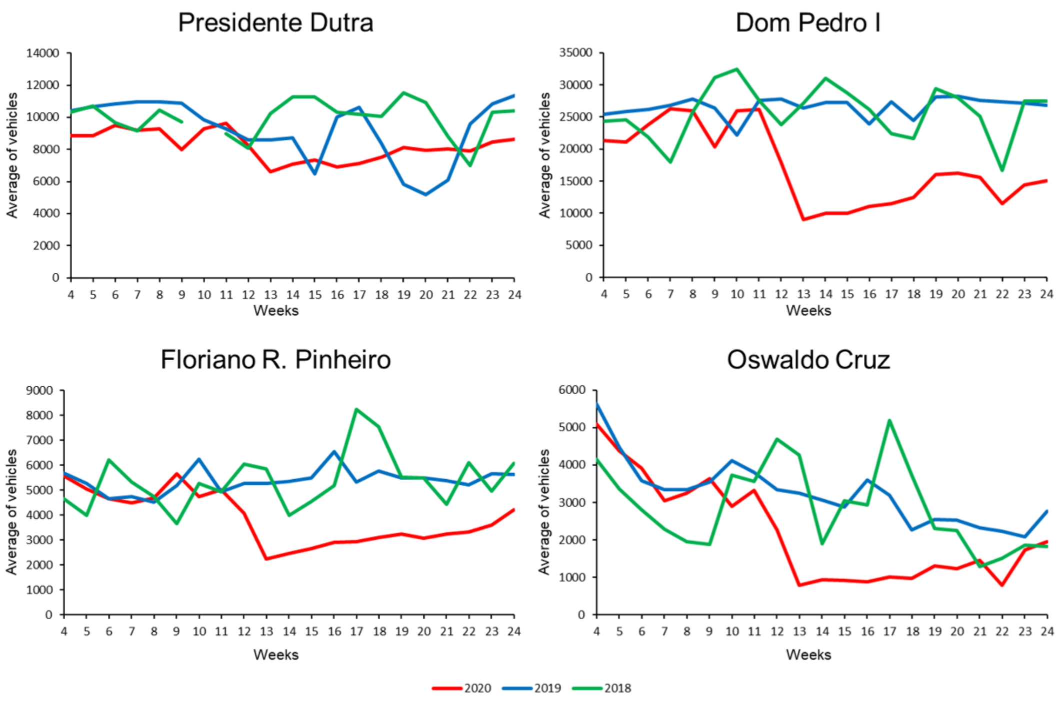
Source: Produced by the authors.

We selected data from devices installed at four different highways that are relevant for the traffic of people and goods in the region, and representing different contexts of regional integration: a) SP060-RAD-004, located at Km 4 of the Presidente Dutra Highway (SP-060); b) SP065-RAD-002, located at Km 2 of the Dom Pedro I Highway (SP-065); c) SP123-RAD-011, located at Km 11 of the Floriano R. Pinheiro Highway (SP-123), and; d) SP125-RAD-088 located at Km 88 of the Oswaldo Cruz Highway (SP-125). The exploratory analysis proceeded from graphs for the selected period.

4.1 Traffic control data analysis

The general quarantine decreed for the state of São Paulo included the suspension of tourist, economic, student, and labor activities that caused agglomeration. Notwithstanding the inconstant behavior of the vehicles flow over the years (Figure 4.1), it is evident a differentiated behavior from the 13th epidemiological week of 2020, presenting an expressive reduction in the weekly averages of vehicles. However, there is a trend of gradual increase along with the quarantine. This traffic reduction in the regional roads is corroborated by data from the Intelligent Monitoring System of the Government of São Paulo. On São José dos Campos, after the quarantine's start, the isolation index flow between 40 and 60% (State of São Paulo, 2021).

Figure 4.1 - Weekly average of vehicles, per epidemiological week, from 2018 to 2020.



Source: Produced by the authors.

Equipment allocated on the Presidente Dutra Highway (SP-060) is located in the municipality of Queluz, very close to the state boundary between São Paulo and Rio de Janeiro. There was a similar vehicle average in the first weeks of 2018 and 2020. Then, from week 13, there was a reduction of 22% when compared with the previous week, which can be due to the measures to contain the COVID-19 pandemic in 2020. Another notable event was the truckers' strike between weeks 21 and 23 in 2018.

Equipment allocated on the Dom Pedro I Highway (SP-065) is located in the municipality of Jacareí, at the beginning of the highway, connecting the RMVPLN to the Campinas Metropolitan Region. At this point, the reduction in vehicle traffic was evident during the pandemic, especially in the months of March and April. The weekly average of vehicles decreased from 20.000 to 10.000 (50%) after week 12.

The equipment on the Floriano R. Pinheiro Highway (SP-123) is located in the municipality of Taubaté, on the Floriano Rodrigues Pinheiro highway, connecting Taubaté to Campos do Jordão. This highway is widely used for winter tourism, which occurs from June (~week 23) to September. It is observed that the average of vehicles decreased in 2020 compared to the other years. Approximately, the average number of vehicles in week 13 of 2020 was 2,000, which represents a third when compared to the same week of 2019, which was 6,000. The equipment on the Oswaldo Cruz highway (SP-125) is located in the municipality of Ubatuba. This highway connects the Presidente Dutra Highway to the coastal municipalities, and its traffic is associated with cargo transportation and mainly with summer tourism. As winter approaches, there is a reduction in the average of vehicles in all years. However, in 2020, this reduction was more accentuated, approximately 75% in week 13 compared to 2019.

The distribution of holidays affects the behavior of vehicle traffic measures. Peaks in the weekly averages of vehicles are perceived in weeks with long holidays in RMVPLN's highways, as they are access routes to tourist municipalities. Carnival Tuesday and Easter Sunday were, respectively, in weeks 7 and 14 in 2018, 10 and 17 in 2019; and 9 and 16 in 2020. The four pieces of equipment registered an increase in the number of vehicles in the weeks close to Carnival and Easter in 2019. In 2020, the increase occurred similarly in the weeks close to Carnival, however, it was less pronounced during Easter, when quarantine had already been established.

The Tiradentes holidays (04/21) and the International Worker Day (05/01), occurred, respectively, in the weeks 16 and 18 of 2018; 17 and 18 of 2019; and 17 and 18 of 2020. There was a marked increase in the average of vehicles in 2018 and 2019 in these weeks, mainly in the equipment on the Floriano R. Pinheiro and Oswaldo Cruz highways. This is justified since such equipment is installed on highways that provide access to tourist municipalities.

Tiradentes holiday and Easter Sunday occurred on the same day in 2019, resulting in only one peak in 2019 compared to 2018. Thus, the curves for 2019 vehicle averages were less irregular than those for 2018 curves for the same period. It is also noticed that, due to quarantine, in 2020, vehicle averages were much lower than in previous years during these holidays.

In 2018, between the 21st and the 23rd week of 2018, there was a general strike by truck drivers in Brazil. The shortage of fuels and the closing of some lanes in this period reduced the average of vehicles. It is clear, however, that the impact of the 2020 pandemic on vehicle circulation was greater than that of the truckers' strike in 2018.

The volumetric counting of vehicles, as presented here, enables characterizing the regional circulation in the highways and the effects of events and holidays throughout the year. The COVID-19 pandemic can be considered as an event since the social distance measures adopted in the state coincided with the reduction of the average number of vehicles circulating on the highways. Although punctually, the radar data recorded a reduction in the flow of vehicles circulating on the highways, due to COVID-19.

5. FINAL REMARKS

The use of ancillary data has been put in evidence in the track of human mobility in the context of COVID-19. A long-time growing number of papers have established a close relation between nighttime lights and socioeconomic activities around the world. Overall, the correlation between nighttime lights derived metrics and socioeconomic variables is not generalizable and dependent on regional economic, political, and infrastructure factors.

At the municipal level, nighttime metrics were sensible to the restrictions of mobility caused by the COVID-19 pandemic, independent of the regional pattern. Considering the technical aspects of the VIIRS instrument, specifically the local crossing time, the traffic regime is one of the most obvious daily life aspects that could cause such difference in the expected and observed radiance levels at night. The designed algorithm showed that some roadways' radiance levels at night are not that different from pseudo-unlit samples with a similar spectral response. On the other hand, some roadways have enough high basal radiance level at night that the use of control samples might be useful only to access if the magnitude of the differences between distinct periods is different from the ones naturally expected.

At the roadway level, some specificities must be addressed. Firstly, the analysis of traffic data showed that the road traffic in four main roadways in the RMVPLN suffered a reduction after the pandemic-related mobility restrictions. Moreover, depending on the roadway, these reductions are uneven and, in previous years, the curves have different peaks associated with holidays. These observations indicate that this type of analysis is better suited if the time units and scales associated with holidays are considered, once they are the main drivers of the floating number of vehicles registered in the same month but different weeks.

This holiday-driven dynamic behavior of the traffic imposes limitations to the traffic volume estimation from NTL monthly composites. Monthly composites of nighttime lights from the DNB sensor are products yet to be fully exploited, but some major changes on the product distribution would be welcome. Regarding the context of this exercise and considering that just a few days of the month end up in a monthly composite, either due to bad pixels or cloud cover, it would be highly beneficial to the research community if additional quality information was provided in the monthly composites: a) the specific dates of acquisition of the pixels that were processed and ended up in the monthly composites; b) further supplementary data that could help to propose radiative transfer models adapted to the nightscape scenario, manly aspects of the moon-earth-instrument-light source geometry and; c) the original values of the pixels' radiances registered by the DNB and filtered in by the EOG's algorithm, so the research community can decide what metric is supposed to generate the monthly or even weekly composite.

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