CONTRIBUTION OF DAILY GENERAL MOBILITY TO PM10 CONCENTRATION DEVELOPMENT IN SISAK-MOSLAVINA COUNTY, CROATIA DURING THE COVID-19 PANDEMIC IN 2020

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Resume

Carbon and pollutant emissions drive climate change and affect health and daily life. The Covid-19 pandemic created an unprecedented opportunity to understanding the impact of carbon and pollutant emission. In this paper were identified Telecommunications records-derived general mobility indices as contributors to the PM10 pollutant concentration development in industry-intensive Sisak-Moslavina County, Croatia, during the Covid-19 outbreak in 2020. Time-series of daily mean PM10 concentrations and mobility changes indicators are analysed for their statistical properties identification, decomposed, and the decomposing components examined for association using Tailored software developed in the R environment for statistical computing.

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1 Introduction

Modern technology-based civilisation creates a considerable impact on environment and climate through a vast range of socio-economic activities. Carbon and pollutant emissions affect drive climate change and affect health and daily life, thus calling for monitoring and suitable management, as well as need for a change in socio-economic process to curb the adversarial effects [1-2]. Recent Covid-19 pandemic added an unprecedented challenge to understanding the impact of carbon and pollutant emission and for rendering socio-economic activities and common practices sustainable and environment-friendly [3-4].

Here is given a contribution to the very complex subject with the presentation of a research aimed at assessing the effects of daily mobility patterns of general public on PM10 concentration during the Covid-19 epidemic outbreak in 2020 in Sisak-Moslavina County, Croatia, an industry intensive region. Sisak-Moslavina County is situated in central Croatia and covers the area of 4,468 km^2, as depicted in Figure 1.

The PM10 refers to air particulates of natural (such as sand) and anthropogenic materials, including elementary carbon and poly-cyclic aromatic hydrocarbons, in the form of coarse particles with a diameter of between 2.5 μm and 10 μm [5-6]. The PM10 has a profound health effects, as particles accumulates in lungs in an irreversible process. The health effect has been recognised, with the world-wide regulation set for continuous monitoring of the PM10 concentrations using the agreed objective methodology [2, 7]. The regulation has been imposed for the daily mean PM10 concentration not to exceed 50 μg/m^3, among the others [8].

The air pollution is considered to be driven by socio-economic activity, including transport and the general mobility of population. General mobility refers to daily local migration of the general population. Traditionally, general mobility is estimated using various methods and expressed with tailored indices. Recent developments exploit extensively telecommunications records for estimation of general mobility. Endorsed by advanced satellite- [9] and network-based positioning methods and co-operative localisation [10], general mobility may become contextualised through its enhancements towards the mobility patterns [11-12], mobility means [13] and purpose of mobility recognition [11], based on telecommunications activity records.

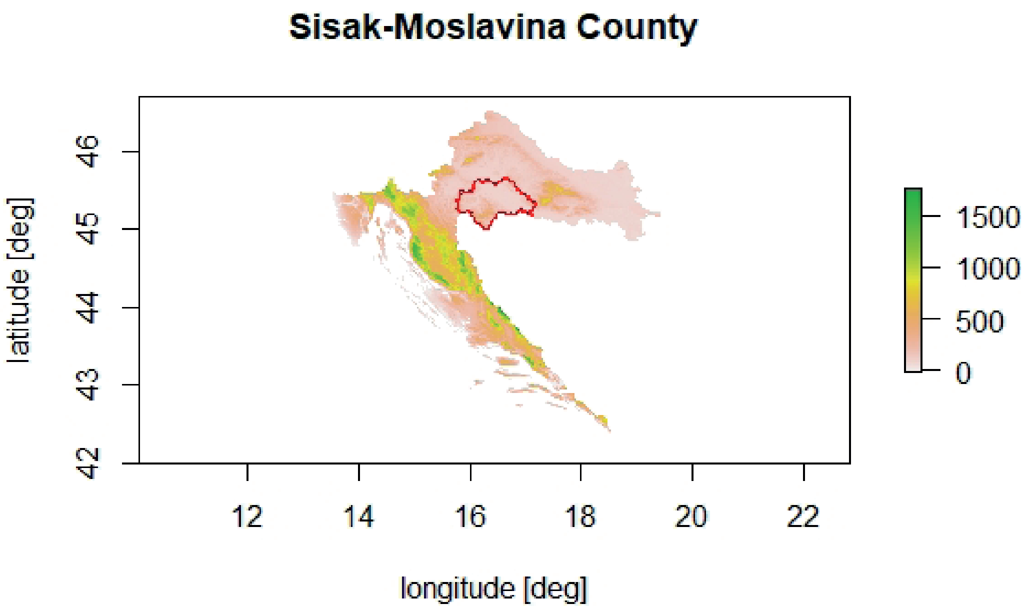

Figure 1 *Sisak-Moslavina County (red contour) in Croatia, with altitudes in legend in [m]*

Telecommunications networks and telecommunications activity-generated data have been considered recently an important epidemiology management tool [14].

The research presented here aims at identification of contribution to PM10 concentration development of the general population mobility contextualised in the sense of classes of mobility targets (purposes). The Covid-19 pandemic has caused an extraordinary and substantial impact on the contextualised mobility, thus providing the foundation for a research scenario in which PM10 concentration contribution of the contextualised classes of general population mobility may be identified. As local habits and traditions shape the contextualised general population mobility, a socio-economically and culturally well-defined region in central Croatia was selected for the purpose of the research presented. While a number of other predictors [5-6], such as meteorological conditions descriptors, determines the PM10 concentration, this research focuses specifically on the PM10 contribution of the contextualized mobility, exploring the socio-economic context as a generator of air pollution.

The county shape is depicted in Figure 1 using bespoke R script utilising spatial data from GADM (https://gadm.org/) and WorldClim (https://www.worldclim.org) internet databases, utilising methodology outlined in [15]. Its population totals 172,439, as per the latest 2011 census data, with the resulting population density of 39 inhabitants per km^2. The Sisak-Moslavina County is industry-active region, hosting one of three Croatian oil refineries, a large thermal power plant and a number of Small and Medium Enterprises of chemical, electronics and mechanics industries. City of Sisak, a County's capital, hosts a river port. County population traditionally use cars, railways, buses, as well as bicycles for daily commutes. Social-economic, in particular the industrial, activities in the County are potentially capable of rising the PM10 concentration significantly, so the continuous air quality monitoring procedure has been set, with the data openly available.

This research was conducted based on publicly available data of pollutant emission, continuously monitored made openly available, as required by Croatian national regulations and on telecommunications activity-derived general mobility indices, determined and provided openly by Google, Inc. company in an effort to curb effects of the Covid-19 pandemic through the advanced data analysis and modelling.

A data set was assembled comprising daily mobility indices and the mean daily PM10 concentration observations and the data was treated as the time series [16]. Exploratory analysis of time series was conducted and statistical analysis, using related statistical tests, was performed to identify the mobility means that produce a contribution effect to the PM10 pollutant concentration. Authors faced a challenge of the Covid-19 epidemiological measures, which rendered the observed time series non-stationary. The effects of the epidemiological measures on stationarity are successfully mitigated by deployment of the Granger causality statistical test.

This manuscript is structured, as follows. After the problem statement and research aim declaration in current Section, Section 2 outlines the research methodology and data description and exploratory analysis results. Research results of identification of mobility means contributors to PM10 concentration are presented in Section 3. Interpretation and discussion of research results, along with the conclusion, are given in Section 4.

2 Method and data

This research aims at identification of the mobility indices as drivers of the PM10 concentration, thus contributing to air quality deterioration. With a variety of the Covid-19 epidemiological measures [17] imposed during 2020, the general mobility means diversified, thus opening the space for research on the effects of mobility habit changes on the PM10 concentrations. The mobility indices and PM10 were considered from the time-series perspective and a battery of statistical tests for identification of mobility contributors to PM10 concentration development was deployed.

2.1 Method

Common approach is utilised in statistical analysis of the data time series [16], including graphical presentation, exploratory statistical analysis (means, variances, quartiles, box-plot diagrams), augmented Dickey-Fuller test for the stationarity assessment [18] and experimental statistical distribution estimation for every variable examined. Methods for exploratory data analysis are utilised for the purpose of identification of normality in data and feasibility to assess potential associations, as well as the cause-effect relationship. Furthermore, results of the exploratory analysis are used in the stationarity, bias and variance in data analysis, time series analysis and the statistical comparison between different data sets.

Mutual correlation between pairs of variables is quantified with the utilisation of the Pearson correlation coefficient. Statistical significance of a correlation coefficient is assessed using a statistical test based on the t-score of the Pearson correlation coefficient r determined on the n-element sample, as set with equation (1) and with the null-hypothesis of ***H0****: true correlation is equal to 0*. The p-value of statistical test is used for inference of statistical significance.

$$t = \frac{r \cdot \sqrt{n-2}}{\sqrt{1-r^2}}. \quad (1)$$

The elementary statistical analysis is followed with statistical variables relation assessment. The cross-correlation analysis is to reveal linear associations between variables. Finally, pending the confirmation of non-stationarity, the Granger causation statistical test [19], is to be deployed on the pairs of variables: individual mobility indices, as presumed predictors and PM10 concentration, as the presumed outcome. A time series X Granger-causes a time series Y, if evolution in time of the time series Y is predicted better based on both its own past values and the past values of X, than predictions consider just the past values of Y alone. Granger [19] defines the causality between the two time series X and Y under the following presumptions: (i) the cause occurs prior to its effect and (ii) the cause holds a unique information about the future values of its effect. Assuming these two presumptions are fulfilled, Granger [19] proposed identification of a causality effect of the time series X on time series Y by testing the hypothesis, as follows:

$$P[Y(t+1) \in A | I(t)] \neq P[Y(t+1) \in A | I_{-X}(t)], \quad (2)$$

where P denotes probability, A denotes an arbitrary non-empty set, $I(t)$ denotes the information at the time t on the whole space of observations and $I_{-X}(t)$ denotes the information at the time t on the whole space of observations excluding X. If the above-stated hypothesis was to be retained, one says that the X Granger-causes Y.

The Granger causality test does not require the time series stationarity and it handles well the situations concerning the non-Gaussian nature of the underlying process [20]. The Granger causality test was found to be suitable to the data concerned in both perspectives.

Finally, the time series of concern was examined from the perspective of delayed and prolonged effects, with the application of the Granger causality test on the lagged time series. Using that approach, it was possible to identify the lag(s) when and for how long the Granger causality test p-value falls below the significance level $\alpha = 0.05$. In the manner described, the Granger causality test implementation is to reveal the lag intervals when the hypothesis of causality between the two variables (a mobility index and PM10 concentration) is to be retained.

2.2 Data

Hourly PM10 concentration data taken at the monitoring station in Sisak, Sisak-Moslavina County, Croatia are available from the European Environmental Agency (EEA) internet archive [21]. The annual data set consists of the observation from the most of the year 2020, with the DOY227-DOY255 gap. No explanation is given on the nature of the data loss. Following national and the EU regulations on maximum allowed PM10 concentration [8], the daily mean (average) PM10 concentrations were distilled to form the PM10 time series.

The Google, Inc. analysed anonymised telecommunications activity data and derived daily rate of changes in mobility indices, defined as the percentage change in relation to the 5 weeks-baseline (3 Jan - 6 Feb, 2020) in the number of visits to: (i) retail and recreation (including pubs, bars and restaurants) facilities, (ii) groceries and pharmacies, (iii) transit stations, (iv) workplaces and offices and (v) residential areas [22]. The Google mobility indices are used in the research presented as representative contextualised mobility predictors of contributors to the PM10 concentration,

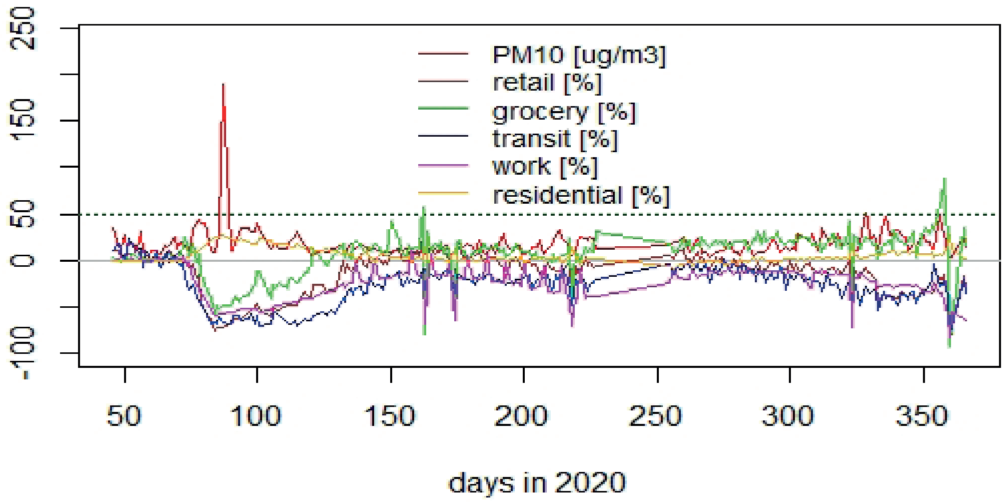

Figure 2 *Time series of the daily mean PM10 concentrations (red) and the relative changes in the telecom activity-derived mobility indices*

assumed a target. Presented in the form of the Covid-19 Community Mobility Reports with data in CSV format, mobility indices are an invaluable source of data on general mobility during the Covid-19 pandemic. The annual 2020 dataset for the Sisak-Moslavina County was used as distilled from the global data set provided by Google, Inc.

The PM10 concentration and the mobility indices for the Sisak-Moslavina County in 2020 are assembled in a single data frame, which is utilised for this research.

2.3 Practical implementation of methodology

Data handling and assemblage, statistical analysis and statistical testing are performed using the bespoke software developed for the purpose of this research in the open-source R environment for statistical computing [23], with utilisation of the additional freely available R packages lubridate, for data handling and arrangement, PerformanceAnalytics for cross-correlation analysis and *lmtest*, for performing the Granger causality test.

3 Research results

The assembled Sisak-Moslavina County data set comprising the PM10 concentrations and the County mobility indices data is processed in compliance with the methodology outlined in Section 2 using the R-based software developed by the research team.

The time series are depicted in Figure 2, of the daily mean PM10 concentrations (red) and the relative changes in the telecom activity-derived mobility indices in comparison to the baseline 3rd Jan - 6th February, 2020 levels: visits to retail and recreation facilities, including bars and restaurants (brown), groceries, pharmacies and food shops (green), public transport transit hubs (blue), work facilities and offices (magenta) and residential areas (orange) in Sisak-Moslavina County, Croatia in 2020. Dotted green horizontal line denotes the maximum daily mean PM10 concentration allowed. Graphical presentation does not indicate stationarity, which is later confirmed through implementation of Augmented Dickey Fuller Test. Furthermore, the Figure 2 diagrams do not extend visible seasonality, trends and cyclicity, as numerous Covid-19 counter- epidemic measures discourage such developments.

Exploratory analysis of observations reveals several additional insights (Figure 3). The PM10 concentrations seem to comply with the regulations by counting for more than 35 cases of daily PM10 concentrations exceeding 50 $\mu g/m^3$ in 2020 [5, 8]. A single maximum was caused probably by an impact of the Aralkum Desert dust storm that affected the South-Eastern Europe [3, 24 - a case of unusual meteorological conditions bringing a large concentrations of sand particles in the air. Still, the PM10 concentration annual mean was significantly higher than the baseline value.

The results of correlation analysis of the daily mean PM10 concentration and mobility indices are summarised in Figure 4. Mobile indices are generally loosely correlated with PM10 concentration. The correlation coefficients for the retail and recreation faculties and residential visits extend a high statistical significance, while the statistical significance of visits to residential areas and transit hubs is a level lower. Statistical significance of the determined Pearson correlation coefficients is expressed in graphical terms based on the related statistical test p-values, as follows: (i) *** denotes $0 < p < 0.001$, (ii) ** denotes $0.001 < p < 0.01$, (iii) * denotes $0.01 < p < 0.05$, (iv). denotes $0.05 < p < 0.1$ and (v) no mark denotes $0.1 < p < 1$.

Public mobility fell in general during 2020, as a result of the counter-epidemic measures at various scales, including the lock-down imposed from 18 March, 2020 to the late May, 2020. The mean values of mobility indices were lower than in the baseline period, with

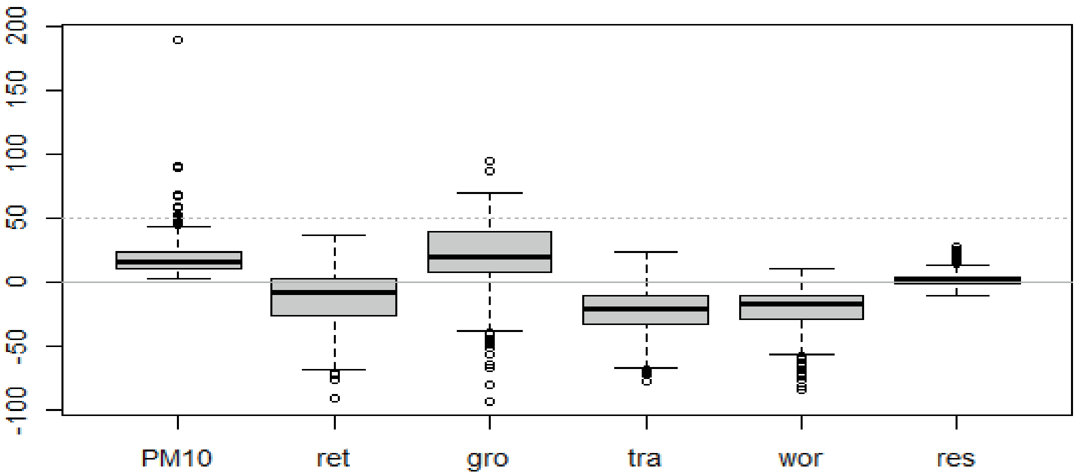

Figure 3 *Box-plot diagrams of the daily mean PM10 concentration and mobility indices, as statistical variables. Dotted grey horizontal line denotes the maximum daily mean PM10 concentration allowed*

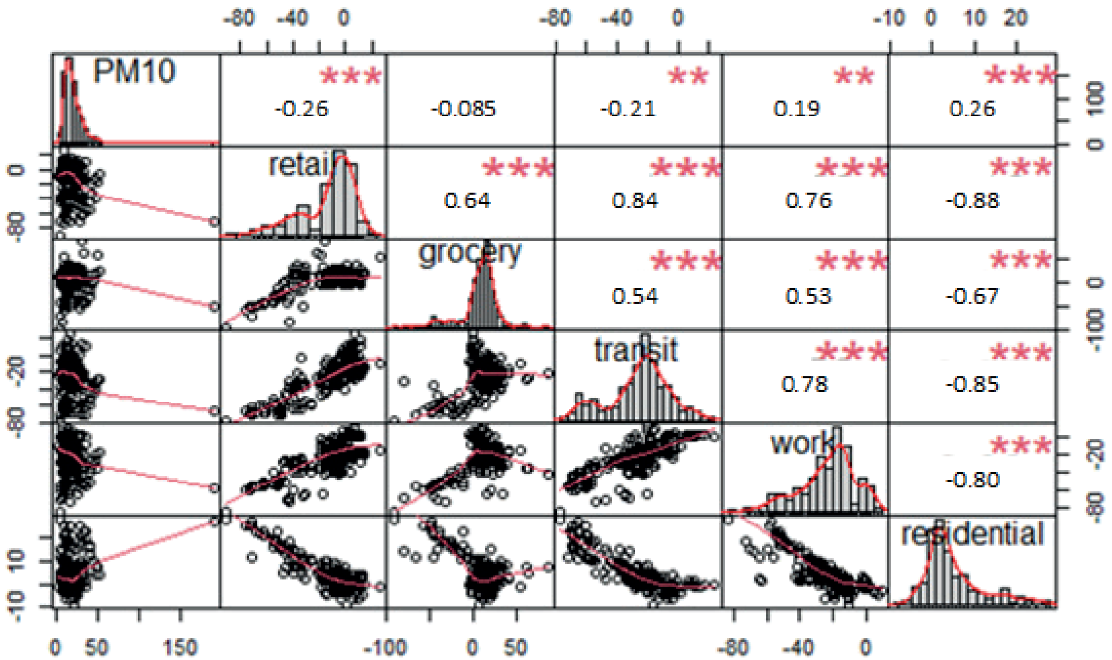

Figure 4 *Correlation analysis of the daily mean PM10 concentration and mobility indices, as statistical variables*

the exception of visits to groceries and food shops. The exception may be understood as a result of restricted and limited access to essentials. Related time series extends numerous outliers, as a result of a range of restriction levels. Visits to transit hubs and workspaces and offices were significantly lower, both on average and concerning the box-plots, as a result of restricted general mobility and transition to on-line work at home.

Mobility in residential areas was affected the least, with a number of outliers of occasionally intensive mobility, probably for visiting neighbours.

The results of the lag-related Granger causality analysis are comprehensively presented in Figure 5. In support of the cross-correlation analysis, the Granger causality analysis reveals causal relationship between PM10 concentration and the retail and residential mobility, respectively, at statistical significance of $\alpha = 0.05$.

With $p < \alpha = 0.05$, the causal effect of driving PM10 concentration with visits to retail and recreational facilities remains significant across the range of 1 - 10 lag (days) used in research. The causal effect of the residential mobility index on the PM10 concentration ceased to be effective after the 7 days' lag. The results are interpreted in terms of travelling duration, as people need more time to travel to shopping malls, restaurants, pubs and bars and the other retail and recreational facilities, than to visit the people in their neighbourhoods. Further to this, visits to transit hubs have a delayed effect lasting 4 - 6 days after the actual commencements. In the analogue interpretation, visits to groceries and pharmacies have a 4 day-lagged effect on the PM10 concentration development.

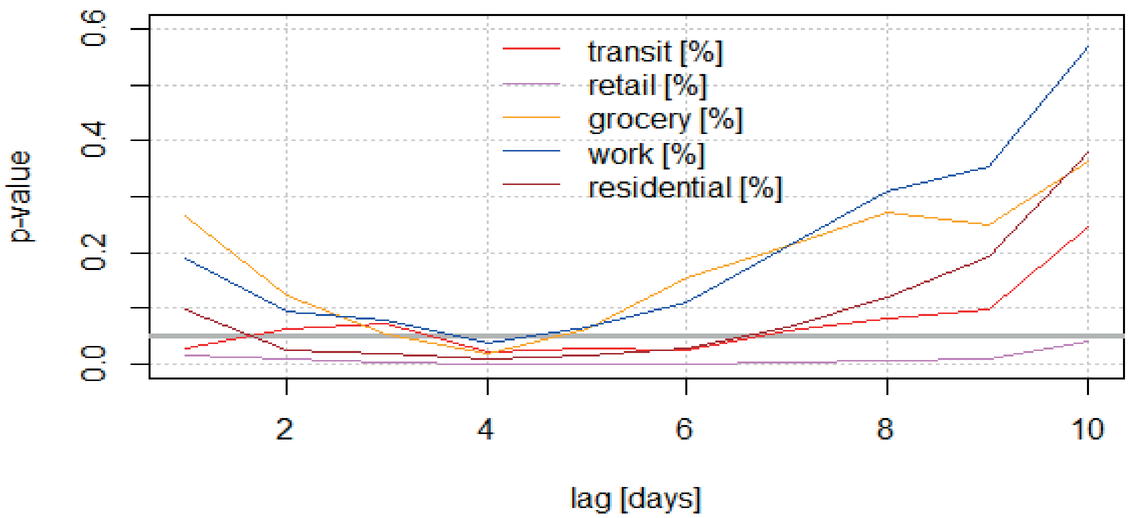

Figure 5 *The Granger causality test p-values (α = 0.05) of the daily mean PM10 concentration and individual mobility indices pairs*

4 Conclusions

This research aimed at identification of statistically significant contextual general mobility indices as contributors to the PM10 pollutant concentration development in industry-intensive Sisak-Moslavina County, Croatia during the Covid-19 outbreak in 2020. The general mobility is described on a daily basis with percentage change to baseline status, taken as mobility indices, of visits to (i) residential areas, (ii) retail and recreation facilities, (iii) transit hubs, (iv) groceries and pharmacies and (v) working premises, as derived from the anonymised telecommunications activity records.

The study contributes to the subject with the contributions, as follows. (1) A year-long time-series data set of daily samples of maximum PM10 concentrations observed in the Sisak-Moslavina County in Croatia and percentage changes indicators in mobility classes related to the pre-Covid-19 pandemic period in Sisak-Moslavina County in Croatia, derived from the anonymized telecommunications records and provided by Google, Inc., is assembled and structured. (2) Time-series of the PM10 and mobility changes indicators in the Sisak-Moslavina County in Croatia are analysed for their statistical properties identification, including stationarity and the related cross-correlation. (3) Time-series of the PM10 and mobility changes indicators in the Sisak-Moslavina County in Croatia are decomposed and the decomposing components were analysed for the characteristic patterns. (4) Pairs of the non-stationary time-series of the PM10 and mobility changes indicators in the Sisak-Moslavina County in Croatia are analysed for cause-and-effect using the Granger statistical tests, as an alternative to traditionally used ANOVA.

(5) Considering the results of the Granger statistical test implementation and determined p-values resulting from the Granger analysis, visits to residential areas ($p = 0.02658$) and to retail and recreational faculties ($p = 0.008048$), including bars and restaurants, are found as statistically significant ($\alpha = 0.05$) contributors to the PM10 particles concentration development. Lagged Granger analysis finds the prolonged 4-7 days' effect on the PM10 concentration.

The research results presented here may serve to epidemiologists attempting to conceive advanced counter-epidemic measures, as well as to national and local authorities intending to curb adversarial effects of epidemic on socio-economic activities.

Authors will continue this research in further examination of association between the mobility and air quality, taking into account common practices and exceptional socio-economic and health circumstances.

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