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The disturbance of urban mobility in the context of COVID-19 pandemic

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ABSTRACT

Since the COVID-19 outbreaks, extensive studies have focused on mobility changes to demonstrate the pandemic effect; some studies identified remarkable mobility declines and revealed a negative relationship between mobility and the number of COVID-19 cases. However, counter-arguments have been raised, exemplifying insignificant variations, recuperated travel frequency, and transitory decline effect. This paper copes with this contentious issue, analyzing time series mobility data in comprehensive timelines. The assessment of the pandemic effect builds on significant change rate (SCR) ceilings and the density of the semantic outliers derived from the kernel-based approach. The comparison between pre- and post-pandemic periods indicated that mobility decline pervaded Australia, Europe, New York, New Zealand, and Seoul. However, the degree of the effect was alleviated over time, showing decreased/increased SCR ceilings of negative/positive outliers. The changes in resulting outlier density and SCR ceilings corroborated that the pandemic outbreaks did not lead to persistent mobility decline. The findings provide useful insights for predicting epidemics and setting appropriate restrictions and transportation systems in urban areas.

Over the past two years, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread across the globe. The emerging mutation accelerates virus transmission, posing severe burdens on the health departments and medical institutions. The ongoing COVID-19 pandemic has changed daily mobility, travel times, journey purposes, and social connections. However, despite a growing number of relevant studies, the interpretation of the pandemic effect diverges; some studies identify a negative relationship between the number of COVID-19 cases and urban mobility (Balbontin et al., 2021; Borkowski et al., 2021; Chan et al., 2020; Huang et al., 2020; Long & Ren, 2022; Shakibaei et al., 2021; Warren & Skillman, 2020; Zhou et al., 2021), whereas other ones have substantiated the resilience of transit ridership and insignificant changes of mobility and transit demands (Askarizad et al., 2021; Kim & Kwan, 2021; Li et al., 2021; Liu et al., 2020; Parady et al., 2020). The findings and statistical tests depend on the travel purpose, case area, and pandemic phases, but there are underlying limitations. The verification is based on questionnaire data and straightforward arithmetic (e.g., the sum of total travelers or arithmetic average), which shows vulnerability to provide comprehensive insights into this protracted pandemic effect on human mobility. The travel activities leave consecutive footprints in the spatial and temporal dimensions, and the magnitude of travel frequency and time series variation would reflect the pandemic effect. In this sense, this paper aims to derive dynamic variations and assess the pandemic effect on intercity and international mobility.

In general, continued high rates of infection and emerging viral variants lead to incremental preventive measures, thereby controlling daily routines, individual travel behaviors, and massive intercity movement. Several countries have encountered three challenging phases, showing more cases during winter in 2020 and after midsummer in 2021 (Fig. 1A). This paper used various mobility data obtained from New York (NY), Seoul (SU), Europe, Australia (AU), and New Zealand (NZ) (Fig. 1B). The road traffic data in NY and SU and apple data in AU and NZ show domestic mobility, whereas flight data (Fig. 1E) shows the international movement bounding for Europe. Apple data (Fig. 1D) sorts travel modes into driving/transit/walking and provides change rates of data-stream with respect to the post-pandemic period. In AU and NZ, the transit showed excessive zeros, which leads to the focused analysis of driving and walking. Meanwhile, the metropolitan area has attracted vehicle inflows occasioned by functional centrality (You, 2022b). The patterns of detected outliers would be prevalent in metropolitan areas, given that high population density is the most significant predictor of infection rates. Midtown Manhattan in US, Jung-gu, Yeongdeungpo-gu, and Gangnam-gu in South Korea serve as business districts. Daily traffic flow heading for each sub-district shows an aggregated volume of nonresident travelers whose residence location is outside of SU and NY data shows the number of yellow taxi passengers. This paper argues the impact of the pandemic based on inter-year
mobility variations and statistical verification. The exposition builds on the spatial time series outliers that serve as a measurement of mobility disturbance. Their international patterns and comparison between pre- and post-pandemic periods underpin the argument on the pandemic effect. The outlier detection approaches build on the concept of similarity, wherein the data-adaptive method can reveal emerging or diminishing patterns in spatial and temporal dimensions. Kernel density estimation (KDE) has been widely used for nonparametric density estimation. You (2022a) present a kernel-based data mining technique called STDAC. Given Gaussian kernel density estimate and the k-fold cross-validation, data-driven bandwidths determine the temporal and semantic proximity, while filtering semantic outliers with an unacceptable variation. The definition of semantic neighbors $N_{semantic}$ can be applied to extract dissimilar observations for mobility variation in the pandemic context. For each time interval and region, this paper extracts semantic outliers whose time series values deviate from those of the pre-pandemic period. The positive outliers (POs) or negative outliers (NOs) denote the time series points composing each stream, where change direction (positive or negative) is determined by bandwidth $h_i$.

Positive outlier $(PO_i) = \text{Value of time series point}_i > \text{previous value}_i + h_i$

Negative outlier $(NO_i) = \text{Value of time series point}_i < \text{previous value}_i - h_i$

Providing data-adaptive criteria for setting significant variate, this kernel-based approach avoids technical challenges arising with basic arithmetic calculations that may dilute dynamic time series patterns.
Fig. 2. The SCRs obtained from the comparison between pre- and first pandemic years.
Fig. 3. Spatial distribution of semantic outliers in 2020.
Fig. 4. The SCRs obtained from the comparison between pre- and second pandemic years.
Fig. 5. Spatial distribution of semantic outliers in 2021.
The concentration of detected outliers quantifies the degree of mobility variations, which is associated with the means of transport, government measures, case areas, and pandemic phases.

The findings are elucidated in Figs. 2–5 and Tables 1–2. Figs. 2 and 4 illustrate inter-year mobility variations, where significant change rates (SCR) denote the proportion of semantic outliers in the consecutive timeline. The time series patterns differ across the time intervals (06:00–13:59/14:00–21:59/22:00–05:59), travel modes (air flight/driving/walking), and case areas. The semantic outliers showed several high-level distributions when 60% is set as the minimum criterion. During the first year of the COVID-19 pandemic, the mobility decline became apparent in Europe and NY. These countries have undergone continuous mobility decline, maintaining NOs at high levels. However, this paper uncovered the dwindling SCRs in Europe, which imply that the higher infection may not lead to more mobility decline, given the inter-year comparison identified the reversals between the attribute of SCR ceilings and POs/NOs; for each area, greater SCR ceilings of NOs and POs were incompatible and alternated each year. This tendency was more manifest in SU amid the first and second global phases.

The semantic outliers intensively or sparsely arose, whose spatial distribution is illustrated in Fig. 3. Temporal traffic mobility (Fig. 3A and B) was more variable in SU, whereas NY showed static distributions. Mobility decline spread all around SU, and the tendency of mobility increase (the increment of POs) gradually headed for northern areas. The semantic outliers in AU and NZ pertain to travel modes and high-level SCR was identified in several areas, while the POs did not form the dense distribution whose SCRs were below the minimum criterion (Fig. 3C and D). This tendency also appeared in Europe, showing dominant NOs and zero POs (Fig. 3E).

As the pandemic enters its second year, an unprecedented crisis has arisen (see the third global phase in Fig. 3A). The high concentration of NOs would reflect the severity of the confirmed cases if increased infection fear and reinforced government measures led to more protective behaviors. However, the comparison between the pre- and second pandemics years (Fig. 4) propounds that the degree of COVID-19 upsurge was not relevant to the magnitude of mobility decline. Europe, NY, and SU maintained high-density distributions at a specific time interval (22:00–05:59) or travel mode (flights), but the concentration of NOs abated or showed consecutive lower SCR levels than those of the previous year, especially during the third global phase. The reduced concentration and low SCR levels were also identified in other time intervals and walking. This prevailing tendency adds uncorrelation between the magnitude of mobility decline and rising COVID-19 cases, notwithstanding an exceptional case in NZ (Fig. 4d: driving). The contention can be underpinned by the POs laying on the enhanced SCR level. The concentration of POs indicates mobility resilience, which appeared in AU (driving/walking) and ZU (driving), and SU (14:00–21:59). In particular, AU and ZU have undergone significant recuperation and SU attained high-level SCR amid the second and third COVID-19 phases.

The mobility resilience can be identified from a spatial perspective (Fig. 5); AU, Europe, NZ, and SU assigned more areas to the upper classes. The ostensible distribution of NOs was analogous to the previous year. However, given the inter-year comparison of NOs and their proportion, the mobility decline was attenuated in the majority of regions in AU (23%/0% for driving/walking), Europe (17%), SU (49%), and NZ (5.8% for walking). The increment of NOs was only identified in NY (70.4%) and NZ (52% for driving). Undergoing the prolonged pandemics, intercity and international mobility have changed the time series pattern, and the mobility recuperation implies transitory COVID-19 effect on mobility reduction even in the pandemic severity.

Tables 1–2 exhibit statistical tests for the difference in two population proportions, wherein a specific rate stated by the alternative hypothesis (H1) denotes the SCR ceiling. The statistically verified value serves as the measurement of the mobility variations, and the low SCR ceiling indicates that the variations were insignificant. The SCR ceilings derived from NOs showed larger values than those of POs, which reveals the pandemic outbreaks have mainly incurred impediments to the intercity and international mobility. NY has undergone severe mobility reduction, showing a maximum SCR ceiling of NOs, and the value was over the predefined criterion. The finding may pertain to the second global phase, not the third phase showing the unprecedented upsurge of COVID-19 and unlikely alleviation in mobility reduction (Fig. 4A). The mobility decline appeared as a pervasive phenomenon, but most counties recuperated the mobility in 2021. The mobility resilience even prevailed decline effect in AU (driving). Meanwhile, the inter-year comparison identified the reversals between the attribute of SCR ceilings; for each area, greater SCR ceilings of NOs and POs were incompatible and alternated each year. This tendency was more manifest in SU (06:00–13:59), Europe, AU, and NZ.

The resulting mobility variations and SCR ceilings reveal that mobility decline and rise pertain to the travel mode, case areas, and time intervals. Several areas have undergone significant mobility decline, which emerged in Europe (2020) and NY (14:00–05:59, 2021). However, the degree of COVID-19 severity did not lead to considerable degradation. Most areas showed mobility resilience and the mobility decline was attenuated in the majority of regions, despite an unprecedented COVID-19 upsurge in 2021. The findings were corroborated by the decreased/increased SCR ceilings of negative/positive outliers. Overall low-level SCR ceilings refute a prevalent belief: COVID-19 threat and anti-coronavirus restrictions have led to mobility decline. The conclusion is in line with the latest research; pandemic effects on human mobility and transit demands were insignificant to change travel behavior (Askarizad et al., 2021; Parady et al., 2020), especially over long periods (Kim & Kwan, 2021; Liu et al., 2020). Since the unprecedented health crisis, a lack of empirical evidence on the effect of the pandemic has increased uncertainty in policy decisions and urban mobility. This paper provides a practical reference for establishing future epidemic countermeasures by corroborating that the pandemic effect was ineffectual and transitory.

### Data

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Table 2
Validation of SCR ceilings using daily traffic data (significance level < 0.05).

| Countries | Travel modes | Year | SCR ceilings of POs/NOs (p-value) |
|-----------|--------------|------|----------------------------------|
| Europe    | Flight       | 2020 | 0.000 (0.036)/0.65 (0.027)       |
|           |              | 2021 | 0.001 (0.047)/0.44 (0.049)       |
| AU        | Driving      | 2020 | 0.008 (0.035)/0.134 (0.049)      |
|           |              | 2021 | 0.089 (0.049)/0.058 (0.048)      |
|           | Walking      | 2020 | 0.009 (0.045)/0.246 (0.048)      |
|           |              | 2021 | 0.059 (0.049)/0.092 (0.049)      |
| NZ        | Driving      | 2020 | 0.094 (0.049)/0.375 (0.049)      |
|           |              | 2021 | 0.134 (0.048)/0.327 (0.049)      |
|           | Walking      | 2020 | 0.008 (0.039)/0.107 (0.049)      |
|           |              | 2021 | 0.008 (0.041)/0.082 (0.048)      |

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CRediT authorship contribution statement
Geonhwa You: Conceptualization, Methodology, Analytical review, Supervision, Technique application, Writing- python code, Original draft, and Revision.

Declaration of competing interest
The author declares no conflict of interest.

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