**Abstract**

The UK government imposed a lockdown across England in the spring of 2020 reduce the community transmission of COVID-19 and prevent health services from being overwhelmed. This study examined spatio-temporal dynamics in mobility over the course of the pandemic using mobile phone data collected. It shows that temporal trend in mobility varied geographically during the pandemic in England. It also demonstrates a consistent V-shaped recovery in mobility patterns, but the shapes of these patterns were not uniform; they varied markedly across England. We identified four distinctive clusters using time-series analysis. Focusing on the internal heterogeneity to characterise a speed and intensity of mobility reduction with recovery, compared to pre-pandemic levels. The results show that distinct spatial distributions of mobility trends were correlated with sociodemographic factors, accessibility levels, and local COVID-19 risk using a penalised regression model. Adaptability and resilience in mobility has been introduced that helps to explain the geographical variations in temporal trends of mobility levels. The paper concludes by discussing the post-COVID travel behaviours after the pandemic becomes endemic.

**Keywords:** COVID-19; First wave; Time-series clustering; Adaptability; Resilience.

**Introduction**

The COVID-19 pandemic has rapidly changed our daily lives. People have been adapting to life with COVID-19 to mitigate the risk of infections. Greater reductions in mobility have been experienced since a wide array of social distancing measures were implemented, compliance with stay-at-home orders and other travel restrictions at the national level (Hale et al. 2021; Kishore et al. 2021). People must be aware of higher risks in face-to-face meetings, thus required to adapt to radical disruptions, such as an almost total ban on social gatherings, to prevent the spread of the virus as the outbreak evolves. The risk for COVID-19 infection has contributed to and will continue to influence people’s day-to-day lives, including travel behaviours. Various countermeasures have led to an increase in home-based activities, such as a shift from on-site work to remote working (Beck & Hensher 2020a; Budnitz & Tranos 2021), and a modal shift towards private transport and greater use of active modes, such as bicycling and walking (Hu et al. 2021a; Kim et al. 2021; Zhu et al. 2022).

Despite the challenges posed by the COVID-19 pandemic, it also offers new opportunities for researchers to explore mobility in pandemic times (Oliver et al. 2020). Many studies have focused on the short- and long-term effects of COVID-19 on travel behaviours using large mobile phone datasets (Xiong et al. 2020; Hong et al. 2020; Hu et al. 2021b). The evolution of mobility under nationwide lockdowns and strict quarantines were taking place in the first wave. These measures effectively tackled the spread of the virus and reduced COVID-19 infections and deaths before the vaccine was introduced (Haug et al. 2020; Ross et al. 2021). However, it has also led to several negative effects on the economy (Rose et al. 2023), and society, such as mental health problems (Mouratidis & Yiannakou 2022), while stay-at-home orders were extended to keep up with strong social gatherings.

In most existing studies, less attention has been paid to the exploration of the spatio-temporal developments of mobility in pandemic times. The first wave of the pandemic proposed quantification of four distinct phases based on the different magnitude of mobility reductions; original, disruptive, recovery, and new steady phases (Wang et al. 2022; Liu et al. 2023). A growing body of literature on the disruptive phase has focused on the effect of (nationwide) lockdown measures to uncover spatial variation of mobility reductions against the original phase. Extensive evidence has been found that overall levels of people’s mobility have dropped instantly against the pre-pandemic baseline, as seen through the lens of data-driven mobility metrics using large-scale mobile phone data (Enoch et al. 2021; Lee et al. 2021; Lucchini et al. 2021; Kim & Kwan 2021; Weill et al. 2020), and also through online panel survey data with GPS traces (Borkowski et al. 2020; Bohman et al. 2021; Molloy et al. 2020; 2021). Several studies have further been considered to demonstrate the uneven ability to restrict everyday mobilities among individuals. By examining reduced travel distances with shrunk activity spaces, it has been found that these differences vary greatly by region and are associated with inequalities in occupations and earnings (Chang et al. 2021; Glodeanu et al. 2021; Lou et al. 2020; Lee et al. 2021; Long & Ren 2022).

The subsequent recovery phase has sought to capture rebounds in mobility levels. Researchers have exhibited V-shaped trends between two phases (Kim & Kwan 2021; Noi et al. 2022; Kellermann et al. 2022; Yabe et al. 2023). This is reflected in the gradual easing of restrictions when reported cases seemed to be falling sharply. It would be also associated with the phenomenon of “quarantine fatigue”, in which people feel tired of staying at home for several months since strict travel restrictions w (Kim & Kwan 2021; Kwan 2021). Finally, a substantial recovery has been identified in a new steady phase have revealed the restoration of mobility levels and reshaping travel behaviours in a pandemic way, accounting for the final extent of the recovery though less so for public transport (Stanesby et al. 2023) and for vulnerable groups like the elderly (Wang et al. 2022).

In overview, the literature has found that overall mobility levels have evolved throughout the first wave. Also, it has fluctuated widely over a wide range of geographies (Beck & Hensher 2020b), and for population groups by using longitudinal data analysis (Dueñas et al. 2021; Kim & Kwan 2021; Li et al. 2022). Mobility resilience in times of the COVID-19 pandemic can be defined as the capacity to live and develop with change and uncertainty, to minimise the negative impact. However, it could be extended to the ability to bounce back (Wang et al. 2022; Liu et al. 2023; Rockström et al. 2023). A few studies have assessed time-varying mobility resilience by drawing a triangle with mobility reduction and recovery periods, and the quantity of mobility change (Duenas et al. 2021; Wang et al. 2022; Liu et al. 2023), but a focus on the first wave continues to dominate existing literature. This is because of changes and uncertainties in the impact of containment and closure policies to battle COVID-19 during the subsequent waves. The implementation of non-pharmaceutical interventions (NPI) has been neither stable nor consistently effective across space and time (Ge et al. 2022).

Apart from theoretical arguments, trends in mobility may well look differently when the spatial scale at which they are assessed is varied. Therefore, there are theoretical and methodological reasons why paying detailed attention to spatio-temporal trends in mobility is warranted (see the “Discussion” section below). This is why our study accounting for adaptability and resilience has contributed to trajectories of mobility during the first wave that may differ geographically.

To elucidate this issue further, this paper examines how mobility reductions varied over time and space during England's first nationwide lockdown. We used anonymised call-detail records (CDRs) data collected from mobile phones during the entire first wave of the pandemic, spanning from two months before and after the lockdown (i.e., lockdown period with ±2 month). A set of variables have prepared that we expect to be related to place-specific trends in mobility levels. Three sets of variables help to characterise differences in overall mobility changes over space. Sociodemographic profiles composed of income level, occupation, housing type, economic activity, and ethnic composition. Accessibility levels consist of geographic accessibility to health facilities and household car ownership. Local COVID-19 risks in the earliest stages of the pandemic. Not surprisingly, it has become very influential in shaping national policy and public debate whilst also exhibiting distinct geographic differences.

Additionally, the timing and prevalence of government measures can result in differences in COVID-19-related outcomes (Presti et al. 2022) in respect of the degree of fixity among individuals and regional variations (Kim et al. 2017). The relative lateness of England’s national lockdown policies would have contributed to likely increased scale, severity, and duration of the first wave (Arnold et al. 2022). Similarly, the late timing of England’s nationwide second lockdown measures have temporary effects despite strong restrictions and might have resulted in large resurgences of hospitalisations and deaths (Davies et al. 2021).

**Conclusion**

This paper examines spatio-temporal extent of mobility changes during the first wave of the pandemic using novel data resources. Whereas previous studies have focused on temporal trends of mobility as a single facet, we have shown that place-specific trends in mobility level were not stationary over time. We added those findings by quantifying a speed and intensity of reduction in mobility with recovery, as well as trajectories of mobility, which varied substantially across geographical space.

Of keynote, people’s mobility levels have changed over time, in compliance with the magnitude of lockdown policies during the first wave in England. A consistent V-shaped recovery in mobility levels was observed across England, but their shapes varied geographically, as illustrated by temporal curves of mobility levels of each LTLA. Those patterns also appear to be correlated with sociodemographic factors more than accessibility and COVID-19 risk, although all of these have contributed to characterising each trajectory of mobility. To do this, we used two data mining techniques. A shape-based time-series clustering method was deployed to identify an internal heterogeneity in the temporal properties of mobility developments over the four distinct phases in the first wave. Next, penalised regression was used to exhibit distinct spatial distributions of temporal trends of mobility that correlated with sociodemographic profiles, accessibility levels, and local COVID-19 risks, yet the magnitude of the correlations varied substantially.

This paper also contributes to the theoretical development. We suggested new conceptualisations of adaptability and resilience in mobility from the transport perspective (Schwanen 2021). It helps to explain the variations over time in mobility levels that have occurred geographically during the first wave in England. Adaptability can be defined as people’s capabilities to shift their travel behaviours, such as to adapt work patterns in a pandemic way, while resilience in mobility is understood as the ability to recover and bounced back to the pre-pandemic routines. Within this context, we have looked the extent of variability in trajectories of mobility through the concepts of adaptability and resilience in mobility.

Greater short-term adaptability and lower resilience have led to the fastest pace of reduction followed by the slowest pace of recovery in mobility levels over the first wave of the pandemic, dominated in London. However, we caution that faster adaptability may have been due to a higher perceived risk in the early stage of the pandemic in these areas, as the epidemic reached London 15 days earlier than the rest of the country (Knock et al. 2021). On the contrary, strong resilience have attributed to the marginal deviations in mobility levels, overrepresented in the northern regions in England. However, these tendencies might be different among people depending on their necessity, urgency, and (perceived) risk.

We have learned from the COVD-19 pandemic, but it leaves us with the question for us of how much travel behaviours will continue to change after the pandemic becomes endemic. We could already observe some hints that behavioural tendencies have shifted and continuing, but this also varies markedly across England. Office for National Statistics (2022) provides empirical evidence of increased homeworking even after the pandemic[[1]](#footnote-1). London has seen the highest increase in homeworkers (37%), while the North East (22.4%) and Yorkshire and the Humber (26.2%) have shown the lowest increase. Perhaps people who exhibited lower resilience were more likely to adapt to their new normal way of life, such as by increasing homeworking, shifting to active modes of transportation, ordering food delivery more often, and spending more on online shopping.

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1. Guidance and legal requirements on homeworking throughout the coronavirus (COVID-19) pandemic varied between administrations but England, Scotland, Wales, and Northern Ireland all ended the legal requirement to work from home at the end of January 2022. [↑](#footnote-ref-1)