ARTICLE TEMPLATE

# WFH and broadband speed (title needs rework)

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**ABSTRACT**
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covid; internet; working from home; broadband speed; time series clusters

## 1. Introduction

- our google doc

During the pandemic, working from home using Information and Communication Technologies (ICT), whether partially or exclusively, was transformed from a niche means of accessing work, albeit one that had been on a slow, upward trend, to a widespread way of life in many countries (Felstead and Reuschke 2020). **HANNAH, DO WE REALLY NEED A REFERENCE IN THE PREVIOUS SENTENCE?** The ability to work from home or telecommute meant millions retained their jobs and, to a varying extent, maintained productivity during periods of strict lockdown around the world. However, this ability has not been evenly distributed socially or spatially, creating a new type of digital divide. On one side are those who can work from home and have been able to enjoy both economic resilience and greater personal safety. On the other side, previously employed individuals have been forced to accept furlough or redundancy packages unless they are part of the cadre of essential workers, who are potentially at high risk of infection. Using the UK as a case study, this paper aims to improve our understanding of the spatial and social dimensions of this new digital divide by assessing the resilience of broadband speeds in terms of both quality and reliability of service, and whether this reinforces or redresses prior digital divisions. To do so, we employ unique volunteered geographic data on individual broadband speed tests and state-of-the-art time-series clustering methods, which enable us to create clusters of UK local authorities with similar temporal signatures of experienced internet speeds. We then associate these clusters of local authorities with their socioeconomic and geographic characteristics to explore whether they are linked with existing divides and the economic geography of the UK. **HANNAH, HOW**

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**DOES THIS SOUND?** Our analysis enables us to better understand how telecommuting and technology intersect at a time of extreme demand, and what lessons this time has for a future where telecommuting is likely to remain a common means of accessing work and broadband services, as well as infrastructure, must be fit for purpose. **LET'S LEAVE IT FOR NOW, BUT I THINK WE CAN CRYSTALISE MORE THE RQ**

The capability to work from home has previously been studied from the perspective of whether work tasks in a given occupation both can be and are allowed to be performed independently of location or co-location with colleagues, including supervisors (**insert refs**). However, successful telecommuting also requires that the quality and reliability of ICT services, particularly home internet connection speeds, enable the completion of work tasks with a minimum of delay or interruption. In reality, the performance of broadband speeds with respect to telecommuters has never been tested before at scale, as working from home and connecting to colleagues and workplace resources via broadband has previously been the purview of a small minority of workers. This papers understands telecommuting as a function of the quality of ICT services, particularly home internet connections, and whether work tasks in an occupation can be performed independently of being in a particular location or co-locating with colleagues

The shift towards telecommuting during various stages of lockdown around the world has been drastic and, importantly, speculations indicate that the post-Covid tendency to work from home will be much higher than the pre-Covid one. A back of the envelope calculation suggests that up to 40% of the working force could work from home in the UK (Batty 2020). Observational data pointed an even higher share of people in employment in the UK who worked from home in April 2020 (47%), while the same figure only reached 5% the year before (ONS 2020a,b). Similar figures have been reported for other countries around the world (Felstead and Reuschke 2020). For instance, 37% of the workforce worked from home in Europe in April 2020 with countries like Finland reaching 60% (Eurofound 2020). In the US almost half of the working population worked from home during the same period because of the pandemic (Brynjolfsson et al. 2020). More broadly, a recent estimate indicated that 37% of all jobs in the US can be permanently performed entirely from home (Dingel and Neiman 2020).

There is a consensus that opportunities for working from home especially during the current pandemic are not equally spread across the workforce. Dingel and Neiman (2020) indicated that in the US managers, educators, as well as those working in computer-related occupations, finance, and law can easily work from home. On the contrary, workers in farming, construction, and manufacturing do not have such opportunities. Not surprisingly, occupations with opportunities to telecommute are associated with higher earnings. This is not the case for the workforce occupied in less footloose occupations as they tend to be lower-income, non-white, without a university degree, live in rental accommodation and lack health insurance (Mongey, Pilossoph, and Weinberg 2020). Although these figures refer to the US, similar trends can be observed for other countries. For example, 75% of workers with tertiary education worked from home in Europe during spring 2020, while the same share for workers with secondary and primary education dropped to 34% and 14% respectively. Moreover, employees living in cities, women and younger employees were have worked from home (Eurofound 2020).

None of these changes could have happened in the absence of reliable ICT infrastructure – both in terms of software and hardware. But while software innovations are easily diffused across space and society[1], the same does not apply for ICT hardware infrastructure such as internet broadband connectivity. The literature exemplifies digital divides in terms of internet access and its quality. For instance, Riddlesden and Singleton (2014) highlighted the broadband divides in the UK, while the systematic review from Salemink, Strijker, and Bosworth (2017) reinforced our understanding for the infrastructure quality differences between urban and rural areas.

Our framework to understand telecommuting as a function of occupations and quality of ICT infrastructure is aligned with current debates on digital divides. While the, so-called, first level digital divides are associated with access and quality of internet connectivity, the second level ones are linked to the necessary skills to effectively utilise ICT and the internet (Blank and Groselj 2014; Van Deursen and Van Dijk 2011). Importantly, the capacity to telecommute, which to a certain extend is related to the first and second level digital divides, leads to differentiated outcomes regarding the economic resilience of people and places against the current pandemic. And to the extend that the quality of the internet infrastructure and occupation variation are spatially dependent and clustered in space, the spatial footprint of telecommuting is of great interest. In a way similar to the third level digital divide, which focuses on the differentiated returns of internet use (Stern, Adams, and Elsasser 2009; Van Deursen and Van Dijk 2014; Van Deursen and Helsper 2015) places with high rates of telecommuting during the Covid pandemic illustrate higher economic resilience against the current pandemic. This is aligned with the regional economic resilience literature, which underlines the differentiated capacity of cities and regions to escape or recover from economic crises (Martin 2012; Kitsos and Bishop 2018).

The long-term effects of such drastic changes in telecommuting and attitudes towards working from home are difficult to predict. Nevertheless, they span through various aspects of economy and society: from changes to transportation planning due to altered commuting patters, to changes in land use and urban planning to accommodate people who work from home (Budnitz, Tranos, and Chapman 2020); and from productivity and innovation changes, to changes in agglomeration externalities and the attraction of large cities (Nathan and Overman 2020) just to name a few. This paper is positioned to support endeavours in understanding the effects of increased telecommuting by exposing the spatial and social dimensions of telecommuting including the resilience of broadband speeds in terms of both quality and reliability of service, and whether this reinforces or redresses prior digital divisions. **HANNAH, HOW DOES THIS SOUND**

The structure of this paper is as follows. . . .

**MORE SOURCES:**

- `https://www.coronavirusandtheeconomy.com/question/why-has-coronavirus-affected-cities-more-rural-areas`
- EPB commentaries
- `https://www.coronavirusandtheeconomy.com/question/what-has-coronavirus-taught-us-about-working-home`
- `https://www.coronavirusandtheeconomy.com/question/who-can-work-home-and-how-does-it-affect-their-productivity`
- `https://www.coronavirusandtheeconomy.com/question/how-will-economic-effects-coronavirus-vary-across-areas-uk`
- `https://www.coronavirusandtheeconomy.com/which-parts-uk-have-been-hit-hardest-covi`
- `https://www.coronavirusandtheeconomy.com/question/`

[1] See for example the huge success of videoconferencing apps (Marks 2020).

`why-has-coronavirus-affected-cities-more-rural-areas`

## 2. Literature review

### 2.1. *broadband studies, divides, broadband tech stuff*

- PARA about Contention??

The infrastructural demands of working from home on internet services have been minor compared to the demands of leisure users, such that the broadband performance offered by different Internet Service Providers (ISPs) has been benchmarked according to download speeds during the evening 'primetime', when video streaming services are at their peak, rather than during the working day (**OfCom, 2017**). Yet the pandemic has fundamentally changed not only how many people work from home, but also their technical requirements when doing so. Whilst it may have been common in the past for telecommuters to complete solitary work tasks at home, but still visit their workplace for meetings (**ref?**), during the pandemic the replacement of face-to-face contact with bandwidth-intensive video conference calling was seen as essential to suppressing the spread of infection. This type of broadband use can particularly affect upload speeds **ref?**. This paper offers a framework to assess the quality and reliability of upload speeds by time of day and day of the week across local authorities in the UK during the time when the population were told to work from home if at all possible.

### 2.2. *from telecommuting to #WFH*

- Introduce space-time geography
- circumstances where work can be carried out more flexibly in space and time
- how relate to digital divides
- capability theory of mobility? suppressed demand...

Some new papers google recommended to me:

- `https://urbanstudies.uva.nl/binaries/content/assets/subsites/centre-for-urban-studies/working-paper-series/wps_43.pdf`
- `https://link.springer.com/article/10.1007/s11116-020-10136-6`
- `https://www.sciencedirect.com/science/article/pii/S0966692319311305`
- check who cites the above and what they cite

In this analysis, the terms 'teleworking' and 'working from home' are used interchangeably. An appropriate definition of teleworking is 'the remote provision of labour that would otherwise be carried out within company premises' (European Commission, 2020b). In practice, during the COVID crisis, most such work was carried out in the homes of individual employees rather than any other location. (Eurofound 2020)

### 2.3. *covid and working from home, cities, urban structure*

- economic geography of UK

## 3. Data and descriptive statistics

The experience of upload speeds is not the same as the maximum speeds offered by an ISP or possible speeds over a particular type and length of connection. Therefore, we use volunteered geographic information in the form of speed-checks run by users to test their experienced broadband speeds, upload and download. Meanwhile, the quality and reliability of upload speeds, like ICT more generally, vary in time and space due to both supply and demand-side influences, and can be measured in a number of ways. These include: a) mean, experienced connection speed, b) standard deviation or the amount of fluctuation from the mean, and c) the variation in speeds at particular times of day when working from home is more likely to take place. We take account of all three measurements in order to describe upload speeds as fully as possible. We start by calculating the mean upload speed for every local government district in the UK for each hour of each weekday, excluding midnight to 6:00, weekends and bank holidays. We then cluster the local authorities by these temporal profiles, allowing us to identify patterns and describe the overall means, standard deviations, and other relevant statistics for each spatial cluster. Thus we aim to answer the first part of our research question: How resilient are broadband speeds as experienced in different parts of the UK during a time of extreme demand?

The cause of these different experiences of broadband resilience may be different in different areas, as they may reflect similarities in patterns of demand or similar quality of infrastructure. Our approach is also limited by potential endogeneity, as for example, better quality connections with high mean speeds may enable more working from home, but greater demand may cause slower speeds, less reliability and greater variability of speed at different times of day or week. Therefore, we avoid attributing any cause to our analysis of the experienced level of quality and reliability of upload speeds. Instead, we run auxilliary regressions in order to understand how the spatial and temporal patterns of internet service relate to the economic geography of the UK. We discuss how the different patterns might support or undermine efforts to work from home and maintain safe productivity and whether they reinforce existing spatial and social inequalities. From this analysis, we hope to provide a greater understanding of how telecommuting and technology intersect at a time of extreme demand, and what lessons this time has for a future where telecommuting is likely to remain a common means of accessing work and broadband services, as well as infrastructure, must be fit for purpose.

The primary data analysed in this paper was provided by Speedchecker Ltd, a private company that allows internet users to check their own broadband upload / download speeds, and stores every speed-check with a timestamp and geolocation.

Our approach involves aggregating all the speed-checks during the 13 weeks of March to May inclusive for weekdays in 2020 by each hour of the day and day of the week. As our research aims to identify the geography of internet service resilience for work purposes, bank holidays and the hours between midnight and 6am were also excluded. The composite week time series thus comprise 18 hours multiplied by 5 weekdays or 90 time points per series. These time series were calculated for each of the 382 Local Authority Districts (LADs) in the UK, standardised, and then a k-means clustering algorithm was applied, including dynamic time warping. The LADs were assigned to 10 clusters for upload speeds. The cluster id for each LAD is then reattached to the speed-check dataframe to identify the characteristics of each cluster, including number of LADs, and the descriptives statistics of upload speeds in that cluster, and the temporal profile by hour of the day and day of the week.

**Data details and some figures, descriptive stats - include whole sample time profile for 2019 and 2020 frequency of tests run as part of why we chose to create the time profiles by hour of the day and day of the week rather than daily over the whole period.**

## 4. Time series clustering

The core of the methodological framework of this paper lies upon clustering methods. Clustering is a widely used family of techniques in geography (**ADD REF**), which can be defined within the modern machine learning framework as an unsupervised learning task, which involves partitioning unlabeled observations into homogeneous groups known as clusters (Montero, Vilar et al. 2014). The key idea is that observations within clusters tend to be more similar than observations between clusters. Clustering is particularly useful for exploratory studies as it identifies structures within the data (Aghabozorgi, Shirkhorshidi, and Wah 2015).

Various applications of clustering can be found within geography: **ADD EXAMPLES**

Key characteristic of these studies is the cross-sectional nature of the data they employed. Indeed, most clustering problems in geography deal with observations that are fixed in time. However, for this paper we are interested in creating clusters of local authorities in the UK with similar temporal signatures of experienced internet speeds over time. Hence, we deviate from the established geographical clustering tools and employ time series clustering methods.

Time series clustering methods have been developed in order to deal with clustering problems linked to, for instance, stock or other financial data, economic, governmental or medical data as well as machine monitoring (Aggarwal and Reddy 2013; Aggarwal, Hinneburg, and Keim 2001; Hyndman, Wang, and Laptev 2015; Warren Liao 2005). The main challenge – and also the difference with cross-sectional clustering problems – is data dimensionality given the multiplicity of data points for every individual included in the data set. Time series data are dynamic data as the value of the observations change as a function of time (Aghabozorgi, Shirkhorshidi, and Wah 2015). This high dimensionality leads to (i) computational and algorithmic challenges regarding handling these data and building algorithms to perform clustering over long time series, and (ii) open questions regarding the choice of similarity measures in order to cluster similar times series together considering the whole length of the time series and overcoming issues around noise, outliers and shifts (Lin et al. 2004; Aghabozorgi, Shirkhorshidi, and Wah 2015).

Time series clustering methods utilising the whole length of time series can be grouped in three categories. The first – model-based approaches – is based on recovering the underlying model for each time series and then apply clustering algorithms on the model parameters (Aghabozorgi, Shirkhorshidi, and Wah 2015). The main criticism is the cluster accuracy for near clusters (Mitsa 2010). The second approach is a based the formation of vectors of features based on the original time series. These new data of reduced dimensionality is then clustered using conventional clustering algorithms.

For this paper we utilise the third category of time series clustering methods known as shape-based approaches. The main idea is to match any two sperate time series based on the similarity of their shapes through the calculation of distances among these two shapes.

Sardá-Espinosa (n.d.) Ideally, all members of the same cluster are similar to each other, but are as dissimilar as possible from objects in a different cluster.

Time-series is a common type of dynamic data that naturally arises in many different scenarios, such as stock data, medical data, and machine monitoring, just to name a few (Aghabozorgi et al., 2015; Aggarwal and Reddy, 2013). They pose some challenging issues due to the large size and high dimensionality commonly associated with time-series (Aghabozorgi et al., 2015). In this context, dimensionality of a series is related to time, and it can be understood as the length of the series.

the data and how the underlying grouping is performed. One classification depends on whether the whole series, a subsequence, or individual time points are to be clustered. On the other hand, the clustering itself may be shape-based, feature-based, or model-based.

In the context of shape-based time-series clustering, it is common to utilize the Dynamic Time Warping (DTW) distance as dissimilarity measure (Aghabozorgi et al., 2015). The calculation of the DTW distance involves a dynamic programming algorithm that tries to find the optimum warping path between two series under certain constraints

## 5. Results

### 5.1. *Upload Clusters / cluster description*

The temporal profiles used to cluster the local authorities have been summarised in graph [.], which shows a composite profile of mean upload speeds per hour per day for each cluster. For upload speeds, 345 of 382 local authorities, or over 62 million people, fall into cluster 6 or cluster 9. Graph [.] shows that both of these clusters have relatively similar temporal profiles, which are flatter than the other, smaller clusters, suggesting better reliability of service. However, the upload speeds at all times for cluster 9 are substantially higher than for cluster 6, which is an indication of better quality of service. This difference is reflected not only in the mean speeds for these clusters for the whole sample, but also the mean upload speeds in the morning peak from 9:00-10:59, as well as the evening peak period from 19:00-20:59. In comparison, the time profile in graph [.] shows upload speeds in cluster 1 are on average lower at certain times of day during the study period than any other cluster, whilst the profile for cluster 3 appears to show speeds fluctuating as much as cluster 1, but at levels usually higher even than cluster 9.

The variability of the smaller clusters may be related to the fewer speed tests from fewer local authorities that have been averaged, whilst averaging greater numbers of speed tests could artificially flatten the profile. This appears not to be the case for cluster 9, as there is negligible difference between morning and evening upload speeds, at 1% slower in the morning, confirming a high level of reliability of service. In comparison, upload speeds in cluster 6 are 4% slower in the morning than in the evening and experienced the joint highest ratio of standard deviation to mean across the time period under assessment. This suggests that although the time profile is relatively flat in graph [.], the experience is one of speeds that fluctuate from a lower mean, and therefore might more often impact on online activities. Still, in most of the smaller clusters the reliability of service is worse than in cluster 9 in terms of the ratio of standard deviation to mean and worse than cluster 6 as well in terms of the ratio of upload speed in the morning peak compared to the evening peak. In five of the smaller clusters, which are home to almost 3 million people, speeds are 12-19% slower between 9:00-10:59 compared to 19:00-20:59.

The quality and reliability of broadband service is thus much better in the 115 Local Authority areas in cluster 9, which are mostly in urban or suburban areas, compared to cluster 6. These include 13 London Boroughs (of 32), 8 of the 10 local authorities of Greater Manchester, 5 of the 7 constituent authorities of the West Midlands Combined Authority, as well as cities like Glasgow, Leicester, Nottingham, Sheffield, and the Portsmouth and Southampton conurbation. There are also some notable medium-sized cities, including Aberdeen, Cardiff, Oxford, Milton Keynes, and York, and many suburban districts from the South East of England to South Tyneside. Meanwhile, the 230 local authorities in cluster 6, which have lower speeds on average and more variation in service still include major urban areas, such as Bristol, Liverpool and Leeds, and many suburban areas, but also include some of the most rural areas in the country. Meanwhile, Cluster 1, with 10 local authorities that are home to over 1 million people has the second slowest speeds in the morning compared to the evening 'peaks' and the second highest ratio of standard deviation to mean. This cluster's most populous area is Westminster in central London.

**further description of temporal profiles of other clusters - include all in graph?** Indeed, the only cluster where upload speeds were slower in the evening than in the morning was cluster 5, made up of 2 local authorities with less than 200,000 people: Three Rivers, a suburban district north of London, and Fylde, a seaside suburb of Blackpool. However, these are likely to be outliers and may not have many tests from which the clusters are calcualted. **Take out smaller clusters?** The exceptions can be found in seven of the eight much smaller clusters including 35 local authority districts, where AM peak upload speeds are between 6% and 18% slower than PM peak upload speeds, although the mean speeds for each cluster are higher than cluster 6. Indeed, in 25 local authorities with a combined population of almost 3 million, speeds are 13% or more slower in the morning than in the evening. Included in this latter group are central London borough of Westminster and the London Borough of Newham, rural authorities like Eden and West Devon, and small cities like Dundee and Carlisle.

### 5.2. *aux regressions*

Auxiliary regressions indicate that the speed tests in cluster 9 authorities are also more likely to have been run on services provided by Virgin Media, suggesting they are in the half of the country with the most lucrative ICT market, which originally attracted the cable TV provider (OfCom...). For example, although auxiliary regressions show that Cluster 6 local authorities are more likely to be in the South of the UK than Cluster 9, the cluster notably includes Southern rural districts from Cornwall to North Norfolk. Slower speeds could reflect the lower quality of service in rural areas compared to urban and suburban areas. There is frustration, however, as auxiliary regressions show that those living in cluster 6 had the highest probability of testing their broadband between 9:00 and 11:00 of any of the 10 upload speed clusters.

the finding in the auxiliary regressions that those in cluster 9 ran the fewest speed tests per person during the morning period of any cluster. Now this may be an indication of fewer people working from home, less contention, and less resultant frustration. Cluster 9 comprises many central urban areas and has the lowest number of established businesses per inhabitant, which could be interpreted as a dominance of large employers. However, the job density is lower than cluster 6, meaning there are not as many jobs per resident in these areas. As the cluster includes many suburban areas too, which may be largely residential, could the quality and reliability of internet service be reinforcing patterns of telecommuting by those in wealthier suburbs who can work from home? Earnings in cluster 9 are second highest of all the clusters, with only Cluster 2 (comprising just North East Lincolnshire and East Lothian, population 265k) earning more per person.

The auxiliary regressions show that compared to the two authorities in cluster 5, all the other clusters had a lower percentage of working people in managerial, professional and administrative jobs.??? Yet the auxiliary regression suggests that there are not many tests being run during the am peak in cluster 1. This may be because there are fewer people working at home checking their broadband than in most other clusters. Indeed, the auxiliary regressions indicate that cluster 1 has the highest job density or proportion of jobs to working-age population, which is likely to due to the presence of Westminster, central London, cluster 1's most populous local authority. Westminster not only has more workplaces than residents, but it is reasonable to presume that many who would normally work in Westminster, but be able to work from home during lockdown are likely to live outside central London and not be subject to the fluctuating speeds there. Workplaces, meanwhile, some of which would still have been open, could be running programmes that cause the slowdown and variation, but would be more likely to have their own in-house diagnostics, rather than using a service like Speedchecker Ltd.

## 6. Conclusions


### Acknowledgement(s)

An unnumbered section, e.g. `\section*{Acknowledgements}`, may be used for thanks, etc. if required and included *in the non-anonymous version* before any Notes or References.

### Funding

An unnumbered section, e.g. `\section*{Funding}`, may be used for grant details, etc. if required and included *in the non-anonymous version* before any Notes or References.


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## 7. Appendices

Any appendices should be placed after the list of references, beginning with the command `\appendix` followed by the command `\section` for each appendix title, e.g.

```
\appendix
\section{This is the title of the first appendix}
\section{This is the title of the second appendix}
```

produces:

**Appendix A. This is the title of the first appendix**

**Appendix B. This is the title of the second appendix**

Subsections, equations, figures, tables, etc. within appendices will then be automatically numbered as appropriate. Some theorem-like environments may need to have their counters reset manually (e.g. if they are not numbered within sections in the main text). You can achieve this by using `\numberwithin{remark}{section}` (for example) just after the `\appendix` command.

Please note that if the `endfloat` package is used on a document containing appendices, the `\processdelayedfloats` command must be included immediately before the `\appendix` command in order to ensure that the floats in the main body of the text are numbered as such.

## Appendix A. Troubleshooting

Authors may occasionally encounter problems with the preparation of a manuscript using LaTeX. The appropriate action to take will depend on the nature of the problem:

(i) If the problem is with LaTeX itself, rather than with the actual macros, please consult an appropriate LaTeX $2_\varepsilon$ manual for initial advice. If the solution cannot be found, or if you suspect that the problem does lie with the macros, then please contact Taylor & Francis for assistance (`latex.helpdesk@tandf.co.uk`).

(ii) Problems with page make-up (e.g. occasional overlong lines of text; figures or tables appearing out of order): please do not try to fix these using 'hard' page make-up commands – the typesetter will deal with such problems. (You may,

if you wish, draw attention to particular problems when submitting the final version of your manuscript.)
(iii) If a required font is not available on your system, allow TEX to substitute the font and specify which font is required in a covering letter accompanying your files.

## Appendix B. Obtaining the template and class file

### B.1. *Via the Taylor & Francis website*

This article template and the `interact` class file may be obtained via the 'Instructions for Authors' pages of selected Taylor & Francis journals.

Please note that the class file calls up the open-source LATEX packages booktabs.sty, epsfig.sty and rotating.sty, which will, for convenience, unpack with the downloaded template and class file. The template calls for natbib.sty and subfigure.sty, which are also supplied for convenience.

### B.2. *Via e-mail*

This article template, the `interact` class file and the associated open-source LATEX packages are also available via e-mail. Requests should be addressed to `latex.helpdesk@tandf.co.uk`, clearly stating for which journal you require the template and class file.