communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-021-00234-3 OPEN

Ground vibrations recorded by fiber-optic cables reveal traffic response to COVID-19 lockdown measures in Pasadena, California

Xin Wang[1,2,3], Zhongwen Zhan[3✉], Ethan F. Williams[3], Miguel González Herráez[4], Hugo Fidalgo Martins[5] & Martin Karrenbach[6]

The COVID-19 lockdown has unprecedently affected the dynamics of our society. As traffic flow is a good proxy for societal activity, traffic monitoring becomes a useful tool to assess the lockdown's impacts. Here we turned two strands of unused telecommunication fibers in Pasadena, California into a seismic array of ~5,000 sensors and detected ground vibrations caused by moving vehicles along the streets above the cable. We monitor the number of vehicles and their mean speed between December 2019 and August 2020 in high spatial and temporal resolution, and then analyze the traffic patterns change due to the COVID-19 lockdown. Our results show a city-wide decline in traffic volume and an increase in speed due to the lockdown, although the level of impact varies substantially by streets. This study demonstrates the feasibility of using telecommunication fiber optic cables in traffic monitoring, which has implications for public health, economy, and transportation safety.

[1] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. [2] CAS Center for Excellence in Deep Earth Science, Guangzhou, China. [3] Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA. [4] Department of Electronics, University of Alcalá, Polytechnic School, Alcalá de Henares, Spain. [5] Instituto de Óptica, CSIC, Madrid, Spain. [6] OptaSense Inc., Brea, USA. ✉email: zwzhan@gps.caltech.edu

Transportation is a critical component of people's lives. Therefore, traffic data has become an important manifestation of societal activity, and to some extent, social patterns. In particular, changes in traffic due to external forcing occur at broad time scales, from minutes or hours (e.g., accidents) to days (e.g., holidays and road constructions), even years (e.g., an economic boom or recession). The spatial pattern is often multi-scale as well, ranging from state-wide highway networks to local streets, from business centers to residential areas. Thus, multi-scale continuous traffic monitoring in high spatial and temporal resolution is critical for an accurate understanding of social patterns.

The outbreak of the Coronavirus Disease 2019 (COVID-19) pandemic has unprecedently affected all aspects of society. Due to the rapid and easy spread of COVID-19, governments around the world issued a series of guidelines and orders to slow down the spread of COVID-19, including social distancing, restrictions on large public gatherings, and state-wide lockdowns, etc. The COVID-19 pandemic and the accompanying measures brought massive changes to the way we live, work, and interact with each other. As traffic flow is a good proxy for societal activity, traffic monitoring becomes a useful tool to see how COVID-19 has changed our daily lives and how society has performed in preventing the virus spread[1–5].

To better monitor and manage traffic, a variety of technologies have been applied in the last decades, from stationary sensors (e.g., radar guns, manual counters, embedded roadway sensors, cameras) and onboard GPS systems (e.g., in-car sensors, mobile devices)[6,7]. The stationary sensors can provide high-accuracy and high-resolution traffic data, though they suffer from spatial sparseness due to the high costs of installation and maintenance. On-board GPS systems have higher spatial coverage, owing to the rapid development of wireless communication networks and widespread use of mobile phones in recent years; yet they suffer from low sampling rates. In particular, using mobile phone location data in traffic monitoring has major privacy concerns; inadequate sampling (some use location services other not, likewise some use Android others on iPhone) could result in biases according to cultural background, socioeconomic status, and habits[7]. Thus, the current traffic monitoring methods still face many challenges, as to provide large-scale continuous and accurate monitoring capability in high spatial and temporal resolution.

Distributed acoustic sensing (DAS) is an emerging technology that may be employed to overcome the above limitations to improve traffic monitoring[8,9]. DAS converts a standard single-mode optical fiber into an array of distributed sensors that can detect tiny vibrations from earthquake shaking, vehicles moving, etc. There have been several previous studies showing that DAS contains rich traffic information, including the low-frequency quasi-static deformation caused by vehicle loading and high-frequency (>3 Hz) surface waves radiated by vehicle-road dynamic interaction[10–17]. Previous studies have demonstrated the feasibility of using DAS to estimate the vehicle counts and vehicle speeds[13,17]. Thus, the high spatial resolution (meter-scale), high temporal sampling (up to 1 kHz), long-distance range (up to 50 km), and continuous running mode of DAS allows us to conduct large-scale continuous traffic monitoring in high spatial and temporal resolution[13,17–19]. Especially, by leveraging the pre-existing roadside telecommunication fibers in urban areas, we are able to conduct city-wide traffic monitoring in an affordable and scalable way.

In November 2019, the California Institute of Technology (Caltech) and the City of Pasadena, California cooperated to turn two strands of unused ~37 km telecommunication fiber cables in Pasadena, California into a city-wide DAS array (hereinafter referred to as the Pasadena DAS array, Fig. 1)[14]. The Pasadena DAS array continuously records strain measurements at an 8–10 m channel spacing with a total of ~5000 channels. In this study, we used the Pasadena DAS array to demonstrate the feasibility of DAS in traffic monitoring. In particular, the continuous operation mode and broad city-wide coverage of the Pasadena DAS array provide us a rare opportunity to understand the traffic patterns change due to the COVID-19 pandemic in multi-scales.

Results and discussion

Traffic monitoring using DAS. Here, we use DAS records to constrain two fundamental traffic parameters: traffic volume and mean speed. Traffic volume is defined as the total number of vehicles that pass a section of road during a given time period and the mean speed refers to the average speed of all the passing vehicles[6]. We take advantage of the array nature of DAS to estimate the traffic volume and mean speed using a beamforming technique (see Methods and Supplementary Figs. S1–S4). Figure 2 shows examples of traffic stream parameters estimated for one of the DAS subarrays located on an arterial street in Pasadena (E. Colorado Blvd., Fig. 1). Clear periodic patterns at different time scales (weekly and daily) and the effect of COVID-19 lockdown can be observed from the data. The large quantity of traffic data in high spatial and temporal resolution obtained by our method allows us to assess the impact on traffic patterns due to the COVID-19 lockdown across multiple scales.

Effect of COVID-19 lockdown on traffic patterns. The COVID-19 lockdown and the accompanying measures have undoubtedly affected the traffic, but by how much and on what temporal and spatial scale? A global-scale analysis of high-frequency seismic noise, presumably caused by human-related activities, shows that there was a ~50% drop of anthropogenic noise between March and May 2020, compared to pre-lockdown level[20–24]. Telematics data (e.g., Apple and Google mobility reports) also show that traffic in major cities around the world has declined by around 50–70% during the lockdown period, followed by a gradual rebound with the reopening of the economy (Fig. 3b)[1,2]. However, both the high-frequency noise and telematics measurements suffer from low spatial and temporal resolution and do not have real vehicle counts. Moreover, these measurements tend to be biassed toward some specifics, e.g., high-frequency noise measurement is highly related to the station location and the local geology, while the telematics data tend to be biased by the user behaviors (e.g., the difference in Apple and Google mobility reports in Fig. 3b). In contrast, our results contain objective and reliable measurements of vehicle volume and speed with a high spatial and temporal resolution, thus we can more precisely quantify the multi-scale impact on traffic patterns due to COVID-19 lockdown.

To examine how the COVID-19 lockdown has impacted the traffic, we chose one of the subarrays located on the arterial street in Pasadena (E. Colorado Blvd., Fig. 1) to show traffic volume changes over time. Before the lockdown, the traffic volume shows clear weekly cycles (except holidays) but remains largely constant, with an average daily traffic volume of 24,500 vehicles in working days. After the rapid increase of new COVID-19 cases in the middle of March and the implementation of state-wide lockdown order on 19 March, there was an abrupt ~40% drop in traffic volume compared to the pre-lockdown level (from 01 December 2019 to 18 March 2020; the pre-lockdown is referred to the aforementioned period unless otherwise specified). The initial decline in traffic volume preceded the official lockdown order by several days, coinciding with the rapid increase of new confirmed COVID-19 cases (Fig. 3). This suggests that the Pasadena

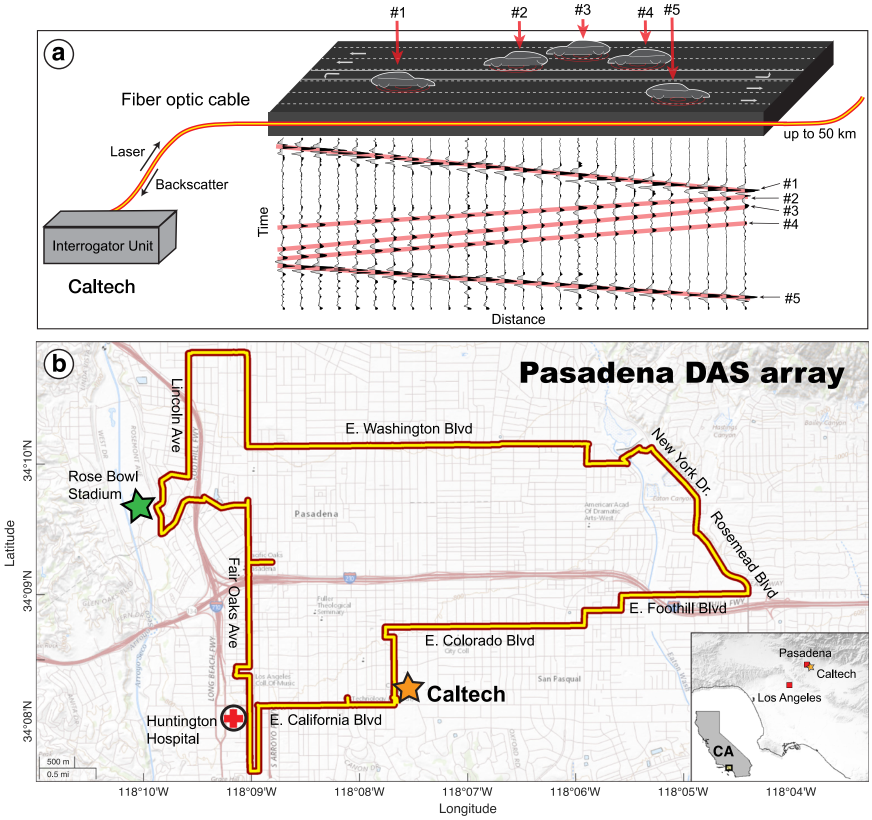

Fig. 1 The Pasadena distributed acoustic sensing (DAS) array. a The sketch shows the principle of traffic monitoring using DAS. DAS transforms an along-road fiber optic cable into a distributed array of seismic sensors. Vehicles moving along the road generate vehicle-loading quasi-static deformation that can be detected by the DAS array. The recorded signals (real data recorded by the Pasadena DAS array, filtered to 0.25–2.0 Hz) along the array represent the trajectory of moving vehicles, with the slope showing the vehicles' speed. **b** The map shows the locations of the Pasadena DAS array, with the symbols showing featured locations near the Pasadena DAS array. Basemap is generated by MATLAB geographic plotting functions and is hosted by Esri.

community responded quickly and spontaneously to the COVID-19 outbreak. After the dramatic initial drop, the daily traffic volume remained at a relatively low level for about 3 weeks, indicating the local residents were strictly following the "Stay-at-Home" order to help prevent the spread of the virus. Then, the traffic volumes have slowly crept upward since the middle of April. The increase in volume began about a month prior to the first loosening of lockdown orders on May 8th, suggesting that local residents' reactions to the "Stay-at-Home" order evolved over time. At the end date of our analysis on August 1, 2020, the traffic volume remained about 75% of its pre-lockdown level, due to the ongoing closure of schools and restrictions on business operations as the COVID-19 cases kept increasing.

In addition to the long-term variation, our traffic data reveals clear weekly and diurnal patterns, though the behavior is quite different before and after the COVID-19 lockdown (Fig. 3b, c). On a weekly scale, before lockdown, the traffic volume remains largely consistent from Monday to Saturday, with a sudden decline on Sunday. After the COVID-19 lockdown, the weekly cycle shows clear peaks from Thursday to Saturday. The periodic pattern is more pronounced in the first few weeks in April, which can be directly observed in the original data (Fig. 3). The periodic weekly pattern shows that people prefer to go outside on Friday and Saturday during the lockdown period, though the reasons and motivations are unclear. On a daily scale, the COVID-19 pandemic and accompanying "Stay-at-Home" order has caused a drop in traffic volume throughout the day, with the most substantial traffic volume reduction (~65%) observed during the morning and evening. During the daytime, the average traffic volume drop is less prominent (~20%), as essential business and travel are still ongoing. Here, we acknowledge that our traffic volume estimates tend to be saturated during the extremely rush hour (Supplementary Figs. S5–S7), thus the actual peak hour traffic change may be more substantial than the current estimates.

As our traffic data cover city-wide areas with a high spatial resolution (Fig. 1), we can quantify the effect of COVID-19 lockdown on traffic on different roads. We estimated the average daily (working days) traffic volume before and after lockdown order and then used their ratio to calculate the traffic volume change due to the COVID-19 lockdown. As shown in Fig. 4a, the COVID-19 pandemic and the accompanying "Stay-at-Home" order generally drove an average ~15% drop in traffic volume compared to the pre-lockdown level. However, the level of impact largely varies by road. We select six locations to provide a representative sample of city-wide traffic patterns (Fig. 4b–g). The most dramatic drop in traffic volume is on roads near Caltech, with an average of 50% (up to 65%) decrease in traffic volume throughout the day (Fig. 4g). While on the arterial streets, the traffic volume drop is on average 30% (Fig. 4e, f), with the largest traffic volume reduction during morning and night (up to 50%). The large drops in traffic volume in the morning and evening are expected, as fewer people are commuting for work and bars and restaurants are closed during the lockdown period. For some of the busiest roads in Pasadena (e.g., Fig. 4d), the traffic volume did not decline substantially from its pre-lockdown level, suggesting that essential business is still ongoing. In contrast, the traffic volume has increased near the main hospital, especially in the daytime (Fig. 4b), indicating that the hospital is seeing a surge in demand during the COVID-19 pandemic. Visualizing the data

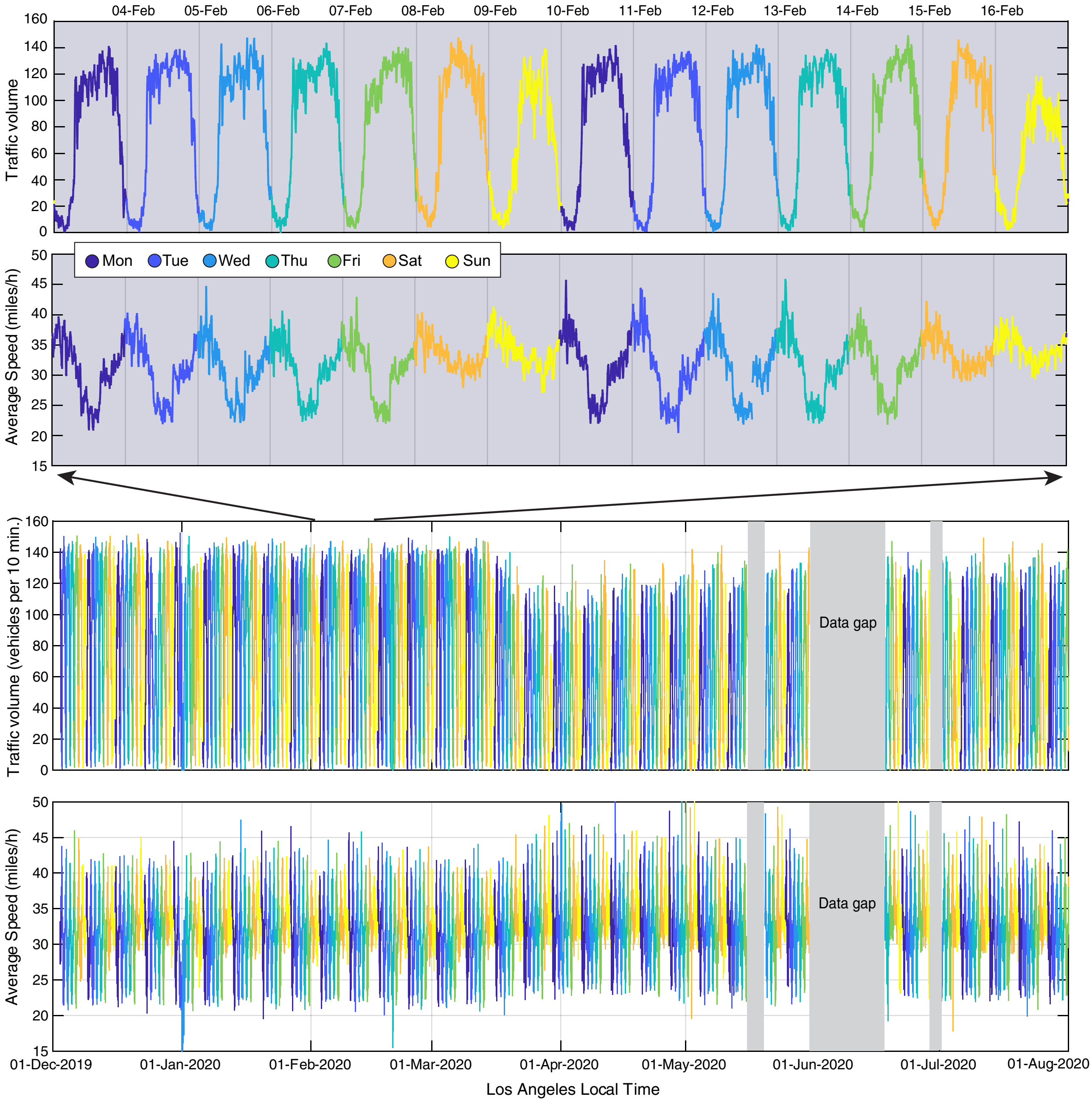

Fig. 2 Traffic stream parameter estimation results. The long-term variations of traffic parameters for one of the subarrays located on an arterial street in Pasadena (E. Colorado Blvd). A zoom-in figure is shown in the upper panel to highlight the periodic patterns at daily and weekly scales.

provides a clear assessment of where particular areas are mostly affected by the COVID-19 pandemic.

The dramatic drop in traffic volume during the COVID-19 lockdown period means less traffic congestion, potentially suggesting a higher mean traffic speed. We estimated the mean traffic speed before and after the lockdown order and then used their ratio to define the degree of traffic speed change due to the COVID-19 lockdown. Similar to the traffic volume, the level of impact on traffic mean speed largely varies by road. In general, there is very little change of speed before and after the lockdown on streets with pre-lockdown traffic speed already close to or slightly above the speed limit, suggesting that people still follow their travel behavior and drive as they normally do. On the other hand, a substantial traffic speed increase happens in areas where congestion normally occurs (Fig. 5). For example, on the road near the Huntington Hospital (Fig. 5b), the mean speed increased from below the speed limit before lockdown to close to the speed limit after the COVID-19 lockdown. This is mainly because fewer vehicles on the road lead to less congestion and allow traffic to move closer to its "free-flow" speed. Less congestion can be directly observed from the speed-volume relation (Fig. 5b–g), which describes how traffic behavior changes non-linearly as a function of traffic stream state[6]. On the speed-volume diagram, the uncongested traffic is shown on the top part of the curve; with the increase of traffic volume, traffic flow becomes saturate and the congestion happens, which causes the traffic speed to fall abruptly. The exact speed-volume dynamics for each street depend on the many factors (e.g., road design, traffic lights, and stop signs), but comparing the speed–volume before and after on each individual road shows that city-wide there is less congestion during the COVID-19 lockdown period (Fig. 5b–g). Visualizing the data provides a clear indication of congestion within the city,

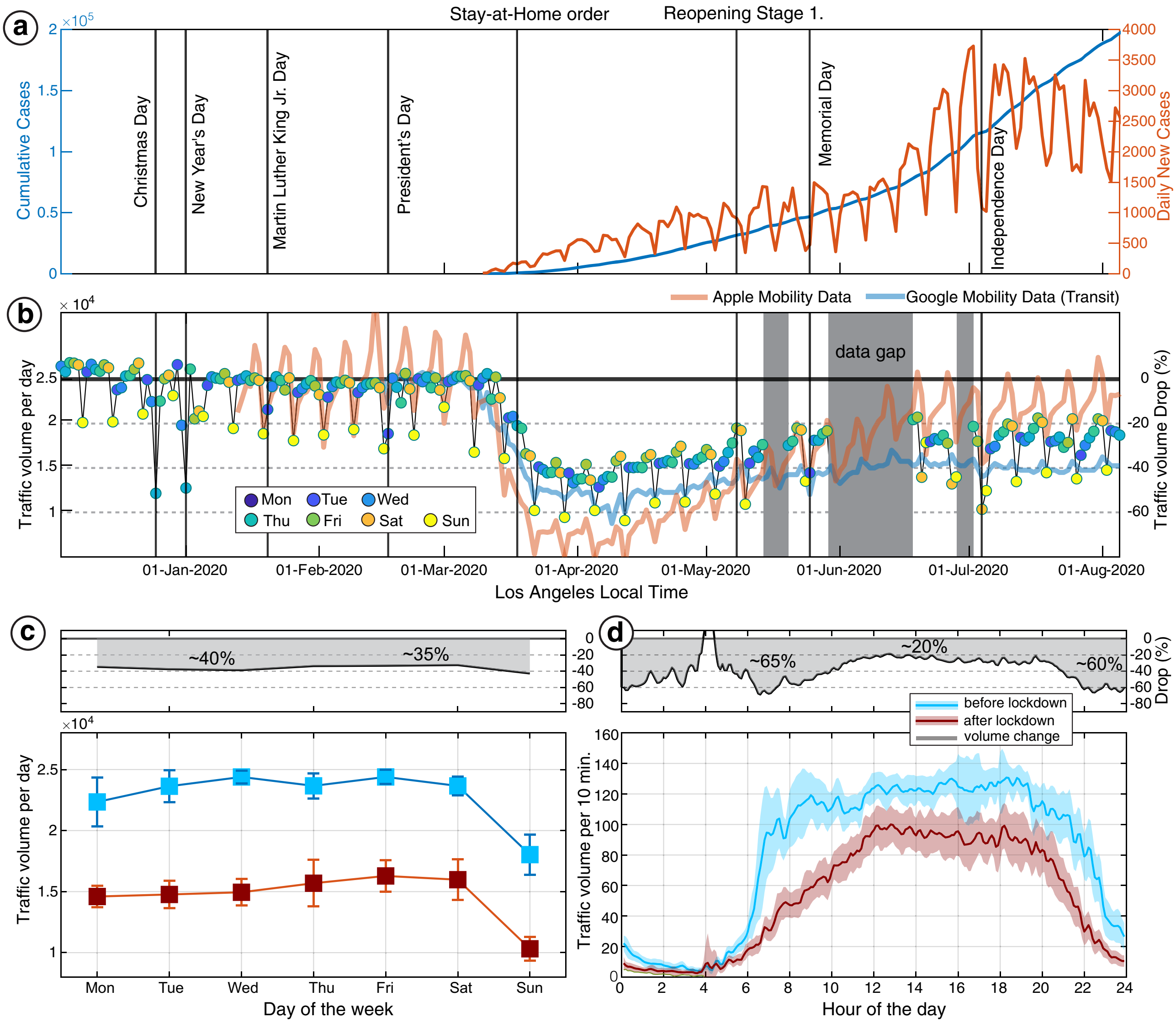

Fig. 3 The impact on traffic volume due to the COVID-19 pandemic in multiple time scales. a The daily new confirmed COVID-19 cases and cumulative COVID-19 cases in Pasadena, CA, sourced from ref. [28]. **b** The long-term variations of daily traffic volumes are shown as circles, colored by the day of the week. The vertical lines mark several important dates during the observation period. The pink and blue lines show the Apple (Region: Los Angles; Type: Driving) and Google (Region: Los Angles, Type: Transit) mobility reports, respectively. Note the Apple and Google mobility reports are only available at urban and/or regional scales. **c** The weekly patterns of daily traffic volume before and after the lockdown order, with the gray shadowed region shows the traffic volume change compared to the baseline (pre-lockdown level). **d** Similar to (**b**), but for the diurnal periodic pattern. The error bars represent one standard deviation.

which allows city Department of Transportation engineers to better understand the performance of each section of the road.

The consistency between our study and the conventional measurements by the Department of Transportation (Supplementary Figs. S5–S7) and the mobility reports (Fig. 3b) demonstrates the feasibility of using pre-existing telecommunication fiber-optic cables in traffic monitoring. In a similar DAS-based traffic monitoring study[13], Lindsey et al. (2020) analyzed the low-frequency quasi-static ground deformation caused by moving vehicles along a DAS array in Palo Alto, CA, and employed a template matching detection algorithm to estimate the traffic volume and its response to the COVID-19 lockdown. However, due to the need for different templates for each channel and day in their methods[13], they only studied two representative locations along with the DAS array over the early days of the lockdown. Moreover, their method can only provide traffic volume estimates. In comparison, we estimated both traffic volume and speed for each section of the fiber, and thus our results contain detailed city-wide traffic patterns and allow us to conduct the congestion analysis to understand the spatial variation of traffic dynamics. Finally, using longer durations of data, we have captured the response of traffic patterns to the COVID-19 lockdown at several time scales, from changes in daily/weekly routines to long-term recoveries.

Conclusion

The COVID-19 pandemic and accompanying measures have brought massive changes to our daily lives. In this study, we conduct city-wide high spatial and temporal resolution traffic monitoring using a 37-km long DAS array in Pasadena, California to understand changes in traffic patterns due to the COVID-19 lockdown. Our results show that there in general has been a decline in traffic volume and an increase in speed city-wide compared to the pre-lockdown level, however, the level of impact

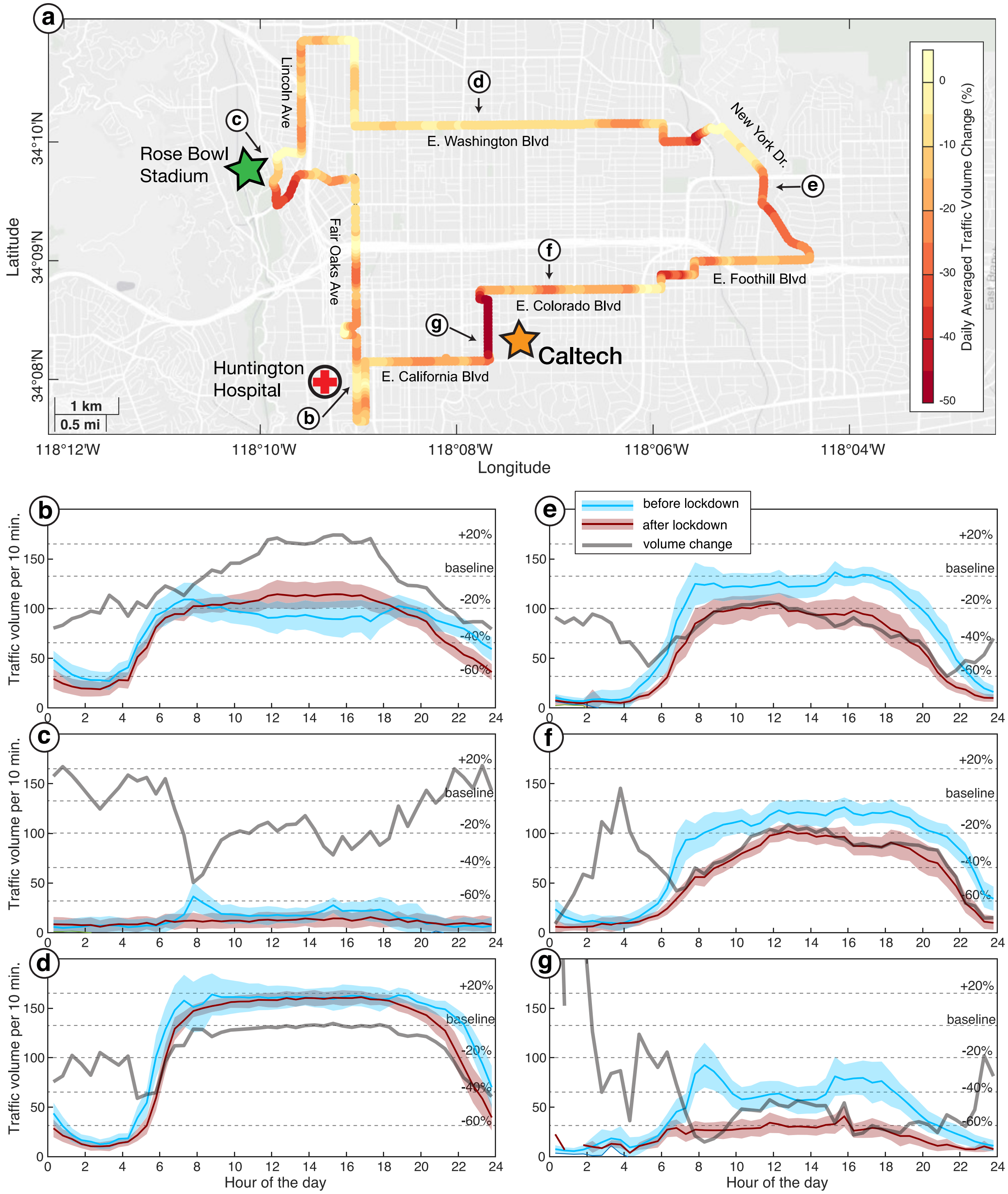

Fig. 4 The impact of traffic volume due to the COVID-19 pandemic on different roads. a The map shows the average daily traffic volume change before and after the lockdown from DAS-based transportation analysis. **b–g** Diurnal periodic patterns before and after the lockdown at six representative locations city-wide, with their locations shown in (**a**). The gray lines show the traffic volume change due to the COVID-19 pandemic, compared to the baseline (pre-lockdown period). The error bars represent one standard deviation. Basemap is generated by MATLAB geographic plotting functions and is hosted by Esri.

largely varies by region and time. The most dramatic drop in traffic volume is near university campuses (up to 60%); while the traffic volume drop is less on arterial streets, as the essential business and traveling are still ongoing. In contrast, the road near the hospital shows a clear increase in traffic volume after the COVID-19, suggesting that the hospital is seeing a surge in demand during the COVID-19 pandemic. In terms of traffic mean speed, very little change of speed happens to streets that were already close to or slightly above the speed limit, while the most noticeable traffic speed changes come in areas where

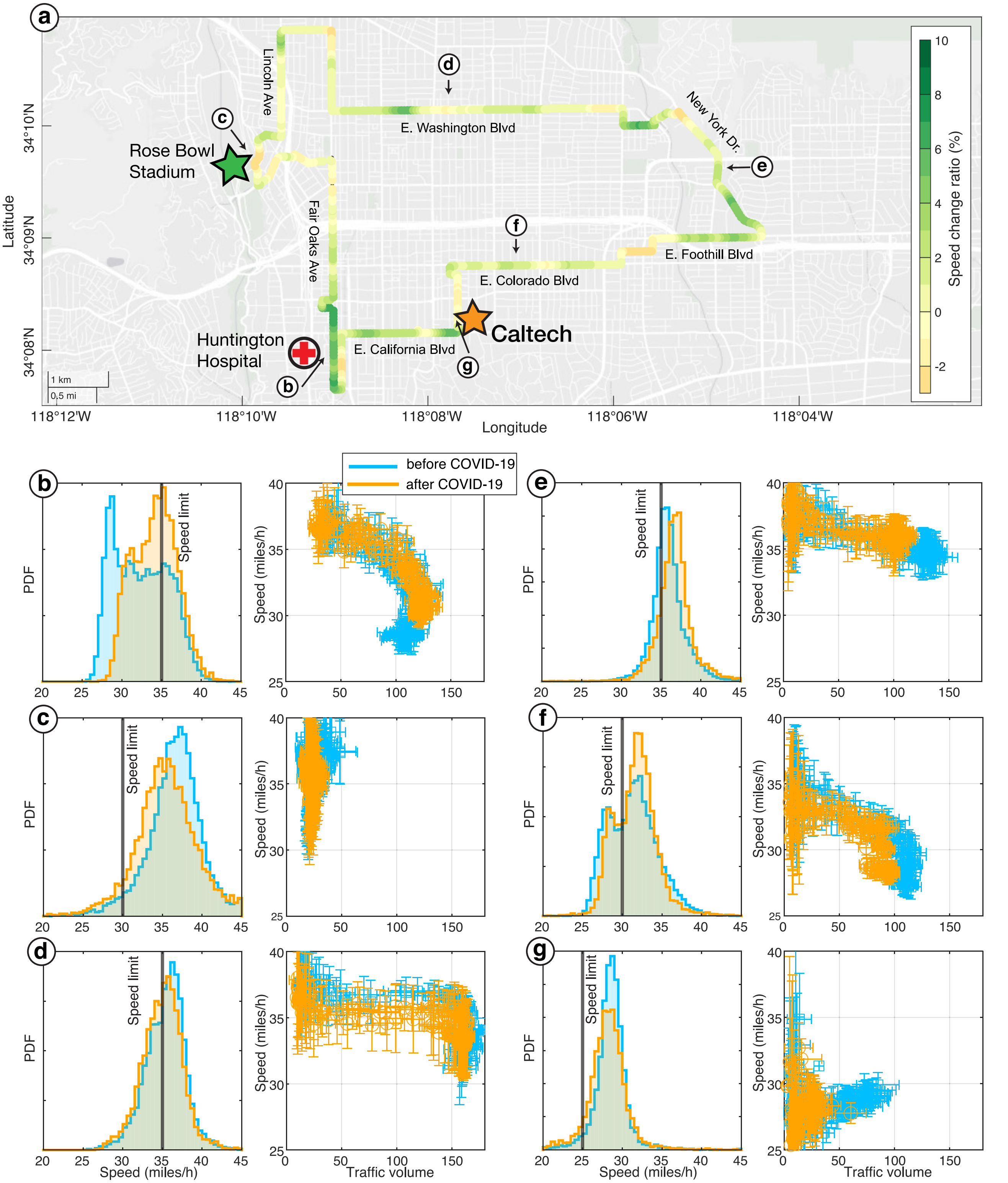

Fig. 5 The impact on traffic mean speed due to the COVID-19 pandemic on different roads. a The map shows the degree of mean traffic speed change before and after the lockdown from DAS-based transportation analysis. **b**–**g** Mean speed and speed–volume relation before and after the lockdown. The black lines show speed limits on each road. The error bars represent one standard deviation. Basemap is generated by MATLAB geographic plotting functions and is hosted by Esri.

congestion normally occurs. The change in speed is mainly due to fewer vehicles on the road, which has less congestion and allows traffic to move closer to its “free-flow” speed. The change in traffic patterns before and after the COVID-19 pandemic will help governments determine the impact of COVID-19 on traffic in different locations, and has potential implications for public health, the economy, traffic safety. This study also demonstrates the feasibility of using pre-existing telecommunication fiber optic cables in traffic monitoring. The objective, accurate, reliable, and continuous traffic data obtained by DAS allow the city

Department of Transportation engineers to assess the performance of the current state of each road, which ultimately leads to improvement in designing further roads and transportation efficiency.

Methods

In this study, we take advantage of the array nature of DAS to estimate the traffic volume and mean speed using a beamforming technique. More than 50 TB of continuous DAS data were recorded by the Pasadena DAS array during the nine-month study period (2019/12–2020/8). For our analysis, we divided the continuous DAS time series into 10-min segments with 25% overlapping to reduce the variance of the traffic estimation. For each 10-min segment, we removed the linear trend, the mean value, and the common-mode noise following the standard DAS processing procedures[25]. We filtered the data with a bandpass filter of 0.25–2.0 Hz for vehicle identification, as spectrogram analysis shows clear traffic signals within this frequency band (Fig. S1). We then divided the entire DAS array into overlapping sub-arrays, with each sub-array containing 21 channels sliding every 5 channels. For each sub-array, we first conducted data quality control by removing those channels with a cross-correlation coefficient with adjacent channels smaller than 0.5. We then used 4th root slant stacking[26] to estimate the vehicle speed over the 15 mph (~24 km/h) to 80 mph (~128 km/h) speed range (Fig. S2). Instead of tracking individual vehicles, this study aims to focus on the statistical behavior of traffic parameters. Thus, we use local maxima analysis to find the peaks whose amplitude is above the average amplitude to estimate the vehicle counts and mean speed per 10 min (Fig. S2). However, the local maxima analysis tends to underestimate the traffic volume if vehicles are passing in close proximity of each other (e.g., during rush hour, Fig. S2). Thus, we measure the duration of the signal over the median value of the minimal identified peaks from the local maxima analysis (Fig. S3), and we convert the duration to traffic volume using the averaged statistical duration of a single vehicle (Fig. S4).

To verify the accuracy of our method, we compared our DAS-based traffic volume data with the real traffic counts from the Traffic Count Database System from the Department of Transportation (DOT), Pasadena[27]. Note that the DOT traffic counts were measured using stationary devices, thus the DOT measurements are only available at sparse locations and at particular dates (the exact counting date of each measurement is based on the DOT's schedule), due to the high costs of installation and maintenance. We used the pre-lockdown (from 01 December 2019 to 19 March 2020) DAS-based traffic volume data to calculate mean diurnal (working days) traffic volume, and we randomly selected 10 representative DOT locations across the entire fiber path (TCDS counting dates within 2010-2020, as we do not have concurrently operated stationary sensors for a direct comparison) and used the nearest DAS channel for comparison. Calibration with the real traffic counts data from the DOT shows that our method can generally resolve the traffic volume (Figs. S5-S7), though some of the locations show clear differences between the two studies (e.g., DOT6 and DOT9 shown in Fig. S7). As the DOT measurements were conducted at a particular date, the difference in DOT measurements and our study could be due to the long-term evolution of traffic volumes with the development of economy, population, travel habits, etc., and/or the short-term variation of traffic volumes due to the weather conditions or other stochastic processes (Figs. S8–S10), as well as the limitations of dark fiber installations (e.g., coupling, cable position, the multi-lane road against a single road-side fiber). To better estimate, the traffic volume, including the amplitude information, high-frequency signals, or using more sophisticated methods (e.g., machine learning) is required, which will be left for further studies.

Data availability

The obtained traffic data (in MATLAB format, a MATLAB script is also provided to load and plot the data) in this study can be downloaded from CaltechDATA achieve at https://doi.org/10.22002/D1.2022.

Code availability

The codes used in this study are available from Dr. Xin Wang (wangxin@mail.iggcas.ac.cn) upon reasonable request.

Received: 12 April 2021; Accepted: 23 July 2021;
Published online: 11 August 2021

References

1. Apple. Mobility Trends Reports. https://www.apple.com/covid19/mobility (2020).
2. Google. COVID-19 Community Mobility Reports. https://www.google.com/covid19/mobility/ (2020).
3. Li, Y. E., Nilot, E., Zhao, Y. & Fang, G. Seismology for urban activity monitoring in Singapore under the impact of COVID-19. OSF Preprints https://doi.org/10.31219/osf.io/tvj2w (2020).
4. Moslem, S. et al. Best–worst method for modelling mobility choice after COVID-19: evidence from Italy. *Sustainability* **12**, 6824 (2020).
5. Parr, S., Wolshon, B., Renne, J., Murray-Tuite, P. & Kim, K. Traffic impacts of the COVID-19 pandemic: statewide analysis of social separation and activity restriction. *Nat. Hazards Rev.* **21**, 04020025 (2020).
6. Hall, F. L. Traffic stream characteristics. *Traffic Flow Theory. US Federal Highway Administration* **36** (1996).
7. Järv, O., Ahas, R., Saluveer, E., Derudder, B. & Witlox, F. Mobile phones in a traffic flow: a geographical perspective to evening rush hour traffic analysis using call detail records. *PloS ONE* **7**, e49171 (2012).
8. Zhan, Z. Distributed acoustic sensing turns fiber-optic cables into sensitive seismic antennas. *Seismol. Res. Lett.* **91**, 1–15 (2019).
9. Lindsey, N. J. & Martin, E. R. Fiber-optic seismology. *Annu. Rev. Earth Planet. Sci.* **49**, 309–336 (2021).
10. Dou, S. et al. Distributed acoustic sensing for seismic monitoring of the near surface: a traffic-noise interferometry case study. *Sci. Rep.* **7**, 1–12 (2017).
11. Jousset, P. et al. Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. *Nat. Commun.* **9**, 2509 (2018).
12. Ajo-Franklin, J. B. et al. Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection. *Sci. Rep.* **9**, 1–14 (2019).
13. Lindsey, N. J. et al. City-scale dark fiber DAS measurements of infrastructure use during the COVID-19 pandemic. *Geophys. Res. Lett.* **47**, e2020GL089931 (2020).
14. Wang, X. et al. Rose parade seismology: signatures of floats and bands on optical fiber. *Seismol. Res. Lett.* **91**, 2395–2398 (2020).
15. Yuan, S., Lellouch, A., Clapp, R. G. & Biondi, B. Near-surface characterization using a roadside distributed acoustic sensing array. *The Leading Edge* **39**, 646–653 (2020).
16. Shen, J. & Zhu, T. Seismic noise recorded by telecommunication fiber optics reveals the impact of COVID-19 measures on human activity. *Seismic Rec.* **1**, 46–55 (2021).
17. Chambers, K. Using DAS to investigate traffic patterns at Brady Hot Springs, Nevada, USA. *The Leading Edge* **39**, 819–827 (2020).
18. Liu, H. et al. Traffic flow detection using distributed fiber optic acoustic sensing. *IEEE Access* **6**, 68968–68980 (2018).
19. Hall, A. J. & Minto, C. Using fibre optic cables to deliver intelligent traffic management in smart cities. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making*. 125–131 (ICE Publishing, 2019).
20. Lecocq, T. et al. Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures. *Science*. **369**, 1338–1343 (2020).
21. Poli, P., Boaga, J., Molinari, I., Cascone, V. & Boschi, L. The 2020 coronavirus lockdown and seismic monitoring of anthropic activities in Northern Italy. *Sci. Rep.* **10**, 1–8 (2020).
22. Xiao, H., Eilon, Z. C., Ji, C. & Tanimoto, T. COVID-19 societal response captured by seismic noise in China and Italy. *Seismol. Res. Lett.* **91**, 2757–2768 (2020).
23. Guenaga, D. L., Marcillo, O. E., Velasco, A. A., Chai, C. & Maceira, M. The silencing of U.S. campuses following the COVID-19 response: evaluating root mean square seismic amplitudes using power spectral density data. *Seismol. Res. Lett.* **92**, 941–950 (2021).
24. Cannata, A. et al. Seismic evidence of the COVID-19 lockdown measures: a case study from eastern Sicily (Italy). *Solid Earth* **12**, 299–317 (2021).
25. Lindsey, N. J., Rademacher, H. & Ajo-Franklin, J. B. On the broadband instrument response of fiber-optic DAS arrays. *J. Geophys. Res.* **125**, e2019JB018145 (2020).
26. Rost, S. & Thomas, C. Array seismology: methods and applications. *Rev. Geophys.* **40**, 27 (2002).
27. Traffic counts from the Department of Transportation, Pasadena. https://www.cityofpasadena.net/transportation/traffic-engineering-operations/#traffic-volumes (2020).
28. Pasadena COVID-19 Cases Dashboard. https://www.cityofpasadena.net/covid-19/#dashboard (2020).

Acknowledgements

We thank the City of Pasadena for contributing its fiber optic cables to our research. The DAS instruments used in this study were provided by the OptaSense, University of Alcala, and Aragon Photonics. We thank Lisa LaFlame, Victor Yartsev, Steve Cole, and Vlad Bogdanov for their assistance in acquiring the data used in this study. We are grateful for numerous discussions with people in the Department of Transportation, Pasadena. We are also grateful to the editor, reviewer Yunyue Elita Li, and two anonymous reviewers for their suggestions and comments, which help improve the quality of this paper. This work is supported by NSF CAREER award #1848166; the Young Elite Scientists Sponsorship Program by CAST (grant 2020QNRC001); the Key Research Program of the Institute of Geology & Geophysics, CAS (grant IGGCAS-201904); the Spanish MICINN (RTI2018-097957-B-C31, RTI2018-097957-B-C33); the European

Research Council (OCEAN-DAS: ERC-2019-POC-875302). The work of HFM was supported by MINECO ("Juan de la Cierva" postdoc contract IJCI-2017-33856).

Author contributions

X.W. and Z.Z. conceived the main ideas, led the project, and wrote the initial draft of the paper. X.W., Z.Z., E.F.W., M.G.H., H.F.M. and M.K. discussed the results and contributed to the writing of the final paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-021-00234-3.

Correspondence and requests for materials should be addressed to Z.Z.

Peer review information Communications Earth & Environment Materials thanks Yunyue Elita Li, Siyuan Yuan and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Clare Davis.