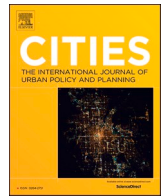




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Spatio-temporal variations of traffic congestion under work from home (WFH) arrangements: Lessons learned from COVID-19

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ABSTRACT

Traffic congestion has been a persistent problem in cities globally. Theoretically, commuting-related congestion can be relieved by promoting working from home (WFH). Amid the COVID-19 pandemic, WFH arrangement has been encouraged or enforced to reduce the spread of the coronavirus. Under these circumstances, it was reported that traffic congestion has been alleviated in many cities. However, changes in congestion patterns within a city have not been studied in-depth. In this study, we analysed the congestion index (CI) at peak hours, when commuting-related congestion is typically most serious, throughout different waves of the pandemic in Hong Kong. Results show that under WFH arrangement, peak-hour congestion has been alleviated. Within a day, morning peak congestion was more relieved. Spatially, significant drops in CI were found not only in the central business district and urban cores but also in some new town areas. This paper has significant implications for urban planners in creating more sustainable cities that duly consider the commuting needs of residents, and cautions against the optimism that WFH can relieve urban transport problems despite jobs-housing imbalance. While the WFH arrangement has potentials to ease commuting congestion, future e-working and transport measures need to take spatial and temporal dimensions into account.

1. Introduction

Traffic congestion has been studied as a common problem in cities worldwide (Arnott et al., 2005; Hamilton et al., 2013). Despite various measures to enhance network capacity and to reduce traffic demand, commuting peak traffic congestion is still persistent and causes unsustainable externalities (Sutton, 2015). The stress associated with severe traffic congestion can affect the wellbeing of the urban population; and understanding the geographical pattern of congestion is important for formulating effective policies (Zhao & Hu, 2019). With the development of information communications technology (ICT), working from home (WFH) has been seen as a technically feasible alternative solution in relieving the urban commuting peaks (Loo & Wang, 2018; Nilles et al., 1976). The practice, however, was not widely adopted until the outbreak of the COVID-19 pandemic. With COVID-19, human mobility and activity patterns have been severely disrupted. Since the outbreak of the COVID-19 pandemic, the number of WFH workers, e-workers or teleworkers has soared to an unprecedented level under various lockdown or confinement measures (Katherine & Isabel, 2020; Milasi et al., 2020). In this paper, WFH workers are defined loosely as full-time or

part-time workers who have designated work places but are not working at these places for a substantial portion of their working hours (Gajendran & Harrison, 2007; Gray et al., 1996; Loo, 2012; Martin & MacDonnell, 2012). During COVID-19, the sudden increase in WFH was mainly associated with government- or employer-imposed measures of closing down work places or restricting employees to work at regular work places. Though face-to-face working style is still the mainstream in the following COVID period, it is expected that WFH arrangement would become more widely practised in the longer term, rather than just being a stop-gap measure (Bonacini et al., 2021; Jain et al., 2022). Notably, several companies (e.g., Twitter, Facebook) have already introduced permanent WFH policies (Ian, 2020). When the work arrangements change, people's travel activities and the road traffic pattern can change substantially.

WFH, telecommuting or e-working, as an alternative working style supported by ICT, has emerged since the 1970s (Loo, 2012; Mokhtarian, 1991b). Initially, it was proposed as a potential solution to reduce the number of trips to alleviate traffic congestion and improve air quality (Bernardino et al., 1993; Mokhtarian, 1991a). With the development of ICT, WFH has also been proposed in relation to the smart cities

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development recently (Cheng et al., 2022; Hopkins & McKay, 2019; Xinhua, 2020). Different from the conventional working style, WFH is more flexible regarding work locations and working hours (Kwan, 2007). Over the years, scholars have attempted to investigate the impacts of home-based e-working on traffic (Andreev et al., 2010; Giovanis, 2018; Nilles, 1988; Zhen & Wei, 2008). Existing literature generally suggests that the promotion of WFH can alleviate urban commuting congestion (Loo & Wang, 2018; Mitomo & Jitsuzumi, 1999). However, among these studies, the focus was mainly on changes in travel behaviour, while the changes in road traffic situation *per se* have received limited attention. In other words, the literature has proved inconclusive in terms of the effectiveness of WFH arrangement on congestion alleviation (e.g. speed, travel time). Furthermore, existing studies usually concentrate on the entire city, while less attention was given to the spatio-temporal variations of traffic under the WFH arrangement (Rhee, 2008). Though telecommuting or e-working has been advocated for decades, the adoption rate was low before the outbreak of the COVID-19 pandemic (Belzunegui-Eraso & Erro-Garcés, 2020). Consequently, results may not be able to depict the traffic situation under large-scale or territory-wide WFH arrangement. In this study, the major contribution is to provide some empirical evidence through revealing changes in road conditions under WFH arrangement throughout a city. Shifting from travel behaviours to road conditions, changes in road traffic can more directly reflect the effectiveness of WFH arrangement for relieving road traffic congestion.

Since the outbreak of COVID-19, many scholars have examined changes in transport systems (Hendrickson & Rilett, 2020). In this study, Hong Kong is selected to explore changes in peak-hour congestion during the COVID-19 pandemic. Unlike other cities, the Government of the Hong Kong Special Administrative Region (HKSAR) has never implemented a full lockdown policy within the city (Wong et al., 2020). Despite the imposition of various confinement measures (e.g. WFH arrangement, border closure, group gathering limitation, and special restaurant opening hours), movements within the city have largely been unrestricted. In other words, while the WFH requirement was implemented across both the private and public sectors during specific periods, Hong Kong residents were relatively free to make local trips. Moreover, with heavy border restrictions, tourists have been largely reduced in the city. Hence, changes in the road traffic pattern are mainly reflecting behavioural changes of Hong Kong residents. It is anticipated that under the city-wide WFH policy but without lockdown measures or local travel restrictions, results from this “large-scale WFH experiment” can provide innovative insights on changes in road traffic, thereby furnishing policy implications to address urban traffic congestion.

To evaluate variations of the intensity of congestion, an indicator, namely the congestion index (CI), is used. This study aims to answer this main research question: How have the spatio-temporal patterns of the CI changed in the city under the WFH arrangement? The article is organized as follows. The study background and research questions are provided in the next section. Then, the data and methodology are explained. In Section 4, statistical tests of the level of congestion differences are conducted at different spatial scales and different periods. The last section discusses the lessons learned.

2. Background

2.1. Literature review

Scholars and policymakers have endeavoured to address the severe urban traffic congestion after realising its negative impacts (Downs, 1992). As increasing the transport system capacity only cannot solve traffic jams (Arnott & Small, 1994), traffic demand management has been extensively investigated. For instance, congestion charging has been regarded as one of the effective remedies (Gu et al., 2018; Noordeggraaf et al., 2014). After the implementation of congestion charging in Singapore, London, and Stockholm, a plethora of studies have examined

the impacts of the policy on road conditions (Eliasson, 2008; Santos, 2005; Santos & Shaffer, 2004; Tuan Seik, 2000). Similarly, the impact of vehicle restriction policy on traffic conditions has been scrutinized (Li & Guo, 2016; Liu et al., 2018). These studies on changes in traffic conditions (e.g. speed, travel time) are valuable in understanding of the effectiveness of congestion relief policies. Albeit many have believed that WFH is also a feasible solution in ameliorating traffic congestion (Eldér, 2020), research focusing on the direct nexus between WFH and traffic conditions has still been rare (Hopkins & McKay, 2019). And the effectiveness of WFH arrangement on relieving urban traffic jams is still questionable.

Over the past decades, the impacts of ICT on transportation have received much scholarly attention (Cheng et al., 2022; Mokhtarian, 1990, 1991b; Salomon, 1986). Theoretically, there are three main types of impacts of ICT on travels, namely substitution, complementarity, and modification or neutrality (Salomon, 1986). Travels, in turn, are heavily dependent on activity type and locations. And the trichotomy of activities, namely mandatory, maintenance, and discretionary, is widely adopted in the existing literature (Andreev et al., 2010). Specifically, mandatory activities are work-related or school activities, maintenance activities aim to satisfy physiological needs, and discretionary activities refer to leisure activities (Andreev et al., 2010). As a potential solution to ease commuting congestion, empirical studies have attempted to understand changes in travel behaviour of WFH workers. For instance, based on a questionnaire survey, Kitamura et al. (1990) found that trips were reduced during peak hours among WFH workers in California. Similarly, relying on travel diary data, Mokhtarian and Varma (1998) concluded that travel distance has been reduced significantly among WFH workers under the Neighborhood Telecenters Project. In Sweden, Eldér (2020) used the Swedish National Travel Survey to investigate the impacts of WFH on travel behaviours. The study shows that travels of WFH participants were reduced throughout the day and congestion relief can be achieved under the WFH arrangement. Besides, some studies have found support for the complementarity effect of WFH on travels. He and Hu (2015) argued that more trips were generated among WFH workers by analyzing a set of 2007 Chicago Regional Household Travel Survey data. All of these studies have provided valuable insights in understanding the impacts of WFH on travel behaviour theoretically and empirically, but there is still a significant research gap. Results of these studies were mainly dependent on survey/questionnaire data, impacts on empirical traffic conditions (e.g. speed) were not fully depicted. Specifically, existing studies mainly focused on travel behaviours of telecommuters and their households, while traffic conditions-related indicators have not been fully investigated. Deciphering the changes in traffic conditions can reflect the impacts of WFH on the whole society (i.e. beyond telecommuters). Existing studies on WFH also merely mentioned briefly about spatial variations within a city. Yet, the geographical pattern of congestion is important for formulating transport and planning-related measures and policies (Ma et al., 2017; Zhao & Hu, 2019). Hence, this study aims to fill the current research gap by revealing the spatial-temporal variations of traffic conditions under WFH during the COVID-19 pandemic.

2.2. The local context

According to the Transport and Housing Bureau (2017), 90% of the passenger trips in Hong Kong are made through public transport services, which is among the highest in the world. Among these, buses, railways, and taxis accounted for 48%, 44%, and 7%, respectively (Transport Department, 2017). Yet, similar to many global cities, traffic congestion is still a severe problem that decision-makers and planners cannot ignore. To tackle this, various remedies have been proposed and implemented over the years. To expand the road transport capacity, more than ten tunnels, bridges, and highways have been constructed over the last two decades (e.g. Western Harbour Crossing, Route 8, Central-Wan Chai bypass tunnel, etc.). However, as suggested by the

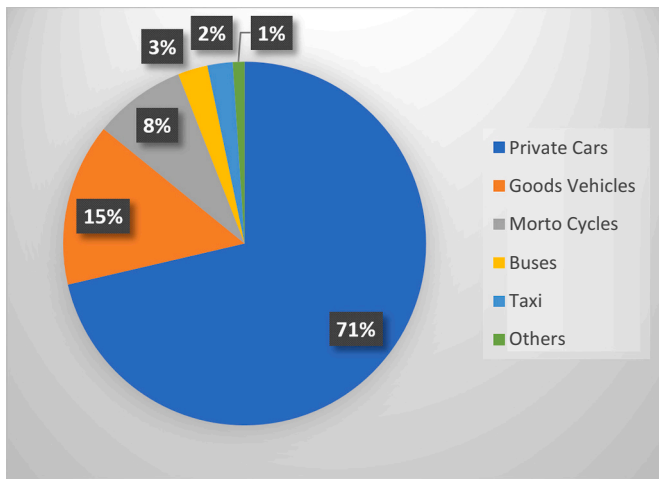


Fig. 1. Classes of vehicles in Hong Kong 2021.
 Notes: There are 802,265 licensed vehicles in Hong Kong. Buses include public buses, private buses, public light buses, and private light buses. Others are special purpose vehicles and Government vehicles.
 Source: td.gov.hk.

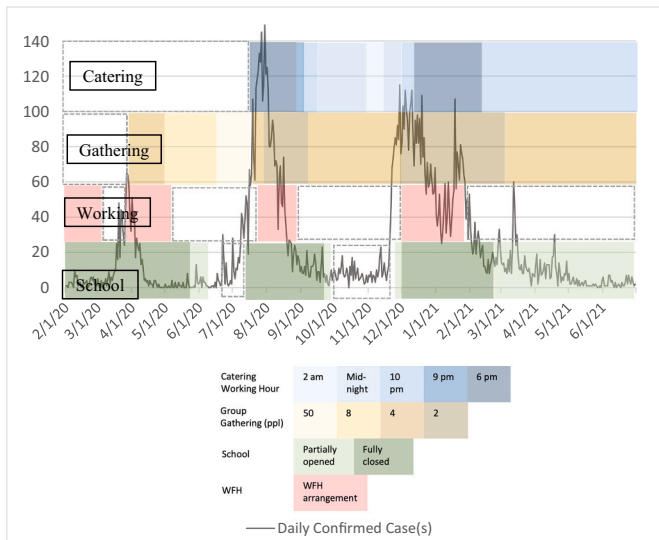


Fig. 2. Confinement measures in Hong Kong during COVID-19.
 Source: info.gov.hk.

Pigou Knight-Downs paradox, building new roads alone will not reduce traffic congestion, and it may become worse on the contrary (Arnott & Small, 1994). This situation occurred in Hong Kong as well. Up to 2018, the total number of licensed vehicles has increased by 36.4% and 56.7%, compared to 2008 and 1998, respectively (Transport Department, 2019). To tackle the increasing number of vehicles on the road, the government raised the first registration tax for private cars in 2011. Moreover, the railway network has been extended to reduce the burden of road transport (Loo et al., 2017). Nonetheless, as of January 2021, private cars still accounted for the majority of licensed vehicles in Hong Kong with a high percentage of 71%, and goods vehicles followed at 15% (shown in Fig. 1). During rush hours, private cars and taxis contributed most to traffic congestion (Transport Department, 2019). The underlying jobs-housing imbalance, similarly found in many cities, has led to a strong uni-directional commuting flow to the central business district and severe congestion at strategic roads during peak hours (Loo & Chow, 2011). For a long time, urban planners have tried to decentralize jobs and reduce excess commuting but without much

success (Kim & Choi, 2019). Though WFH during COVID-19 has aroused the attention of some scholars (Vyas & Butakhieo, 2020), the effectiveness of WFH arrangement on relieving urban traffic jams has not been examined in close detail.

2.3. COVID-19 and city-wide WFH arrangement

As of 31 July 2021, one year and a half after the first COVID-19 infection case was detected in Hong Kong, there were a total of 11,984 confirmed cases (Data, 2021), and the confirmed cases per million population rate was about 1584. During the pandemic, the HKSAR government has adopted the “suppress and lift” strategy to implement confinement measures in light of the number of newly confirmed cases (HKSAR Government, 2020). Within the city, there were four main types of confinement measures, namely school closure, WFH arrangement, group gathering limitations, and restriction on restaurant and bar operations and/or operating hours. These four types of measures are shown with a green, pink, gold, and blue background respectively in Fig. 2 (detailed measures are provided in Table 5 in the Appendix A). Moreover, the darker the colour, the stricter the restriction measures. For instance, the number of persons allowed in group gatherings in public places was 2, 4, 8, and 50 in different periods. For gathering, the darkest gold background stands for the periods of 2-person restriction, while the lightest gold represents the 50-person restriction. Gray dash line boxes delineate the periods when the relevant type of measures was not implemented. It is observed that gathering and catering-related measures were implemented consecutively since 29 March and 15 July 2020, respectively. Regarding school closures and the WFH arrangement, there were different waves of measures implementation. Nonetheless, the HKSAR government did not implement a full lockdown policy within the city so far (Loo et al., 2021; Wong et al., 2020). Throughout the study period, citizens were allowed to travel within the city without any restrictions.

Again, Hong Kong has not been the only city implementing these confinement measures. Many governments have introduced non-pharmaceutical interventions (NPIs) such as social distancing, bans on mass gathering, school closure, and WFH arrangements to reduce the risk of disease transmission. These NPIs have various impacts on the economic, environmental, and social domains (Atkeson, 2020; Le Quéré et al., 2020; Li et al., 2020; Zhang et al., 2021). The impacts on urban traffic patterns and traffic congestion, however, have only been induced from general mobility data (such as Google Community Mobility reports) *ad hoc* surveys (McKinsey, 2020). Lessons learned from an in-depth analysis of changes in empirical traffic situation should inform policy-makers about the feasibility of modifying some of these NPIs with an aim of reducing traffic congestion and enhancing the liveability of cities.

3. Data and method

3.1. Data collection

This study uses two main sets of data, namely, a geodatabase including road centrelines and speed limit from data.gov.hk, and traffic speed from TomTom. For the geodatabase, road centrelines and the speed limit in 2018 were used in this study. TomTom Traffic API measures real-time travel speed on each road segment based on millions of consumer GPS tracking records (TomTom, 2012).¹ For the empirical traffic speed, through the TomTom Traffic API, traffic speed in 76% (2262 km out of 2979 km) of the named roads was captured and stored hourly in this study. Each speed record is geo-referenced for spatial

¹ Details of the TomTom API can be found on <https://developer.tomtom.com/traffic-api/documentation/traffic-flow/flow-segment-data/#request-parameters>

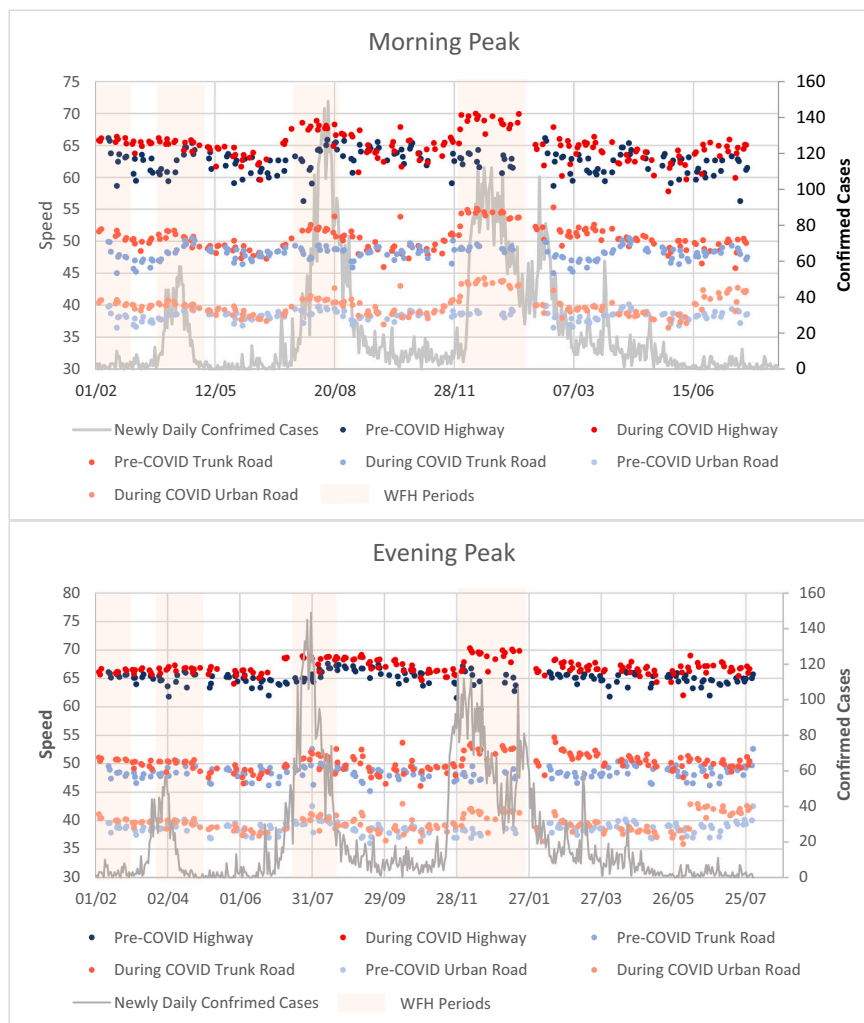


Fig. 3. Peak-hour average speed on different types of road.

analysis.

3.2. Study design

As the focus of this study is on peak-hour congestion, it is important to identify commuting periods before data processing. In this study, data on weekdays except for the day before and after the weekend and holidays were chosen. The two peak-hour periods were from 8 a.m. to 10 a.m. and from 5 p.m. to 7 p.m. To offset the seasonal variations of traffic, a year-on-year analysis was conducted. We compared the traffic conditions during the COVID-19 pandemic (i.e. from February 2020 to January 2021) and the same period in the pre-COVID period (2019). Based on the selection criteria, 343 weekdays met our requirements. Overall, 288 out of 343 (84%) days have been captured for the WFH analysis in this study. In the following 6 months after the fourth wave of WFH arrangement in January 2021, the number of daily confirmed cases in Hong Kong was quite stable, staying at a low level. Under the prevention and control of disease regulations (e.g. wearing of mask in public areas, social distancing, etc.), the city has entered a “new normal” period. Hence, we also supplemented the analysis with the “new normal” period from February 2021 to July 2021.

3.3. Research method

The research method used can be repeated for other cities with the above two main sets of data. When more updated data are available, the

study period can also be extended. Depending on the situation, the analysis may be extended by prolonging the last stage of “new normal” or repeating the stage of another wave of city-wide WFH arrangement. Before the data processing, data cleaning is needed. Regarding the temporal dimension, traffic speed data were extracted and grouped by year (before and during COVID) and period (morning and evening peak hours). Based on the timeline in Table 5 (in the Appendix A), traffic speed data were further grouped into WFH and non-WFH periods. Accordingly, eight sets of traffic speed data were compiled: WFH and non-WFH periods at morning and evening peaks in pre-COVID and during COVID periods. In each set of data, the average speed in each link was calculated. The next step is to derive the level of congestion, CI, on each road. The equation of CI is shown below (Loo & Huang, 2021). As shown in Eq. (1), a higher CI indicates a more congested road, and when CI is equal to 100, the road comes to a standstill. When speeding occurs, negative CI values may result. Since this study only concentrates on the level of congestion, negative CIs are regarded as zero, which means no traffic jams were found.

$$CI = \frac{Speed\ Limit - Actual\ Speed}{Speed\ Limit} * 100 \tag{1}$$

As the speed limit data is provided in the geodatabase, it needs to be linked to the traffic speed data via the geographical coordinates and verified by the road name. In the geo-coding step, speed limit and traffic speed data were connected first, and the CI in each road was thereby calculated. The same procedures were applied to all eight sets of speed

Table 1
CI differences between pre- and during COVID.

		Pre- COVID	During COVID	Mean difference
Study period (up to Jan.)	Morning	33.46	31.69*	-1.84***
	Evening	33.14	32.57**	-0.57**
WFH periods	Morning	33.07	30.14	-2.93***
	Evening	32.32	31.43	-0.89***
Periods between WFH	Morning	33.73	32.35	-1.38***
	Evening	33.69	33.56	-0.12

*** P value < 0.001.

** P value < 0.01.

* P value < 0.05.

data. In order to investigate the spatial variations of CI, roads were categorized by large tertiary planning units (LTPU).² The geodatabase of LTPU data is provided by data.gov.hk, and the function “Intersect” was used to select the roads. As the latest downloadable traffic speed in the TomTom database is stored by road only, we have weighted the CI values for roads intersecting with several LTPUs by the TomTom historical speed data of individual road segments in the last 2 years. By the end of this step, the roads in all LTPUs and the CI values were derived. Finally, a series of paired *t*-tests were conducted to examine whether the level of congestion has changed significantly. Regarding temporal variations, CI values of all roads in the city are compared between different periods. In terms of spatial variations, CI values of roads in each LTPU during WFH periods are compared with corresponding periods in the previous year.

4. Results

First of all, there seems to be a general increase in traffic speed during COVID-19. Fig. 3 presents the traffic speed in Hong Kong from February 2020 to July 2021. During the COVID-19 pandemic, traffic speed on all types of roads in Hong Kong has actually increased during peak hours. Regarding the speed limit, there are three main types of roads in Hong Kong, namely, highway (speed limit >80 km/h), trunk road (speed limit ≤80 km/h & >50 km/h), and urban road & private road (speed limit ≤50 km/h). Each dot represents the average traffic speed of a road category during the morning or evening peak of the day. In other words, people have been able to take advantage of less crowded roads to travel faster on Hong Kong's road network. Shadows indicate periods when the city was under WFH arrangement. It is observed that for all roads, vehicular speed during COVID-19 was slightly higher than in the previous year, especially during the morning peak hours. Meanwhile, the speed difference around the WFH periods was larger than in other periods. The increase in traffic speed may not reflect a relief of urban traffic congestion, as some roads have not initially suffered from traffic jams. Therefore, in the next subsections, the indicator CI will be used to investigate changes in the level of congestion over space and time.

4.1. Traffic congestion under WFH arrangement

With respect to the level of congestion, the situation has also improved. CIs in different periods are summarised in Table 1. Overall, statistically significant but moderate reductions of CI were observed. With a CI of 31.69 during COVID (February 2020 to January 2021), the morning rush hours CI was 1.84 (or 5.5%) lower when compared with the corresponding period in the previous year. As for the evening peak, the difference is -0.57 (or -1.7%) at a significance level of 0.003, which is one-third of the morning CI difference. Generally, the peak-hour

² For urban planning purposes, there are 289 TPUs, and 153 large TPUs in Hong Kong.

traffic congestion has been eased in Hong Kong during the pandemic, though the differences were not great.

Compared with the non-WFH periods, bigger CI differences were found under WFH periods. As shown in Table 1, the morning CI under WFH arrangement was 30.14, which is 2.93 (or 8.9%) lower than the same period in the previous year. Regarding the evening CI difference during WFH, it was only -0.89 (or -2.8%). In addition, it is also observed that the evening peak CI difference under non-WFH arrangement was not statistically significant compared with the previous year.

During the pandemic, when WFH arrangement was imposed, higher CI differences can be observed compared with the non-WFH periods. Over a day, WFH has a greater impact on morning peak traffic congestion. As to the evening peak, the impact of WFH was mild. Results are in line with the previous hypothesis that WFH can alleviate both morning and evening commuting peaks (Zhang et al., 2005). Notwithstanding, our results reveal different effects on morning and evening peaks, that is, WFH has a more significant impact on morning peak congestion.

4.2. Spatial variations of CI within the city

In this section, we focus on the WFH periods during the pandemic. To focus on local planning implications, CI and CI difference at the spatial scale of LTPU are discussed. Among all 153 LTPUs in Hong Kong, except for four without data, the remaining 149 were analysed. Table 2 shows the descriptive statistics of CI in LTPU during the pandemic. It is observed that LTPUs' CI is spatially varied in Hong Kong with a standard deviation of about 15 CI points. This indicates that aggregating the CI of the entire city would mask substantial spatial pattern of changes in traffic congestion, which is vital in transport management.

Table 3 summarizes the CI differences between the pre-COVID and WFH periods during COVID by LTPU. At morning peak hours, the CI difference ranged from 21.11 to -16.36, while it varied from 24.38 to -9.06 at evening peak hours. A series of paired *t*-tests were conducted to examine whether the LTPU's CI has changed significantly at the level of 0.05. Results show that the majority of LTPUs (57.0%) have experienced a statistically significant CI reduction during morning peak hours during the WFH periods. At evening peak hours, the share of LTPUs with statistically lower CI was only 32.2%, while 65.1% of LTPUs did not show significant CI reductions.

Spatially, Fig. 4 shows the patterns of CI difference across Hong Kong under WFH periods. The category of each LTPU is determined by paired *t*-tests. Those LTPUs that CI did not change significantly were regarded as unchanged, while others are either more congested (positive CI difference) or alleviated (negative CI difference). To differentiate the planning units, six types of LTPUs are identified, namely statistically significant increase (CI difference > 0), no statistically significant change, statistically significant drop but magnitude was small (CI difference > -2), statistically significant drop but magnitude was moderate (-5 < CI difference < -2), statistically significant drop and magnitude was high (-8 < CI difference < -5), and statistically significant drop but magnitude was very high (CI difference < -8). With reference to the territory-wide CI at about 30–35, the labels used are more congested, unchanged, slightly alleviated, moderately alleviated, alleviated, and greatly alleviated. Conceivably, the central business district (CBD), as well as many urban core areas, has experienced a sharp CI reduction at morning peak hours compared with the previous year. With regard to evening peak hours, though CI has dropped significantly in the CBD, the difference was lower than morning peak hours. Generally, most of the areas with traffic congestion alleviated were concentrated near the urban core (along the Victoria Harbour); yet, some scattered green polygons (north and the north-west) were located in new towns. In other words, the urban form of the city has great implications on the traffic impact of WFH arrangement.

To further examine the impact of urban form, we sub-divide Hong Kong into the CBD, urban core, new towns, and suburbs (Loo & Chow, 2008). The Sankey chart in Fig. 5 depicts the relationships between the

Table 2
Descriptive statistics about CI values of LTPUs.

		Max	Min	Mean	Std
Morning	Pre-COVID	68.69	2.77	35.09	15.09
	WFH periods during COVID	64.50	0.55	31.63	15.46
Evening	Pre-COVID	69.24	3.13	34.07	15.51
	WFH periods during COVID	66.69	3.20	32.60	15.69

Notes: Mean values are slightly different from Table 1 as some roads are double-counted in LTPU analysis.

urban structure and CI difference during WFH periods. During the morning peak, CIs in more than half of suburb LTPUs (21 out of 38) have not changed significantly. Among the remaining suburb LTPUs, “moderately alleviated” accounted for the highest share (10 out of 17 LTPUs), followed by “alleviated”, and a small proportion has experienced a slight alleviation of congestion. New town LTPUs have shown a similar pattern as suburb areas. In contrast, all six categories of CI difference can be found in the urban core. Among which “unchanged” and “moderately alleviated” LTPUs accounted for 34.2% and 32.9%, respectively. It is also observed that urban LTPUs have taken up the majority of “very greatly alleviated” LTPUs (71.4%). Meanwhile, the only two “more congested” LTPUs were located in the urban cores. Turning to the evening peak hours, the spatial patterns are slightly different. “Unchanged” LTPUs accounted for 50.0%, 63.0%, 66.7%, and 68.4% of CBD, urban core, new town, and suburb LTPUs, respectively. Under these circumstances, less “moderately” to “greatly alleviated” LTPUs were found. Different from the morning peak hours, “greatly alleviated” LTPUs were only found in new towns, one “more congested” LTPU was recorded in the suburb area. Regarding the CBD, the CI difference during evening peak hours was also much smaller than the morning peak hours.

It is clear that changes in the level of traffic congestion during WFH periods of the pandemic are spatially varied within the city. Areas with peak-hour congestion most significantly alleviated were concentrated in the CBD and urban core, where more jobs are found. To some extent, our results reflect the urban structure of Hong Kong. Due to the jobs-housing imbalance in Hong Kong, commuting congestion is common and has already happened in some new towns before the pandemic (Hui & Yu, 2013; Loo & Chow, 2008). Under the WFH arrangement, some new town areas have also experienced moderate to substantial relief of peak-hour traffic congestion. Nonetheless, it is noteworthy that the level of traffic congestion has remained unchanged in many other areas within the urban core, new towns, and the suburb. Previous empirical studies have reported that there will be fewer trips to CBD under the WFH arrangement, and results in this study have supported this finding (Shabanpour et al., 2018). In fact, commuting peaks in suburb or new town areas have been observed in some other cities as well (Zhao & Hu, 2019). Spatial patterns of the CI difference in this study also indicate that suburb or new town congestion may be alleviated through the WFH arrangement.

4.3. Variations over the day

Under the WFH arrangement, some scholars have envisaged that the commuting congestion might be spread to off-peak hours in a day (Balepur et al., 1998; Lachapelle et al., 2018). To understand variations over the day, we depict the hourly average CI over a day during WFH periods and the previous year before the COVID-19 pandemic (Fig. 6).

Table 3
CI Differences between the pre-COVID and during WFH periods by LTPU.

	CI difference				No. of LTPUs (percentage)		
	Max	Min	Mean	Std	Unchanged CI	Increased CI	Decreased CI
Morning	21.11	-16.36	-3.46	4.02	62 (41.5)	2 (1.3)	85 (57.0)
Evening	24.38	-9.06	-1.47	4.06	97 (65.1)	4 (2.7)	48 (32.2)

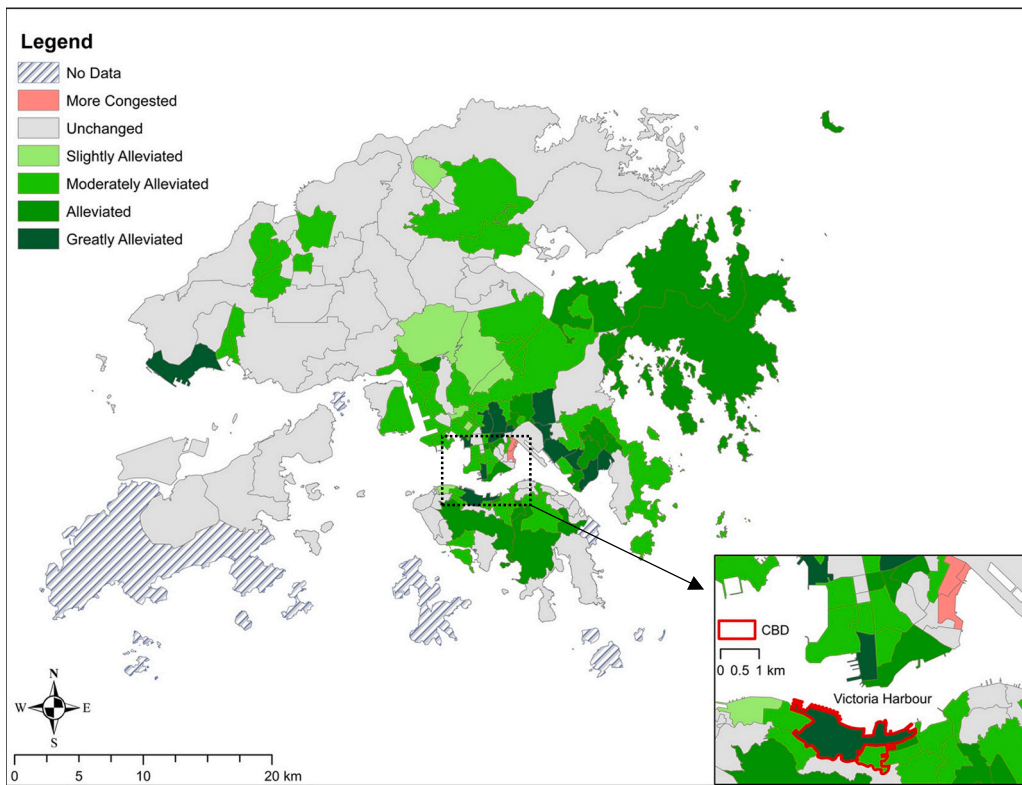
The maximum difference can be found at the morning peak (8 am), while the least CI difference is observed at the evening peak at 6 pm. It is clear that the two typical commuting peaks still existed during the WFH periods. There are some reasons behind. Firstly, not all occupations are suitable for e-working (Handy & Mokhtarian, 1995). For instance, jobs like construction, food service, and in-store retail are required to work on-site (Lund et al., 2021). Secondly, it was common that employers in Hong Kong would still require a proportion (e.g. one-third or one-half) of employees to work in the working places on rotation, though the government has appealed for the wide adoption of WFH practice.

As shown in Fig. 6, the average level of traffic congestion under four rounds of WFH arrangement was always lower than the pre-COVID level. After the morning peak, CI has slightly decreased till the evening peak. In other words, WFH has flattened the traditional morning congestion peak without creating new peak hours at other hours. Nevertheless, the congestion relief or CI difference during the evening peak was subtle. Overall, both commuting peaks (i.e. morning and evening) under the WFH arrangement have remained identifiable under the WFH arrangement.

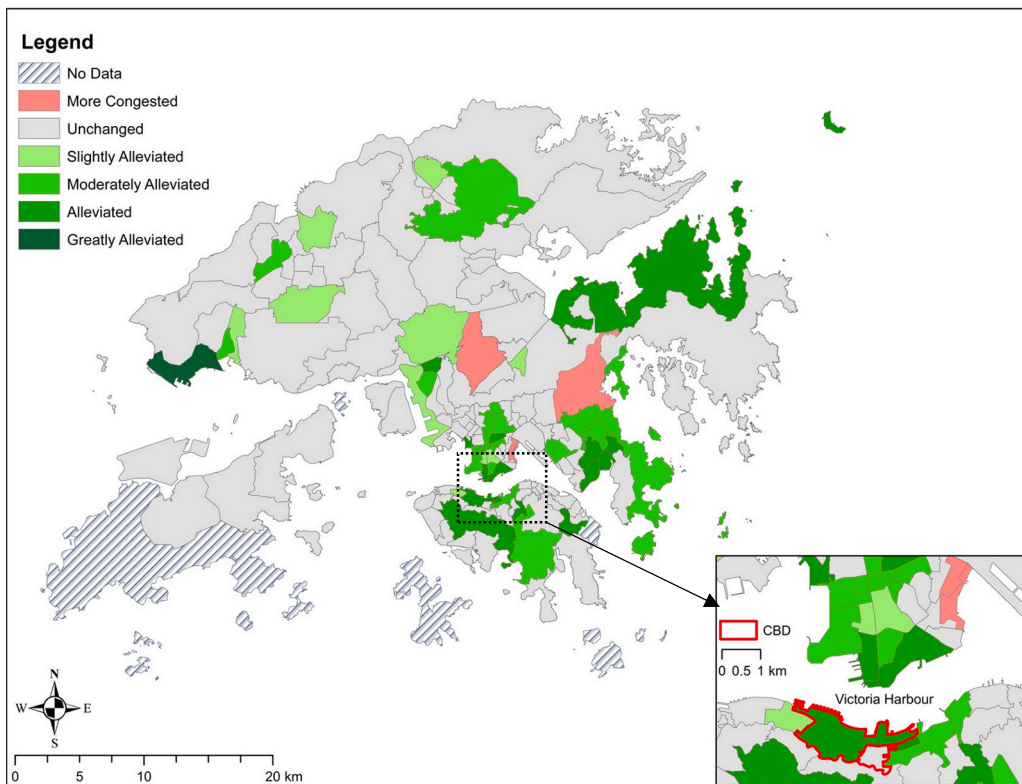
4.4. The “new normal”

In the following 6 months (February 2021 to July 2021) after the fourth wave of WFH arrangement, the number of daily confirmed cases in Hong Kong was quite stable, staying at a low level. Hence, the city has entered a “new normal” period. In this period, while some companies have still adopted flexible working arrangements, face-to-face working style has largely resumed and employees were generally required to return to working places (Wu & Murdoch, 2021). Under these circumstances, it is not surprising that the level of CI has bounced back during the morning peak hours. On average, the CI difference has decreased from -3.46 in the WFH periods to -2.43 in the “new normal” period. As shown in Table 4, CI in a large proportion of LTPUs (69.8%) did not change significantly compared to the previous typical year. To recall, this share was only 41.6% during the WFH periods. Spatially, it is observed that without the announcement of WFH arrangement by the HKSAR Government, the level of congestion in the CBD under the “new normal” has returned to the pre-COVID level. During the evening peak, the number of LTPUs with traffic congestion relieved (CI decreased) has dropped from 48 to 36. Nonetheless, when compared to the pre-COVID period, about one-quarter of the LTPUs were still having a lower level of peak-hour traffic congestion during the “new normal”. The territory-wide peak-hour congestion levels under the “new normal” were still lower than the pre-COVID period.

Furthermore, an in-depth analysis of the spatial and temporal patterns of CI difference in the “new normal” period shows new insights about WFH arrangement. A closer look at Fig. 7 shows that, without the WFH policy interventions, the morning peak in the CBD has reoccurred and rebounded to the pre-COVID level (i.e. no change in CI), while moderate congestion relief was still observable at the CBD in the evening peak. This suggests that COVID-19 has a much more persistent impact on suppressing people's evening social and leisure activities around the CBD under the “new normal”. It is clear that CBD traffic congestion at the morning peak has resumed without the WFH arrangement.



(a) Morning Peak Hours



(b) Evening Peak Hours

Fig. 4. Maps of the CI. under WFH arrangement

(a) Morning peak hours

(b) Evening peak hours.

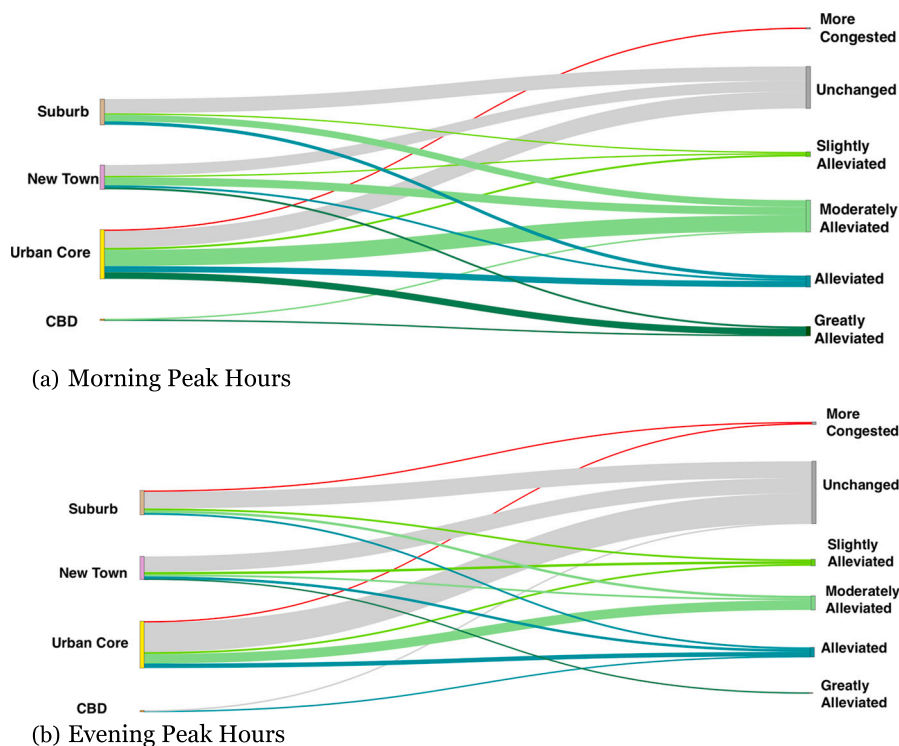


Fig. 5. LTPUs' land use and ci difference category.
 (a) Morning peak hours
 (b) Evening peak hours.

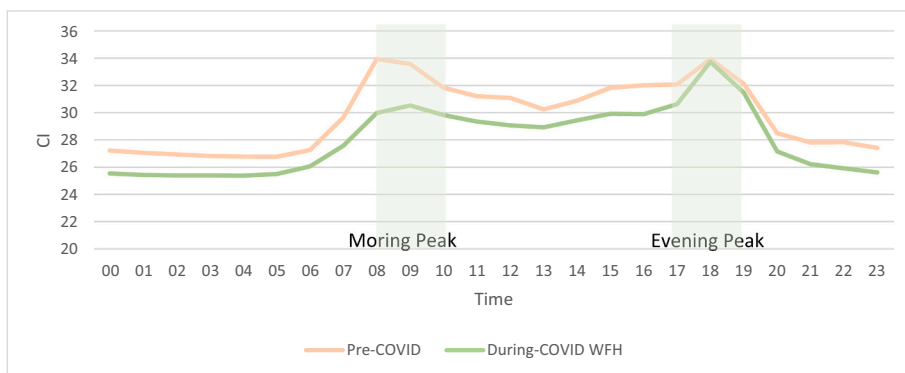


Fig. 6. Average CI over the day.

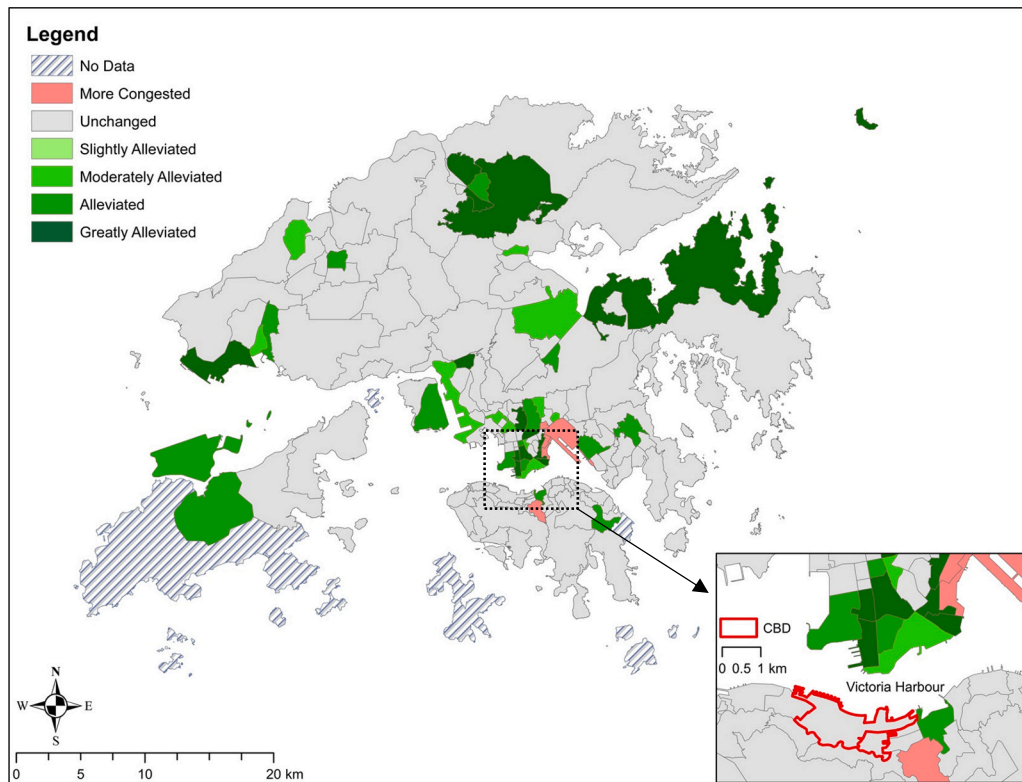
5. Discussion and conclusion

The outbreak of the COVID-19 pandemic since 2020 has changed people's life style tremendously. From a transport sustainability perspective, scholars have attempted to investigate the impacts of various measures during the pandemic (Molloy et al., 2021; Zhang et al., 2021). Though many of these measures, e.g. lockdown, were temporary (He et al., 2020), it is still anticipated that lessons learned from COVID-19 can provide academic and policymaking insights for the future. In this study, we focused on the traffic conditions under the WFH

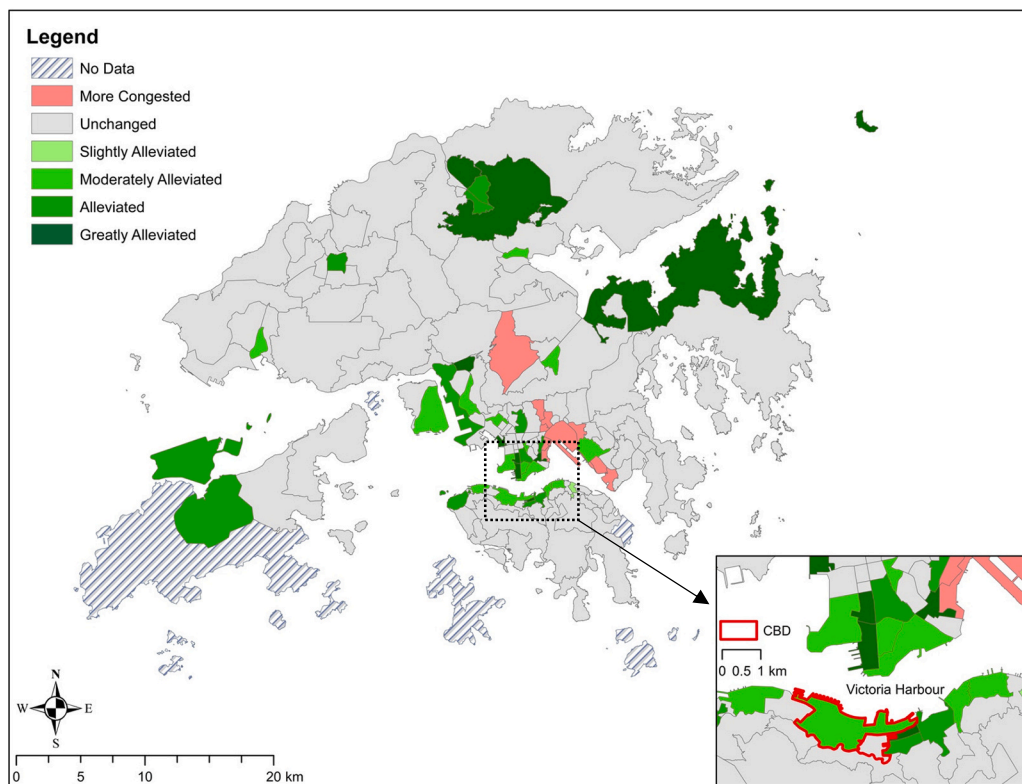
arrangement in Hong Kong during COVID-19. By comparing the level of congestion with the previous year, the spatial and temporal dynamics of urban traffic congestion in Hong Kong under the pandemic were analysed. While traffic congestion was eased during WFH periods, the CBD traffic congestion at the morning peak has resumed without the WFH arrangement. Under the “new normal”, the underlying planning problems of jobs-housing imbalance have led to the re-emergence of traffic congestion at the CBD during peak hours. In the near future, the wide adoption of WFH will still have to rely on policy interventions. Continuous efforts to address the jobs-housing imbalance through

Table 4
 CI Difference of the “new normal” period (compared with the previous year) at LTPU level.

	CI difference				No. of LTPUs (percentage)		
	Max	Min	Mean	Std	CI unchanged	CI increased	CI decreased
Morning	17.26	-14.67	-2.43	4.85	104 (69.8)	5 (3.4)	40 (26.9)
Evening	28.34	-11.58	-1.50	5.84	103 (69.1)	10 (6.7)	36 (24.2)



(a) Morning Peak



(b) Evening Peak

Fig. 7. Maps of the CI difference at morning and evening peaks in the “New Normal” period.

(a) Morning peak hours

(b) Evening peak hours.

planning interventions are still needed.

Urban traffic congestion is a vexing problem associated with transport negative externalities. Over the years, governments have attempted to implement various mitigation measures, such as building more roads, promoting public transport, restricting car ownership, adopting congestion charging, etc. Yet, severe traffic jams in cities are still pervasive. With the burgeoning development of ICT over the last two decades, scholarly attention has been given to the potentials of relieving traffic congestion in smart cities (Guo et al., 2020; Loo & Tang, 2019). Theoretically, the impact of ICT on personal travel could be substitutional, complementary, or modified/neutral (Senbil & Kitamura, 2003). Based on the existing literature, it is generally concluded that WFH can reduce commuting trips and alleviate peak-hour traffic congestion (Atkeson, 2020). However, changes in traffic conditions associated with WFH arrangement have not been examined within a city. This study fills the gap and finds that congestion relief, though statistically significant at morning peak hours, has neither been happening across all districts nor persisted beyond the large-scale WFH policy led by the Government.

Moreover, this study finds that the two traditional commuting peaks were still identifiable during the WFH periods. With detailed traffic speed data over the territory from January 2020 to July 2021, we tried to capture changes in the level of traffic congestion within the city during different periods (COVID-19 and WFH, COVID-19 and non-WFH, and the “new normal”). Over a day, this study shows that the WFH arrangement has a bigger impact on relieving morning peak-hour congestion than its evening counterpart. During morning peak hours, as trips are dominated by work-related activities, they are more concentrated spatially and temporally (He, 2013; Szeto et al., 2017). Different from the morning peak, trips in the evening peak are more diversified. Other than journeys back home, discretionary activities may be conducted before returning home (Yu et al., 2019). The departure time after work is also much less flexible than arrival at work (De Palma & Lindsey, 2002).

Spatially, CBD and some urban cores have shown a (statistically) significant reduction in traffic congestion under the WFH arrangement. Due to the jobs-housing imbalance in Hong Kong, commuting congestion in new towns was also partially relieved. Yet, CI in around half of the LTPUs did not show statistically significant changes. Job characteristics (e.g. employment density, occupation composition) could be a major factor in affecting the spatial variations of CI under the WFH arrangement. For example, the traditional commercial area, Yau Tsim Mong district (in the north of the Victoria Harbour), has experienced a great reduction in peak-hour CI during the WFH periods. This area is known to be one of the job centres in Hong Kong (Loo & Huang, 2021). According to the Planning Department (2021), about half (46.7%) of these areas belonged to commercial/business and office, and government, institutional and community facilities. In contrast, the Kowloon City district with worsened congestion (increased CI) was undergoing redevelopment led by the government and, 34% of land in this region was classified as vacant land/construction in progress (Planning Department, 2021). The increased activities and traffic congestion might be more related to the new developments, rather than the impact of COVID-19 or WFH arrangement. One major limitation of our study is that the researchers cannot control all factors in the before and after periods. As the entire study period is rather short, updated population and other socio-economic data are not available annually at the LTPU level to enable us to model them as control variables. While substantial changes in land use and other socio-economic data are not likely within a year at the city level, care needs to be exercised when small spatial units are considered. And as smaller spatial units (e.g. LTPUs with higher CI) are considered, other local factors need to be taken into account in interpreting the results.

Hong Kong is the epitome of a metropolis confronting limited space,

high-population density and jobs-housing imbalance. The significance of this empirical study in Hong Kong under the WFH arrangement is two-fold. By investigating the spatio-temporal dynamics of peak-hour traffic congestion, this study provides an innovative perspective to understand the impacts of WFH on the urban transport system. A more comprehensive perspective on the impacts of WFH arrangement on traffic speed during the morning and evening peak hours and in different parts of the city has been gained. The findings also highlight the more fundamental urban structure and job-housing imbalance of the city. Empirical evidence reinforces the view that commuting peaks measured by CI can be alleviated partially by promoting WFH. Extra attention, however, needs to be paid on local variations. Based on the findings, it is suggested that congestion relief studies in the future should give heed to the spatio-temporal patterns of road traffic conditions (e.g. speed) in planning new employment and residential areas.

Given the specific changes in traffic conditions over the space and time, results indicate that WFH is not a magic bullet in relieving urban traffic congestion. Over the years, due to limited empirical studies related to traffic conditions, the effectiveness of implementing WFH arrangement may have been overestimated. People intuitively believe that as long as WFH is promoted, urban traffic congestion can be relieved significantly. With a surging number of teleworkers in the post-COVID era, policymakers and urban planners have to reinvestigate the impacts and externalities of implementing WFH or flexible working schemes on the transport system. As observed in this study, congestion in many of urban areas and during evening peak may not be affected remarkably. Integrating with other measures such as implementing congestion charging, further promoting transit-oriented development, and advocating jobs-housing balance (Loo & Chow, 2011; Zhao et al., 2011) as a policy package to tackle the urban traffic congestion is necessary. In particular, implementing congestion charging may generate not only first-order effect on changing travel behaviour but also second-order and third-order effects in affecting land-use decisions and the urban hierarchy (Zhong et al., 2015). Overall, transport and land use interactions need to be duly considered to ease traffic congestion in cities.

Finally, there are limitations in this study. Under the COVID-19 pandemic, other factors could have affected the commuting congestion in cities as well. Future studies can incorporate other external factors, such as major development projects and land-use changes, in the analysis. It is noteworthy that empirical vehicular flow data will further enrich our analysis. However, as territory-wide vehicular flow data are only published once a year and with a one-year lag in the official Annual Traffic Census, we have only focused on the CI based on the real-time traffic speed and speed limit. Future studies would take traffic volume into account. In addition, the territory-wide WFH arrangement was rather extreme under the pandemic. Further investigations are required to understand the impacts of different forms of e-working (e.g. WFH on selected days of the week only) on urban traffic congestion. This is a future research direction for scholars interested in examining the potential impacts of WFH policies on urban transportation.

CRediT authorship contribution statement

Becky P.Y. Loo: Methodology, Supervision, Writing – original draft, Writing – review & editing. **Zhiran Huang:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A

Table 5
Measures implemented in Hong Kong during COVID-19 pandemic (29-Jan-2020 to 20-Jan-2021).

Categories	Phase	Measures	Start Date	End Date
WFH WFH means work from home arrangement is implemented	1	WFH	29-Jan-20	1-Mar-20
	2	Normal	2-Mar-20	22-Mar-20
	3	WFH	23-Mar-20	3-May-20
	4	Normal	4-May-20	19-Jul-20
	5	WFH	20-Jul-20	23-Aug-20
	6	Normal	24-Aug-20	1-Dec-20
	7	WFH	2-Dec-20	27-Jan-21
	8	Normal	28-Jan-21	31-Jul-21
School Partially opened means schools opened for some grades or half day	1	All closed	25-Jan-20	26-May-20
	2	Partially opened	27-May-20	14-Jun-20
	3	All opened	15-Jun-20	14-Jul-20
	4	All closed	15-Jul-20	22-Sep-20
	5	Partially opened	23-Sep-20	28-Sep-20
	6	All opened	29-Sep-20	22-Nov-20
	7	Partially opened	23-Nov-20	1-Dec-20
	8	All closed	2-Dec-20	21-Feb-21
	9	Partially opened	22-Feb-21	31-Jul-21
Group gathering Number of persons allowed in public area	1	4ppl	29-Mar-20	7-May-20
	2	8ppl	8-May-20	18-Jun-20
	3	50ppl	19-Jun-20	14-Jul-20
	4	4ppl	15-Jul-20	28-Jul-20
	5	2ppl	29-Jul-20	10-Sep-20
	6	4ppl	11-Sep-20	1-Dec-20
	7	2ppl	2-Dec-20	3-Mar-21
	8	4ppl	4-Mar-21	31-Jul-21
Catering working hour Only take-away will be allowed for restaurants/caterers from the time to 4.59 am of the subsequent day. Vaccine bubble means flexible opening hours were adopted based on the vaccination rate.	1	6 pm	15-Jul-20	28-Jul-20
	2	whole day	29-Aug-20	30-Jul-20
	3	6 pm	31-Jul-20	27-Aug-20
	4	9 pm	28-Aug-20	3-Sep-20
	5	10 pm	4-Sep-20	17-Sep-20
	6	mid night	18-Sep-20	29-Oct-20
	7	2 am	30-Oct-20	15-Nov-20
	8	mid night	16-Nov-20	1-Dec-20
	9	10 pm	2-Dec-20	9-Dec-20
	10	6 pm	10-Dec-20	17-Feb-21
	11	10 pm	18-Feb-21	29-Apr-21
	12	10 pm (Vaccine bubble)	30-Apr-21	31-Jul-21

Note: Phase 2 in catering is not shown in Fig. 2.

Data source: info.gov.hk.

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