Cities 135 (2023) 104223

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

Understanding individual-level travel behavior changes due to COVID-19: Trip frequency, trip regularity, and trip distance

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ARTICLE INFO

Keywords:
COVID-19
Pandemic
Travel behavior
Trip frequency
Trip regularity
Trip distance

ABSTRACT

Understanding different mechanisms in trip changes depending on transportation modes due to COVID-19 pandemic is the key to providing practical insights for healthy communities. This study aimed to investigate the impact of the COVID-19 pandemic on individual-level travel behavior in Daejeon Metropolitan City, South Korea. Using smart card and private vehicle records, we explored different travel behaviors exhibited while using buses and private vehicles. An individual's travel behavior was represented in trip frequency, trip regularity, and trip distance and was compared weekly for about three months, including the initial period of pandemic. A significant decrease in trip frequency during non-peak hours on weekdays and during weekends indicates that people reduced non-mandatory trips more than commuter trips. This was also verified in that, as the number of infection cases increased, trip regularity with 24-hour intervals intensified. People maintained the size of their activity boundaries but reduced their daily trip distances. The interesting point is that private vehicle usage increased for shorter trip distances while bus usage dropped regardless of the ranges of trip distances under the pandemic. The findings provide evidence of possible inequality issues in transportation during the pandemic and can help make precautionary policies for future pandemics.

1. Introduction

Coronavirus disease 19 (COVID-19, SARS-CoV-2) was first reported in December 2019 (World Health Organization, 2020a), and in early 2020, it rapidly spread worldwide with a high reproduction rate (> 2.0) (World Health Organization, 2020a). The World Health Organization (WHO) declared COVID-19 a global pandemic on March 11, 2020, considering the public health risk resulting from the disease (World Health Organization, 2020b). After the WHO declaration, most countries in the world introduced various countermeasures to hinder the spread of the disease, such as teleworking, closure of public facilities, and social distancing (Balmford, Annan, Hargreaves, Altoè, & Bateman, 2020; Romanillos et al., 2021; United Nations, 2020; World Health Organization, 2020c). These countermeasures imposed in response to general concerns about the pandemic have significantly affected the lifestyle of populations around the world (Ammar et al., 2021; Arimura, Ha, Okumura, & Asada, 2020; Hsiang et al., 2020).

Travel demand in cities has been inevitably affected by the COVID-19 pandemic as governments and populations made new safety- and health-related travel standards against COVID-19. Many studies verified the COVID-19 impacts on travel behaviors, targeting diverse cities in the world, and they, in common, revealed a significant reduction in travel demand (Dahlberg et al., 2020; Hsiang et al., 2020). Some studies found different changes in travel demand by transportation modes—especially, more a significant decrease in public transit demand and intensification of car dependency (Bian et al., 2021; Chang, Lee, Yang, & Liou, 2021; Jenelius & Cebecauer, 2020; Kim, Lee, Ko, Jang, & Yeo, 2021; Park, 2020; Schaefer, Tuitjer, & Levin-Keitel, 2021)—although the amount of its changes varied depending on the variety of countermeasures from the government (Heiler et al., 2020; Hsiang et al., 2020; Xin, Shalaby, Feng, & Zhao, 2021; Zhang et al., 2021). Such different reduction in travel demand is because, during the pandemic, people considered the infection potential as the top priority in their choice of transportation mode, and thereby, they tended to avoid taking public transit where adequate personal space cannot be guaranteed and unnecessary contact with strangers can easily occur (Abdullah, Dias, Muley, & Shahin, 2020; Barbieri et al., 2021; Eisenmann, Nobis, Kolarova, Lenz, & Winkler, 2021; Kamplimath, Shivam, & Goenka, 2021; Przybylowski, Stelmak, & Suchanek, 2021; Shamshiripour, Rahimi, Shabanpour, & Mohammadian, 2020).

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https://doi.org/10.1016/j.cities.2023.104223
Received 7 August 2022; Received in revised form 16 December 2022; Accepted 27 January 2023
Available online 1 February 2023

However, the previous studies have some limitations in sufficiently explaining how the COVID-19 pandemic has affected individual travelers. Most of them used count-based trip data representing trip demands (e.g., traffic volume or transit ridership), but such aggregated demand cannot characterize travel behaviors observable at an individual level, the level at which fundamental changes happen. As a simple example, with the aggregated data, it is hard to identify whether the same amount of decrease in public transit ridership was caused by a reduction in the number of users or a similar reduction in trip volumes of each user (Jenelius & Cebecauer, 2020). Identifying this kind of cause for a decrease in trip demand is possible through individual-level analysis. This can help decision-makers introduce more practical mobility strategies for the public: for instance, in the case of a reduction in the number of users, it may be effective to increase the number of fleets for assuaging concerns about an infection; and in the case of a similar reduction in trip volumes of each user, it may be practical to reduce fleets at a level of ensuring social distancing for operational efficiency.

A few studies tried to examine changes in travel behaviors due to pandemics at an individual level, but they covered only a single transportation mode, public transit (Dueñas, Campi, & Olmos, 2021; Jenelius & Cebecauer, 2020). Travel-related behavioral changes at an individual level can be different by transportation modes with great possibility, given that the pandemic impacts on travel demand differed according to them (Bian et al., 2021; Chang et al., 2021; Kim et al., 2021; Schaefer et al., 2021). Therefore, it is required to investigate and compare the pandemic impacts on individual-level travel behaviors using different transportation modes to understand the part that remained still ambiguous. The findings from the comparison can provide useful information for designing proactive and mode-customized policies under a pandemic emergency.

To fill the research gap abovementioned, this study aims to evaluate the impacts of the COVID-19 pandemic on individual-level travel behavior using the primary transportation modes used in daily life within a city—buses and private vehicles. We conducted an empirical study on Daejeon City, South Korea, during the initial period of the pandemic (January 13 to March 29, 2020). The initial period of the pandemic has been regarded as a proper temporal scope to investigate changes in travel behavior because the pandemic during the corresponding period induced its most significant changes (Brough, Freedman, & Phillips, 2021; Hsiang et al., 2020; Jiao & Azimian, 2021). Moreover, during the initial period, South Korea experienced significant reductions in public transit and road traffic demand, even without strong anti-contagion policies (Lee et al., 2020; Park, 2020). Travel demand reduction in Daejeon City, our study site, was also approximately 40 % and 12 % for each bus and private vehicle during the corresponding period (Kim et al., 2021). Daejeon City manages rich mobility data with anonymous user information, which provide an opportunity to trace each traveler spatially and temporally. We collected bus trip record data (via the smart card system) and private vehicle record data (via Road Side Equipment: RSE) and measured travel behavior indicators in three categories (trip frequency, trip regularity, and trip distance). The indicators were calculated and compared on a weekly basis, which allowed us to investigate the dynamic responses of people toward the pandemic over time. Furthermore, a comparison of mobility indicators between two transportation modes at an individual level can provide the different mechanisms of travel demand reduction by transportation modes, which has novelty to previous studies. It can shed light on the possible inequality issues in intra-city mobility. In the end, we expect this study to be able to suggest strategies for transportation operations to maintain intra-city mobility opportunities regardless of transportation modes and control the spread of the virus in people's mobility.

The remainder of this paper is organized as follows. Section 2 describes the study area and individual-level trip data for bus and private vehicles. Section 3 describes indicators representing individual-level travel behaviors in spatial and temporal dimensions, and Section 4 reports the analysis results from the weekly comparison of indicators. Section 5 discusses the findings in this study and suggests their implications for safe and effective urban transportation during pandemics. Finally, Section 6 presents the conclusions from this study.

2. Study scope and data description

2.1. Scope of study

Daejeon Metropolitan City, the target of this study, is the fifth largest city in South Korea and is located in the middle of the country, with a population of 1.47 million and an area of 539.8 km^2. As of 2020, the city

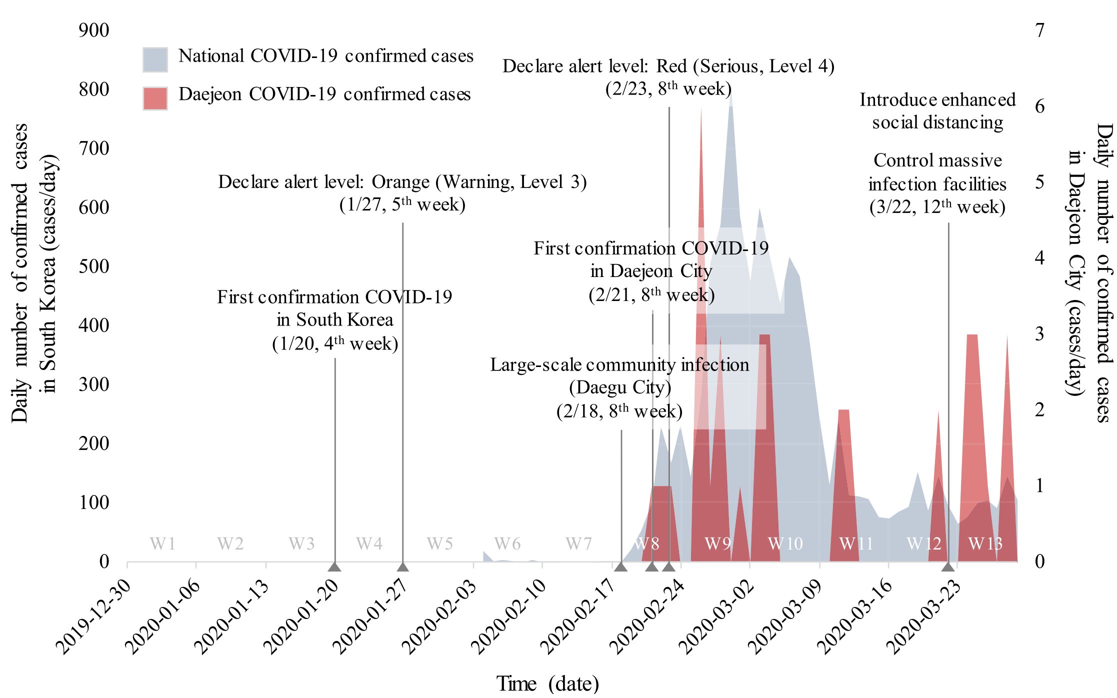

Fig. 1. COVID-19 status in Daejeon and South Korea and temporal study scope.[1]

[1]A single week was defined as a set of days from Monday to Sunday to consider the social perception of the week in South Korea.

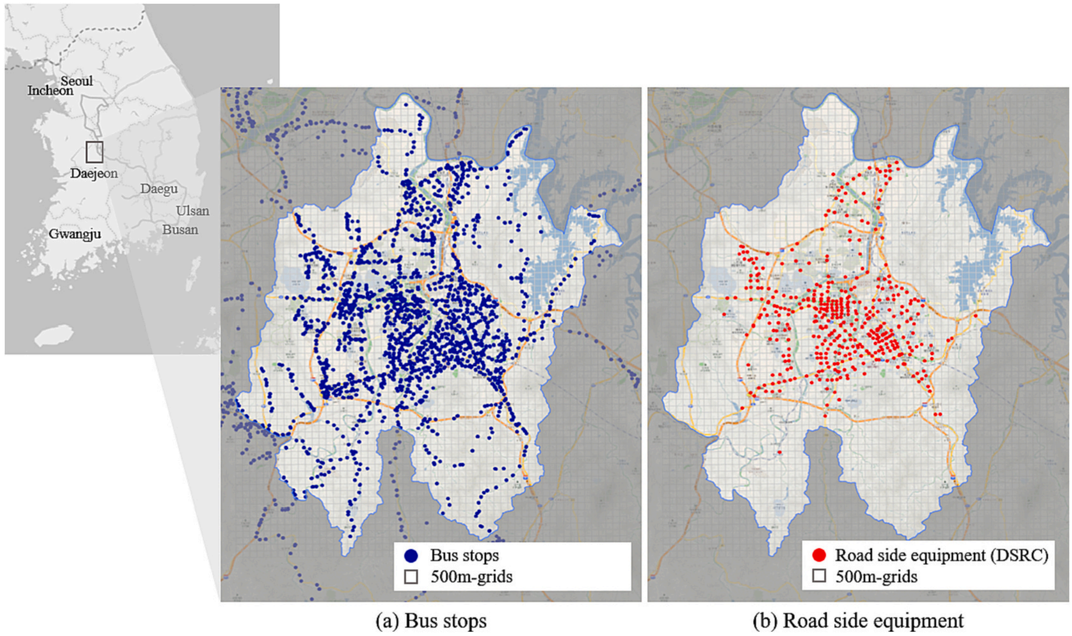

Fig. 2. Bus stops and road side equipment deployment in Daejeon Metropolitan City, South Korea.

had a road network of about 2146 km (Korean Statistical Information Service, 2020) and over one hundred bus routes that carry almost 290,000 passengers per day (Daejeon Metropolitan City, 2020a). Daejeon has a relatively higher dependency on cars than other metropolitan cities in South Korea. The modal split in Daejeon is 42.2 % for cars and 14.5 % for buses, while, in Seoul and Busan—two of the most populous metropolitan cities in South Korea—20.4 % and 31.5 % of travel are handled by cars, and 24.2 % and 20.5 % by bus (The Korea Transport Institute, 2020).

We investigated individual-level travel behavior during the period spanning January 13 to March 29, 2020. This period includes the initial phase of the pandemic when it is expected to be able to see the responses of people to the pandemic unaffected by external interventions such as government policies, as explained in the Introduction. The first case of COVID-19 in South Korea was reported on January 20 (see Fig. 1). A large number of confirmed cases from community transmission was first observed on February 18. Against the spread of disease, the government raised the alert level from Orange (warning, level 3) to Red (serious, level 4) on February 23. Until that time, a total of 843 confirmed cases had been reported in the country (Ministry of Health and Welfare, 2020). The number of newly confirmed cases had an incremental trend until early March. On March 22, the government consequently introduced the first measure for the pandemic, social distancing, to impede community infection.

In Daejeon, the first case was confirmed on February 21, 2020, which was the month after the first COVID-19 infection in South Korea (Daejeon Metropolitan City, 2020b). Similar to the national trend, the number of newly confirmed cases in Daejeon sharply increased and peaked on February 26. During the initial phase of the COVID-19 pandemic, although Daejeon had a relatively lower number of COVID-19 confirmed cases than other cities in South Korea, the city experienced a substantial decrease in activities and travel demand due to the virus (Daejeon Sejong Research Institute, 2020; Kim et al., 2021; Lee, Chai, Lee, An, & Jang, 2020).

2.2. Data description

Daejeon manages the travel generated by multiple transportation modes in the city and collects travel information using the Advanced Transportation Management System (ATMS). Using this well-developed system, we obtained the individual-level trip data of bus users collected from the smart card system and of private vehicles collected from Dedicated Short-Range Communication (DSRC) technology. To examine changes in travel behavior from the spatial perspective, we additionally acquired latitudinal and longitudinal data for about 2740 bus stops and 407 RSEs, which cover most of the urban areas in Daejeon. Fig. 2 shows the location of Daejeon City and the geographical distribution of bus stops and RSEs in the city. In the case of bus stops, the coverage was extended to neighboring regions. The penetration rate of smart cards in Daejeon exceeded 95 % in 2017 (Newsis, 2017), and the DSRC system had a penetration rate of 12.3 % in 2018.[1]

Because both kinds of data include the encoded identity number of travelers—smart card number for bus data and probe device number for private vehicle data (i.e., DSRC data)— we were able to trace trips at an individual level during our temporal scope. However, smart card data and DSRC data include different information. The smart card data (i.e., bus trip data) records the time and location (i.e., bus stops) of each passenger's trip (consisting of one boarding and one alighting). Each record of DSRC data is generated when a vehicle communicates with an RSE on roads and includes information on communication time and the RSE identifier. Therefore, we first estimated the origin-last destination information in terms of activity-based travel units (i.e., trip-chain record) from both kinds of trip data to analyze individual-level travel behavior based on actual travel information. In this process, we excluded bus trip records whose origin and destination were the same or whose destination information was missing. For the private vehicle trips, we removed the trips whose travel time was less than a minute or more than 2 h, considering the geographical size of our study site. As a result, during the 3rd week of 2020, just before the first national COVID-19 infection, more than two million bus trips were made by 560,746 bus users and four million vehicle trips by 510,278 probe vehicle owners.

[1] The penetration rate of DSRC was calculated using the ratio of the number of probe vehicles to the total number of vehicles crossing each intersection. We estimated this rate over 20 different intersections in Daejeon on average. Considering that a penetration rate over 7.5 % could provide reliable traffic data (Gayah & Dixit, 2013), the data from the DSRC system should represent the general private vehicle trips made in Daejeon.

3. Methods

3.1. Resident identification

To avoid possible bias by random trips by visitors, it was necessary to extract the travels of residents who consistently appeared in the city. For its extraction, we defined the residents as travelers who made trips every week during the pre-pandemic period (from the 1st week to the 3rd week in 2020). As illustrated in Fig. 3, for example, if someone used buses or drove in Daejeon City at least once a week for all three weeks, he/she was considered a resident. If not traveling even once in one week out of three weeks, he/she was considered a visitor. The weekly number of trips by individual travelers was counted based on the encoded identity numbers (smart card numbers for bus data and probe device numbers for private vehicle data). The final data set of residents contains trip records of 213,320 bus users and 182,356 private vehicle users.

3.2. Indicators of travel behavior at individual level

Four indicators were used to measure travel behaviors at an individual level in three categories: i) trip frequency (average daily trip frequency), ii) trip regularity (inter-visit interval), and iii) trip distance (average daily trip distance and radius of gyration). We computed them using the origin-destination information of trip-chain records that we made from sub-trip records of buses and private vehicles, and expressed travel behaviors based on activity-based demands. To examine the impact of COVID-19 on residents, we compared indicators of individuals weekly. The calculation of indicators is elucidated in the following subsections.

3.2.1. Trip frequency

The first indicator is the 'average daily trip frequency' of individual travelers, which is closely related to the number of activities. This indicator was calculated weekly and separately for two day types—weekdays and weekends. This indicator is expressed by Eq. (1).

$$f_{i,d}^{w} = \frac{n_{i,d}^{w}}{|d^{w}|} \quad (1)$$

Here, $f_{i,\ d}^{w}$ is the average daily trip frequency of resident i on day type $d = \{\text{weekdays}, \text{weekends/holidays}\}$ in the w^{th} week. The term $n_{i,\ d}^{w}$ denotes the sum of the trip frequency of resident i on day type d in the w^{th} week and $|d^{w}|$ represents the number of dates for day type d in the w^{th} week. For example, if one resident made three weekday trips and one weekend trip in a certain week without any national holiday, his/her average daily trip frequency for 'weekdays' would be 0.6 (3 trips / 5 days), and for 'weekends/holidays' would be 0.5 (1 trips / 2 days). Therefore, normalizing trip frequency by $|d^{w}|$, not the number of actual trip dates, can avoid over- and under-estimating the daily trip frequency due to dates without trips or trips concentrated on only a few dates. In the case of no trips, we assigned zero to the average daily trip frequency to examine changes in the travel demand due to behavioral responses to the pandemic, such as trip cancellation and mode alternation.

3.2.2. Trip regularity

Trip regularity is the generic concept used to represent the degree of repetition of trips from spatial and temporal perspectives (Gonzalez, Hidalgo, & Barabasi, 2008; Sun, Axhausen, Lee, & Huang, 2013; Williams, Whitaker, & Allen, 2012). In this study, trip regularity was represented as the time interval between trip events arriving at the same locations by each traveler, which is referred to as an 'inter-visit interval' — a universal indicator used to measure the temporal regularity for certain locations (Williams et al., 2012). Because some activity types accompany specific trip patterns that are regularly generated, comparing this indicator over time enables us to infer which types of activities were more affected by COVID-19. For example, a commuter who has to arrive at an office before 9 am makes trips from his/her home to the office during morning peak hours within about 24 h every weekday. Meanwhile, non-mandatory trips, such as for shopping, leisure, and errands, occur mainly during non-peak hours or on weekends and have less regularity or are completely irregular. Such types of trips are usually generated over longer intervals than commuting trips.

As displayed in Fig. 2, we used a square grid with edges of 500 m as a unit for spatial tolerance of the RSE and bus stop locations, which is a common tessellation method. The equation of an 'inter-visit interval' is defined as:

$$I_{i,l,k} = ts_{i,l,k} - ts_{i,l,k-1} \ (k \geq 2) \quad (2)$$

where $I_{i,\ l,\ k}$ signifies the interval length in seconds between k^{th} and $k-1^{th}$ visits to location l of resident i, and $ts_{i,\ l,\ k}$ denotes the timestamp of the k^{th} visit to location l of resident i. Here, measuring the inter-visit interval was applied to all residents, but locations that the residents visited just once during the study period were excluded from computation ($k \geq 2$).

3.2.3. Trip distance

Two indicators were used to see changes in the trip distance due to the pandemic: 'average daily trip distance' and 'radius of gyration.' These indicators were measured for residents only who made trips at least once a week for every week in the temporal scope to exclude changes in trip distance influenced by changes in trip frequency.

The 'average daily trip distance' is defined as:

$$\overline{D}_{i,d}^{w} = \frac{D_{i,d}^{w}}{|d^{w}|} \quad (3)$$

where $D_{i,\ d}^{w}$ is the sum of trip distances that resident i made for days corresponding to day type d in the w^{th} week, i.e., the same logic as calculation of the average daily trip frequency $f_{i,\ d}^{w}$.

While the 'average daily trip distance' shows a total trip distance made by an individual traveler, the 'radius of gyration' represents the size of the activity area of a traveler. Previous studies have used this indicator to define activity boundaries from their center locations in their daily lives (Gonzalez, Hidalgo, & Barabasi, 2008; Lu et al., 2013; Pepe et al., 2020; Xu, Belyi, Bojic, & Ratti, 2018). The center locations of individuals are generally defined as home in terms of home-based round trips. Therefore, the radius of gyration can capture how far the trips of an individual extend from his/her home. In this study, we first calculated the radius of gyration of resident i for each trip date d' using Eq. (4).

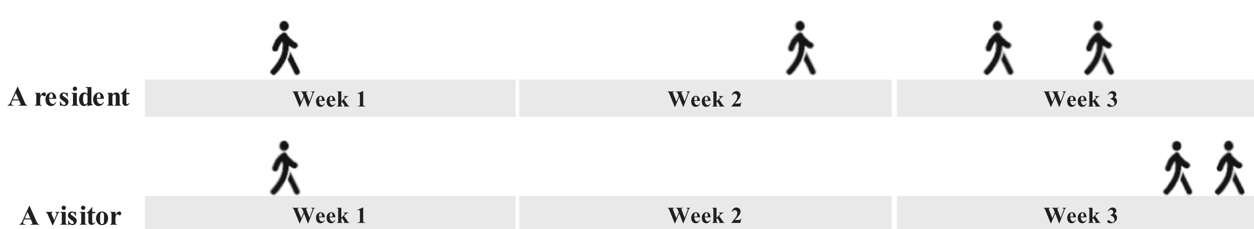

Fig. 3. Definition of residents.

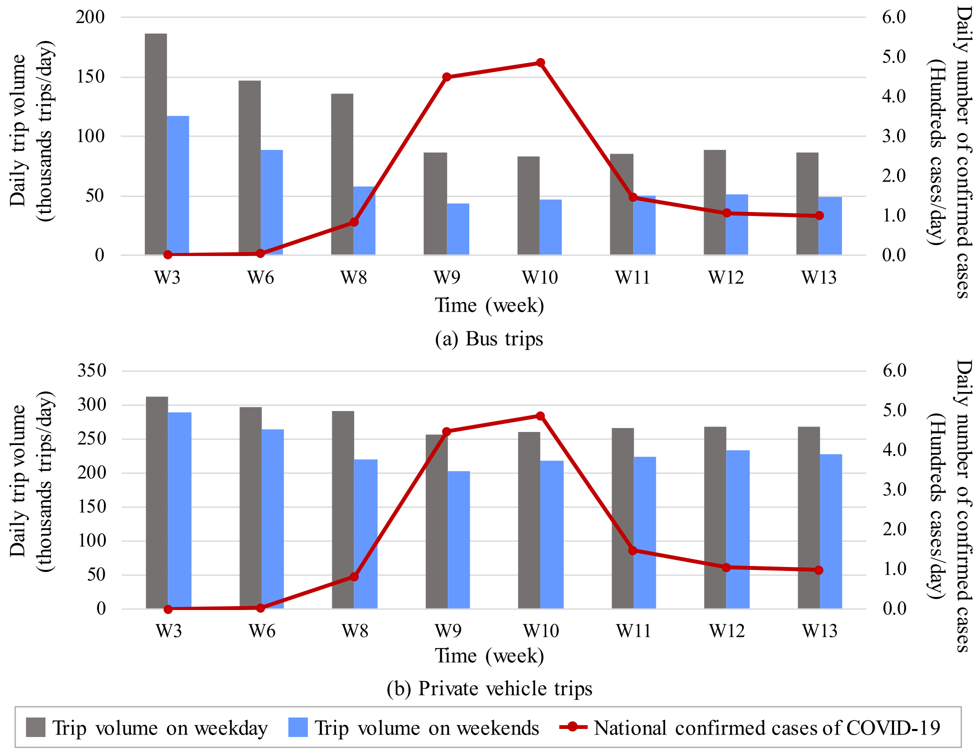

Fig. 4. Changes in trip demand of bus and private vehicles in relation to confirmed cases of COVID-19.

$$r_{i,d'} = \sqrt{\frac{1}{n_{i,d'}}\sum_{t=1}^{n_{i,d'}} distance^2\left(l_{i,d',c}, l_{i,d',t}\right)} \tag{4}$$

where $n_{i,\ d'}$ is the number of trips by individual i on date d', and the coordinates of the center location and of the t^{th} destination are $l_{i,\ d',\ c}$ and $l_{i,\ d',\ t}$. To express weekly changes in the radius of gyration on the day types, we computed a simple average for week w and day type d, to which date d' corresponds, which was defined as $\bar{r}_{i,d}^{w}$.

4. Results

4.1. Changes in time-of-day travel demand

After the day of the first case of COVID-19 in South Korea, the trip demand of residents significantly decreased for both bus and private vehicle modes, as shown in Fig. 4. In the 6th week of 2020, the number of bus and private vehicle trips of residents decreased by about 23 % and 7 %, respectively, compared to the 3rd week. The first case of local transmission in Daejeon was reported on Friday of the 8th week, right before the government reported the highest number of confirmed cases nationwide within the temporal scope of this study. The explosive spread of the COVID-19 virus made the trip demand drop even more. In the 9th week, trip demand decreased by about 58 % for buses and 24 % for private vehicles, compared to the 3rd week. The greater decrease in bus-trip demand than in private-vehicle demand implies that, even without the closure of public transit, the increase in infection cases by local transmission aroused resident anxiety over using public spaces and led them to prefer personal transportation modes.

Fig. 4 also shows that the residents responded to the pandemic by reducing their trips more on weekends than on weekdays. During the 9th week, bus trips decreased as much as 54 % on weekdays and 63 % on weekends, compared to the 3rd week. The difference in the reduction rate between weekdays and weekends was most clearly observed in private vehicle trip demand. It decreased by only 18 % on weekdays but was greater on weekends, 30 %. Moreover, in Fig. 5, the distribution of hourly travel demand shows that, on weekdays, the demand reduction was much greater during the non-peak hours than during peak hours: in the 9th week, bus trips declined by 47 %, and private vehicle trips by 9 % during a peak hour (from 8 am to 9 am). In contrast, they fell by 64 % and 21 % during a non-peak hour (from 12 pm and 1 pm), compared to the 3rd week. This lesser drop in peak hours on weekdays is regarded as a natural result because activities generated during weekends or non-peak hours on weekdays usually involve non-mandatory and irregular trips (Gim, 2018). The result implies different responses of residents to the pandemic by transportation modes and time of day.

Interestingly, the number of confirmed cases in the country and in Daejeon fell greatly after the 10th week, and there was a faint sign of a recovery in travel demand, especially for the weekend trips. In the 12th week, the decrease rate of bus and private vehicle trips remained at 53 % and 14 % on weekdays, while on weekends, it slightly declined to 56 % (from 63 %) and 19 % (from 30 %) for buses and private vehicles (see Fig. 4). During the first social distancing period in South Korea, travel demand on weekends (Sunday of the 12th week) seemed to be on the decline again. During the 13th week, the decrease rate on weekends was 58 % for bus trips and 21 % for private vehicle trips, compared to the 3rd week. On weekdays, the decrease rate still had a trend similar to those in previous weeks: 54 % for bus trips and 14 % for private vehicle trips.

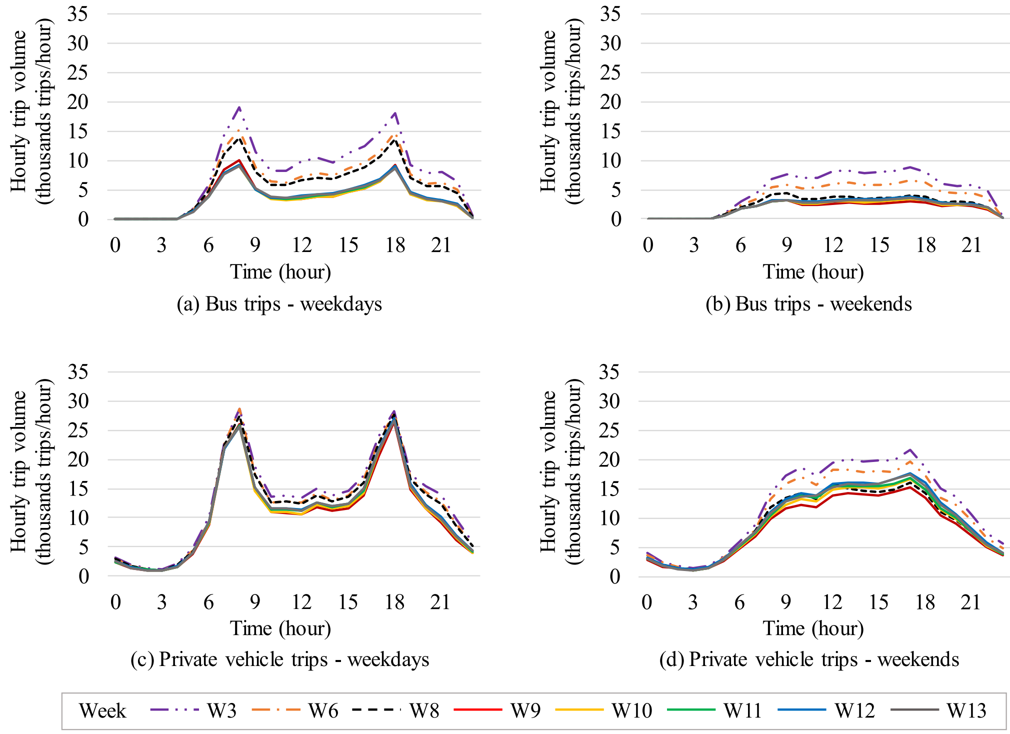

Fig. 5. Changes in hourly trip demand of bus and private vehicle.

4.2. Changes in trip frequency

In the 3rd week (i.e., non-pandemic condition), >90 % of residents used buses or private vehicles at least once a day on weekdays. Fig. 6 shows that about half of bus users took buses 0–1 times per day and one-third of private vehicle users used cars 2–3 times per day on weekdays in the corresponding week. On weekends, the portion of residents who made trips decreased for both buses and private vehicles, and especially, its portion for buses significantly decreased to 54 %. While the portion of bus users by trip frequency diminished, the portion of private vehicle users who made trips more than three times per day slightly increased to 14 % on weekends from 12 % on weekdays. This trend implies that the residents usually use buses for essential weekday activities, such as commuting, which is different from the behavior of using private vehicles.

The proportion of users who made trips by buses and private vehicles largely decreased in the 9th and 10th weeks after the outbreak of the first case in Daejeon. This follows the same trends as the trip demand reductions illustrated in Fig. 4 and Fig. 5. In the 9th week, the portion of private vehicle users who did not make car trips reached 13 % on weekdays and 29 % on weekends. Moreover, 53 % and 79 % of bus users did not make bus trips on weekdays and weekends, respectively. This different reduction in the number of actual users by transportation modes means that people may consider bus riders more susceptible to infection than those in private vehicles during the pandemic. However, after this largest reduction, the increased proportion of non-trip users slightly declined, mainly on weekends. In the 12th week, it was 24 % for private vehicle users and 75 % for bus users.

The notable point here is that the user reduction rate is more significant in the groups with greater trip frequencies. On weekdays in the 9th week, the portion of bus users who made 2–3 bus trips per day decreased by 58 %, while those who made 0–1 bus trips per day decreased by about 44 %, compared to the 3rd week. The same trend is also observed in private vehicle trips, except for 0–1 trips per day. The portion of private vehicle users with 0–1 trips per day rather increased during the pandemic, compared to the 3rd week; while in the 9th week, it increased by 11 % on weekdays and 19 % on weekends. This result indicates that private vehicle users maintained the use of their transportation mode, at least for mandatory activities. In contrast, many bus users may have given up taking buses due to infection risk.

This result extends the finding in Section 4.1 by showing that the reduction in the number of trips resulted from decreases in travelers and their trip frequencies. Furthermore, to see the individual changes in trip frequency, we traced each resident's average daily trip frequency over weeks. The changes were measured by comparing the trip frequency of the 3rd week (i.e., non-pandemic period) and other weeks in the study period, and then classified into three states: 'maintain' (residents made the same number of average daily trips in a certain week compared to the 3rd week), 'decrease' (residents made fewer average daily trips), and 'increase' (residents made a greater number of average daily trips). Fig. 7 shows changes in the proportion of residents included in each state ('maintain,' 'decrease,' and 'increase') over weeks by transportation modes and day types.

In bus trips, about 70 % of users made fewer trips on weekdays starting from the 9th week than in the 3rd week. The proportion of the 'decrease' state of trip frequency rose and peaked in the 10th week at 72 %. In addition, the proportion of the 'increase' state dropped more than a half; it was 27 % in the 6th week and decreased to 13 % in the 9th week. On weekends, the proportion of 'decrease' grew from 33 % in the 6th week to 43 % in the 10th week, while the proportion of 'increase'

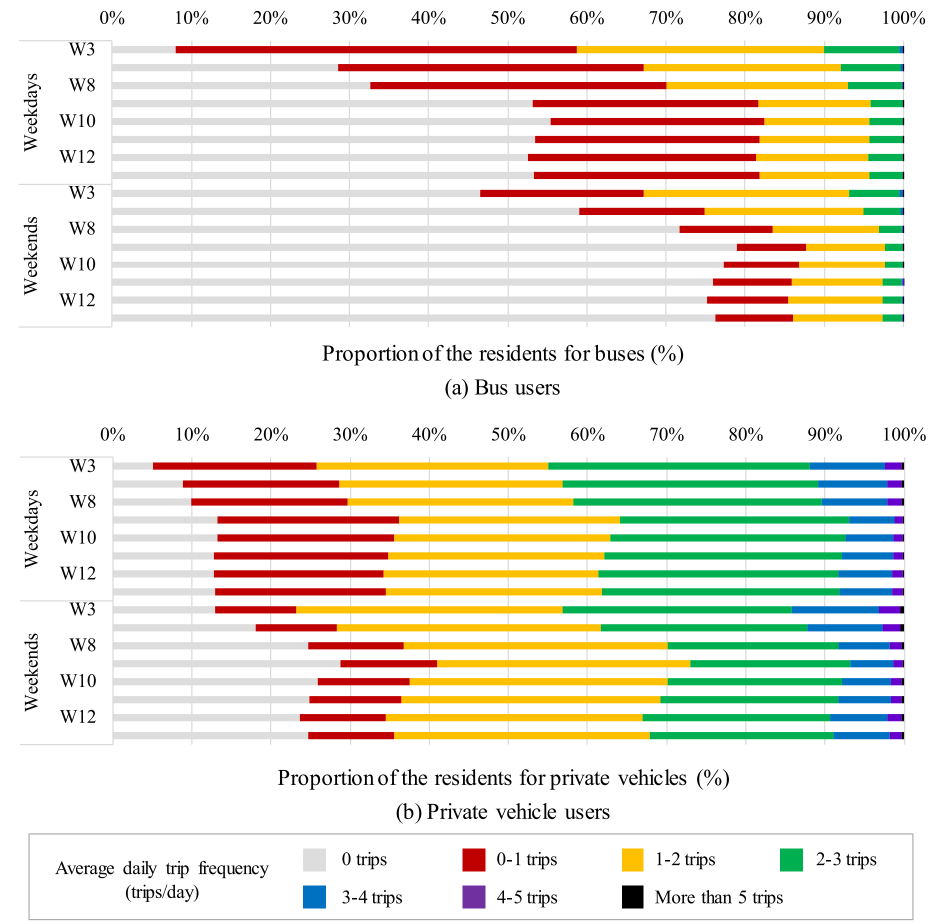

Fig. 6. Share of residents by individual daily trip frequency ($f^{w}_{i,d}$) of (a) Bus users and (b) Private vehicle users.

diminished from 19 % to 10 % during the pandemic (see Fig. 7 (b)). The proportion of 'maintain' on weekends in the pandemic condition seemed to change little, which is different from the result of bus trips on weekdays. This is because many bus users did not make bus trips on weekends even before the pandemic, and they did the same during the pandemic. This result indicates that residents still did not make or reduce their bus trips on weekends as a response to the pandemic.

During the 6th week, private vehicle users included in the 'decrease' and 'increase' states of trip frequency occupied similar portions of about 45 %. However, with spreading of the pandemic, the proportion of 'decrease' grew while that of 'increase' shrank; more than half of private vehicle users (56 % on weekdays and 55 % on weekends) reduced their private vehicle trips in the 9th week.

After the 10th week (the peak of demand reduction), an increase in trip frequencies was observed, which was different by transportation mode. As the number of infection cases declined, the proportion of bus users included in the 'increase' state of trip frequency rose by 2 % each on weekdays and weekends: it changed from 13 % in the 9th week to 15 % in the 12th week on weekdays and from 9 % to 11 % on weekends. Furthermore, private vehicle users responded more briefly to the declining infection trend, which seems to indicate an intension to resume their activities. This change appeared much greater on weekends. The proportion of private vehicle users included in the 'increase' state was 24 % in the 9th week and 30 % in the 12th week. On weekdays, the value increased from 30 % to 33 %. This result implies that private vehicle users may have felt less threatened by infection because of their separate spaces when traveling. Meanwhile, in the 13th week, when the policy of enhanced social distancing was officially introduced in the community, the trend in recovery of the travel demand seems to have been interrupted weakly. The portion of the 'increase' state decreased by about 1 % for both bus and private vehicle trips.

4.3. Changes in trip regularity

The inter-visit interval expresses the time intervals of repeated trips visiting a specific place. This study focused on the inter-visit intervals for weekdays to see changes in trips related to mandatory activities (i.e., commuting). This is because the intervals of weekend trips are very similar to those of weekday trips (Agarwal, 2004; Song, Qu, Blumm, & Barabási, 2010), but activity attributes that can be inferred by location characteristics are various and difficult to interpret with trip data only. In the calculation, we excluded the interval value on Monday because the value arriving at weekday routine locations (such as workplaces) on Monday includes the length of weekends. This enables avoiding overestimation of the interval pattern in revisiting the important places. Therefore, this indicator can show the impact of COVID-19 on mandatory and non-mandatory trips.

As shown in Fig. 8, the distribution of 'inter-visit interval' shows that residents make regular trips, mainly at one-day intervals (i.e., within 24 h). In other words, people are likely to visit the same places at the same

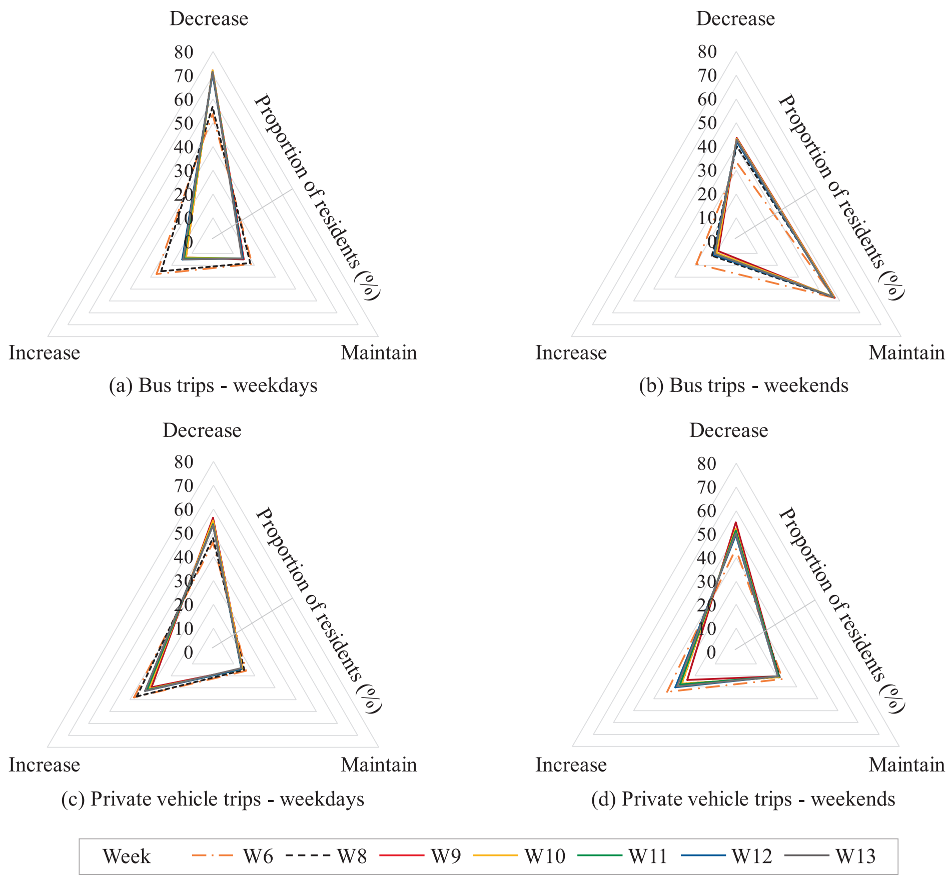

Fig. 7. Proportion of residents by change in the average daily trip frequency.

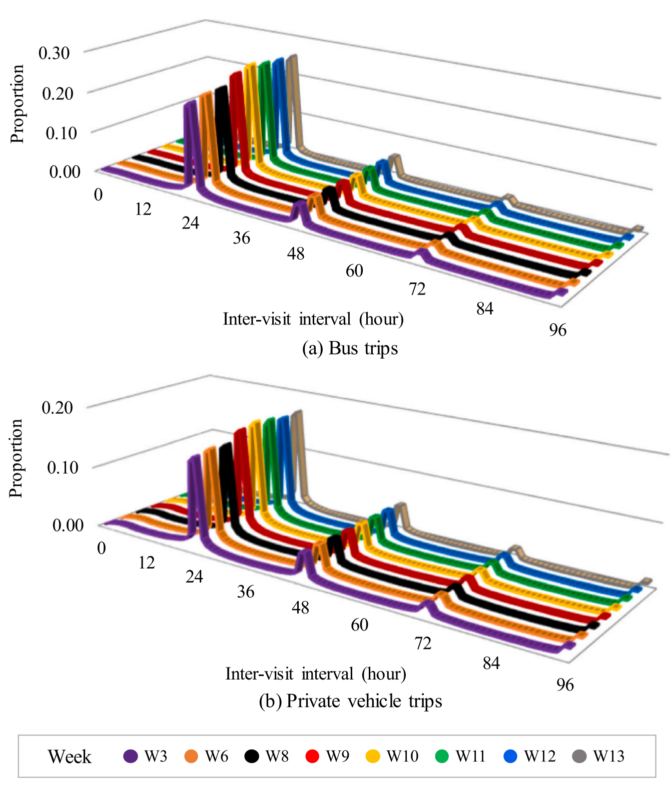

Fig. 8. Distribution of inter-visit intervals ($I_{i,\ l,\ k}$) by transportation modes.

time of the day. In addition, the probability of an inter-visit interval has several peaks at multiples of 24 h, which shows the cycles of essential activities in their daily lives. In the 3rd week, the probability at the 24-hour interval point was 23 % for bus trips and 15 % for private vehicle trips. As the pandemic spread, the probability at the 24-hour interval point gradually increased over weeks and peaked in the 10th week with 27 % for bus trips and 18 % for private vehicle trips. This indicates increased trip regularity due to the pandemic, which might have resulted from reducing many irregular or unnecessary activities compared to regular activities.

However, after the 10th week, the proportion of regular trips slightly decreased until the 12th week when the social distancing policy was introduced. In the 12th week, the proportion of regular trips with 24-hour intervals was 26 % for buses and 17 % for private vehicles. Considering the changes in individual trip frequency and trip volumes during these periods, this suggests that residents began to make less regular or irregular trips again.

To verify our inference of the repeated trips at the interval of 24 h ($I_{i,\ l,\ k} = 24$ h), we calculated the proportion of those trips by the time of day: morning peak, daytime, evening peak, and nighttime. As shown in Fig. 9, the morning peak trips are most likely to have 24-hour regularity, followed by evening peak trips. This result supports the notion that trips during both peak times are more closely related to mandatory or daily trips (e.g., commuting) than other trips are. In the 3rd week, the proportion of regular trips during the morning peak was 69 % for buses and 53 % for private vehicles (out of all trips during each time). With a trend similar to the result in Fig. 8, the proportion of regular trips during the morning peak gradually increased until the 10th week, when it was 74 % for buses and 58 % for private vehicles.

This increased regularity in trips can also be observed during other times of day, especially during the evening peak. Because most residents

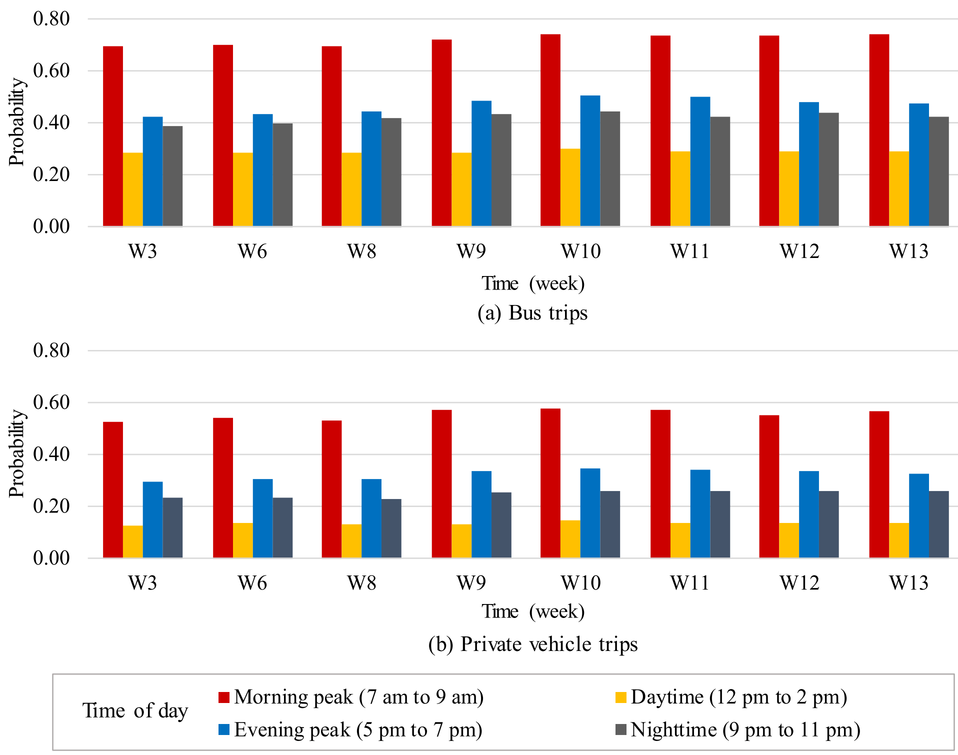

Fig. 9. Probability of occurrence of 24-hour revisit trips over times of the day (morning peak, daytime, evening peak, and nighttime).

return home and do no additional activities after work, the proportion of regular trips significantly increased, and this amount was higher for buses than for private vehicles. The proportion for buses increased to 51 % in the 10th week from 42 % in the 3rd week, while private vehicles increased to 35 % from 30 %. The lower regularity of trips during the evening peak than during the morning peak would result from the behavior of residents who avoided unnecessary activities—such as social or recreational activities that mainly occurred after general office hours (Agarwal, 2004)—due to their perceived risk of local transmission.

4.4. Changes in trip distance

4.4.1. Average daily trip distance

The number of users for buses and private vehicles was first counted by the ranges of their average daily trip distances to see how residents changed their trip distances. To avoid overestimating the degree of changes in trip distance due to dormant residents, we counted it only for 'active users' who made bus or car trips at least once a week for both day types during the targeted weeks. The number of active users decreased in most trip-distance ranges, as shown in Fig. 10, which is similar to the increase in non-trip users (see Fig. 6).

Suppose that daily trips with a distance of >20 km are the 'long' daily trips and that those under 20 km are the 'short' daily trips.[2] Compared to the 3rd week, there were similar decreases of bus users traveling short distances (52 %) and long distances (53 %) on weekdays in the 9th week. However, on weekends, bus users reduced their short trips more. The number of bus users with a short daily trip distance decreased by 63 % in the 9th week, and those with long daily trip distance decreased by 58 %. Given that residents mainly used buses for mandatory activities such as commuting during the pandemic (confirmed in Section 4.3), this may have been because active bus users had fewer alternative options for transportation modes, regardless of their trip distances. Meanwhile, with private vehicle trips, the longer the daily trip distance was, the more the users decreased. In the 9th week, the number of users decreased by 12 % for short daily trips and by 18 % only for long daily trips on weekdays. The gap between short and long trip distances for private vehicles became wider on weekends: it dropped by 24 % for short daily trip distance and 34 % for long daily trip distance. This means that private vehicle users (for whom trips were relatively easier to make) reduced activities that were subsidiary or required long drives during pandemic weekends.

The noteworthy point here is that the number of private vehicle users who traveled under 2 km in a day after the 9th week was greater than those in the 3rd week. Moreover, it is similar to the increase in private vehicle users with 0–1 trip frequency. This increasing trend peaked at 13 % on the weekend of the 8th week and 15 % on the weekdays of the 9th week. This may have resulted from private vehicle users maintaining their car use, but reducing their trip frequency or narrowing their activity boundary. After this peak, a decline started and, on weekends with enhanced social distancing, the number of these short-distance users was lower than those in the 3rd week.

In addition, we compared the daily trip distances of individuals by week. Compared to the 3rd week, if the daily trip distances changed by ±1 km, the state was labeled 'maintain.' When the daily trip distance decreased by >1 km, we called it the 'decrease' state. The case of increase in daily trip distance by >1 km was labeled the 'increase' state. Fig. 11 shows that the proportion of residents who shortened their daily trip distances became greater, which resulted from decrease in the individual trip frequency during the early pandemic.

Active users for both transportation modes seemed to shorten their daily trip distances, and this change peaked in the 9th and 10th weeks. For bus trips in the 9th week, the proportion of 'decrease' was 41 % on weekdays and 35 % on weekends (which was 31 % on both weekdays and weekends of the 6th week). This increased proportion of 'decrease' was maintained within a 1 % margin of change rate until the 13th week.

[2] The average travel distance (per trip) in South Korea was 12.8 km for private vehicle trips and 11.1 km for bus trips in 2018 (The Korea Transport Institute, 2020). Considering that people usually make a home-based round trip in a day, we simply defined the long- and short- daily trip distance with a baseline of 20 km.

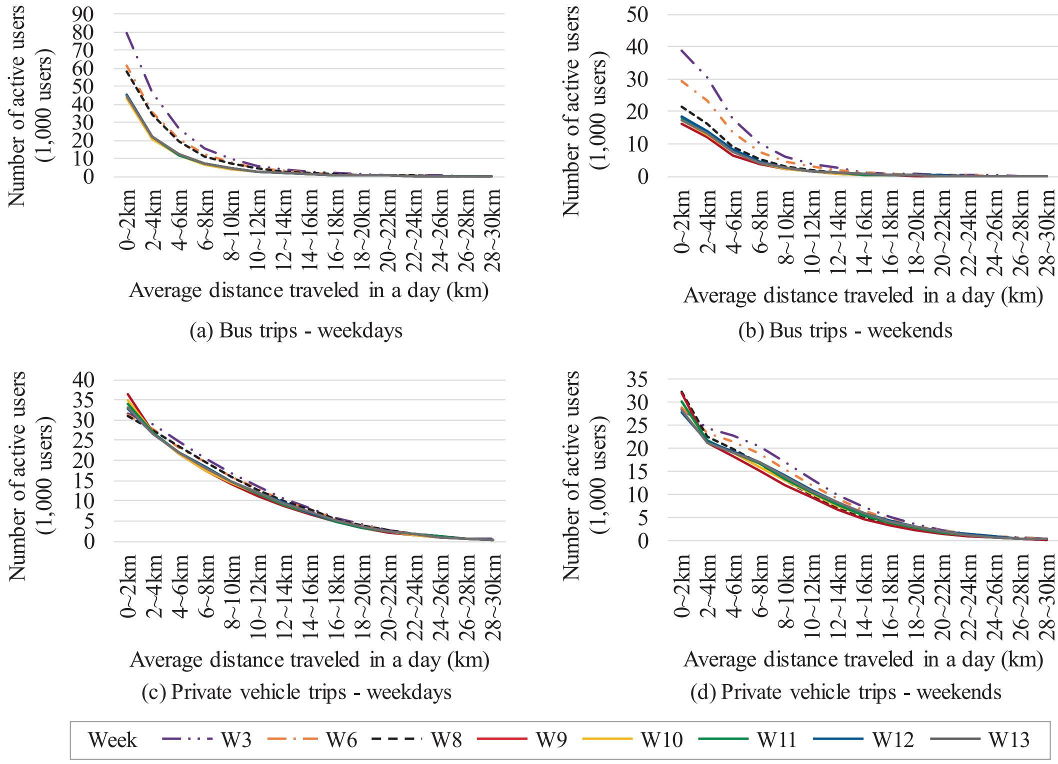

Fig. 10. Distribution of active users by average daily trip distance ($\overline{D}_{i,d}^{w}$).

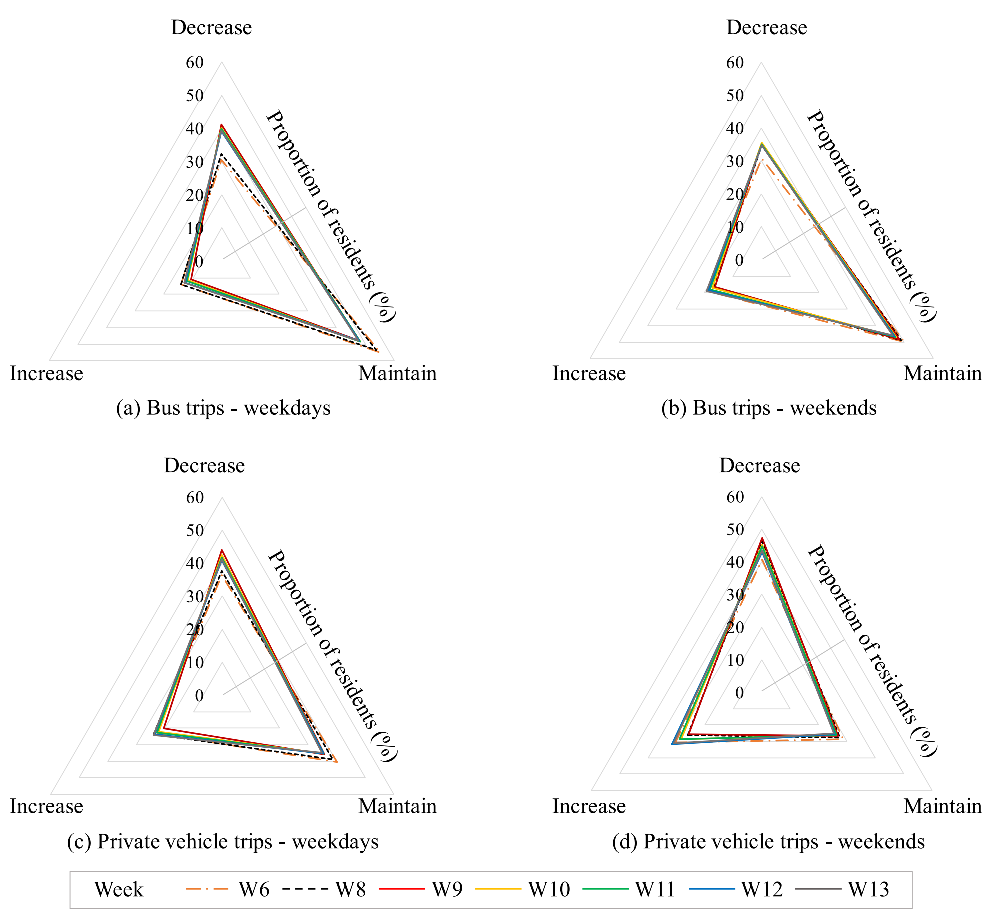

Fig. 11. Proportion of residents by the change in daily trip distances.

On the other hand, the proportion of bus users who increased daily trip distances (excluding non-trip users) on weekdays decreased from 14 % in the 6th week to 11 % in the 9th week, but rebounded to 13 % in the 13th week. Likewise, in the case of weekends, the proportion of 'increase' (19 %) dropped to 16 % in the 9th week and increased to 19 % in the 13th week. The same patterns were observed for private vehicle trips. The proportion of 'decrease' on weekdays increased from 36 % in the 6th week to 44 % in the 9th week, but again decreased to 41 % in the 13th week. On weekends, it increased to 47 %, but then dropped to 44 %. In addition, the proportion of 'increase' declined, but then returned in the 13th week to the same level as in the 6th week.

At the individual level, both private vehicle users and bus users tended to reduce the distances of the trips they made in a day. However, the number of residents by daily trip distances had different change patterns. For the early period of the pandemic, the number of private vehicle users with short trip distances increased, which might be affected by user shifts from the group of longer distances to shorter distances while keeping vehicle usage consistent. In contrast, the number of bus users traveling short distances decreased, which may have been because users shifted to shorter distances. Still, the explosive increase in residents not using buses during the pandemic (see Fig. 6) would have offset this and significantly affected the decrease in demand for short-distance traveled in a day.

4.4.2. Radius of gyration

The radius of gyration can capture changes in the size of the activity area of travelers. To observe how COVID-19 affected the resident activity boundaries, we compared the number of active users over the lengths of the radius of gyration by weeks. Fig. 12 shows that large decreases in the number of users in most radius ranges occurred after the first national and local infection cases—which is consistent with the results shown in Fig. 6 and Fig. 10. However, the patterns of decrease were different from those of daily trip distance. In the case of daily trip distance for buses on weekdays, the decrease rates of users were similar regardless of distance. However, the decrease rate in the radius of gyration was greater on the longer radius, especially over 16 km. On weekdays of the 9th week, the number of bus users with a short radius (under 10 km) decreased by 48 %, and those with a longer radius (over 10 km) decreased by 50 %, compared to the 3rd week. These rates of decrease continued until the 13th week. On weekends, the drop rates for short and long radiuses were similar. The demand of short radius trips decreased to about 60 % in the 9th week from 23 % in the 6th week. After this peak period, the demand for short and long radiuses recovered to 54 % and 52 % in the 13th week.

Meanwhile, for private vehicle trips, the decrease rate of users within short activity boundaries (except for those with radius under 1 km) was higher than of those within long activity boundaries on both weekdays and weekends. On weekdays of the 6th week, the rate of decrease in the number of private vehicle users with short activity boundaries (compared to the 3rd week) was 5 % and increased to 7 % in the 9th week. It rose from 5 % to 15 % on weekends. Meanwhile, in the same week, for the radius under 1 km, private-vehicle demand increased to 24 % on weekdays and 11 % on weekends, compared to the 3rd week; it is similar to the demand increase in the trip frequency of 0–1 times per day and the daily travel distances under 2 km.

The demand for long activity boundaries by private vehicles tended to increase. Considering that the trip distance per trip, which can alternatively mean the radius of gyration, is longer for private vehicles than for buses (The Korea Transport Institute, 2020), people generally prefer to use their private vehicles to visit a place far from their home. Conversely, the shorter activity boundaries of residents using buses may be because of the inconvenience of public transit for moving long distances. This preference, which varied by boundary ranges, became more notable due to pandemic conditions because residents using buses would be concerned about staying confined with a large number of strangers for a long time and becoming infected by them (Beck, Hensher, & Nelson, 2021; Shamshiripour et al., 2020). This anxiety might have led to the different reduction patterns by boundary length by transportation modes.

Fig. 13 displays the proportion of active users by each state of changes in their length of activity boundaries. It shows that most active users responded to the pandemic by keeping the size of the activity boundary similar, while reducing the daily trip frequency. This involves a reduction in the daily total trip distance. The portion of 'decrease' slightly increased from 18 % in the 6th week to 20 % in the 9th week for bus trips, and from 19 % to 22 % for private vehicle trips. However, at the same time, the 'increase' share also rose over weeks for bus and private vehicle trips. In particular, compared to the 3rd week, the

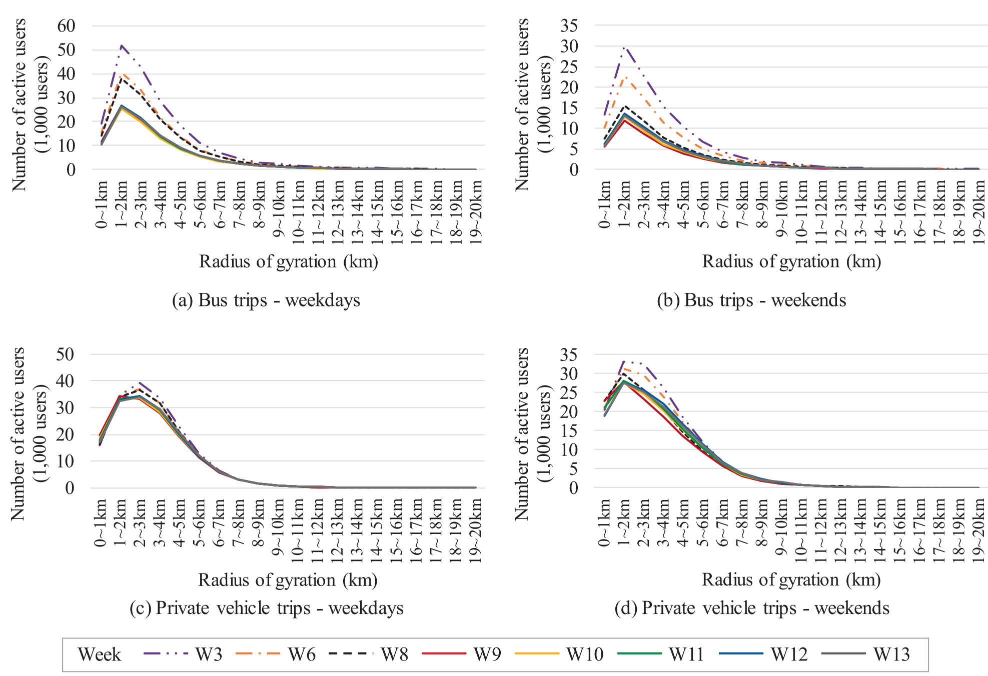

Fig. 12. Distribution of active users by radius of gyration ($\bar{r}^{w}_{i,d}$).

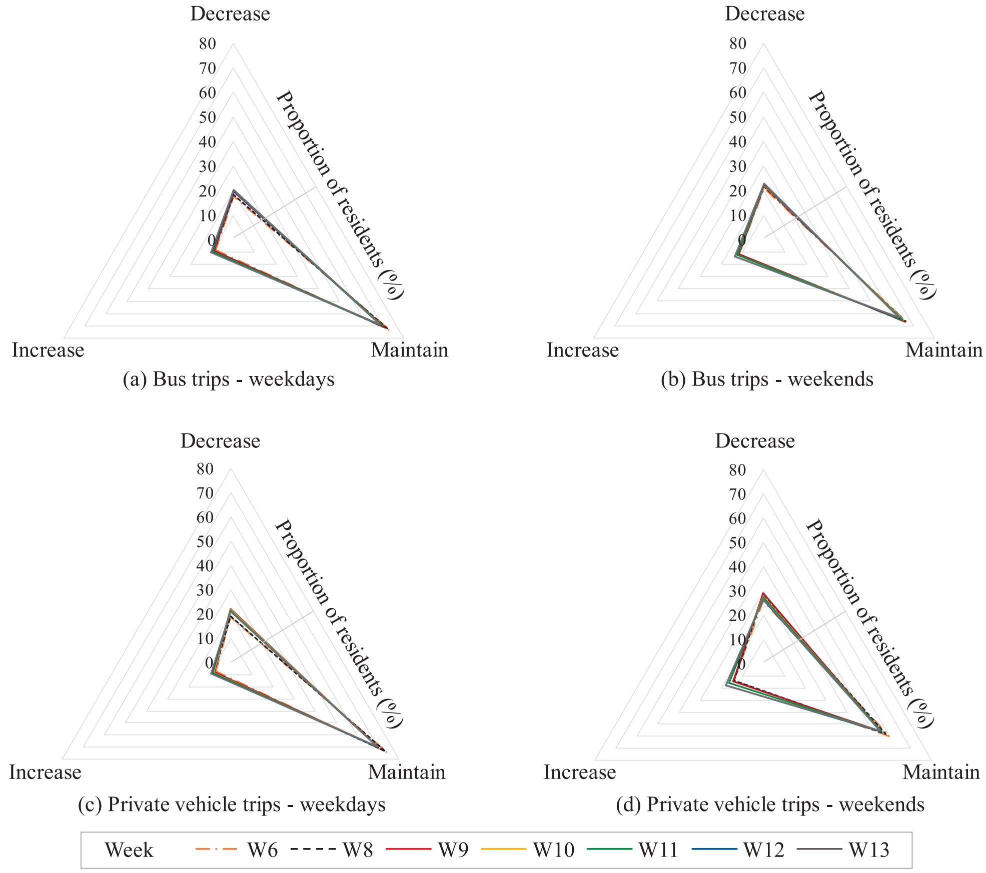

Fig. 13. Proportion of residents by change in the radius of gyration.

number of private vehicle users extending their travel radius on weekends increased to 18 % in the 13th week from 14 % in the 6th and 9th weeks. Even with the guidelines intended to discourage external activities, this travel behavior might be due to the temporary decrease in the number of infection cases.

5. Discussion

In Daejeon City, South Korea, the residents reduced their trip frequency and trip distances, and moreover, increased their trip regularity, during the pandemic. Such changes peaked in the 9th and 10th week, right after the first local infection case and a rapid increase in nationwide infection cases were reported. Meanwhile, the activity boundary of residents had remained at similar levels before and during the pandemic. Given the increased trip regularity, this result implies that the essential trips that seem to be the farthest (longest distances) from home, such as commuting trips (Korea Transportation Database, 2018), were quite consistently made even when the demand for other activity trips decreased. In the early period of the pandemic, including the 9th and 10th weeks, only a few measures were taken to impede the transmission of viruses in South Korea. The social distancing and other policies (e.g., prohibiting religious and welfare activities and encouraging work from home), were introduced later in our study period. This means that the reaction of local communities was faster than the implementation of health interventions (Chan, Chen, Ma, Sze, & Liu, 2021).

The decrease in travel demand occurred more significantly in bus trips than private vehicle trips during the early pandemic. In particular, the trip demand decreased for buses by 58 % and for vehicles by 24 % right after the first infection case in Daejeon City, compared to the pre-pandemic. This demand drop different by transportation modes is comparable to other cities and countries in the early phase of the pandemic with no or less strict anti-contagion measures. New York City had more confirmed cases than Daejeon City, but vehicle traffic has decreased by about 29 %, while bus users have decreased by about 47 % after the emergency declaration (Bian et al., 2021). The United Kingdom also experienced a significant decrease in car and bus trips by about 20 % and 50 %, respectively, before its first lockdown (Department for Transport, 2020a). Even in Australia with stay-at-home orders, the trip demand also decreased more in public transit trips (about 80 %) than in private vehicle trips (about 50 %) (Beck et al., 2021).

The reason for these drastic demand drops in public transit and the gap between buses and private vehicles can be found in survey-based works. People gave infection-related factors priority when choosing transportation modes during the pandemic. The concerns about local infections caused public transit, in which contact with strangers is inevitable, to be considered the riskiest among the intra-city transportation modes (Abdullah et al., 2020; Barbieri et al., 2021; Eisenmann et al., 2021; Kamplimath et al., 2021; Przybylowski et al., 2021; Shamshiripour et al., 2020). The negative perception of public transit during the pandemic hinders vibrant public transit usage. Strengthening sanitation in public transit, such as more frequent disinfection and ventilation in the fleets, and keeping a safe physical distance between passengers are highly required to protect them from the virus (Gkiotsalitis & Cats, 2021; Shen et al., 2020). At the same time, advertising such measures for sanitation in public transit to passengers through various media and campaigns is also essential to raise the perception of public transit (Abdullah, Ali, Dias, Campisi, & Javid, 2021; Gkiotsalitis & Cats, 2021; Javid, Abdullah, Ali, & Dias, 2021; Shen et al., 2020). Furthermore, active strategies for education on the guidelines should be formulated, focusing on people with information poverty such as rural residents, low-income groups, and the elderly because they mainly use public transit rather than private vehicles (Abdullah et al., 2021; Ul Haq, Shahbaz, & Boz, 2020).

This difference in reaction toward using transportation modes provides evidence of possible transportation inequality issues in the pandemic era. The first possible inequality can occur during commuting hours. The result shows a lower decrease in trip demands during commuting hours (usually 7 to 9 am and 5 to 7 pm on weekdays) at which time the demand is mainly concentrated, compared to other times of the day. It is in the same line as the survey targeted at Daejeon citizens. They responded that their activities for commuting, despite the Korean government's recommendation for flexible working, were less affected by the pandemic than others, such as religious-related activities and meeting friends (Daejeon Sejong Research Institute, 2020). In the case of private vehicle trips where a separate space is guaranteed, traveling during pandemics might not matter. However, in a bus, the probability of physical contact increases because people share a compact space, and this can result in a higher viral transmission rate. This difference in densities in a fleet can cause mobility inequality and might become more serious during rush hours. To dispel this issue, transit operators should provide fleets with shorter headway during rush hours to redistribute passengers in mass transit and should maintain lower passenger density in fleets. If there are constraints on the operating budget, they might be able to allocate resources used on weekends to add operational capacity during the commuting hours on weekdays. This is because of the large decrease in the demand for travel on weekends due to the pandemic. It could help commuters who do not have alternatives to public transit face less risk of infection while using public transit.

The findings in trip distance imply a second possible transportation inequality during pandemics. For the decrease in daily trip distances, the shift of private vehicle users from longer to shorter distance groups seems to have occurred while bus users reduced trips similarly over entire distance ranges. In addition, there was a large increase in private vehicle trips for distances under 1 km. Given that instrumental activities for daily living and health (e.g., going for groceries or to clinics) are generated in their home neighborhood (Chen, Guo, Yang, Ding, & Yuan, 2021; Department for Transport, 2020b; Korea Transportation Database, 2018), the behavioral changes of private vehicle users may be associated with the relative increase in private vehicle usage for those activities to fulfill basic needs. However, the decrease in demand for bus trip in all distance ranges implies that residents felt unsafe when using buses, even with few trips and for close destinations, during the pandemic. Residents with public transit as their only travel option may have restrictions on doing instrumental activities and be more easily exposed to viruses (Oluyede, Cochran, Wolfe, Prunkl, & McDonald, 2022). Therefore, the related authorities should first devise complementary measures to improve the availability of short-distance trips to overcome such inequality in transportation. For people with no other options except for public transit, authorities could implement policies to introduce or expand personal and shareable mobility systems (such as electric scooters or bike-sharing systems), with investment, education, and relaxation of regulations (Campisi et al., 2020). Car-sharing programs should also be considered for long-distance trips.

6. Conclusions

The COVID-19 pandemic has brought a new norm to daily lives and made significant changes in travel behaviors. This study measured the impact of this pandemic on intra-city travel behaviors at individual and city levels by using smart cards and private vehicle records collected from Daejeon Metropolitan City in South Korea for the initial stage of the pandemic. We used four indicators—trip frequency, inter-visit intervals, trip distance, and activity boundaries—to quantify individual travel behavior regarding bus and private vehicle usage. The weekly comparisons indicate that people reduced their daily trip frequencies and distances during the pandemic. In addition, trip regularity increased at 24-hour intervals and maintenance of activity boundaries suggest that people refrained from unnecessary activities and continued mandatory activities such as work. Considering that there were few countermeasures during the initial period of the pandemic, the findings in this study can draw different meanings and insights from those in other studies analyzing cities with strict anti-pandemic policies such as lockdown and closure of public transit.

This study is meaningful as a study analyzing changes in travel behavior at an individual level due to the COVID-19 pandemic and contributes to academic society by providing important, novel findings in the realm of pandemic-related research. It is well known that the COVID-19 crisis has reshaped people's mobility in a way to avoid dense space and defend against infection risk. In particular, cities with high population densities, such as cities in South Korea, are more vulnerable to the pandemic, so it is necessary to establish urban and transportation management policies considering density (Arimura et al., 2020; Lee, 2020). In this context, this study provides insights into practical strategies to sustain high-dense cities as healthy communities in another possible pandemic era.

Despite our novel findings, a few limitations remain. First, we cannot connect travel demand changes different by transportation modes to the actual mechanism of the modal shift from buses to private vehicles. For better understanding of dynamic behavioral changes during pandemics, it is necessary to understand this modal shift mechanism and explain it in terms of socioeconomic attributes such as gender, age, and occupation. Second, this study mainly focused on the initial period to reveal natural changes in travel behavior, so it cannot capture the different impacts of the pandemic as the pandemic continued and the influence of pandemic-related policies on people's mobility. To complement these limitations, future studies analyze the long-term trip data and observe the different effects of diverse government policies on travel behaviors during the pandemic according to socioeconomic features. In this process, we will survey modal shift behaviors between public transit and private vehicles and compare the survey result to the outcomes of this study.

Funding

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) [2021R1A4A1033486]; the National Information Society Agency (NIA) funded by the Korea government (MSIT) [2021-Data-we-28]; and Daejeon Metropolitan City, South Korea.

CRediT authorship contribution statement

Sujin Lee: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Eunjeong Ko:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft. **Kitae Jang:** Methodology, Validation, Data curation, Writing – review & editing, Funding acquisition. **Suji Kim:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

None.

Data availability

The authors do not have permission to share data.

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