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How has the Covid-19 pandemic affected wheelchair users? Time-series analysis of the number of railway passengers in Tokyo

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The Coronavirus disease 2019 (COVID-19) has posed 'new barriers' to people with disabilities (PwDs) who have already experienced many barriers to using public transportation. However, there is limited quantitative knowledge of how PwDs have been affected by the COVID-19 pandemic. This study investigated the impact of the COVID-19 pandemic on the use of public transportation by PwDs over time. Specifically, we analysed time-series data on wheelchair rail passenger numbers and all rail passenger numbers in Tokyo from April 2012 to December 2021. The impact of COVID-19 was more accurately assessed by excluding seasonal variations in the time-series, and two key findings were obtained. First, the change point for the decline in the number of passengers owing to the COVID-19 pandemic was March 2020, one month earlier than the declaration of the state of emergency. Second, using the time-series model, the actual and estimated values were compared, and we found that wheelchair rail passenger numbers reduced by approximately 20 percentage points on average compared with all rail passengers. Wheelchair rail passengers were more severely affected by the COVID-19 pandemic than all rail passengers. Based on previous studies, these findings demonstrated that opportunities to participate in society were disproportionately reduced for PwDs during the COVID-19 pandemic. This study's quantitative data and the resulting conclusions on wheelchair users are useful for inclusive planning for mitigating the pandemic's impact by national administrations and public transport authorities.

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Introduction

The COVID-19 pandemic has significantly affected public transport users. Within months of the first case reported in Wuhan, China, on 8 December 2019, the number of cases increased worldwide, and the World Health Organisation (WHO) declared it a pandemic on 11 March 2020 (WHO Director, 2020). As a result of the rapid spread of the infection, measures to ensure social distancing and restrict movement have been undertaken in many countries owing to the lack of access to effective treatments and vaccines (Kissler et al., 2020; Zhang et al., 2021b). Fear of COVID-19 motivated the introduction of teleworking (Osorio et al., 2022). Telework and e-learning directly affect changes in activity and travel behaviour (Nguyen, 2021; Irawan et al., 2022). In addition, a marked modal shift occurred from public transport to other modes of travel (Basu and Ferreira, 2021; Khadem Sameni et al., 2021; Loa et al., 2021; Thombre and Agarwal, 2021; Zhang et al., 2021a). Consequently, the number of people using public transportation has decreased significantly (Vannoni et al., 2020; Xin et al., 2021).

There are concerns that the decline in public transport owing to the reduced number of users will create a downward spiral for vulnerable people in society (Monahan and Lamb, 2022). The COVID-19 pandemic has also created 'new barriers' for PwDs and heightened the need to incorporate the perspectives of people with disabilities into public health responses (Armitage and Nellums, 2020; Pineda and Corburn, 2020; Epstein et al., 2021). PwDs at high risk of infection are highly concerned about whether facilities for mobility are disinfected, as much as eliminating existing physical barriers, such as steps and gaps (Arashima et al., 2021). Enforced social distancing and fear of infection have affected the use of and access to transportation for PwDs (Koon et al., 2022). The pandemic reduced the use of outpatient services by PwDs and reduced their opportunities to interact in society (Ito et al., 2021; Sato et al., 2022). The seriousness of the impact that PwDs have suffered in the COVID-19 pandemic has been established. However, quantitative knowledge of how PwDs are affected by the COVID-19 pandemic is still limited. This is because the challenges faced by PwDs vary according to their diverse disability characteristics, making it difficult to discuss general trends as a single population. Lunsky et al., (2021) examined access to virtual and face-to-face healthcare among adults with intellectual and developmental disabilities during the COVID-19 pandemic, and found that appropriate methods varied according to a person's abilities, support skills, and medical problems. It is, therefore, necessary to focus on individual disability characteristics. In addition, the quantitative analysis is difficult as the absolute number of characteristic subjects is small. In other words, despite PwDs being more affected by the pandemic, not many previous studies have quantitatively demonstrated how challenging the problems faced by PwDs are. Bhattacharyya et al., (2022) quantitatively analysed transport barriers during the COVID-19 pandemic period, focusing on two groups: people with disabilities and low-income households, but did not discuss disability characteristics separately; Nielsen (2023) focused on the mobility behaviour of people with psychosocial disabilities, but used a dense qualitative method of interviews.

This study focuses on wheelchair users, who face particularly severe physical barriers when using public transport, and quantitatively assesses the impact of the COVID-19 pandemic on them. Specifically, the research question set in this study was examined through an analysis of the time-series of rail passenger numbers at nine train stations in Tokyo over a period of nine years and nine months, that is, from April 2012 to December 2021.

RQ: How has the COVID-19 pandemic affected the number of wheelchair users accessing railway services in Tokyo?

The share of rail transport in the Tokyo metropolitan area is approximately 30% (Ministry of Land, Infrastructure, Transport and Tourism, 2017). It is possible to estimate the situation of wheelchair users by analysing the number of rail passengers over time. However, considering annual seasonal variations in rail passengers is essential, while assessing the impact of COVID-19 by removing those seasonal variations from the observed data. Therefore, the seasonal components that existed before COVID-19 were identified, and the impact of COVID-19 was assessed using seasonally adjusted time-series data.

Study criteria and previous work

The COVID-19 pandemic and its response have increased the risk for PwDs (Cochran, 2020). This study presents the empirical findings on this risk by assessing its impact on the number of wheelchair rail passengers in Tokyo during the COVID-19 pandemic. Therefore, this study used the following four criteria:

a. Research on PwDs during the COVID-19 pandemic
b. Comparative research on people with and without disabilities during COVID-19
c. Analysis of transportation during COVID-19 pandemic
d. Time-series analysis during the COVID-19 pandemic.

Criterion [a] aims to study PwDs during the COVID-19 pandemic, focusing on those who have been severely affected by the COVID-19 pandemic. Criterion [b] involves a comparative analysis of people with and without disabilities to determine the magnitude of the impact on PwDs. Criterion [c] analyses the impact of the COVID-19 pandemic on transportation, which was severely affected during the early stages owing to fear and social restrictions, with many people, including PwDs, avoiding travel. However, it also meant reduced opportunities for participation in society, and hence, the extent of this reduction needs to be ascertained. Criterion [d] employed the time-series analysis method, which is appropriate in this context owing to the uncertain and dynamic nature of this phenomenon during the COVID-19 pandemic.

The next section describes six research categories of previous studies related to the four aforementioned research criteria.

Categories of previous studies. The first category consists of studies that investigated the situation of PwDs during the COVID-19 pandemic. Lund et al., (2020), Theis et al., (2021), and Hochman et al., (2022) have analysed the impact of the COVID-19 pandemic and its responses on PwDs. However, these qualitative studies— literature reviews (Lund et al., 2020), free-text questionnaires (Theis et al., 2021) and thematic analysis (Hochman et al., 2022)— for only PwDs met the study criterion [a] in this study (Table 1, Category 1).

The second category comprises studies that compared the impact of disabilities on people with and without disabilities during the COVID-19 pandemic. Lindsay et al., (2021) investigated young people with and without disabilities during the COVID-19 pandemic and noted that PwDs needed more support for social participation. Na and Yang (2022) examined the psychological and behavioural responses of individuals with mobility and/or self-care disabilities during a pandemic. They suggested that people with disabilities require additional support to access resources, exercise, and the outdoors. However, these qualitative studies—in-depth interviews (Lindsay et al., 2021) and online surveys (Na and Yang 2022)—only met research criteria [a] and [b] of this study (Table 1, Category 2).

The third category captures the problems faced by PwDs during the COVID-19 pandemic from two perspectives: difficulty

Table 1 Comparison with previous studies.

Study criteria		[a] Research of PwDs during the COVID-19 pandemic	[b] Comparative research of people with and without disabilities during COVID-19	[c] Analysis of transportation during the COVID-19 pandemic	[d] Time-series analysis during the COVID-19 pandemic
Category 1	Lund et al., (2020)	○			
	Theis et al., (2021)	○			
	Hochman et al., (2022)	○			
Category 2	Lindsay et al., (2021)	○	○		
	Na and Yang (2022)	○	○		
Category 3	Cochran (2020)	○		○	
	Ashour et al., (2021)	○		○	
Category 4	K.Park et al., (2022)	○	○	○	
Category 5	Hu and Chen (2021)			○	○
	Osorio et al., (2022)			○	○
	Zargari et al., (2022)			○	○
Category 6	Wang et al., (2022)	○		○	○
Category 7	This study	○	○	○	○

in accessing transport and challenges faced by transport service providers due to the sharp decline in users. Cochran (2020) concluded that the COVID-19 pandemic and its response aggravated many difficulties in accessing transportation and other essential services that PwDs regularly encountered. Ashour et al., (2021) suggested that transportation operators, whose demand was substantially reduced by the COVID-19 pandemic, should consider improving their resilience to meet the essential mobility needs of PwDs. These studies identified changes in the travel behaviour of PwDs and provided insights into measures for sustainable transport as a lifeline for PwDs. However, qualitative analysis through interviews (Cochran, 2020; Ashour et al., 2021) is limited in capturing uncertain and dynamic changes during the COVID-19 pandemic. The third category met only research criteria [a] and [c] of this study (Table 1, Category 3).

The fourth category comprises studies that assess the travel behaviour and community living of PwDs during the COVID-19 pandemic compared with the general population (Park et al., 2022). However, the studies were qualitative and used online panel data, which have limitations in capturing uncertain and dynamic changes during the COVID-19 pandemic. The fourth category met only research criteria [a], [b], and [c] of this study (Table 1, Category 4).

The fifth category comprises studies that analysed the time-series of transport user numbers during the COVID-19 pandemic. Hu and Chen (2021) inferred the impact of the COVID-19 pandemic on transit ridership, based on 20 years of daily transit ridership data from Chicago and Iran. They noted that ridership decreased more in areas with more commercial land and a higher proportion of white, educated, and higher-income individuals. Osorio et al., (2022) analysed a time-series of bus and train ridership in Chicago and revealed that remote learning and working accounted for the majority of ridership losses. Zargari et al., (2022) performed a time-series analysis using public transit usage and inter-city trip data. They found a significant relationship between the number of people infected with COVID-19 and mobility variables, with both short- and long-term lags.

This category captures uncertain and dynamic changes in transport behaviour during the COVID-19 pandemic but does not capture the situation of the PwDs. Although movement restrictions had some effect on preventing the spread of COVID-19, PwDs were disproportionately exposed to a greater risk, as studies in the first and second categories recognised. The fifth category fulfilled only research criteria [c] and [d] in this study (Table 1, Category 5).

The sixth category comprises studies that conducted empirical analysis using paratransit service records (Wang et al., 2022). Although this study provides a detailed picture of the changes in the transportation behaviour of PwDs during the COVID-19 pandemic period, the paratransit service is a transportation mode dedicated to PwDs, and there are limitations to the comparative analysis of people with and without disabilities. The sixth category of studies met only research criteria [a], [b], and [c] (Table 1, Category 6).

Relationship with this analysis. As mentioned in Section 2.1, several previous studies have been conducted, but none of them met all the criteria set by this study ([a] to [d]). Although some studies have shown that PwDs are at greater risk during the COVID-19 pandemic, the lack of a time-series analysis comparing people with and without disabilities makes it difficult to quantitatively convey the uncertain and dynamic magnitude of the risk faced by PwDs. Therefore, we conducted a time-series analysis of wheelchair rail passenger numbers and rail passenger numbers in Tokyo (Table 1, Category 7). Specifically, we used a difference-in-differences analysis of wheelchair rail passenger numbers and all-rail passenger numbers over time to infer the magnitude of the impact experienced by wheelchair users.

Data. The analysis covered nine train stations in areas around Tokyo. The study period was from April 2012 to December 2021, and the units were daily averages based on monthly data. The number of wheelchair users was based on the number of times the station staff used the ramp boards passed between the vehicle and platform, with each wheelchair user counted as one instance of boarding and alighting, and all ramp board uses were recorded. These data were provided by the East Japan Railway Company. However, the number of wheelchair users was based on handwritten records from railway staff, which has two limitations. First, there is a possibility of oversight or writing errors. However, the possibility of occurrence of errors is limited in Japan owing to the importance of arranging assistance and the possibility of severe complaints from wheelchair users. Second, wheelchair users who did not request assistance were excluded from the study. The stations analysed in this study do not eliminate steps or gaps between the vehicle and platform; therefore, the number of wheelchair users who get on and off without requesting assistance are unlikely to be considerably high, and the

Fig. 1 The nine stations included in the analysis. Graphics programs: QGIS, Adobe Illustrator.

probability of people not requesting assistance is presumed to be constant, regardless of the station or month.

Nine of the 77 stations in Tokyo met the following two conditions (Fig. 1): (1) there were no transfers within the ticket gates and (2) no additional barrier-free facilities had been installed since 2018. These conditions were set to align the counts of wheelchair rail users with the counts of all rail users, and to exclude the impact of additional lifts and platform improvements on the number of wheelchair rail users. The nine stations were on five major lines connecting central Tokyo with the suburbs, and the average daily ridership on the five lines ranged from 170, 000 to 750,000 in 2019. The data in this study represent the actual situation in areas surrounding central Tokyo. The monthly daily averages of wheelchair rail passenger numbers at the nine stations in FY 2019 ranged between 23 and 172, and the number of users was estimated from the number of people exiting ticket gates using smart cards (commuter passes and recharge). The monthly daily averages of all rail passenger numbers at the nine stations in FY 2019 ranged between 290,0000 to a maximum of 960,000. Both wheelchair rail passenger numbers and all-rail passenger numbers are based on data provided by the East Japan Railway Company. The analysis excluded the Tokyo city centre area because many railway stations had additional barrier-free facilities installed in time for the Tokyo Olympics and Paralympics, which were postponed by one year and took place in 2021. In addition, the number of wheelchair users at the nine stations that were studied was combined to avoid ethical issues of individual identification at stations with particularly low numbers of wheelchair users.

In our presentation, the total monthly daily average number of passengers at all nine stations in month n is y_n^τ. τ is a subscript representing the user attribute: $\tau = $ all for all passengers and $\tau = wh$ for wheelchair passengers. Figure 2 shows the original series of wheelchair passengers, y_n^{wh} and the total number of passengers, y_n^{all}.

The number of all rail passengers from April 2012 to December 2019 showed a trend of cyclical fluctuations, rising from approximately 300,000 to approximately 450,000 daily on average per month (Fig. 2). Thereafter, the number of passengers declined sharply to approximately 250,000 in May 2020 in the early stages of the COVID-19 pandemic before recovering to approximately 360,000 by December 2021, with increasing and decreasing numbers. The number of wheelchair rail passengers from April 2012 to December 2019 also showed cyclical fluctuations, rising from approximately 30 to 80 daily on average per month; however, the trend was wavy (Fig. 2). Thereafter, there was a sharp drop to approximately 16 in May 2020, followed by an increase or decrease before recovering to approximately 40 by December 2021.

The period from 2020 onwards was examined in detail. Figure 3 shows the time-series of the number of newly confirmed COVID-19 cases and cumulative deaths, the number of all passengers y_n^{all}, and the number of wheelchair passengers y_n^{wh} in Tokyo from January 2020 to December 2021. There appeared to be no specific relationship between the number of newly confirmed cases and cumulative deaths owing to COVID-19 and the number of all passengers, y_n^{all} and wheelchair passengers, y_n^{wh}. From December 2021, the number of new infections and cumulative deaths was not high in 2020, but the largest decrease in the number of all passengers y_n^{all} and wheelchair passengers y_n^{wh} occurred in April–May 2020. Beginning from around December 2020, the number of newly confirmed cases and cumulative deaths began to increase; however, there was no noticeable change in the number of passengers y_n^{all} or wheelchair passengers y_n^{wh}. States of emergency and restrictions on actions decreed by the Japanese government were issued four times during the observation period. The first emergency declaration coincided with the period when all passengers y_n^{all} and wheelchair passengers y_n^{wh} were at a minimum.

Modelling. When y_n^τ is an l variable time-series, the state-space model can be defined in terms of a pair of equations (Kitagawa, 2020):

$$x_n^\tau = F_n x_{n-1}^\tau + G_n v_n^\tau \tag{1}$$

$$y_n^\tau = H_n x_n^\tau + w_n^\tau \tag{2}$$

Here, x_n^τ is an k dimensional vector that cannot be directly observed and is referred to as the 'state'. v_n^τ is known as 'state noise' and an m dimensional normal white noise following a mean vector of zero and variance-covariance matrix Q_n. Hereafter, v_n^τ is denoted $v_n \sim \mathcal{N}(0, \rho^2)$. w_n^τ is called 'observed noise' and is l dimensional normal white noise following a mean vector of zero and a variance-covariance matrix R_n. F_n is a $k \times k$ transition matrix, G_n denotes a $k \times m$ control matrix, and H_n denotes an $l \times k$ state diffusion matrix. Equation (1) is the state equation and governs the time evolution of the state vector x_n^τ. Equation (2) is the observation equation that links the observed data y_n^τ to a latent k-dimensional state vector x_n^τ.

As stated in Section 3, the time-series of all users and wheelchair users underwent significant changes after the COVID-19 pandemic. Therefore, it is reasonable to assume that structural changes in the time-series model occurred before and after the COVID-19 pandemic. Assuming that the structure of the time-series model changed significantly at a time point n_j satisfying n_i $(= n_0, \ldots, n_N)$ and $1 \le j \le N-1$, the pre- COVID-19 period is $[n_0, \ldots, n_{j\text{-}1}]$ and the post- COVID-19 period is $[n_0, \ldots, n_N]$.

As discussed in Section 3, the number of wheelchair passengers, displayed a wavy trend. For a time-series that displays a wavy trend, it is necessary to consider a short-term variation component, in addition to a long-term trend component to

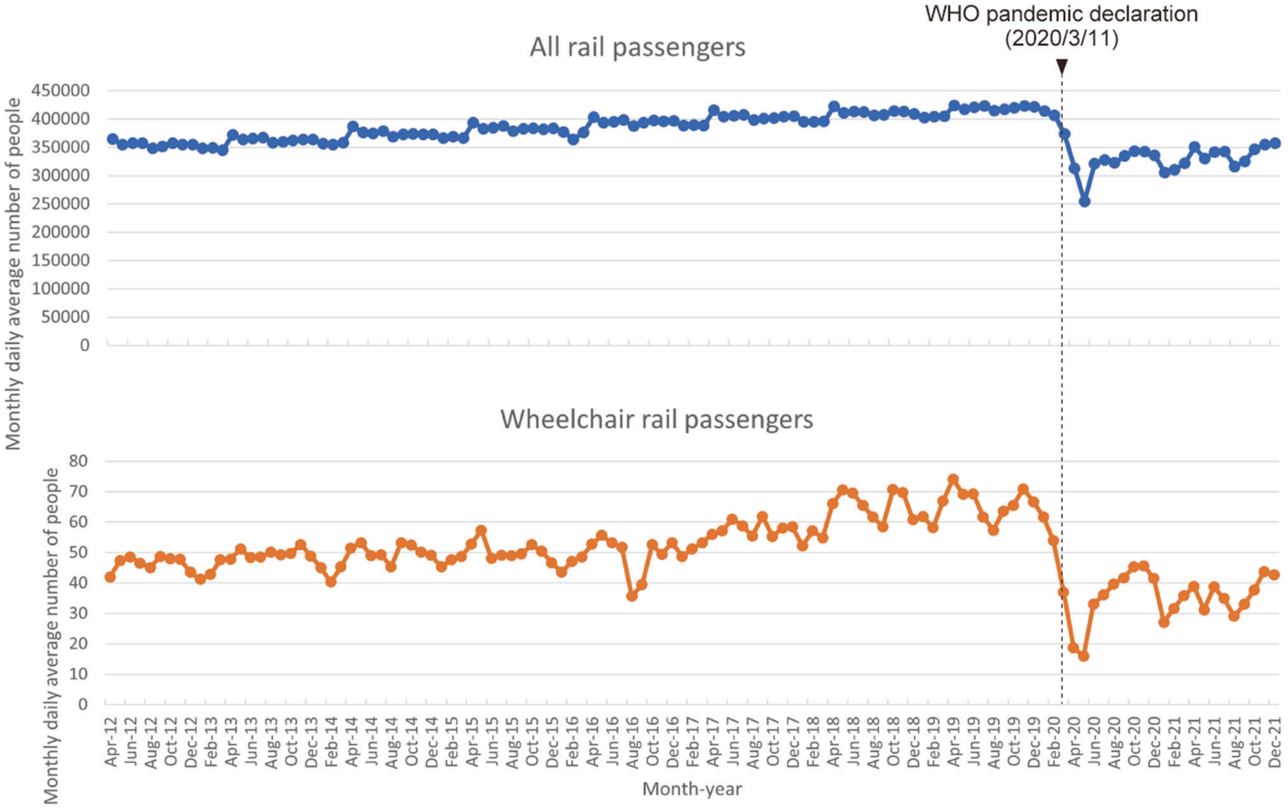


Fig. 2 The observed time-series data of rail passenger numbers from 2012 to 2021. Graphics programs: Microsoft Excel, Adobe Illustrator.

obtain a good model for both long- and short-term forecasts (Kitagawa, 2020). Therefore, in this study, we assume that the time-series y_n^τ can be decomposed into a trend component t_n^τ, seasonal component s_n^τ, stationary autoregressive (AR) component p_n^τ, and noise w_n^τ during the pre-COVID-19 period. Kitagawa (2020) defines the decomposition of a time-series model, including a stationary AR component, as

$$y_n^\tau = t_n^\tau + s_n^\tau + p_n^\tau + w_n^\tau \quad (3)$$

$$t_n^\tau = \sum_{i=1}^{k1} c_i t_{n-1}^\tau + v_{n1}^\tau \quad (4)$$

$$\sum_{i=0}^{f-1} s_{n-i}^\tau = v_{n2}^\tau \quad (5)$$

$$p_n^\tau = \sum_{i=1}^{k3} a_i p_{n-i}^\tau + v_{n3}^\tau \quad (6)$$

where $v_{n1}^\tau \sim \mathcal{N}(0, \rho_1^2)$, $v_{n2}^\tau \sim \mathcal{N}(0, \rho_2^2)$, $v_{n3}^\tau \sim \mathcal{N}(0, \rho_3^2)$ and f is the seasonal frequency.

The equation for the transformation of each of these components into a state-space model is summarised in the Supplementary Material. Using the resulting state-space model, the parameters were estimated using the Kalman filter and fixed-interval smoothing algorithms (Kalman, 1960).

Akaike's information criterion (AIC; Akaike, 1974) for the pre-COVID-19 model was calculated with a maximum order of two and $f = 12$ (Table 2). The pre-COVID-19 model for all passengers had the lowest AIC for the second-order trend, first-order seasonal, and first-order stationary AR components. The pre-COVID-19 model for wheelchair passengers had the lowest AIC for the first-order trend, seasonal, and stationary AR components.

During the post-COVID-19 period, the number of passengers fluctuated significantly owing to requests for social distancing and restrict movement. Therefore, it is inappropriate to include this period in the decomposition of the seasonal variation components. Consequently, the post-COVID-19 model used the seasonally adjusted $y_n^{\tau^*}$, which was obtained by subtracting the seasonal component s_n^τ obtained in the pre-COVID-19 model (Fig. 4). Here, the post-COVID-19 model is defined as

$$y_n^{\tau^*} = y_n^\tau - s_n^\tau = t_n^{\tau^*} + p_n^{\tau^*} + w_n^{\tau^*} \quad (7)$$

$$t_n^{\tau^*} = \sum_{i=1}^{N} c_i t_{n-1}^{\tau^*} + v_{n4}^\tau \quad (8)$$

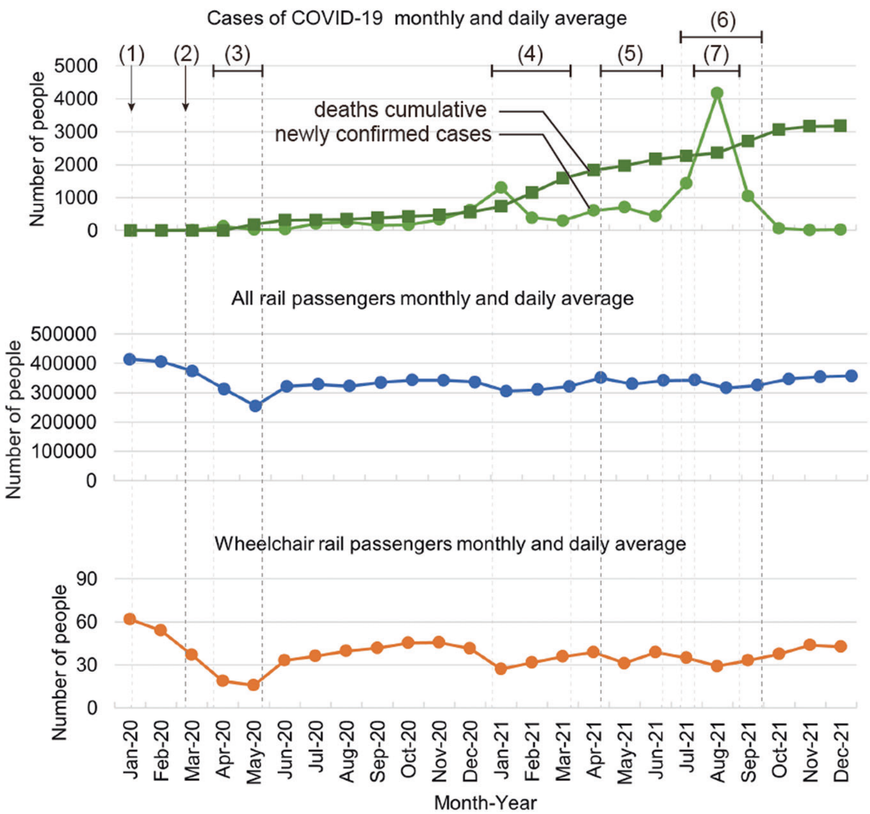
$$p_n^{\tau^*} = \sum_{i=1}^{N} a_i p_{n-i}^{\tau^*} + v_{n5}^\tau \quad (9)$$

where $v_{n4}^\tau \sim \mathcal{N}(0, \rho_4^2)$ and $v_{n5}^\tau \sim \mathcal{N}(0, \rho_5^2)$.

The AIC for each order of the time-series model was calculated for seasonally adjusted $y_n^{\tau^*}$ of the post-COVID-19 model (Table 2). The AIC for each order of the time-series model was calculated for the seasonally adjusted $y_n^{\tau^*}$ in the post-COVID-19 model (Table 2). Models with a stationary AR component of order 0, that is, without a stationary AR component, were also calculated, but the AIC of the model with a stationary AR component of order 1 was the smallest for both the time-series of all rail passengers and wheelchair passengers. Therefore, we considered the assumption of decomposition into four components to be reasonable.

The original time-series was decomposed into trend, seasonal, and stationary AR components. The time-series of all passenger numbers, wheelchair passenger numbers, seasonal components, and seasonally adjusted time-series are shown in Fig. 5. The figures are in the ordinary logarithmic form.

As previously mentioned, the seasonal component was decomposed using the pre-COVID-19 model. The seasonal



Major events

(1) 1st confirmed case of domestic COVID-19 infection (2020/1/15)
(2) WHO pandemic declaration (2020/3/11)
(3) 1st Sate of emergency (2020/4/7-5/25)
(4) 2nd State of emergency (2021/1/8-3/21)
(5) 3rd State of emergency (2021/4/25-6/20)
(6) 4th State of emergency (2021/7/12-9/30)
(7) Tokyo Olympics and Tokyo Paralympics (2021/7/23-2021/9/5)

Fig. 3 The observed time-series data cases of COVID-19 and rail passenger numbers from 2020 to 2021. Graphics programs: Microsoft Excel, Adobe Illustrator.

variation in wheelchair passengers over 12 months was 19 percentage points (9.9%pt in May and −8.8%pt in January, for a total of 18.7%pt). The seasonal variation over the 12 months for all passengers was 6.7 percentage points (4.0%pt in April and −2.7%pt in February).

Analysis

Change points. This section estimates the change points in the time-series model for all passengers and wheelchair passengers. In other words, it estimates the optimal time point for decomposition into pre-COVID-19 and post-COVID-19 models. The change in time point n_j was estimated using the stationary AR model, which utilises the seasonally adjusted $y_n^{\tau*}$ from each of the original time-series data, excluding the seasonal component. When there is a structural change in the stationary AR component at time n_j, the new AR model is applied to the two intervals $[0, n_{j-1}]$ and $[n_j, n_N]$ respectively. The sum of the AIC of the two models is calculated as follows:

$$\mathrm{AIC}_j^{\mathrm{div}} = \mathrm{AIC}_{[0,n_j-1]} + \mathrm{AIC}_{[n_j,n_N]} \tag{10}$$

The $\mathrm{AIC}_j^{\mathrm{div}}$ serves as an indicator of the model's goodness assuming that a structural change occurs at time n_j.

This procedure is known as the locally stationary AR model and has been used for instance, to estimate arrival times of seismic waves (Takanami and Kitagawa, 1993).

The $\mathrm{AIC}_j^{\mathrm{div}}$ for each time point of the locally stationary AR model was calculated for AR orders 2–10 (Table 3), with AR order 2 in March 2020 having the lowest $\mathrm{AIC}_j^{\mathrm{div}}$ (Fig. 6).

This finding suggests that the seasonally adjusted $y_n^{\tau*}$ of all rail passengers and wheelchair rail passengers changed the most in March 2020. No further change points were found for the 8 years spanning from April 2012 to March 2020 and for the 21 months from April 2020 onwards.

The difference-in-differences. We conducted a difference-in-differences analysis under the assumption that wheelchair passengers were more affected by COVID-19 than all passengers. All passengers were assigned to the control group, while wheelchair passengers were placed in the intervention group. As discussed in Subsection 5.1, to avoid the structural change point in the time-series for all passengers and wheelchair passengers around March 2020, we designated January 2019 to December 2019 as period one and January 2021 to December 2021 as period two. The ordinary logarithms of both groups, all passengers, and wheelchair passengers, satisfied the assumption of parallel trends (Fig. 5).

Comparing the total number of passengers in period one and period two for both groups, we observed that the number of passengers decreased by 20 percentage points in period two. By contrast, the number of wheelchair passengers decreased by 46

Table 2 AIC by order in time series models.

Pre-COVID-19 model of all users (y_n^{all})						Pre-COVID-19 model of wheelchair users (y_n^{wh})					
Trend order ($k1$)	Seasonal order ($k2$)	Period (f)	AR order ($k3$)	AIC		Trend order ($k1$)	Seasonal order ($k2$)	Period (f)	AR order ($k3$)	AIC	
0	1	12	0	734		0	1	12	0	515	
0	1	12	1	405		0	1	12	1	187	
0	1	12	2	117		0	1	12	2	−78.2	
0	2	12	0	904		0	2	12	0	685	
0	2	12	1	567		0	2	12	1	350	
0	2	12	2	280		0	2	12	2	82.8	
1	1	12	0	−665		1	1	12	0	−241	
1	1	12	1	−655		1	1	12	1	−242	best
1	1	12	2	−656		1	1	12	2	−239	
1	2	12	0	−513		1	2	12	0	−88.4	
1	2	12	1	−505		1	2	12	1	−88	
1	2	12	2	−506		1	2	12	2	−92.6	
2	1	12	0	−669		2	1	12	0	−214	
2	1	12	1	−675	best	2	1	12	1	−225	
2	1	12	2	−672		2	1	12	2	−222	
2	2	12	0	−517		2	2	12	0	−57.4	
2	2	12	1	−529		2	2	12	1	−73.3	
2	2	12	2	−526		2	2	12	2	−70.8	
Post-COVID-19 model of all users (y_n^{all*})						**Post-COVID-19 model of wheelchair users (y_n^{wh*})**					
Trend order ($k1$)	**Seasonal order ($k2$)**	**Period (f)**	**AR order ($k3$)**	**AIC**		**Trend order ($k1$)**	**Seasonal order ($k2$)**	**Period (f)**	**AR order ($k3$)**	**AIC**	
0	0	12	1	300		0	0	12	1	47.1	
0	0	12	2	−46.5		0	0	12	2	−180	
1	0	12	0	−540		1	0	12	0	−171	
1	0	12	1	−544		1	0	12	1	−270	
1	0	12	2	−553	best	1	0	12	2	−290	best
2	0	12	0	−506		2	0	12	0	−231	
2	0	12	1	−520		2	0	12	1	−247	
2	0	12	2	−536		2	0	12	2	−270	

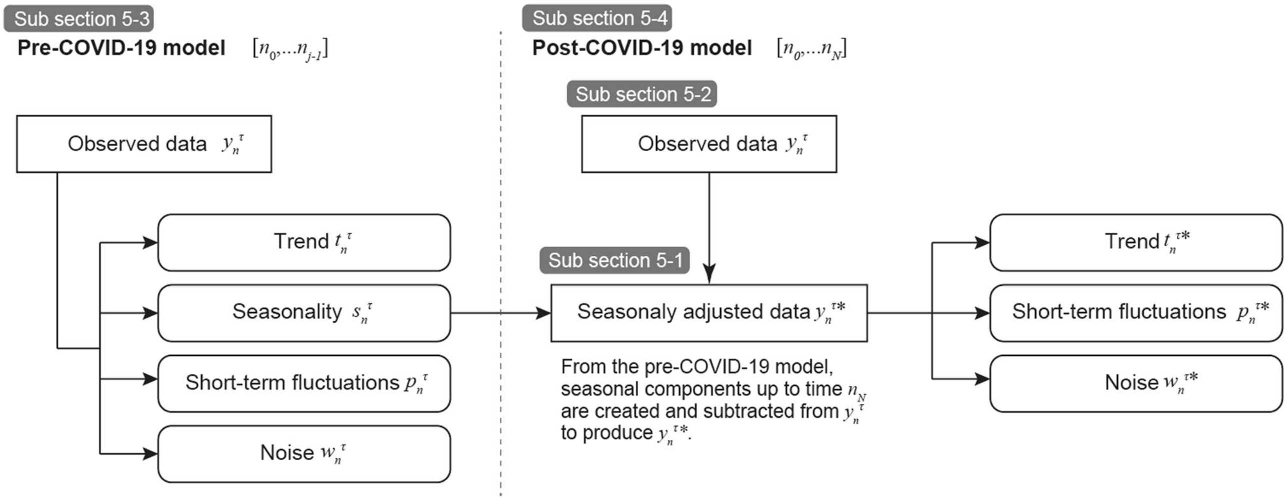


Fig. 4 Flow charts of the pre-COVID-19 model and the post-COVID-19 model. Graphics programs: Adobe Illustrator.

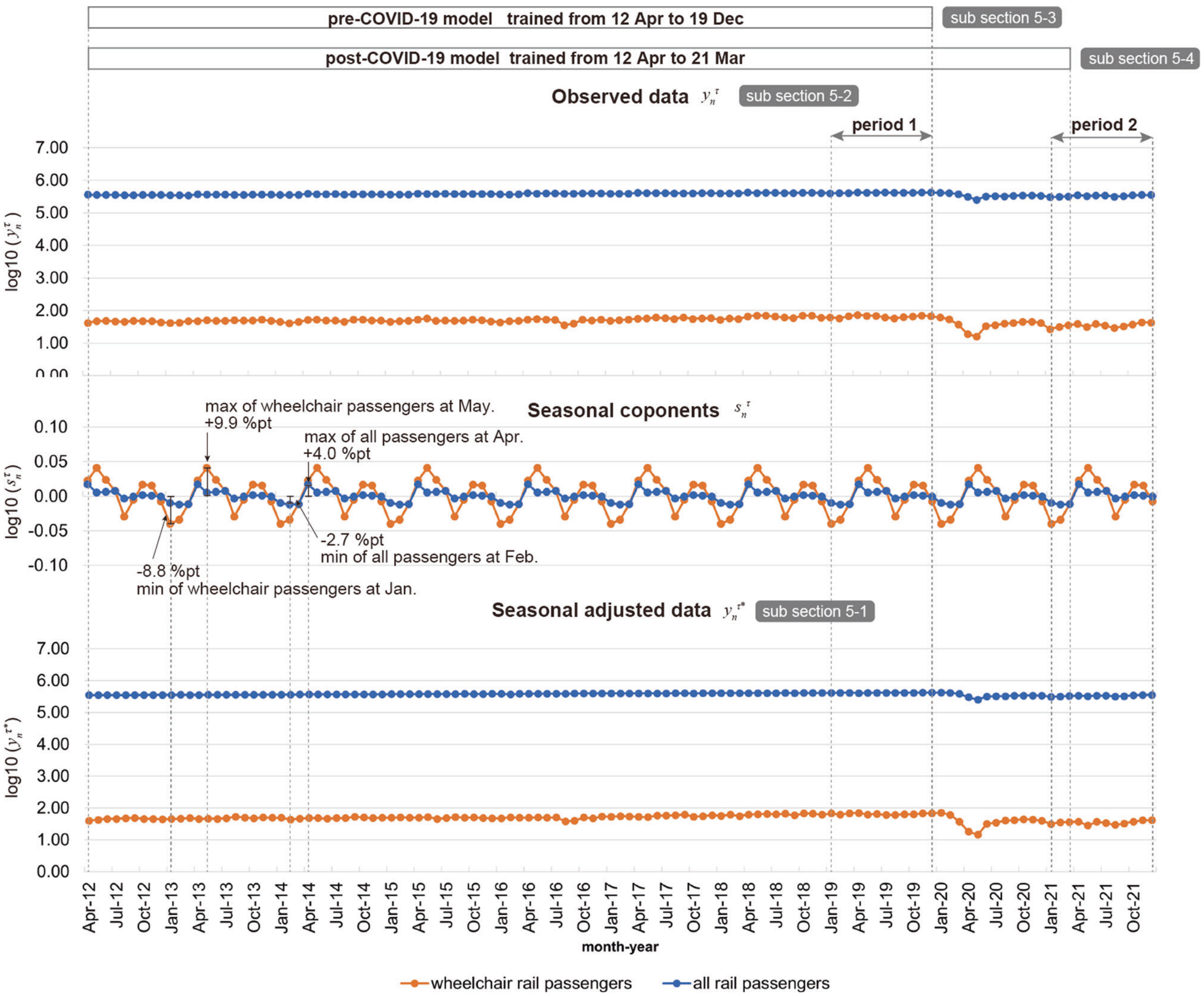


Fig. 5 Time series model components of rail passenger numbers. Graphics programs: R studio (R package TSSS), Microsoft Excel, Adobe Illustrator.

Table 3 Max AR order and change point with min AIC.

r. log10 (av.num. of all uesrs)

Max AR order	subinterval n0	subinterval ne	candidate n1	candidate n2	change point	min AIC	
2	1	117	6	114	96	−895.85	best
3	1	117	8	113	96	−894.31	
4	1	117	10	112	96	−889.33	
5	1	117	12	111	96	−879.9	
6	1	117	14	110	96	−870.3	
7	1	117	16	109	96	−860.3	
8	1	117	18	108	96	−850.46	
9	1	117	20	107	96	−840.36	
10	1	117	22	106	96	−829.8	

r. log10 (av. num. of wheelchair uesrs)

Max AR order	subinterval n0	subinterval ne	candidate n1	candidate n2	change point	min AIC	
2	1	117	6	114	96	−411.77	best
3	1	117	8	113	96	−409.94	
4	1	117	10	112	96	−405.49	
5	1	117	12	111	96	−406.76	
6	1	117	14	110	96	−400.08	
7	1	117	16	109	96	−395.83	
8	1	117	18	108	96	−392.73	
9	1	117	20	107	96	−387.28	
10	1	117	22	106	96	−379.31	

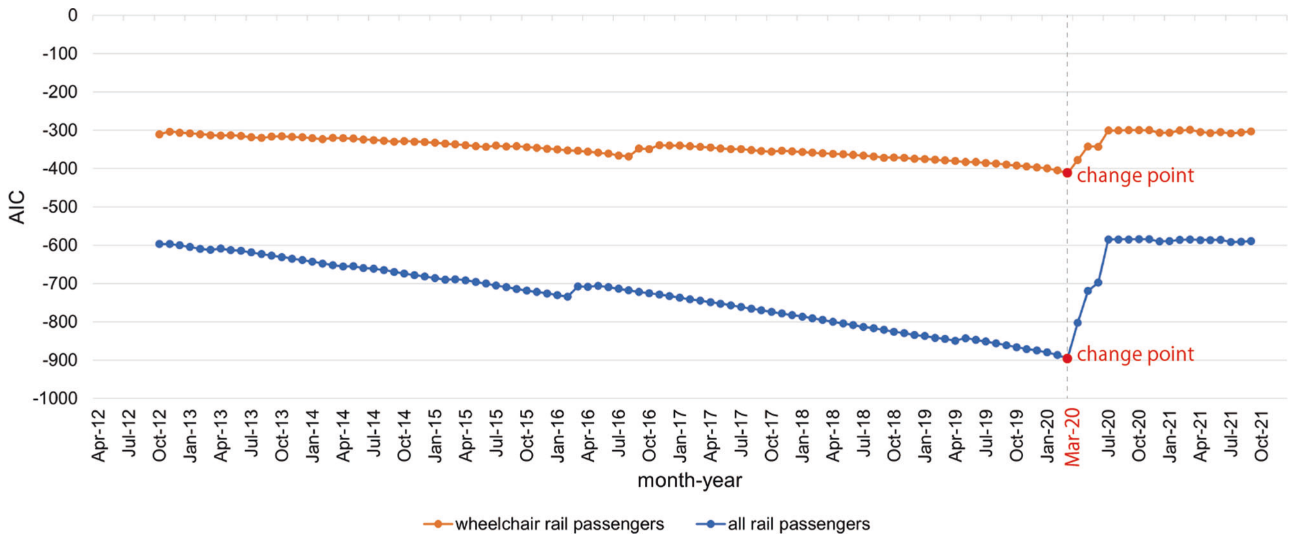


Fig. 6 The change point of seasonally adjusted $y_n^{\tau*}$ of all passengers and wheelchair passengers. Graphics programs: R studio (R package TSSS), Microsoft Excel, Adobe Illustrator.

percentage points, which represents a 26 percentage points greater decrease than that of all passengers (Fig. 7).

Inferring the impact of COVID-19. This subsection uses the time-series model developed in Section 4 to estimate the extent of the decline in the number of wheelchair passengers since the COVID-19 pandemic. We developed a pre-COVID-19 model using observed data up to December 2019 as training data, avoiding structural change points in the number of total passengers and wheelchair passengers. This model was used to produce counterfactual hypothetical forecasts from January 2020 onwards, assuming that COVID-19 had not occurred.

In this study, the predicted values obtained using the pre-COVID-19 model were taken as counterfactuals, and the difference between the predicted value $\tilde{y}_n^\tau$ and observed values y_n^τ was regarded as the causal effect ϕ_n^τ:

$$\phi_n^\tau := y_n^\tau - \tilde{y}_n^\tau \tag{11}$$

Our estimates of the magnitude of the COVID-19 pandemic's impact from January 2020 to December 2021 show that, while the number of all passengers decreased by an average of 21 percentage points, the number of wheelchair passengers decreased by an average of 44 percentage points, with wheelchair passengers being more heavily affected by an average of 23 percentage points (Fig. 8).

The most significant decline owing to the COVID-19 pandemic occurred in May 2020, with an average decline of 41 percentage points for all passengers and 78 percentage points for wheelchair passengers. As of March 2020, the number of wheelchair passengers has declined faster than the total number of passengers by 43 percentage points. Although the decline in both all passengers and wheelchair passengers has slowed down since June 2020, as of December 2021, all passengers were still down by approximately 18 percentage points, and wheelchair passengers were still down by approximately 35 percentage points.

Prediction. This subsection examines the accuracy of the forecasts generated by the post-COVID-19 model. We developed the post-COVID-19 model using training data from April 2012 to March 2021, and forecasting data from April to December 2021 (Fig. 9).

The predictions fall within the range of the standard error, confirming a certain level of prediction accuracy. However, a relatively large error was observed in May 2021. This error can be attributed to the failure to consider the reduction effects of the third and fourth states of emergency, which led to a greater reduction in passenger numbers than anticipated. As the errors in long-term forecasts tend to increase, continuous updating of the model based on the latest observations is necessary.

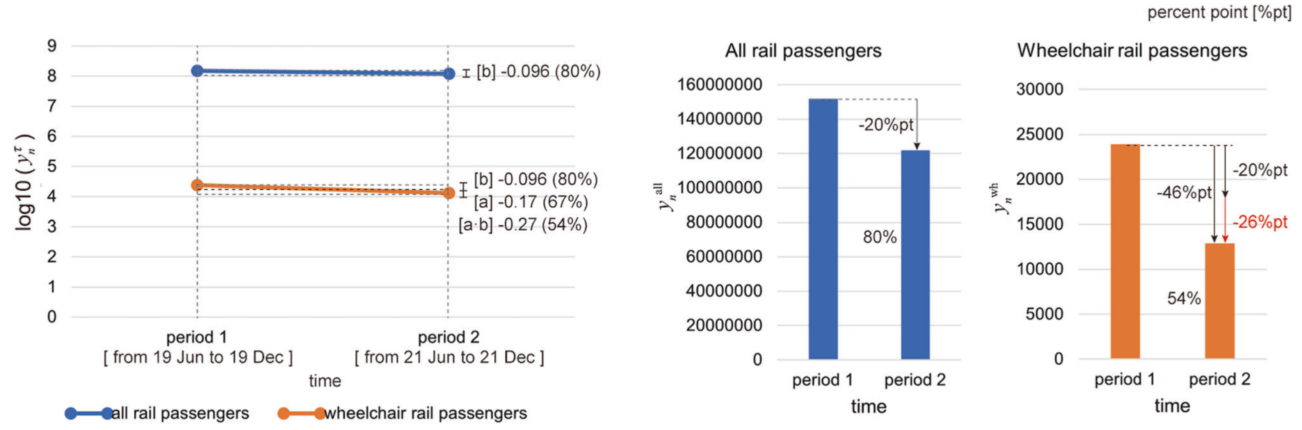


Fig. 7 Pre- and post-comparison of rail passenger numbers of each attribute. Graphics programs: Microsoft Excel, Adobe Illustrator.

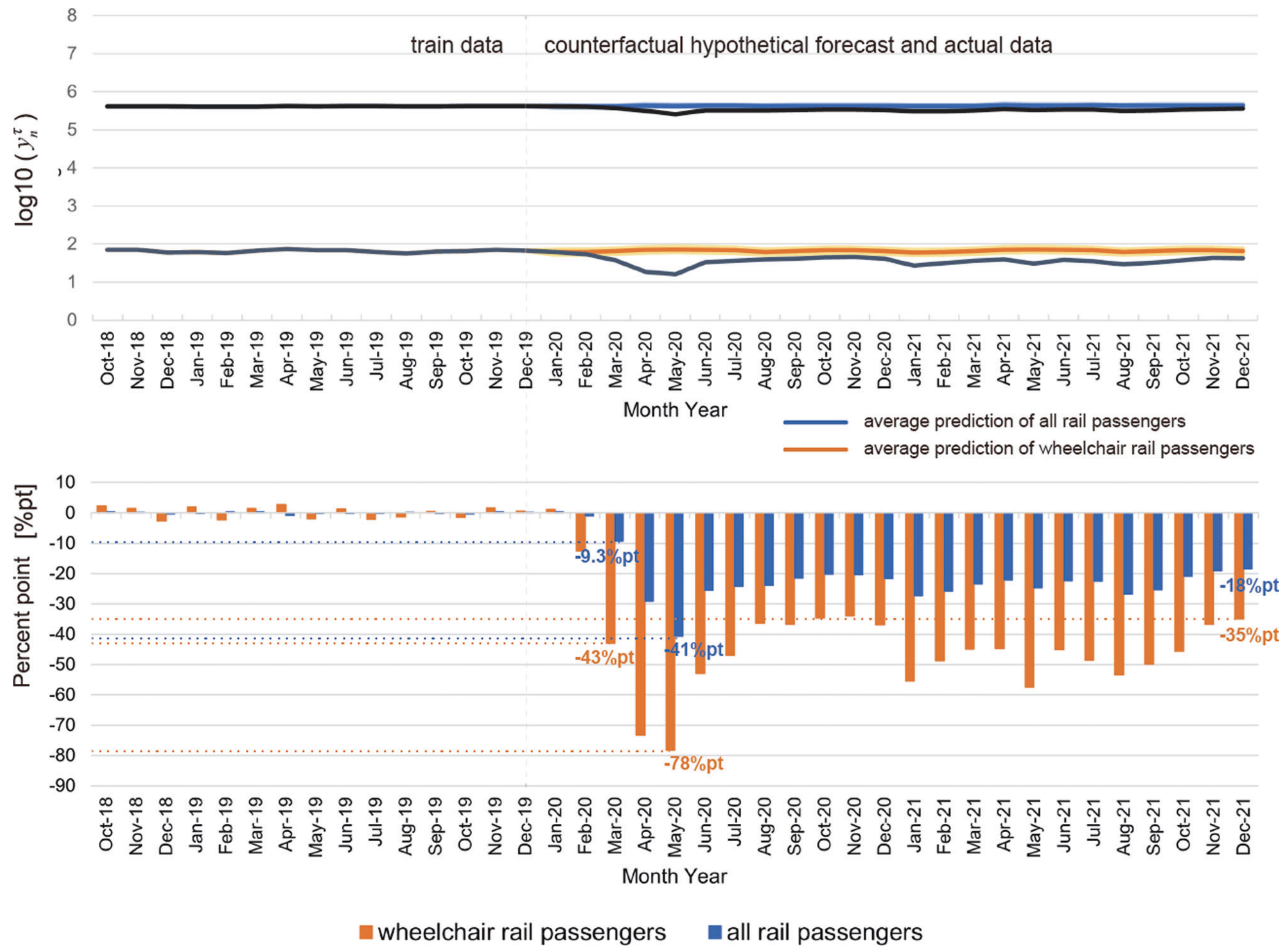


Fig. 8 Inferring the impact on rail passenger numbers of each attribute by the pre-COVID-19 model. Graphics programs: R studio (R package TSSS), Microsoft Excel, Adobe Illustrator.

Discussion

This section discusses the research questions addressed in this study based on the aforementioned analysis.

In Section 4, time-series models were developed for both rail passenger numbers and wheelchair rail passenger numbers. Before the COVID-19 pandemic, the seasonal variation range for wheelchair rail passenger numbers was more than twice as large as the seasonal component of all rail passenger numbers. All rail passenger numbers were highest in April and lowest in January, whereas wheelchair rail passengers were highest in May and lowest in February. These results are consistent with previous findings indicating that travel in Japan tends to be higher in spring at the beginning of the year and lower in winter (Do and Tsukai, 2018). The use of seasonally adjusted data, which removes these seasonal variations, allows for a more accurate assessment of the impact of COVID-19.

In Subsection 5.1, change points were estimated from the seasonally adjusted time-series for all passengers and wheelchair

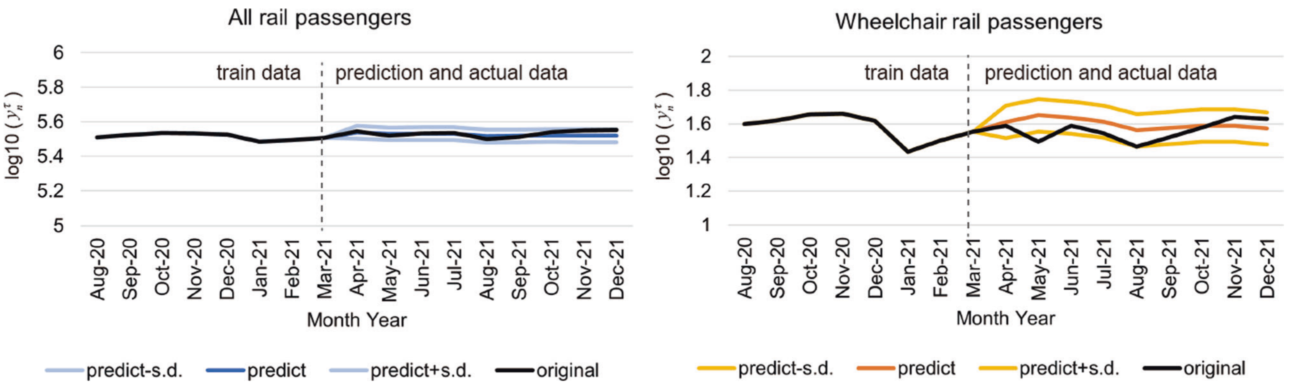


Fig. 9 Prediction of rail passenger numbers of each attribute by the post-COVID-19 model. Graphics programs: R studio (R package TSSS), Microsoft Excel, Adobe Illustrator.

passengers using a local stationary AR model. Both passengers and wheelchair passengers indicated that structural changes occurred in March 2020. There were no other change points above March 2020, in the eight years before and 21 months after that time. In Japan, a structural change in the number of passengers and wheelchair passengers occurred before a state of emergency was declared. This finding is similar to cases in other countries, where fear of infection may have had a greater impact on behavioural change than the government's requests in the early stages of the COVID-19 pandemic (Nguyen, 2021; Osorio et al., 2022). It should be noted that although the increase in COVID-19 cases in Tokyo became more serious after December 2020, no major change occurred as it did around March 2020.

Section 5.2 provides an analysis of the difference between all passengers and wheelchair passengers before and after the COVID-19 pandemic. Avoiding the change points identified in Section 5.1, a comparison of wheelchair passengers and all passengers in 2019 and 2021 shows that wheelchair passengers were affected to a greater extent than all passengers, with a decrease of approximately 26 percentage points. It can be inferred that wheelchair passengers were more affected.

Furthermore, in Section 5.3, the numbers of all passengers and wheelchair passengers are compared over time. The results showed that COVID-19 led to a maximum decline of −41 percentage points and an average decline of −21 percentage points for all passengers and a maximum decline of −78 percentage points and average decline of −44 percentage points for wheelchair passengers. Compared with all rail passenger numbers, wheelchair rail passenger numbers decreased by 23 percentage points on average and were more strongly affected by the COVID-19 pandemic. Many public transport passengers were willing to telework (Ton et al. 2022), suggesting that the decline in total rail passenger numbers was influenced by the prevalence of teleworking and e-learning. However, it is speculated that the greater decline in wheelchair rail passenger numbers was due to stricter infection control measures, particularly in welfare facilities and services due to the higher risk of infection among people with underlying conditions. For example, it has been reported that reduced access to specialised facilities and equipment during periods of behavioural restriction in Japan led to reduced physical activity among older people, resulting in poorer mental health (Maruta et al., 2023). It has also been reported that PwDs, who originally had larger living spaces, had fewer opportunities for social participation during the pandemic (Haruyama et al., 2022). Based on previous studies, the serious decline in the number of wheelchair rail passengers can be interpreted as a demonstration that the COVID-19 pandemic has disproportionately reduced opportunities for PwDs to participate in society.

In Section 5.4, the post-COVID-19 model predictions for all users and wheelchair users were almost within the prediction error range of plus or minus one standard deviation. This suggests that there were no major changes in the time-series structure in 2021, as observed in the early stages of the COVID-19 pandemic. However, the post-COVID-19 model did not consider the impact of the state of emergency, a movement restriction imposed by the Japanese Government. Consequently, there were some errors in the third (April–June, 2021) and fourth (July–September, 2021) emergency declaration periods. The increasing errors in long-term forecasts indicate the need to continue updating the model with the latest observations.

Conclusion

This study aimed to gain quantitative knowledge on the impact of COVID-19 on PwDs. Specifically, we conducted a time-series analysis of wheelchair rail passenger numbers and all rail passenger numbers in Tokyo over a period of nine years and nine-months from April 2012 to December 2021. The impact of COVID-19 was assessed more accurately by excluding seasonal variations in the time-series. Two key findings were obtained: First, the change point for the decline in rail passenger numbers owing to the COVID-19 pandemic was March 2020, one month earlier than the government restrictions on behaviour. Second, wheelchair rail passenger numbers reduced by approximately 20 percentage points compared with all rail passenger numbers.

These findings build on previous studies analysing the impact of the COVID-19 pandemic on PwDs (Arashima et al., 2021; Epstein et al., 2021; Lebrasseur et al., 2021; Monahan and Lamb, 2022) and provide new quantitative evidence for the importance of including PwDs' needs in COVID-19 mitigation measures. Furthermore, this study provides insights into the uncertain and dynamic changes in the transport behaviour of PwDs during the COVID-19 pandemic. This has contributed to a wider debate on the impact of the COVID-19 pandemic on public transportation. Thus, the research questions of this study are answered.

There are two limitations to this study. First, the COVID-19 pandemic has not yet been fully contained and the situation may change rapidly with new mutant strains of COVID-19 or the emergence of new infectious diseases. Therefore, continuous observation is necessary. Second, this study relies on passenger data collected by rail operators and did not include socioeconomic information on passengers. Comparisons of all rail passenger numbers provide a measure of the impact of wheelchair rail passenger numbers. However, background factors need to be interpreted based on previous studies on PwDs during the COVID-19 pandemic.

The significant modal shift from public transport to other modes of travel (Basu and Ferreira, 2021; Khadem Sameni et al., 2021; Loa et al., 2021; Thombre and Agarwal, 2021; Zhang et al., 2021a) is forcing public transport operators to respond to a sharp decline in passenger numbers (Monahan and Lamb, 2022; Hörcher et al., 2022). In some respects, it is unavoidable for public transport operators to consider reducing their transport services in response to shrinking mobility demand. However, the disproportionate decline in the number of wheelchair rail users implies that opportunities for social participation have reduced. The objective assessment of the impacts of wheelchair rail users identified in this study will help improve mutual understanding between stakeholders and help national administrations and public transport authorities plan inclusive mitigation measures and reach social consensus.

Data availability

The datasets analysed in the current study are not publicly available due to the inclusion of confidential company data from the East Japan Railway Company.

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Author contributions
YA and KH conceived the ideas presented. YA developed the theory with the support of KH, YN and TK and collected and calculated the data. YA wrote the manuscript with input from KH, YN and TK All authors discussed the results and contributed to the final manuscript.

Competing interests
The first author was an employee of the East Japan Railway Company. JSPS KAKENHI and the East Japan Railway Company had no control over the interpretation, writing, or publication of this manuscript.

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Ethical approval was not required because this study used anonymised information.

Informed consent
Informed consent was not required because this study used anonymised information.

Additional information
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