EVALUATION OF TIME LOSS DUE TO UNEVEN DISTRIBUTION OF RAILWAY PASSENGERS GETTING ON AND OFF

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Commission IV, WG IV/9

KEY WORDS: Railway station, Passenger, Choice behavior, Carriage, Time loss, Platform.

ABSTRACT:

The behavior of train passengers when selecting a carriage was modeled using five explanatory variables. Using passenger numbers estimated by measuring the total weight of passengers using air suspension pressure gauges, the model parameters were estimated, and the accuracy of the model was validated. From the estimated parameters, we analyzed the ability of the explanatory variables to account for passenger behavior depending on the direction of travel and the time of day. Finally, we estimated the spatiotemporal distribution of passengers on each platform using this model, and discussed the time lost due to the non-uniform distribution of passengers when boarding and alighting from the train.

1. INTRODUCTION

1.1 Research Background and Purpose

Smooth boarding and alighting of passengers at train station platforms is essential for the safe and efficient operation of train services. However, in reality, passengers become concentrated in carriages that stop close to vertical access facilities, such as staircases and escalators, which means that long boarding/alighting times are necessary. This is inefficient, and it is also unsatisfactory from the perspective of passenger safety and comfort.

Therefore, in this study, with the aim of clarifying the mechanisms for the carriage choice behavior of railway passengers, we conduct an analysis using the following procedure. First, we model the influence of various environmental factors of the platform and train, such as the location of staircases, escalators, and other vertical access facilities, the degree of crowding on the platform and in the carriage, and the stopping position of first-class carriages, on carriage choice behavior. Next, we quantitatively assess the influence of environmental factors on carriage choice behavior by parameter estimation using real data relating to railway passengers. Finally, we quantitatively evaluate the inefficiency that arises due to the uneven distribution of passengers getting on and off by calculating the time lost due to the imbalance of passengers (time lost while the train is stopped) according to train station and time of day.

1.2 Past Research and Positioning of This Study

Previous studies have analyzed the boarding and alighting of railway passengers from the perspective of attempting to reduce train stoppage times. Oto et al. [1] conducted experiments using a mock-up of a real carriage at one-quarter scale in length, and showed that boarding/alighting times can be approximated using a quadratic function of the number of passengers getting on and off. From a similar perspective, Takeuchi et al. [2] conducted a simulation by visualizing the standing positions of passengers, and analyzed the relationship between the number of passengers getting on and off and the boarding/alighting time. Additionally, Ogasawara et al. [3] quantitatively analyzed the influence of the environment around the station in one-hour intervals on the numbers of passengers boarding/alighting trains in the morning and evening, and examined the causal relationships.

With regard to previous research on the spatial distribution of passengers on platforms, there have been attempts to estimate the passenger distribution on station platforms based on the staircase locations. For example, Ogata et al. [4] conducted a survey on the relationship between the location of vertical access facilities (staircases, escalators, elevators) and the number of people boarding/alighting at each carriage door on the Chuo Line platform at Tokyo Station before and after construction work that altered the platform layout. They showed that the layout of vertical access facilities has a major influence on the behavior of passengers getting on and off trains, and qualitatively demonstrated the effectiveness of a well-distributed arrangement of vertical access facilities. Additionally, Kawai et al. [5] conducted an opinion poll of passengers to verify this result. They showed that 80% of passengers decided on the boarding position based on the location of vertical access facilities at boarding/alighting stations, and confirmed that passengers were also aware of carriage occupancy to some extent. Aoki et al. [6, 7] modeled the spatial distribution of boarding/alighting passengers according to distance from staircase locations in boarding/alighting stations. The above-mentioned studies are similar to this paper in that they all propose models that describe the number and distribution of boarding/alighting passengers using information on the location of vertical access

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https://doi.org/10.5194/isprs-annals-X-4-W3-2022-197-2022 | © Author(s) 2022. CC BY 4.0 License.

facilities, which means that they serve as useful reference material.
There have also been previous analyses of general passenger flow inside stations using simulations. Oto et al. [8] proposed a system for predicting passenger flow based on the number of people permitted at various points inside a station and confirming changes in the number of people accumulating when staircases were added on a platform.

In this paper, we attempt to construct a model that describes the carriage choice behavior of railway passengers, with the aim of gaining a quantitative understanding of the relationship between the layout of vertical access facilities and the spatial distribution of boarding/alighting passengers, as discussed qualitatively by Ogata et al. [4] and Kawai et al. [5]. In addition to the location of vertical access facilities examined by Aoki et al. [6, 7], we attempt to estimate the spatial distribution of boarding/alighting passengers in more detail by considering the stopping position of first-class carriages and the degree of crowding in carriages and on platforms. Furthermore, by incorporating tendencies in carriage choice that differ greatly according to the time of day into the model, in a similar manner to the method of Ogasawara et al. [3], and by using the research findings of Oto et al. [1], we attempt to calculate the loss in boarding/alighting time due to an uneven distribution and concentration of passengers.

1.3 Overall flow of the paper

In order to make this paper easier to understand, the overall flow of this paper is organized and shown in Figure 1. First, it is difficult to obtain data on the detailed behavior of passengers at railway stations, and this results in requirement to use a combination of multiple available data. Therefore, we start by organizing the analytical data by pre-processing the available data.

Next step, we will build a model that describes which carriage the passenger prefers to choose and board. Specifically, a carriage choice model based on the probability utility theory is constructed and formulated. Next, since the constructed model has a complex structure, it is difficult to estimate unknown parameters by a general estimation method. We develop, therefore, a method for estimating unknown parameters of the model. Next, we actually estimate the unknown parameters of the model and validate the high descriptive power and accuracy of the model.

Next step, we will demonstrate application examples using the estimated model. First, we quantitatively extract the characteristics hidden in passengers' carriage choice behavior, which has been limited to empirical understanding. Next, using the estimated model, the number of passengers trying to get on and off at each station is estimated for each carriage, and its spatial distribution is visualized. Finally, we will discuss what is needed for efficient and effective railway station planning by estimating the time loss caused by the uneven distribution of passengers in carriages and platforms, which is the main concern in this paper.

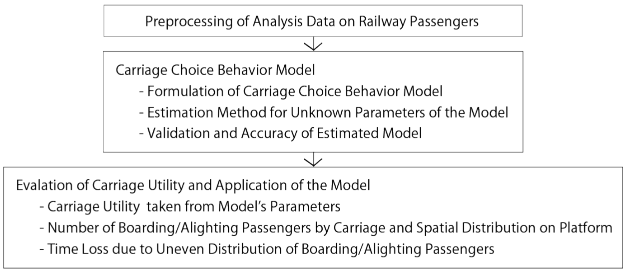

Figure 1. Overall flowchart of the paper.

2. SUMMARY AND PREPROCESSING OF ANALYSIS DATA

A railway line connecting the city center with a suburban district in the Greater Tokyo Area was chosen as the subject of this analysis. The total length of this line is approximately 100 km and it contains 20 stopping stations. The carriage choice tendency of passengers was expected to differ greatly according to the time, so it was examined by dividing time t into 6 periods ($t = 1, 2, \ldots, 6$). Specifically, the time periods are (1) first train–7:00 (early morning), (2) 7:00–10:00 (morning peak), (3) 10:00–13:00 (morning), (4) 13:00–16:00 (afternoon), (5) 16:00–20:00 (evening peak), (6) 20:00–last train (late night).

The "Metropolitan Transportation Census (2010)" and "Data on Passenger Numbers Per Carriage Between Two Adjacent Stations" were used as raw data. The former is data from a large-scale survey conducted by the Ministry of Land, Infrastructure, Transport, and Tourism every five years that looks at volumes of passenger flow, purpose of travel transfers, etc. by mode of transport including train and bus. Using this data, it is possible to find out the number of passengers who got on at station i and got off at station j for time period t, ${}^{t}N_{ij}^{*}$ (total within time period). The latter data consists of passenger numbers estimated by measuring the total weight of passengers using air suspension pressure gauges installed in each carriage, and dividing this value by mean body weight per person (assumed to be 55 kg). Using this data, it is possible to find out the number of passengers in each carriage k between any two adjacent stations (between station l and station $l + 1$), ${}^{t}M_{l}^{k*}$ (total within time period).

The estimation methods used are different, so the data from these two sources is not necessarily consistent. Therefore, the total number of passengers who travelled from station i to station j in time period t is corrected so that it is consistent in both sets of data by finding the correction coefficient in the following equation ${}^{t}C_{ij}$.

$${}^{t}C_{ij} = \frac{1}{j-i}\sum_{l=i}^{j-1}\frac{\sum_{k} {}^{t}M_{l}^{k*}}{\sum_{i\le l}\sum_{j>l} {}^{t}N_{ij}^{*}} . \qquad (1)$$

Besides the above-mentioned data, the stopping positions of trains and locations of vertical access facilities were surveyed on inbound and outbound platforms at each station, and a digital map model of each station was created. The locations of vertical access facilities on each platform were expressed using carriage number k when the train was stopped, in order to make it easier to understand the relationship between train stopping position and vertical access facilities. Specifically, locations were expressed using k =1–10, assigned in order from the carriage closest to the suburban district.

3. CARRIAGE CHOICE BEHAVIOR MODEL

3.1 Formulation of Carriage Choice Behavior Model

The following five factors are considered to influence carriage choice behavior of railway passengers: (1) Location of staircases/escalators (no distinction is made here as they are frequently located side by side) at boarding and alighting stations, (2) location of elevators at boarding and alighting stations, (3) stopping position of first-class carriages, (4) degree of crowding inside carriage (occupancy), (5) degree of crowding on platform (number of people waiting).

First, the utility enjoyed by passengers traveling from station i to station j during time period t when they choose carriage k from among all of the carriages is expressed as ${}^tU_{ij}^k$. In this case, the number of passengers traveling in carriage k from station i to station j during time period t, ${}^tM_{ij}^k$, can be described as follows based on random utility theory using the utility, ${}^tU_{ij}^k$, the number of passengers who travelled between station i and station j, ${}^tN_{ij}^*$, and the correction coefficient ${}^tC_{ij}$.

$$ {}^tM_{ij}^k = \frac{\exp[{}^tU_{ij}^k]}{\sum_k \exp[{}^tU_{ij}^k]}\, {}^tC_{ij} \cdot {}^tN_{ij}^{*} \cdot \tag{2} $$

Next, the utility of carriage k, ${}^tU_{ij}^k$, is described as follows using the five factors mentioned above.

$$ {}^tU_{ij}^k = {}^tW_{Sij}^k + {}^tW_{Vij}^k + {}^tX^k + {}^tY_i^k + {}^tZ_i^k \cdot \tag{3} $$

Factor (1): ${}^tW_{sij}^k$ is the disutility that varies according to distance to staircase/escalator when passengers traveling from station i to station j choose carriage k, and it is described as follows using negative unknown parameter ${}^t\beta_S$.

$$ {}^tW_{Sij}^k = \frac{1}{h_i}\sum_{n=1}^{h_i}\Big({}^t\beta_S \sum_{p_i \in S_{in}} |p_i - k|\Big) + \frac{1}{h_j}\sum_{n=1}^{h_j}\Big({}^t\beta_S \sum_{p_j \in S_{jn}} |p_j - k|\Big), \tag{4} $$

where S_{in} is the set of locations of staircases/escalators on platform n in station i, p_i is a variable representing the location of staircases/escalators in station i, and h_i is the number of platforms in station i.

Factor (2): ${}^tW_{vij}^k$ is the disutility that varies according to distance to elevator when passengers traveling from station i to station j choose carriage k, and it is described as follows using negative unknown parameter ${}_t\beta_V$.

$$ {}^tW_{Vij}^k = \frac{1}{h_i}\sum_{n=1}^{h_i}\Big({}^t\beta_V \sum_{p_i \in V_{in}} |p_i - k|\Big) + \frac{1}{h_j}\sum_{n=1}^{h_j}\Big({}^t\beta_V \sum_{p_j \in V_{jn}} |p_j - k|\Big), \tag{5} $$

where V_{in} is the set of locations of elevators on platform n in station i.

Factor (3): ${}^tX_k$ is the utility of first-class carriage. This is generally considered to be a negative value because an additional fare is paid when using a first-class carriage. Therefore, ${}^tX_k$ is described as follows using negative unknown parameter ${}^t\gamma$,

$$ {}^tX^k = {}^t\gamma\ \delta^k , \tag{6} $$

where δ^k is a variable describing whether or not carriage k is a first-class carriage. If it is, the value is 1; otherwise, the value is 0.

Factor (4): ${}^tY_i^k$ is the disutility of the degree of crowding inside the carriage. When the number of passengers exceeds a certain amount (occupancy exceeds r^*), disutility occurs, and the size of the disutility is assumed to be proportional to the excess (the numerical calculations in the next section assume that $r^* = 1/3$). This means that ${}^tY_i^k$ is described by the following equation using negative unknown parameter ${}^t\lambda$.

$$ {}^tY_i^k = \begin{cases} {}^t\lambda({}^tR_i^k - r^*) & for\ {}^tR_i^k > r^* \\ 0 & for\ {}^tR_i^k \le r^* \end{cases}, \tag{7} $$

where ${}^tR_i^k$ is the occupancy of carriage k at station i and is defined by the following equation:

$$ {}^tR_i^k = \frac{{}^tN_{i-1}^k - {}^tO_i^k}{F^k} \cdot \tag{8} $$

Here, F^k is the capacity of carriage k, ${}^tO_i^k$ is the number of people alighting from carriage k at station i, ${}^tN_{i\text{-}1}^k$ is the number of passengers in carriage k from station i-1 to station i, and they are each defined by the following equations:

$$ {}^tO_j^k = \sum_{i<j} \frac{{}^tM_{ij}^k}{{}^tm(j)}, \tag{9} $$

$$ {}^tN_l^k = \sum_{i \le l}\sum_{j>l} \frac{{}^tM_{ij}^k}{{}^tm(l)}, \tag{10} $$

where ${}^tm(i)$ is the number of trains at station i during time period t.

Factor (5): Lastly, factor (5), ${}^tZ_i^k$, is disutility of number of people waiting on platform, and it is formulated as follows using negative unknown parameter ${}^t\eta$:

$$ {}^tZ_i^k = {}^t\eta \frac{{}^tI_i^k}{\sum_k {}^tI_i^k}, \tag{11} $$

where ${}^tI_i^k$ is the number of passengers boarding carriage k at station i, and is defined by the following equation.

$$ {}^tI_i^k = \sum_{j>i} \frac{{}^tM_{ij}^k}{{}^tm(i)} \cdot \tag{12} $$

3.2 Estimation Method for Unknown Parameters

By calculating the estimated value ${}^tM_{ij}^k$ using the following equation, it is possible to estimate the number of passengers in carriage k between station l and station l + 1, ${}^tM_l^k$.

$$ {}^tM_l^k = \sum_{i \le l}\sum_{j>l} {}^tM_{ij}^k \cdot \tag{13} $$

Specifically, the unknown parameters are estimated so as to minimize ${}^tQ$, which is the sum of the squares of the error between the value estimated using the model, ${}^tM_{ij}^k$, and the measured value obtained by aggregating the measurement data,

${}^tM_l^{k*}$. Figure 2 shows the estimation method for the unknown parameters. Here, the explanatory variables contained in the model, Factors (4) and (5), given by Equations (7) and (11), depend on the estimated value of the model in Equation (2) and have a recursive structure, as is evident by looking at the equations defining them. Therefore, optimal parameter values are estimated by (i) determining the value of ${}^tM_{ij}^k$ below a certain parameter value using a convergence calculation, as shown in the "convergence calculation" part of Figure 2, and (ii) minimizing the value of the sum of the squared error, ${}^tQ$, using a simulated annealing (SA) method. However, because it is difficult to obtain an optimum solution, even using the SA method, and because it is important to ensure the robustness of the estimated parameters, the optimization calculation shown in Figure 2 was carried out 100 times and the mean of the 10 estimated values with the highest goodness of fit (lowest sum of squares of error, ${}^tQ$) was used.

Parameter estimation of the model is performed using a gradient method based on a simulated annealing (SA), and convergence calculation. Since the calculation procedure is somewhat complicated, it is explained using Figure 2. First, [a] Various parameters to be estimated and the value of ${}^tM_{ij}^k$ are initialized by giving random numbers. [b] Increase or decrease the value of one parameter based on a gradient method. The following steps [c]–[f] are convergence calculations. [c] Obtain the values of the number of passengers ${}^tI_i^k$ and ${}^tO_i^k$ from Equations (9) and (12) using the current value of ${}^tM_{ij}^k$. [d] Based on the estimated ${}^tI_i^k$ and ${}^tO_i^k$ values, the values of Factors (1)–(5), that is, the values of utility/disutility, are calculated using Equations (4)–(7) and (11), respectively. [e] Based on the above estimates, update the number of passengers ${}^tM_{ij}^k$ between stations *i*–*j*. [f] Check if the updated value of ${}^tM_{ij}^k$ has converged or not, and if it has not converged, it returns to [c], and if it has converged, exit the convergence process and proceeds to [g]. [g] Find the sum of squared errors ${}^tQ$ between the estimated value of ${}^tM_{ij}^k$ and the observed value of ${}^tM_l^{k*}$. [h] Check if the value of ${}^tQ$ is small enough, and if not, return to [b], if it is small enough, proceed to End.

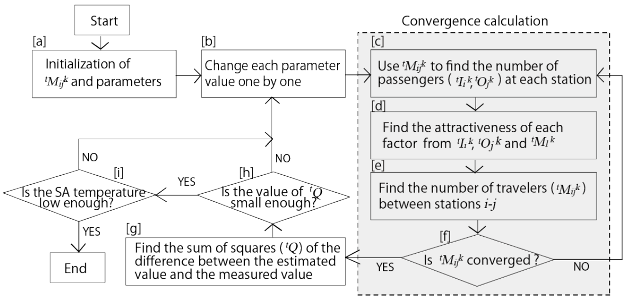

Figure 2. Estimation method for the unknown parameters.

3.3 Estimation Accuracy of Model

Figure 3 shows a part of the correlation coefficients and correlation charts for the estimated ${}^tM_l^k$ and measured ${}^tM_l^{k*}$, i.e., the number of passengers per carriage between two adjacent stations according to time period *t*. The model has a satisfactory goodness of fit for all time periods.

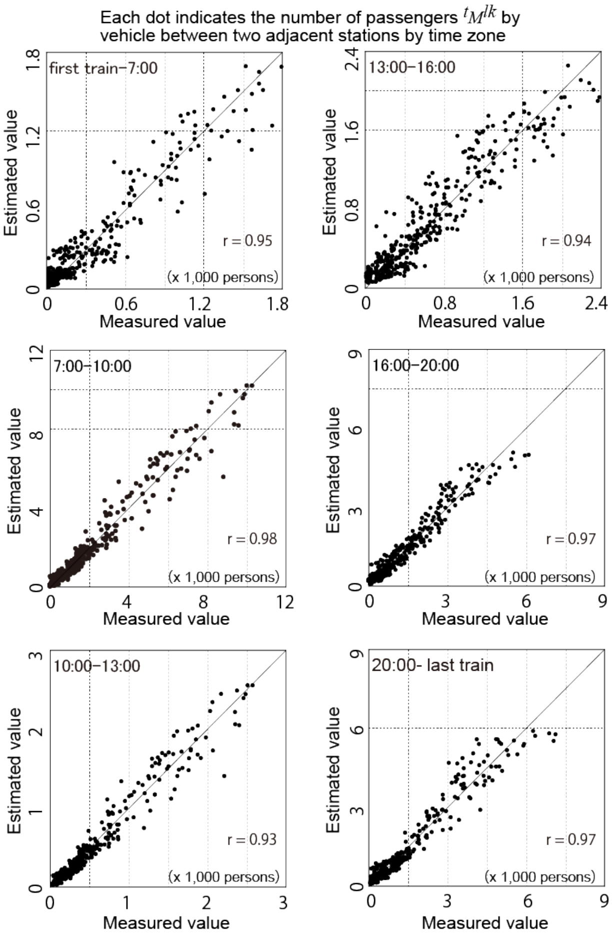

Figure 3. Example of the correlation coefficients and correlation charts for the estimated ${}^tM_l^k$ and measured ${}^tM_l^{k*}$.

4. EVALUATION OF CARRIAGE UTILITY

4.1 Interpretation of Estimated Parameters

Figure 4 shows the values of the estimated parameters. First, looking at parameter ${}^t\beta_s$, which indicates the influence of distance to a staircase/escalator, the value is large and negative during the morning peak. This shows that, during the morning peak, passengers tend to choose a carriage close to a staircase/escalator. Looking at parameter ${}^t\beta_v$, which indicates the influence of distance to an elevator, the value is large and negative in the afternoon (13:00–16:00). This shows that, in the afternoon, when there are relatively large numbers of people who use the elevators, such as elderly people and people with strollers, the influence of distance to an elevator is relatively large compared to other time periods. Looking at the first-class carriage parameter ${}^t\gamma$, no great variation is seen throughout the day, and the degree of influence is stable regardless of time. The parameter ${}^t\lambda$ for the state of crowding in the carriage has a large negative value in the early morning (first train–7:00) and late night (20:00–last train). In other words, during these time periods, a behavioral characteristic of passengers is to try to avoid crowded carriages when boarding a train. Last, looking at parameter ${}^t\eta$, which indicates the influence of the number of people waiting on the platform, the value is large and negative in the afternoon (10:00–13:00). In other words, during the day when the number of passengers is relatively low, people may infer the likelihood of getting a seat in a carriage from the number of people waiting on the platform and choose a carriage where there are fewer people waiting when boarding a train.

Next, we considered the degree of influence (contribution ratio) of factors (1)–(5) on carriage utility ${}^{t}U_{ij}{}^{k}$. Specifically, we found the contribution of factors (1)–(5) combined for all carriages k between station i and station j, based on a total value of 1 for utility in each time period t, ${}^{t}U_{ij}{}^{k}$. Figure 5 shows the mean contribution ratios. First, among the five factors, the influence of factor (1) is the largest. In particular, its contribution ratio during the morning peak is high on both inbound and outbound lines. The contribution ratio of factor (2) is high from daytime onwards on both inbound and outbound lines. The contribution ratio of factor (3) is stable, with a value that is almost constant in all time periods. Factor (4) has a high contribution ratio and a strong influence in the morning on the inbound line and in the evening on the outbound line. As seen earlier, the contribution ratio of factor (5) is high during the day when carriage occupancy is relatively low.

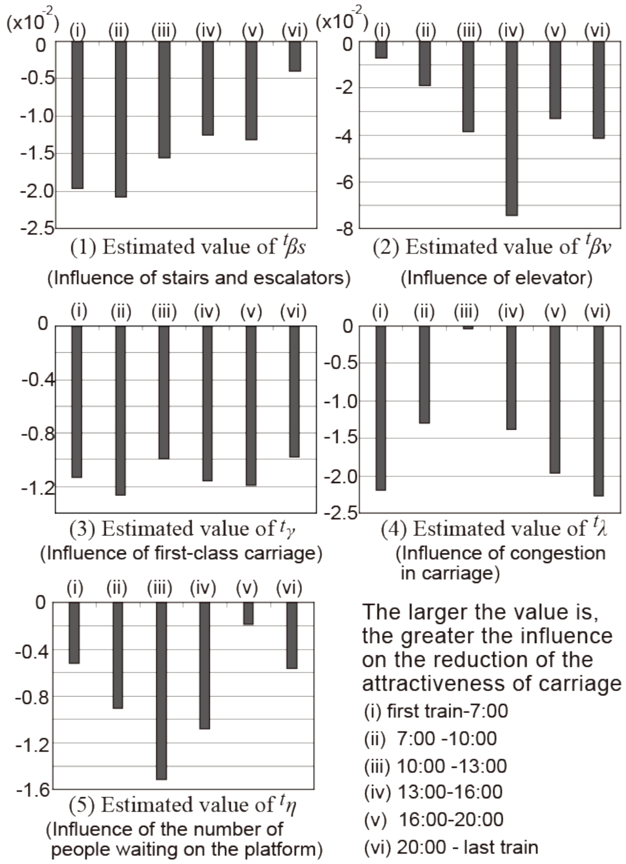

Figure 4. Values of the estimated parameters.

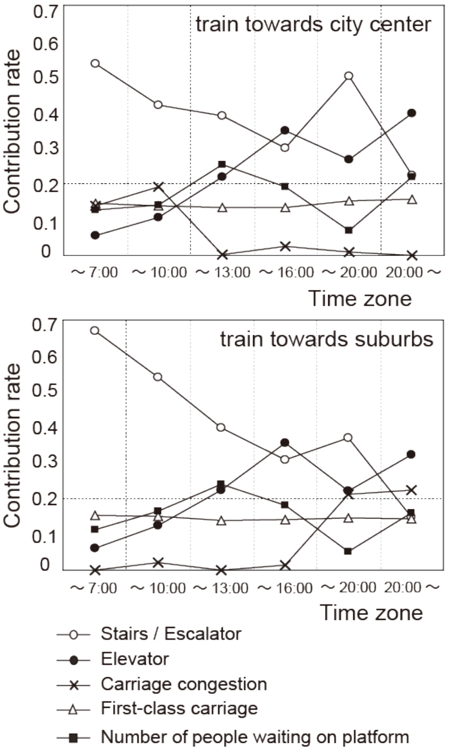

Figure 5. Mean contribution ratios.

4.2 Number of People Boarding/Alighting by Carriage and Spatial Distribution on Platform

Using the above model, we estimated the spatial distribution of the number of passengers boarding/alighting on the platform at each station (mean number of boarding/alighting passengers per carriage per time period). Figure 6 shows examples during the morning peak (7:00–10:00) and the evening peak (16:00–20:00) at Station S, located in the city center area (2nd station from the city center); Station K, located in a mixed residential and business area (4th station from the city center); and Station T, located in a suburban residential area (6th station from the city center).

At Station S, located in the city center area, there are extremely large numbers of people alighting from trains on the inbound line in the morning and boarding trains on the outbound line in the evening, primarily due to the influence of commuters. Passengers concentrate in carriages close to staircases/escalators and elevators in the morning and in the evening, but they also concentrate near Carriage 2, where there are no vertical access facilities in order to avoid crowding. Additionally, the proportion of first-class carriage passengers is relatively high in the evening on the outbound line.

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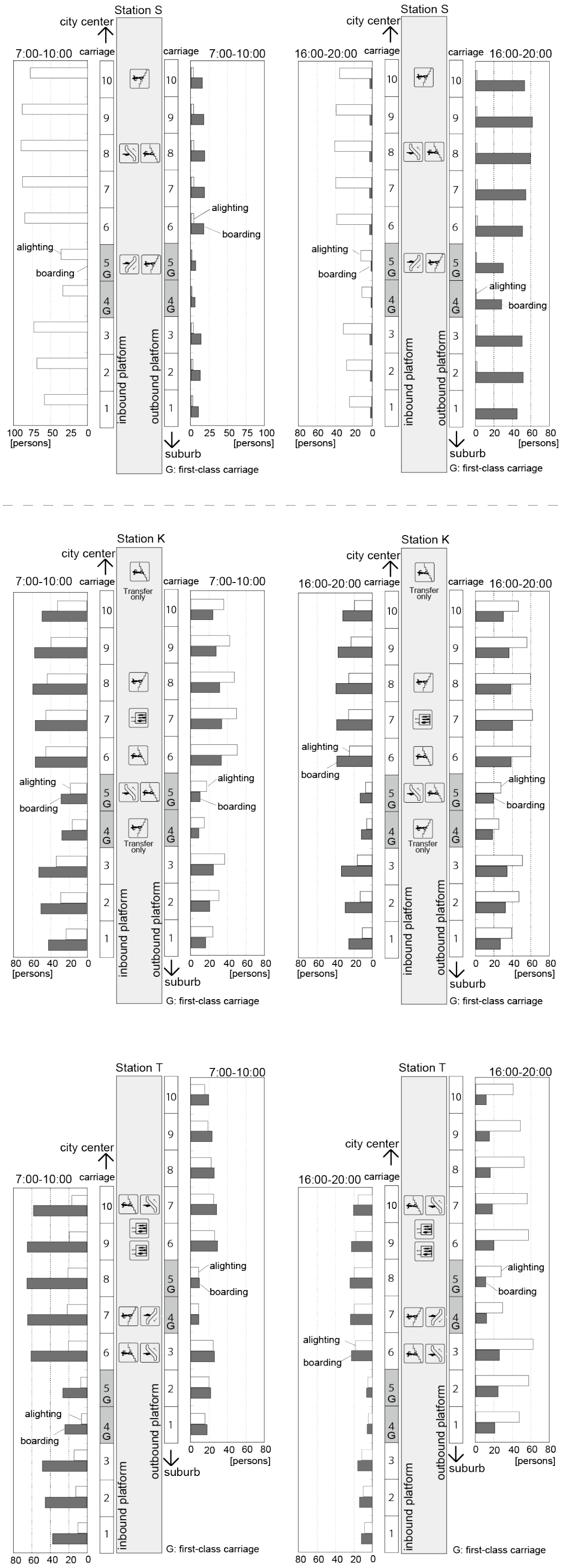

Figure 6. Mean number of boarding/alighting passengers per carriage per time period.

At Station K, which is located in a residential area where there are also offices and factories, there are fairly large numbers of people boarding trains on the inbound line and alighting from trains on the outbound line in both the morning and evening. It is evident that, not only do many passengers travel to work/school from Station K towards the city center, but many also travel to work/school from the city center to the area where Station K is located. A tendency for passengers to choose carriages close to staircases, etc., while avoiding the first-class carriages, can be seen during the morning and evening time periods.

At Station T, located in a suburban residential area, there are large numbers of passengers boarding trains on the inbound line in the morning and alighting from trains on the outbound line in the evening, and this is the opposite trend to Station S. Unlike at Stations S and K, the carriage stopping positions at Station T are different on the inbound and outbound lines. It is possible to see that the distribution of passengers is influenced by the position of vertical access facilities and the position of first-class carriages.

4.3 Time Loss due to Uneven Distribution of Passengers Getting on/off

We found the number of alighting passengers ${}^tO_i^k$ and the number of boarding passengers ${}^tI_i^k$, by time period t, station i, and carriage k, using Equation (12) and (9) respectively, and estimated the time required for all passengers to board/alight by time period, station, and inbound/outbound line. Specifically, using research by Oto et al. [1] as a reference, we estimated the time required for boarding/alighting carriage k (per door), $T({}^tI_i^k, {}^tO_i^k)$, using the equation below. We then found the maximum value among all of the carriages and took this value as the maximum time required for all passengers to board/alight. However, it is possible that this estimated value is slightly too small because it was assumed that the number of passengers getting on/off was the same at all doors (total of 4 doors) in the same carriage.

$$T({}^tI_i^k, {}^tO_i^k) = \{0.0028(\frac{{}^tO_i^k}{4})^2 + 0.719(\frac{{}^tO_i^k}{4})\} + \{0.0033(\frac{{}^tI_i^k}{4})^2 + 0.8626(\frac{{}^tI_i^k}{4})\} \quad (14)$$

Next, we estimated the time required to board/alight in the same way, assuming that the number of passengers getting on/off is the same for all carriages (total of 10 carriages). In this case, boarding/alighting ends simultaneously in all carriages, so this value can be thought of as the theoretical minimum boarding/alighting time. In other words, the loss in time from boarding/alighting due to an uneven distribution of passengers (time loss) ${}^tL(i)$ is defined using the following equation.

$${}^tL(i) = \max_k T({}^tI_i^k, {}^tO_i^k) - T(\frac{1}{10}\sum_k {}^tI_i^k, \frac{1}{10}\sum_k {}^tO_i^k) \cdot \quad (15)$$

Figure 7 shows the results of finding the time lost during time period t at station i. At stations near the city center, there is a maximum time loss of approximately 12 seconds on the inbound line in the morning and approximately 11 seconds on the outbound line in the evening. Time loss is particularly large at Station Y, which is the 5th station from the city center. Meanwhile, time loss in the suburbs is small, with the 16th station from the city center, Station O, having a time loss of only a few seconds.

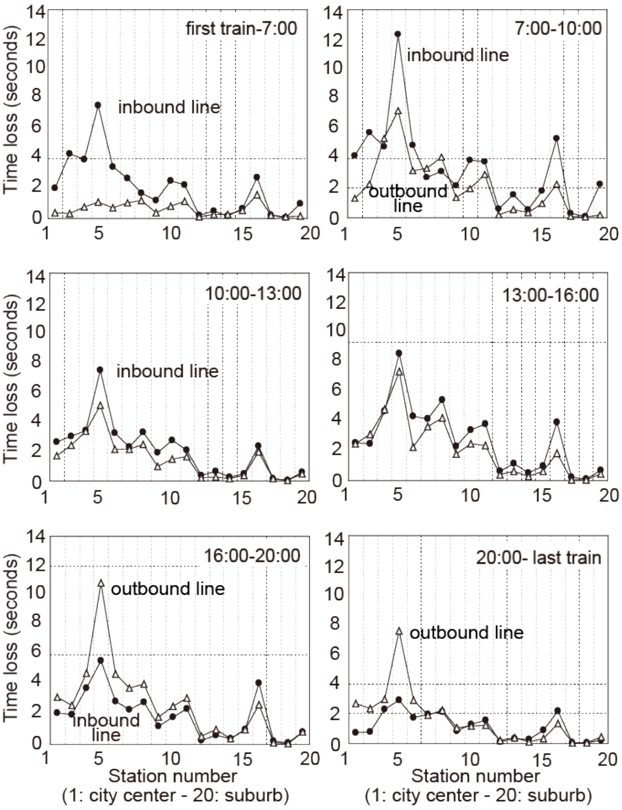

Figure 7. Loss in time from boarding/alighting due to an uneven distribution of passengers.

5. SUMMARY AND CONCLUSIONS

In this paper, we first described carriage utility according to various environmental factors of the train and platform, and then modeled carriage choice behavior of railway passengers. Next, using the "Metropolitan Transportation Census (2010)" and "Data on Passenger Numbers Per Carriage Between Two Adjacent Stations", we estimated the model's unknown parameters and considered the contribution ratio of each factor on the carriage choice behavior of railway passengers. As a result, a tendency for passengers to choose carriages close to staircases/escalators, while avoiding first-class carriages, was identified quantitatively. Additionally, using the constructed model, we estimated the number of passengers getting on and off and their spatial distribution on the platform according to time/station/carriage, and based on this, we evaluated the time lost while the train is stopped. The results showed that the maximum time loss due to uneven distribution of passengers getting on and off was approximately 12 seconds.

Hereafter, we would like to consider the extensibility of this model in order that it becomes a support tool that can be used to design the layout of vertical access facilities and examine the stopping positions of trains, etc., when planning safe, comfortable, and efficient station building spaces. Possible applications for the model include its use as a support tool for planning station buildings by linking it with the system for evaluating passenger flow in stations being developed by Oto et al. [8]. Future work will also include observing and measuring conditions at several stations and attempting to verify the consistency of the model with real crowding.

The proposed model has been employed by an actual railway company that is now planning a renovation plan of a railway station, and discussions on a specific renovation plan have now begun. Until now, renovation plans to respond to the large changes in the number and behavioral distribution of passengers due to new developments in the vicinity of railway stations have been carried out based mainly on the intuition and experience of the planners. However, the proposed model makes it possible to consider efficient and effective refurbishment plans at the planning stage, along with concrete qualitative / quantitative evidence. The authors think this is an innovative point of this research.

ACKNOWLEDGEMENTS

We are grateful for the understanding and cooperation of all parties involved in our use of "Data on Passenger Numbers Per Carriage Between Two Adjacent Stations".

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APPENDIX

The variables used in this paper are listed below.

[Suffixes]

t: Suffix denoting time period ($t = 1, 2, \ldots, 6$)
k: Suffix denoting carriage ($k = 1, 2, \ldots, 10$)
i, j: Suffix denoting station ($i, j = 1, 2, \ldots, 20$)
p_i: Suffix indicating position of staircases/elevators at station i

[Passenger numbers/capacity/carriage occupancy]

${}^tN_{ij}^*$: Number of passengers who traveled between station i and station j according to boarding time period t
${}^tM_l^k$: Number of passengers in each carriage k between two adjacent stations (between station l and station $l + 1$)
${}^tM_l^{k*}$: Value of above-mentioned ${}^tM_l^k$ estimated using air suspension pressure gauges
${}^tO_i^k$: Number of people alighting from carriage k at station i
${}^tN_{i\text{-}1}^k$: Number of passengers in carriage i from station i-1 to station i
${}^tI_i^k$: Number of people boarding carriage k at station i
F_k: Capacity of carriage k
${}^tR_i^k$: Occupancy of carriage k at station i

[Unknown parameters/given constants]

${}^tC_{ij}$: Correction coefficient for making aggregate numbers of railway passengers consistent
${}^t\beta_s$, ${}^t\beta_v$, ${}^t\gamma$, ${}^t\eta$: Negative unknown parameters in utility function
${}^tm(i)$: Number of trains at station i during time period t
h_i: Number of platforms in station i
δ_k: Dummy variable describing whether or not carriage k is a first-class carriage
r^*: Occupancy limit (threshold for degree of crowding that generates disutility)

[Utility]

${}^tU_{ij}^k$: Utility enjoyed by passengers traveling from station i to station j when they choose carriage k
${}^tW_{sij}^k$: Disutility that varies according to distance to staircase/escalator when passengers traveling from station i to station j choose carriage k
${}^tW_{vij}^k$: Disutility that varies according to distance to elevator when passengers traveling from station i to station j choose carriage k
${}^tX_k$: Utility of first-class carriage
${}^tY_l^k$: Disutility of degree of crowding inside carriage
${}^tZ_i^k$: Disutility of number of people waiting on platform

[Sets/number of elements]

S_{in}: Set of locations of staircases/escalators on platform n in station i
${}^tV_{in}$: Set of locations of elevators on platform n in station i

[Evaluation functions]

$T({}^tI_i^k, {}^tO_i^k)$: Time required for boarding/alighting carriage k (per door)
${}^tL(i)$: Loss in time required for boarding/alighting due to uneven distribution of passengers (time loss)