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A Probabilistic Estimation Method for Station Passenger Flow Based on Railway Network Constraints and Passenger Behavior Model

K. Yamamoto and Y. Konishi

**Research and Development Center of JR East Group, East Japan Railway Company
Tokyo, Japan**

Abstract

The passenger flow data is crucial for the future management of railway services. Especially when designing station facilities, the placement and scale of facilities are determined based on the number of passengers in each facilities, which significantly impacts costs. Therefore, we have examined a method to estimate the number of passengers of each train and passenger flow within the Tokyo 100 km radius of JR East without camera footage. We have constructed the basic logic for estimating the proportion of railway network, estimating the number of passengers by train car, and estimating the proportion in the stations. Based on the actual verification conducted between the estimated values by the proposed method and the measurements from the train's load sensors and the camera-based passenger count, it was found that the number of passengers by train car can be estimated with an average error of around 5% to 20%, and the utilization rate of staircases or escalators at the target platform within the station premises can be estimated with an average error of around 4%. In next step, we will tackle issues such as dealing with changes in passenger flows, further improve accuracy, and expand the scope of practical use.

Keywords: origin-destination data, ticket gate, passenger flow, passengers by car, vertical circulation elements, staircase, escalator, demand estimation.

1 Introduction

Railway operators are involved in the movement and daily lives of many customers through various services provided using the railway network. In recent years, with the development of ICT, the accumulation, analysis, and utilization of vast amounts of performance data that are generated daily have become possible. It is expected that the utilization of performance data will contribute to the planning and realization of more reliable and convenient transportation services, as well as the development of transportation quality improvement through transportation planning and operation strategies that are safe, stable, and meet customer needs. Among such performance data, passenger flow data is expected to be utilized for various purposes such as improving transportation quality, designing station spaces of appropriate scale, and optimizing various service businesses such as retail, dining, and advertising in stations, taking advantage of the characteristics of the railway network. Therefore, passenger flow data is crucial for the future management of railway service businesses.

When designing station facilities, it is crucial to estimate passenger flow accurately and conveniently, as it determines the placement and scale of facilities based on the number of users in each area, which significantly impacts costs. The passenger flow survey methods used in the station improvement projects conducted by JR East include:

1) Traffic volume survey: Surveyors count the number of passengers passing through each passage, staircase, escalator, or other vertical facilities per 5 minutes. In some cases, the counts are also conducted using camera footage.
2) Station concourse OD survey: Passengers are given cards at specific locations on the concourse (such as entrances to vertical facilities or near ticket gates), and the cards are collected at the passengers' destinations on the concourse.

However, there are challenges associated with these survey methods. As the station size increases, a larger number of surveyors are required, resulting in significant costs for conducting the flow survey. Additionally, there are concerns about the accuracy of the survey that involves distributing cards, as the card collection rate has been low (less than 20% in past surveys by JR East). These are some of the issues that need to be addressed.

There have been numerous developments in utilizing cameras (CCTV) and sensors installed in stations to count passenger flow in Japan[1][2]. However, these methods face challenges such as data processing speed, video quality, and privacy protection for passengers[3].

Therefore, we have decided to explore a method for estimating train usage and passenger flow in station premises using various data, without relying on camera footage or the installation of new facilities. We will utilize the ticket gate data from almost all stations within the Tokyo 100 km radius of JR East (JRE Tokyo Area).

2 JRE Tokyo Area Networks and Available Data Acquisition

In JRE Tokyo Area, there are over 400 stations and nearly 30 train services. The train services run parallel and diverge from each other, forming a complex railway network. [Figure 1]

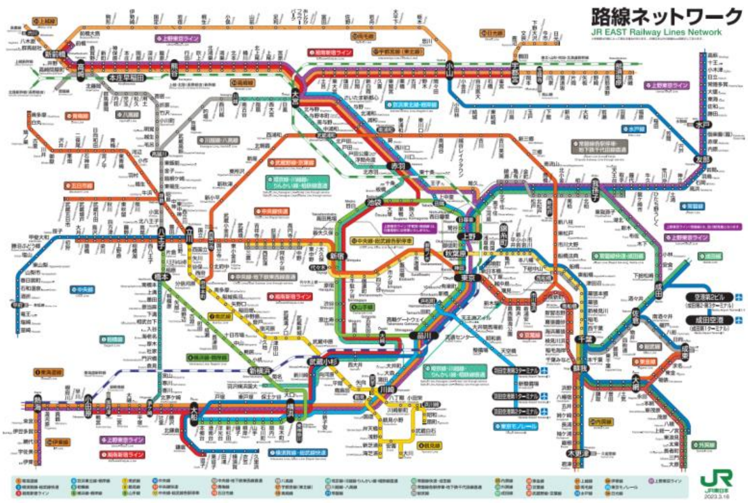

Figure 1. Railway network of JRE Tokyo Area [4]

Within this area, a large amount of data is automatically transmitted and stored in the servers of the operating systems. The main data used in this research and development are as follows:

A) Timetable Data (Planned and Actual)

This data includes the planned timetable based on periodic operational schedule changes and the actual timetable of daily operations. It is obtained from the operation management system and converted into GTFS format. Data acquisition is possible for 365 days, 24 hours.

B) Gate OD Data

This data is automatically aggregated from the gate machines installed at each station in JRE Tokyo area. It can output station-to-station OD data on an hourly basis. Data acquisition is possible for 365 days, 24 hours.

C) Passenger Count Data between Stations by Train (Load Data)

This data represents the number of passengers between each station for each train. Data is collected in real-time and stored on the server for almost all sections of the JRE Tokyo area. It is estimated based on the change in unit car spring pressure, so it is important to note that there may be a gap with the actual number of passengers.

D) Station Facilities Network Data

This data was created for this method. It includes the placement of stairs/escalators on the concourse and platforms of each station, the position of doors for each stopping train, the width of stairs, and the type and operating speed of escalators. By combining this data, the relationship between the doors of the trains and the positioning of the vertical transportation facilities can be determined.

In the following, we use these data to make a model that estimates detailed passenger flow in the stations based on the Gate OD data as the starting point.

3 Method to estimate passenger flow within station premises using Gate OD data

3.1 Over View

As mentioned, the Gate OD data, which is a data that can be collected and accumulated to capture the actual movement of passengers 24/7, only includes counts for the entry, exit, and ticket types at each gate for each time period. Therefore, Gate OD data does not include the specific routes information that each passenger takes from the gate to the train within the station. However, when considering new timetable ,pedestrian spaces at the station, or marketing strategies such as store placement within the station, it is essential to estimate the routes of passengers from the entry gate at the departure station to the exit gate at the destination station. It is believed that there is a significant demand for such estimation.

In this method, we estimate the routes of passengers from the entry gate at the departure station to the exit gate at the destination station by decomposing the Gate OD data as shown in below and Figure 2.

STEP-1: Based on the behaviour choice model, distribute the Gate OD data to each possible route within the JRE Tokyo area, and estimate the number of passengers for each route in each OD and each hour.

STEP-2: Distribute the number of passengers for each route in each OD and each hour obtained in STEP-1 to each train running within the time period. Reaggregate the distribution results to estimate the number of passengers for each OD of each train.

STEP-3: Based on the numbers of passenger for each OD of each train obtained in STEP-2, distribute them to each car of the train based on the passenger car selection model constructed in this study. This allows us to estimate the number of passengers boarding and alighting from each car at each stations.

STEP-4: Based on the station route selection model constructed in this study, distribute the passengers boarding and alighting from each car of each train obtained in STEP-3 to the staircases or escalators used for each station OD. Reaggregate the results to estimate the number of passengers using each staircases or escalators.

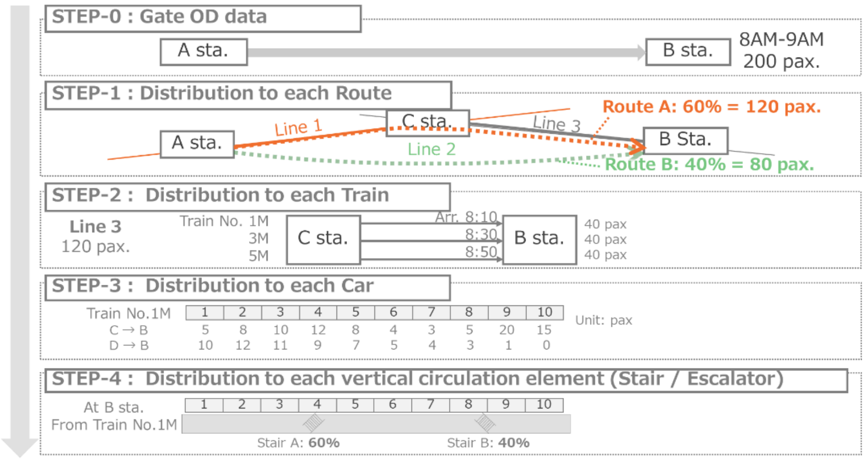

Figure 1: Image of distribution of Gate OD data.

3.2 STEP-1: Distribution to Each Routes

As shown in Chapter 2, the JRE Tokyo area's railway network is complex. However, since ticket checks are only conducted at the entry and exit gates of the departure and destination stations, it is not possible to obtain detailed information on passenger travel routes and the specific trains they use.

We have input the timetable data (GTFS format) for the JRE Tokyo area into Open Trip Planner (OTP) ver. 1.5 and conducted recommended route searches for approximately 400 stations ×400 stations in the area, categorized by time periods. From this, We have created expected route pattern data for each OD pair and calculated the corresponding train usage, travel time, and number of transfers. Furthermore, We have developed a system that applies a route choice model based on previous research[5] to estimate the selection probabilities for each expected route pattern in the aforementioned OD pairs and save the estimated results data.

By re-aggregating the estimated results data by line sections and stations, it has become possible to estimate the number of boarding and alighting passengers, as well as the number of transfer passengers, at each station. Figure 3 shows an example of the estimated number of passengers who enter, exit, and transfer to other direction at a station, extracted by direction.

Unit: Estimated pax.	Enter the gate at this sta. to each direction				From each direction and exit the gate at this sta.				Transfer at this sta. from/to each direction					
時間帯	Enter the gate at this sta. → Line 1 To A	Enter the gate at this sta. → Line 1 To B	Enter the gate at this sta. → Line 2 To C	Enter the gate at this sta. → Line 2 To B	Line 1 To A → Exit the gate at this sta.	Line 1 To B → Exit the gate at this sta.	Line 2 To C → Exit the gate at this sta.	Line 2 To B → Exit the gate at this sta.	Line 1 To A → Line 2 To C	Line 1 To B → Line 2 To C	Line 1 To B → Line 2 To B	Line 2 To C → Line 1 To A	Line 2 To B → Line 1 To A	Line 2 To B → Line 1 To B
4:00-4:15	0.00	15.36	1.17	13.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4:15-4:30	0.00	14.49	6.30	10.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4:30-4:45	4.09	13.88	6.75	10.51	3.63	1.16	2.62	17.38	0.00	0.00	3.29	4.73	13.02	6.03
4:45-5:00	2.75	22.82	30.27	24.89	0.00	3.68	0.00	0.00	1.11	15.27	13.51	0.98	0.90	16.11
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
23:30-23:45	9.00	11.43	18.68	12.36	59.74	20.16	54.24	107.21	49.10	32.14	18.30	42.23	146.49	102.64
23:45-0:00	9.09	7.36	16.92	5.50	80.99	12.00	57.08	105.77	54.77	22.51	18.52	48.86	176.63	73.67
0:00-0:15	8.00	1.94	9.90	5.04	72.07	6.50	60.19	103.64	39.10	30.53	7.91	36.14	137.99	37.73
0:15-0:30	3.00	6.69	1.63	7.07	65.86	16.78	61.46	75.22	29.24	13.57	12.42	52.25	115.21	41.23
0:30-0:45	2.00	0.00	1.00	0.00	60.28	2.50	56.43	83.67	18.05	0.00	0.35	17.10	73.28	17.15

Figure 3. An example of the estimated number of passengers at a station.

3.3 STEP-2: Distribution to Each Train

In this step, we identify the trains that stop at both the boarding and alighting stations within the specified time range using the timetable diagram. We then distribute the passengers for each identified train during that time period.

We considered two distribution methods: Option 1, a simple proportional distribution based on the number of trains, and Option 2, a weighted distribution based on the average number of passengers on each train. The example in Figure 4 shows the distribution of the number of passengers $N_{(T,i,j)}$ from station i to station j during time period T using Option 2, when there are four trains (Train 1 to Train 4) operating. Figure 5 displays the plotted data of the estimated number of passengers per train and the actual number of passengers between each station for both Option 1 and Option 2.

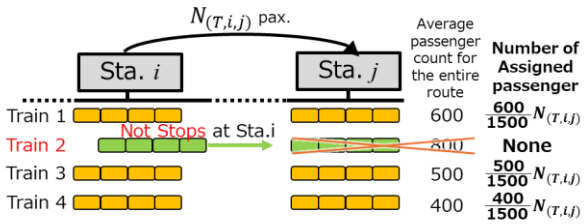

Figure 4: Image of Option 2 (weighted distribution)

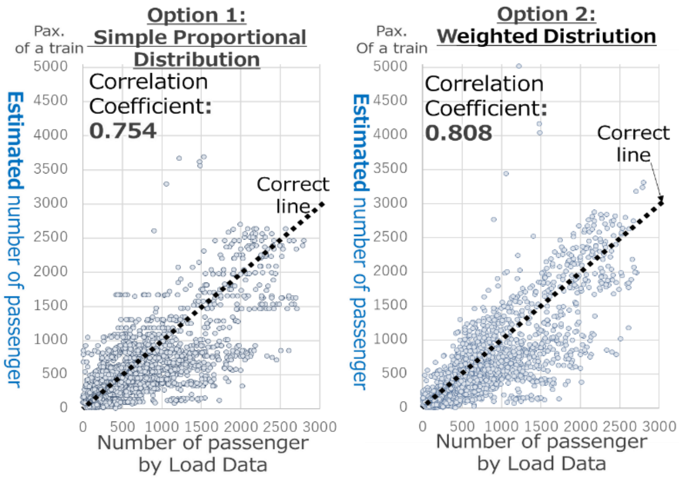

Figure 5: Comparison of Estimated Values for Option 1 and Option 2 with Load Data.

3.4 STEP-3: Distribution to Each Car

We have considered a method to further break down the OD data between each station for each train into individual car data. Regarding the selection behavior of boarding positions on the platform, a survey conducted by the Japan National Railways Tokyo Third Construction Bureau in 1980-1981[6] analyzed the number of passengers boarding and alighting by door location using regression analysis. The results revealed that the number of passengers decreases exponentially as they move away from the maximum value, which represents the location of the vertical circulation elements.

In this method, we have chosen to incorporate the cost of movement within the boarding and alighting stations as factors contributing to the selection of the boarding car. Furthermore, we assume that passengers tend to avoid boarding crowded cars upon train arrival. Therefore, we also include the congestion rate at the boarding station when the train arrives as an additional factor.

The movement cost within the station is calculated as a generalized time based on the distance of movement from the ticket gates to each platform and car. The average equivalent time coefficient for each usage purpose, as determined by a survey conducted by MIC, METI of Japan[7], is used to calculate the movement cost between each gate and train car. Regarding the congestion rate at train arrival, we use the passenger allocation rate for each car based on the accumulated daily train boarding numbers between each station.

We have constructed a model for selecting the boarding car using a logistic regression model, with the following variables as explanatory variables. The utility U_k of choosing car k is set according to the elements mentioned earlier, as shown in Equation (1). The selection probability P_k for each car is determined by Equation (2).

$$\begin{aligned} U_k &= V_k + \varepsilon_k \\ &= w_1 f_k^1 + w_2 f_k^2 + w_3 g_k + \varepsilon_k \end{aligned} \tag{1}$$

f_k^1: The average equivalent time coefficient at boarding station when choosing car k
f_k^2: The average equivalent time coefficient at alighting station when choosing car k
g_k: The congestion rate of car k at the boarding station
$w_{1\sim3}$: Parameters for each item
ε_k: Error term

$$P_k = \frac{\exp(V_k)}{\sum_{j=1}^{n} \exp(V_j)} \tag{2}$$

n: Number of cars in the train

Next, we estimate the parameters $w_{1\sim3}$ for each line and direction separately. To extract the evaluation of the boarding car selection, we focus on the passenger allocation rate S_{xak} for each car in a train. The passenger allocation rate S_{xak} for car k of train a at station x departure is given by Equation (3). For example, in train a , where the number of passengers in the entire train is 1,600, and the number of passengers in car 1 is 160, the passenger allocation rate for car 1 of train a would be 10%.

$$S_{xak} = \frac{N_{xak}}{\sum_{i=1}^{K} N_{xai}} \tag{3}$$

N_{xak}: Number of passengers in car k of train a at departure from station x
K: Number of cars on train a

Since it is unrealistic to obtain a sufficient amount of data on which train and which car each passenger boarded for each OD pair through passenger tracking surveys, etc., we estimate the passenger allocation rate $\tilde{S}_{xak}(w_1, w_2, w_3)$ for car k of train a at station x departure using the aggregated results from the estimated boarding car selection model for each train, as shown in Equation (4). We then calculate the root mean squared error (RMSE) between the passenger allocation rates $\tilde{S}_{xak}(w_1, w_2, w_3)$ calculated using Equation (3) and the passenger count data obtained from the Load Data for all samples. We perform estimation using the grid search method to find the combination of parameters $w_{1\sim3}$ that minimizes RMSE and obtain the optimal solution.

$$V_{(w_1,w_2,w_3)} = \sum_x \sum_a \sum_k \{S_{xak} - \tilde{S}_{xak}(w_1, w_2, w_3)\}^2 \tag{4}$$

We assume that there will be variations in the values of each parameter for each route, direction, and time period. Therefore, we will estimate the optimal solution for each route, direction, and time period. Using the parameters obtained from Equation (4), we can calculate the selection probabilities for each boarding car. With these selection probabilities and the OD data between stations for each train, we can determine the number of passengers boarding and alighting for each car within the train.

3.5 STEP-4: Distribution to Each Vertical Circulation Element

The estimated usage of boarding and alighting facilities is calculated by allocating the number of passengers boarding and alighting for each car within the train to each vertical circulation element using a logistic model. The processing steps in this method are as follows:

1: Extract the set of candidate routes for each car from OD data in the station.
2: Calculate the utility of all routes for each OD in the station, car by car.
3: Calculate the allocation ratios and the number of passengers for each route and OD in the station.
4: Aggregate the number of passengers passing through each vertical circulation element.

The extraction method for the set of candidate routes corresponding to OD data in the station involves extracting all possible combinations of usable vertical circulation elements that allow movement from each car, which serves as the starting point, to the destination such as ticket gates or vehicles, as shown in Figure 6.

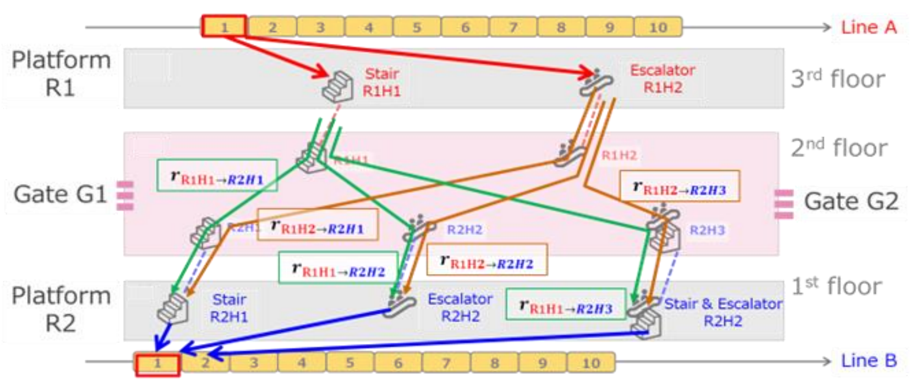

Figure 6: Example of extracting a set of route candidates.

The allocation of all candidate routes extracted for each OD is performed using a logit model. The utility function based on the logit model is given by Equation (5), and the selection probability for each route is calculated using Equation (6).

$$U_{OD} = U_{up}^{b} + U_{dw}^{b} + U_{up}^{a} + U_{dw}^{a} + w_{L1}\log(L_c) + w_{L2}^{b}\log(L_{H\sim K}) + w_{L2}^{a}\log(L_{H\sim K}) \tag{5}$$

U_{OD}: Utility value when moving from O to D within the station
U_{up}^{b}: Efficiency of vertical circulation element with up and boarding the train
U_{dw}^{b}: Efficiency of vertical circulation element with down and boarding the train
U_{up}^{a}: Efficiency of vertical circulation element with up and alighting the train
U_{dw}^{a}: Efficiency of vertical circulation element with down and alighting the train
w_{L1}: Parameters related to distance in concourse
w_{L2}^{b}: Parameters related to distance in platform (boarding)
w_{L2}^{a}: Parameters related to distance in platform (alighting)
L_c: Distance in concourse
$L_{H\sim K}$: Distance from car k to the vertical circulation element on the platform

$$P_{OD} = \frac{e^{U_{OD}}}{\sum_{A_{OD}} e^{U_*}} \tag{6}$$

A_{OD}: Candidate routes for each car from OD data in the station
P_{OD}: Selection probability for each route candidate of OD in the station

By calculating the allocation ratio of each route based on the obtained selection probabilities, it is possible to calculate the number of passengers choosing each route in the station by multiplying the number of passengers boarding and alighting in each train car with the number of passengers choosing each station route. Therefore, by aggregating the results for each vertical circulation element, it is possible to calculate the number of passengers using each route and element.

4 Comparison and Verification with Actual measurement data

We have estimated the number of passengers on each train and car between stations and the number of passengers using vertical circulation element in a station on the survey date (June 5, 2023) by the models. The target lines are Line 1 (Yamanote Line) and Line 2(Saikyo-Kawagoe Line,Osaki - Kawagoe). Line 1 runs in a loop around central Tokyo, and all trains run in 11-car formations. Line 2 runs from central Tokyo to the northern suburbs, and all trains are operated in 10-car formations.

4.1 The Number of Passengers on Each Train and Car between Stations

In Chapter 2, it was mentioned that the Load Data is stored on the server for each train and station pair. However, the train cab records data for each car separately, and this data is recorded for a period of 5 to 14 days. By extracting data directly from the train cars, it is possible to obtain this data. For this study, we obtained the Load Data for the lines during the morning peak hours of the survey day as the correct value, and compared it with the data estimated by the models.

In order to extract the evaluation regarding the model for selecting the boarding car, compare S_{xak} based on the estimated value and S_{xak} based on the correct value described in STEP-3. Table 1 shows the parameters for the four directions of the two line sections and the error rate of the passenger share, and Equation (7) shows the error rate ε of S_{xak}, and Figure 7 is a plot of the combination of the estimated value of S_{xak} and the correct value of S_{xak}.

Items	Line 1 (Yamamote Line)		Line 2 (Saikyo-Kawagoe line)	
	Clockwise	Counter clockwise	To North (Outbound)	To South (Inbound)
Parameter w_1	-0.005	-0.010	-0.010	-0.005
Parameter w_2	-0.005	-0.005	-0.010	-0.005
Parameter w_3	-0.200	-0.800	-0.400	-0.100
Slope of the approximate linear	0.3644	0.4815	0.5925	0.4867
Correlation Coefficient	0.6163	0.7616	0.7541	0.7020
RMSE	0.0148	0.0151	0.0180	0.0130
Error Rate ε	13.4%	14.8%	19.1%	13.3%

w_1: parameters of the average equivalent time coefficient at boarding station
w_2: parameters of the average equivalent time coefficient at alighting station
w_3: parameters of congestion rate at the boarding station (on board / capacity)

Table 1: The parameters and the error rate of the passenger share for each direction

$$\varepsilon = \left| \frac{\overline{S_{xak}} - S_{xak}}{S_{xak}} \right| \quad (7)$$

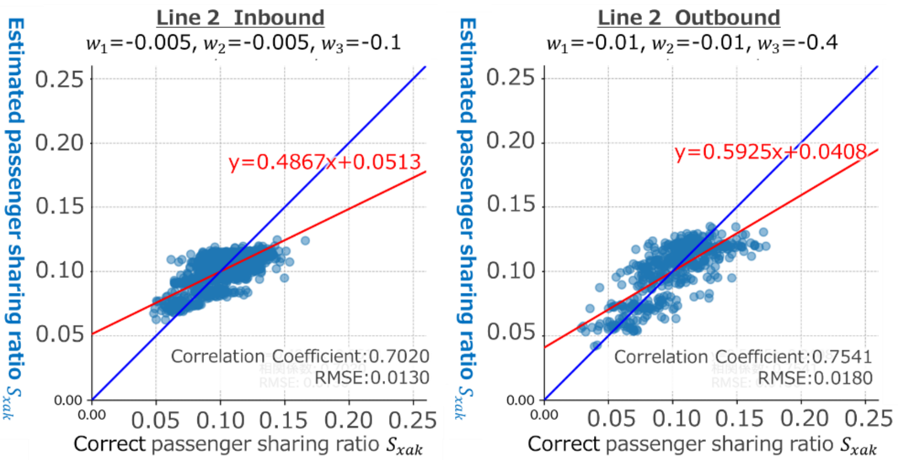

Figure 7: Comparison result of estimated and correct value of S_{xak} (Line 2).

In figure 7, the vertical axis shows the estimated value S_{xak}, and the horizontal axis shows the correct value S_{xak}, and if it is plotted on the blue 45-degree line (blue), there is no error.

From Table 1, The values of parameters w_1 and w_3 differ depending on the direction of each direction, and it can be seen that the sensitivity to the average equivalent time coefficient at the boarding station differs depending on the direction. The slope of the approximate linear straight line is 0.36 to 0.59, and there is a problem that the variation between cars in the estimated value is small compared to the correct value, that is, the bias in the proportion of occupied cars is estimated to be small (Assuming passengers are equally selected in each car). The correlation coefficient in almost directions are over 0.7, indicating a strong correlation, and the correlation coefficient in Line 1 clockwise directions is over 0.6, indicating a correlation.

It can be seen that for the inbound direction of Line 1 and Line 2 Inbound direction, the passenger sharing ratio of each car can be estimated with an average error rate of less than 15%. On the other hand, the average error rate in the Outbound direction is about 5% larger. This may be due to the fact that many trains in the Outbound direction are relatively uncrowded, and passengers tend to select cars differently depending on their purpose of use and level of familiarity.

As a next improvement method, since the correlation coefficients of Table 1 a strong correlation, we will consider methods of correcting estimated values rather than improving data accuracy itself, and verifying the possibility of parameter integration of the lines by verifying the correlation of parameters of the each line and direction.

4.2 The Number of Passengers Using Vertical Circulation Element in a Station

We compare the estimated values and actual measurements at Ikebukuro Station, where the two target lines operate. Ikebukuro Station is an intermediate station where Line 1, 2 and the Shonan-Shinjuku Line operate. It consists of Platforms 1~4 and Concourses 1~4. The configuration of the platforms, directions, and placement of the vertical circulation element are shown in Figure 9 of the station layout.

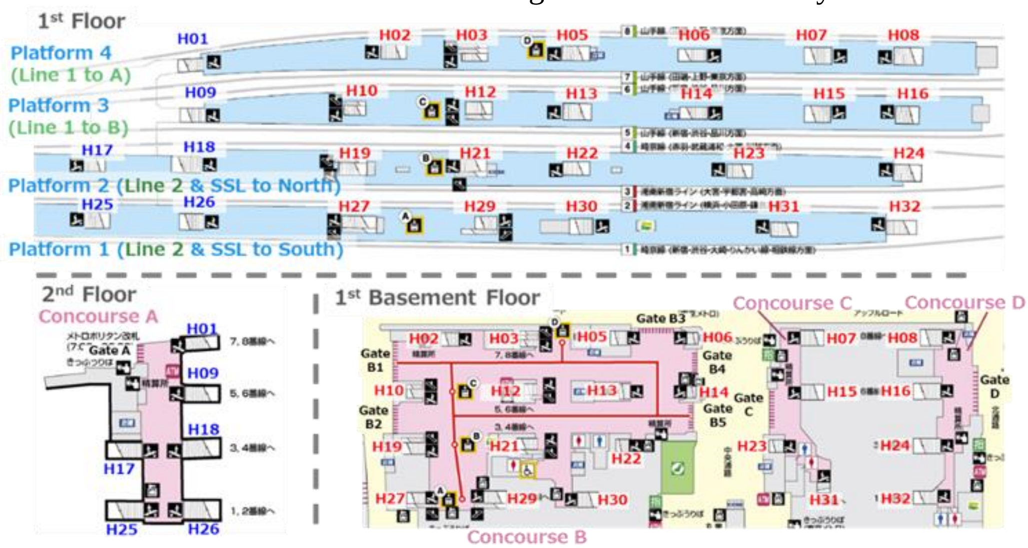

Figure 9: The station layout of Ikebukuro station.[8]

The actual data used in this comparison is the count of the number of passengers for 15 minutes during the morning rush hour from camera footage installed near each vertical circulation element. Below, in order to extract only the accuracy of the station route selection model, we compared the results of calculating the proportion of the number of passengers of each vertical circulation element on platform 3 and 4 (Line

1), when the total number of users of the vertical circulation element connected to each platform is taken as 100%.

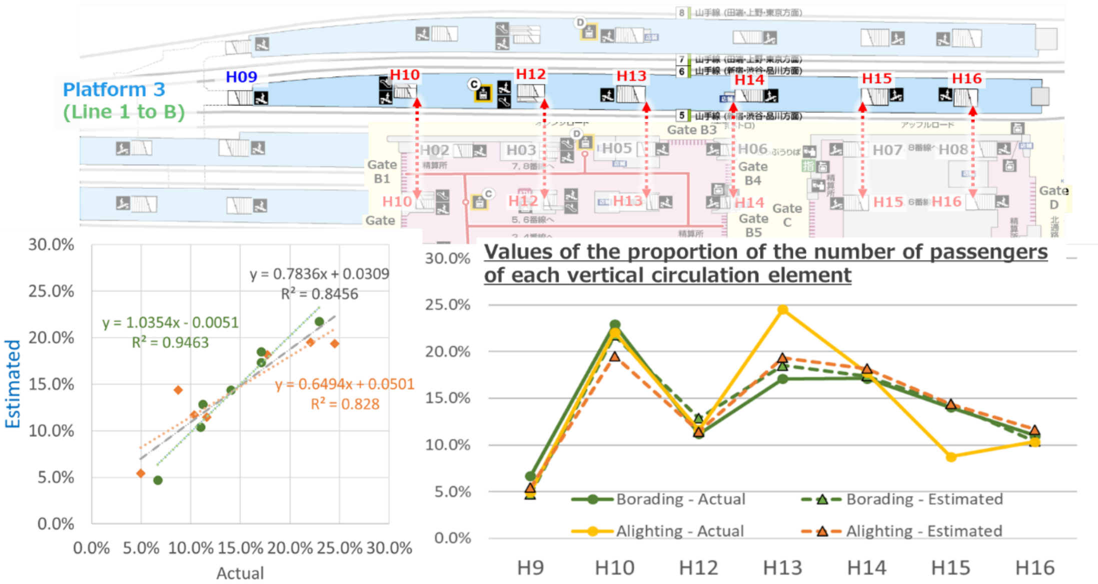

Figure 10: The comparison results between the estimated and actual values of the proportion of the number of passengers of each vertical circulation element (Platform 3,Line 1)[8]

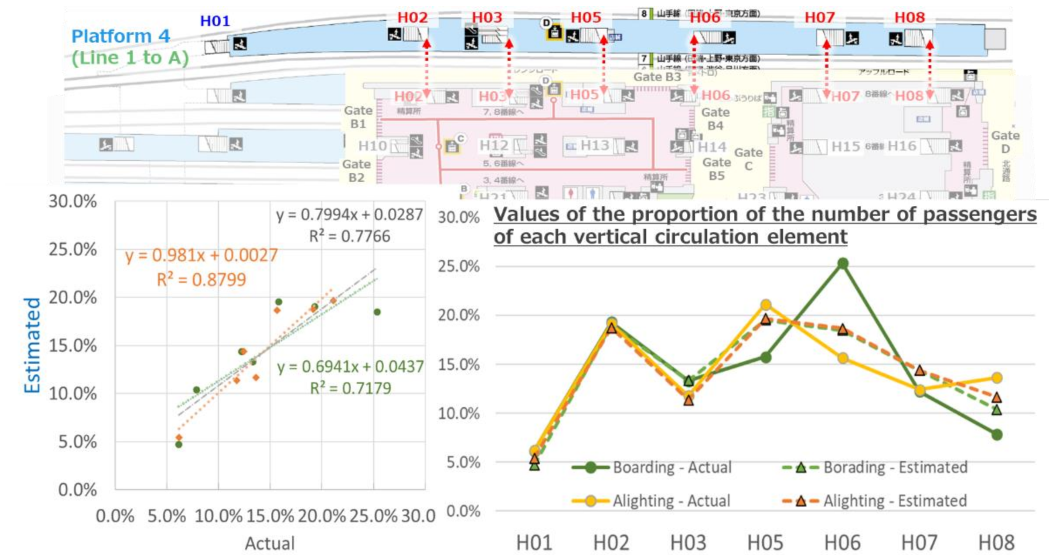

Figure 11: The comparison results between the estimated and actual values of the proportion of the number of passengers of each vertical circulation element (Platform 4,Line 1)[8]

Average error rate [|(Estimated – Actual)|/ Actual]

	Boarding Total	Alighting Total	Total	Average
Platform 3	9.6%	17.6%	13.6%	13.9%
Platform 4	17.9%	10.5%	14.2%	

Table 2: Average error rate.

Figures 10 and 11 show the comparison results between the estimated and actual values of the proportion of the number of passengers of each vertical circulation element on both platforms. The average error rate for each platform and boarding/alighting is shown in Table 2.

From Figures 10 and 11, the estimated values for H01/02/03 and H9/10/12, which connect to Gate 1/2, can be estimated with high accuracy, but for the vertical circulation element that connects to Gate 3-5, there are large errors for both platforms. In particular, it can be seen that there is a difference of more than 5% between H13/15 for disembarkation flow and H05/06 for boarding flow.

Therefore, we conducted a field survey to confirm the reasons why passengers boarding Platform 4 are concentrated in H06 rather than H05. As shown in Figure 12, vertical circulation elements H05 and H06 are adjacent to Gate B3, and the gates at Gate B3 is set to exit on the left side (H05 side) and enter on the right side (H06 side) in Figure 12. Therefore, when there is a flow (Orange) heading towards Gate G3 from H13/H14, etc., the passage to H05 is blocked due to the exit flow, and it is confirmed that the majority of passengers go to H06 instead of going to H05(Green).

It is difficult to express changes in the usage status of vertical circulation element due to flow conditions in the concourse with the model considered in this study. In the next step, estimating this change may be a challenge when improving the accuracy of estimating the number of people using vertical circulation element or estimating the number of people using passages on the concourse.

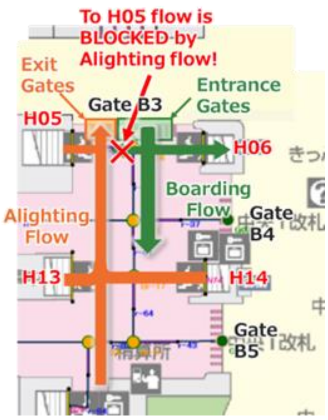

Figure 12: Image of flow obstruction to H05 due to disembarking flow revealed.[8]

5 Conclusions and Contributions

In this paper, we aim to estimate the detailed passenger flow from gate entry at the boarding station to gate exit at the alighting station, in order to facilitate the examination of train diagrams and designing station facilities. We have examined a method to estimate the number of passengers using each car of each train and the passenger flow of station vertical circulation elements in the JRE Tokyo area, using data from Gate OD data and Station Facilities Network Data etc,.

As a result of verifying the accuracy using the studied method, we were able to estimate general trends with an error of 15 to 20% for the passenger sharing ratio between stations by car on the trains, and an average error of about 14% for proportion of the number of passengers of each vertical circulation element on the platforms. However, it also became clear that issues such as improving accuracy remain in order to use passenger flow estimation in a complex concourse with many gates and vertical circulation elements for station design.

In the next step, we would like to proceed with studies that can respond to changes in the usage status of elevator equipment due to the flow conditions in the concourse, and to proceed with further research to be able to make even more detailed estimates for each passage on the concourse.

We will continue to work on developing estimation and prediction techniques, as well as enhancing crucial passenger flow data, in order to support decision-making across the entire railway-related services.

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