A Quantitative Evaluation Method of Seat Arrangement for Commuter Railway Vehicles from the Viewpoint of Comfort and Accessibility*

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In this paper, we propose a quantitative evaluation method for seat and door arrangements in commuter railway cars from the viewpoint of passenger comfort and accessibility. Passenger comfort is defined based on passenger's behavior in selecting a seat, with the assumption that every passenger selects the most comfortable seat from those available. The behavior is modeled by a numerical function. The unknown parameters in the evaluation function are determined by experiments using a full-scale mockup with variable seat and door arrangements. The results of the proposed evaluation functions using computer simulations agreed with experimental results. It was found that the seat arrangement depends on the average passenger traveling time. From the evaluated results, the best seat arrangement for commuter trains is discussed and new seat arrangements are proposed.

Key Words: Railway, Railway Vehicle, Simulation, Experiment, Commuter Service, Evaluation Method, Seat Arrangement, Comfort, Accessibility

1. Introduction

In this paper, we propose a quantitative evaluation method for seat and door arrangements in commuter railway cars. The purpose of this study is to evaluate seat arrangement based on passenger comfort and accessibility, which are of utmost importance during train operation. Improvement of comfort is very important for commuter rail services in urban areas. Personal transportation systems such as automobiles are very convenient and useful; thus, in many cities railway services are confronted with the problem of decreasing number of passengers. However, from the viewpoint of saving energy and air pollution prevention, the amount of the transport by public rail service must be maintained, or even increased.

In rail services, passenger comfort depends on

several points; for example, travel fare, train speed, train departure interval, and so on. One of the most important requirements for passenger comfort is to provide a seat once boarded.

In commuter rail services, one of the most important points to consider is to provide suitable transportation capacity to meet passenger demand. In order to increase transportation capacity, speed-up is necessary, because transportation capacity is proportional to the product of train capacity and speed. Speed-up is also useful step for cut off the traveling time. To increase the average velocity of a train, shortening stopping time is important. Therefore, an improvement in accessibility for getting on and off is required.

To improve the quality of public transportation, we must consider compatibility between two aspects, i.e., passenger comfort and shortening stopping time by improving passenger accessibility.

However, the evaluation method for comfort and accessibility has not been examined in detail in the past. In particular the quantitative evaluation of comfort is a very difficult problem because the concept of comfort has not been defined numerically. We propose an evaluation method of comfort using

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passenger behavior to have a seat as index. We assume that every passenger chooses the most comfortable seat from those available in a train considering the seating condition and proximity to the door. To determine the unknown parameters in the evaluation function, experimental examination was done using a full-scale mockup with variable seat arrangements manufactured exclusively for this study. Finally, using the proposed evaluation method, seat arrangement suitable for Japanese commuter trains is discussed.

2. Background

2.1 Japanese commuting condition

The commuter railway service in urban areas especially the Tokyo Metropolitan area, has such major problems as a transportation demand is much larger than transportation capacity. A typical commuter line transports 100 000 passengers per hour in the morning. Although the trains come every two min. and every train has 10 to 15 cars, the number of passengers is sometimes twice as the designated car capacity. So, only 20% of all passengers can have seats. The traveling time by commuting exceeds one hour on the average because many people are living out of town, as far as 60 km away from the central Tokyo. The Japanese commuting condition is, unfortunately, miserable.

A typical commuter car in the Tokyo metropolitan area has four doors on each side of its 20-m-long body. To increase the capacity of standing passengers, the lateral-sitting type of seat arrangement (long seat) is usually adopted. This arrangement gives quick access to the door but the seat capacity is low. For some long distance trains, a box-type seat arrangement is adopted; however, the number of trains with this seat arrangement is recently decreasing because of poor accessibility.

In order to achieve more efficient transportation in the commuter rail services such as the subway system and suburban railways, to shorten traveling time by reducing the stopping time at the station is important. Six or five doors on each side of cars have been used in Tokyo area to improve accessibility in getting on and off.

In decreasing the number of seats in a car using the long-seat type and increasing the number of the doors, the passenger comfort is dramatically decreased. From the viewpoint of passengers, these conditions are undesirable. Therefore, car designers of commuting vehicles should find optimal solutions. To examine and discuss passenger comfort, a method for numerically evaluating comfort and accessibility with the seat and door arrangements as parameters is

desired.

The objective of this study is therefore to evaluate the effects of such new cars on passenger comfort and accessibility. Moreover, optimal seat arrangement with compatibility between passenger comfort and accessibility is also considered.

2.2 Seat arrangement of commuter trains

Table 1 shows symbols of seat arrangements used in this paper. There are many types of seat arrangements that are actually used or proposed. However, they are combinations of only two kinds of basic components, i.e., lateral sitting seat (long seat) and longitudinal sitting seat (cross seat and box seat). There are three combination methods of basic components; uniform type (All-), unsymmetrical combined type (Half-), and symmetrical combined type (Semi-).

In this study, 20-m-long and 2.95-m-wide vehicles with four doors and six doors on each side are selected as typical commuter cars. There are two types of seat pitches for longitudinal sitting seats. One is the standard type (box-pitch BP=1.5 m, cross pitch CP=0.85 m) which is normally used in Japan. The other is the uniform type (CP=0.8 m, BP=2CP=1.6 m) which has the same area occupied by a passenger as the lateral sitting seat (seat length: 0.55 m + foot space: 0.25 m=0.8 m). However, the cross seat with CP=0.8 m isn't used in this study, because it was too narrow to adopt actually.

Table 1 Symbols of seat arrangement

(Example) **HB4P**

Arrangement	Sitting Seat Type	Doors on Each Side	Pitch
A: All-uniform	B: Box Seat longitudinal & faced sitting	4: 4 Doors, standard section	non: Standard BP=1.5m CP=0.85m
H: Half-combined, unsymmetrical	C: Cross Seat longitudinal & unfaced sitting	4': 4 Doors, longer section	P: Uniformed BP=1.6m CP=0.8m
S: Semi-combined, symmetrical	L: Long Seat lateral sitting, or side seat	6: 6 Doors	

BP: Pitch of Box Seat CP: Pitch of Cross Seat

Table 2 Matrix of seat arrangements

	20-m-long, 4-doors		20-m-long, 6-doors	
	Standard	Uniform	Standard	Uniform
AL	AL4 (54)	-	AL6 (30)	-
AB	AB4 (60)	AB4P (60)	AB6 (40)	AB6P (40)
AC	AC4 (60)	AC4P (60)	AC6 (40)	-
HB	HB4 (57)	HB4P (57)	HB6 (35)	HB6P (35)
HC	HC4 (57)	HC4P (57)	HC6 (35)	-
SB	SB4 (60)	SB4P (56)	-	-
SC	SC4 (56)	SC4P (56)	-	-

(Symbols of seat arrangement and sitting capacity per vehicle are shown in each cell.)

Fig. 1 Concept of evaluation function

Table 2 illustrates symbols for seat arrangements. Some types of seat arrangements for four-door cars have longer distance between two doors than normal types, and are shown by the symbol 4'.

3. Methods for Evaluating Comfort and Accessibility

3.1 Concept of evaluation function

Figure 1 shows the concept of evaluation function of seat arrangement. Function input includes the seat arrangement; door arrangement and operating conditions which are given by the average traveling time t and passenger density η . Function output is comfort value $Ev[m]$ and access time $Et[s]$.

3.2 Definition of comfort

In commuting by railway, there are three kinds of passenger behavior; getting on, traveling, and getting off. Only the traveling with sitting seat is defined as comfortable behavior among them, and the others are defined as uncomfortable behavior. Because traveling without sitting is common in commuting, the following three types of seating conditions are considered using sitting probability p :

Sitting seat: $p=1$; Quasi-standing seat: $0 < p < 1$;
Standing seat: $p=0$

The quasi-standing seat means the standing seat in which a passenger is expected to get a sitting seat at any station on his/her way. For simplification, p for quasi-standing seat is assumed to be $1/2$.

3.3 Definitions on accessibility

As the index of accessibility, the getting-off time for half of the passengers is used, because one of the most important characteristics of train operation is to reduce stopping time, especially the getting-off time at major stations. The getting-off time of a passenger who is sitted the farthest seat from the door is also used, and is nearly proportional to the getting-off time for half of the passengers.

3.4 Evaluation function of accessibility

Getting-off time for half of the passengers Et is:

$$Et = \tau \cdot et \quad (1)$$

$$et = Lr/v \cdot \delta + phs \quad (2)$$

where et is the getting-off time for one passenger from the seat farthest from a door, τ is a proportional constant, v is the average passenger velocity in the

vehicles, Lr is actual distance from a door, δ is the coefficient of blocking of passenger's moving line, and phs is a value of physical resistance.

3.5 Evaluation function of comfort

There has been no commonly used method for quantitative evaluation of human comfort. In this study, the principle of passenger behavior is assumed as follows: 'Every passenger selects the most comfortable seat from among those available.' This axiom makes passenger comfort measurable quantitatively. The comfort value Ev is:

$$Ev = \left(\sum_{i=1}^n \max(ev[i][j]) \right) / n \quad (3)$$

Ev is defined as the average of all passenger comfort value ev . $ev[i][j]$ is the comfort value of seat number j for passenger number i , and n is the total number of passengers.

$$ev = \eta \cdot Ua + \eta \cdot Ud + \frac{1}{\eta} \cdot Cs \cdot t = f(t, \eta) \quad (4)$$

ev is defined as the weighted sum of uncomfortable value for getting on Ua , comfort value per unit for traveling time Cs (uncomfortable value per unit traveling time Us when standing), and uncomfortable value for getting off Ud . These are constant values specified for every seats. Ud depends approximately on Ua . Then, Eq.(4) is transformed into:

$$ev_1 = -L - \alpha \cdot phs + \beta \cdot Cs \cdot t \quad (5)$$

$$ev_2 = -L - \alpha \cdot phs + \gamma Us \cdot t \cdot (1-p) + \beta \cdot Cs \cdot t \cdot p \quad (6)$$

$$ev_3 = -L - \alpha \cdot phs + \gamma \cdot Us \cdot t \quad (7)$$

$$L = Lr/\delta \quad (8)$$

where ev_i is the comfort value of each type of seat (for sitting seat $i=1$; for quasi-standing seat $i=2$; and for standing seat $i=3$), α is the physical resistance factor, β is the comfort value factor for sitting seat, and γ is the uncomfortable value factor for standing seat. Ev is expressed in unit of $[m]$, because Ua is given as negative compensated distance between a seat and a door.

3.6 Passenger behavior described by numerical models in evaluation function

Figure 2 illustrates the functions on the traveling time and the comfort value plane. The line gradient represents comfort value per traveling time Cs or uncomfortable value per traveling time Us . The intercept of lines represents uncomfortable value for getting on and off. Sitting seats A-C, standing seat D, and quasi-standing seat E are also shown. Seat A has larger gradient and smaller intercept than seats B and D. Seat D has larger intercept and smaller gradient than seats A and B. When traveling time is t_1 , seat D is selected; when $t=t_2$, seat B is selected; and when $t=t_3$, seat A is selected.

When seats C are occupied, the line of seat A

Fig. 2 Evaluation of comfort using the proposed equation and explanation of the principle of passenger seating behavior

moves below (a broken line) because of increasing uncomfot value for getting on and off. Seat E is a quasi-standing seat on which a passenger is expected to sit down at time $t = T$. When all sitting seats are occupied, passenger with t_3 will select seat E rather than seat D. These behaviors described in the evaluation function agree well with passengers' actual behavior.

3.7 Identification of unknown parameters

In order to determine the unknown parameters in the function by experiment, a method shown below is developed. From Eq. (7), the comfort value for standing seat D shown in Fig. 2 is:

$$ev_2 = \gamma \cdot U_s \cdot t \quad (9)$$

Otherwise, from Eq. (5), the comfort value for sitting seat i is;

$$ev_0(i) = -L(i) - \alpha \cdot phs(i) + \beta \cdot Cs(i) \cdot t \quad (10)$$

The comfort value of standing seat is equivalent to one of sitting seat at traveling time t_b . This traveling time t_b is called the boundary time from standing to sitting and is measurable in experiments. Eqs. (9) and (10) are transformed into:

$$-phs(i) \cdot \alpha + Cs(i) \cdot t_b(i) \cdot \beta - U_s \cdot t_b \cdot \gamma = Lr(i) \quad (11)$$

All factors are defined by the method of least squares using Eq. (11).

4. Experiments for Parameter Identification

4.1 Full-scale mockup

To determine the unknown parameters in the evaluation function, experimental examination was done using a full-scale mockup with variable seat arrangements. Figure 3 shows the concept of full-scale mockup. The mockup consists of two sections

Table 3 Seat arrangements for experiments

	4		6
AL4 54		AL6 30	
SB4 60		AB6P 40	
AC4 60		AB6 40	
HB4P 57		HB6 35	
SC4' 56		AC6 40

Fig. 3 Concept of full-scale mockup

Fig. 4 Inner view of the mockup (Here is a seat arrangement which is combined with a variety of seat type)

modeled for 4- and 6-door vehicles. Figure 4 shows the inner view of mockup for demonstration arrangement.

4.2 Experiments

The main experimental parameters are the seat arrangements listed in Table 3. The other parameters

Fig. 5 Participants of the experiment

Fig. 6 Getting-off experiment (AC4)

Participant No. 23 who sat along the window side is getting off, but he is blocked by participant No. 17 who is sitting along the aisle side. He will also be blocked by participant No. 5 and 19 along the aisle

are assumed as follows: average traveling time $t=60$ min., and passenger density $\eta=120$ persons per vehicle ($=6.15$ persons/m). The constitution of participants in experiments is shown in Fig. 5. Four kinds of experiments were conducted:

1) Getting-on experiment: All the passengers get on the mockup with five second interval and occupy their chosen seat. The seating order is measured for comparison with calculated seating order by comfort.

2) Getting-off experiment (Half of the passengers): Starting from a fully boarded vehicle, randomly selected half of the passengers get off simultaneously to model for arrival at a major station. Getting-off time is measured to determine accessibility.

3) Getting-off experiment (One passenger on the seat farthest from the door): Starting from a fully boarded vehicle, one passenger on the seat farthest from the door gets off, and the getting-off time is measured. An example of this experiment is shown in Fig. 6.

4) Comfort experiment: Questionnaires on comfort are answered by the participants who actually sit in all the experimental seat arrangements.

4.3 Results

1) Sitting order of box seat and blocking: Figure 7 illustrates the measured sitting probability of the second passenger of BP (Box Pitch) $=1.5$ m and 1.6 m.

Fig. 7 Sitting probability of second passenger in box seats

Fig. 8 Sitting capacity per vehicle and getting-off time for half of the passengers

In both cases, the probability that the first passenger sits on seat a (facing forward, window side) is 100%. The probability of the second passenger sits on seat d (facing rear, aisle side) is 50% in the case of BP $=1.5$ m, and decreases to 28% in the case of BP $=1.6$ m. If the second passenger sits on seat d , the third passenger will sit on seat b , and the way to seat c is blocked by passengers sitting on seat b and seat d . In BP $=1.6$ m, sitting probability of seat c (facing rear, window side) increased to 50%, and the probability of blocking decreased.

2) Getting-off time and sitting capacity: The measured getting-off time depends on seat arrangement. Figure 8 shows sitting capacity and getting-off time for half of the passengers. It seems that getting-off time increases with increasing the sitting capacity. Figure 9 shows the sitting capacity and the getting-off time for one passenger from the farthest seat. The number in parentheses indicate the blocking site. The getting-off time increases with increasing the number of blocking sites, rather than the sitting capacity.

3) Favorable impression of seat arrangements: In the comfort experiments, a questionnaire was

Fig. 9 Sitting capacity per vehicle and getting-off time for one passenger from the farthest seat (The number in parentheses shows that of blocking site)

Fig. 10 Estimation method of comfort value by multiple regression analysis (concept and validity)

distributed to determine the most favorite seat arrangement. It seems that semi- and half-type seat arrangements are more favorable than all-type seat arrangements. Passengers taste varies markedly, some prefer longitudinal sitting seats rather than lateral sitting seats, but some show the opposite preference. Seat arrangements that combine several types of seats are preferred by most passengers, because they can select their favorite seat.

5. Discussion

5.1 Estimation method of comfort value by seat element

In order to evaluate all kinds of seat arrangements, not only for real vehicles used in experiments but also for vehicles in the design state, an estimation method of comfort value by seat element is introduced. Figure 10 illustrates the concept of the proposed method. A seat is divided into five elements, i.e., front, left, right, back side, and traveling direction. The number of elements can be reduced, for example, in the case of the side element, there are only four elements, i.e., window, wall, a person sitting

Fig. 11 Comparison of sitting order between simulations and experiments

(a) Getting-off time for one passenger from the farthest seat. (b) Getting-off time for half of the passengers

Fig. 12 Comparison of getting-off time between simulations and experiments

on the adjacent seat, and a person standing on the aisle. Comfort value of a seat is assumed to be expressed as the sum of the comfort value of four seat elements:

$$Cs = \sum a_n \cdot S_n + a_d \cdot D \quad (n=f, r, l) \quad (12)$$

where C_s : comfort value, S_f : comfort value on front side, S_r : comfort value on right side, S_l : comfort value on left side, D : comfort value on traveling direction, and a_n , a_d : coefficients for each value. Figure 10 also shows a plot of between measured and estimated values from the proposed method. It was found that the estimated values agree well with measured ones.

5.2 Comparison of sitting order

Figure 11 shows a comparison between sitting order obtained by analysis and that measured in experiments, describing the sitting order of each seat. The calculated sitting order agrees well with the measured one. This shows that the principle in which a passenger selects the most comfortable seat holds.

5.3 Comparison of getting-off time

Figure 12 shows a comparison of two kinds of getting-off time between obtained by analysis and experiments. In both cases of getting-off time for one passenger from the farthest seat (a) and for half of the passengers (b), the analyzed value agrees with the measured one. This agreement confirms the validity of evaluation functions.

Fig. 13 Evaluation results for getting-off time (The number in parentheses shows the sitting capacity per vehicle)

Fig. 14 Evaluation results for comfort

5.4 Comparison of seat arrangements

Figure 13 shows the calculated getting-off time for half of the passengers. The symbols of seat arrangements are shown in Table 3. AC6 has the shortest getting-off time, inversely AC4 has the longest one. The reason for this is that AC4 has many blocking sites, in which the way to the exit is blocked by passengers sitting on the seat aisle side or standing on the aisle. Seat arrangements with box seats, especially in the case of BP=1.5 m, have longer getting-off time. Seat arrangements with larger blocking resistance have worse accessibility.

Figure 14 shows the calculated comfort value depending on the traveling time. The comfort values for four doors and six doors are directly comparable, because the values are averages for one passenger. The comfort values vary depending on the traveling time t . When $t > 30$ min., the comfort value of four-door cars is higher than that of six-door cars. Vehicles for $t > 30$ min. should have as large sitting capacity as possible. Inversely, when $t < 20$ min., the comfort value seems to be independent from the sitting capacity. Vehicles for $t < 20$ min., should have better accessibility than larger sitting capacity. It is found

Fig. 15 Evaluation diagram (travel time: 10 min.)

Fig. 16 Evaluation diagram (travel time: 60 min.)

that the most suitable seat arrangement depends on the operating conditions, especially average traveling time.

The total evaluation of seat arrangements using comfort value Ev and access time Et with traveling time $t=10$ min. and $t=60$ min. is shown in Figs. 15 and 16, respectively. Seat arrangements plotted in the lower right region are better, because they have better comfort value and less access time. Using the proposed evaluation method, seat arrangements can be selected from the viewpoint of the compatibility between passenger comfort and accessibility.

One of the remarkable points of the proposed comfort evaluation method is that the influence of the number of doors can be directly compared because the comfort value is for one passenger. The comfort values depend on the traveling time t . Trains operating for a longer time should use cars with larger sitting capacity, for example, four-door cars rather than six-door cars. Inversely, in the case of short traveling time, the comfort value seems independent of the sitting capacity; therefore accessibility is more important than sitting capacity for short-distance trains.

Fig. 17 Proposed seat arrangements

6. Proposed Seat Arrangements for Commuter Trains

6.1 Characteristics of good seat arrangements

Synthesizing the knowledge obtained above, the conditions for optimum seat arrangements are shown below :

- 1) passenger comfort
- 2) accessibility
- 3) favorable impression of passengers

Increasing passenger comfort is nearly equivalent to increasing the number of sitting seats. To reduce access time, blocking resistance must be reduced. To obtain a favorable impression, supply of several types of sitting seats is desirable in order to suit to various passengers' tastes. An optimum seat arrangement should satisfy these three conditions.

6.2 Proposed seat arrangements

The following three types of proposed seat arrangements are illustrated in Fig. 17 :

- 1) HC6t for short traveling time use
- 2) HB4t for intermediate traveling time use
- 3) HB3t for long traveling time use

These arrangements are designed to satisfy the three conditions mentioned above. The point of these proposal is to use longitudinal sitting seats for three passengers (shown by index 't') on the center line of a door and its adjacent door, on where there is no moving lines of getting-off passengers. Therefore, it is possible to satisfy both increase the number of sitting seats and to decrease access time.

6.3 Evaluation

The sitting capacities of HC6t, HB4t, and HB3t are 45, 63, and 70 per vehicle, which are 150%, 117%, and 109% of ordinary all-long-type seat arrangements (AL6, AL4, and AL3), respectively.

Figure 18 shows an evaluation diagram of seat arrangements in the case of 60 min. traveling time.

Fig. 18 Evaluation diagram (travel time: 60 min)

Fig. 19 Comparison between experiments and simulations of getting-off time for one passenger from the farthest seat

	box seat A	box seat B
Experiment		
Simulation		

Fig. 20 Comparison between experiments and simulations with sitting order

The values calculated by the evaluation function are plotted on the plane of comfort value Ev and getting-off time from the farthest seat.

The proposed seat arrangements are plotted on the lower and righter region of the plane than ordinary seat arrangements. This means that the proposed seat arrangements give more comfort and have shorter access time than ordinary ones.

Figure 19 shows a comparison between calculated and measured getting off times, and Fig. 20 shows a comparison between calculated and measured sitting orders. The calculated values show good agreement with experiments in both cases.

From Fig. 20, it is found that the blocking resistance of the proposed box seats for five passengers in

HB4t and HB3t is smaller than that of ordinary box seats for four passengers. The reason for this is that the blocking by passengers sitting aisle side seats is prevented, because that the least comfortable seat is the middle seat for a three-person seat, and the last passenger has no choice but to sit there.

7. Conclusions

In this study, the following results are obtained by experiments using full-scale mockup of commuter vehicles with various seat and door arrangements:

- (1) A quantitative evaluation method of passenger comfort and accessibility for seat and door arrangements in commuter railway cars is developed.
- (2) The basic concept for measuring the passenger comfort is based on the principle of passengers' behavior to obtain a seat.
- (3) A numerical model of passenger seating behavior is made.
- (4) The principle in which a passenger selects the most comfortable seat is proven by the agreement of the calculated sitting order with the experimental one.
- (5) Using the proposed evaluation method, several seat and door arrangements are discussed from the viewpoint of compatibility between passenger comfort and accessibility.
- (6) The most suitable seat arrangement depends on the average passenger traveling time.
- (7) From the evaluated results, the best seat arrangements for commuter trains are discussed and new seat arrangements are proposed for compatibility between passenger comfort and accessibility.

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