Comfort and Accessibility Evaluation of Light Rail Vehicles *

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Abstract

A quantitative evaluation method for passenger rooms of light rail vehicles from viewpoint of comfort and accessibility is proposed as the result of physical modeling of in-vehicle behavior of passengers upon Gibson's ecological psychology approach. The model parameters are identified from experiments at real vehicles at the depot of Kumamoto municipal transport and at the full-scale mockup of the University of Tokyo. The developed model has realized quantitative evaluation of floor lowering effects by abolishing internal steps at passenger doorways and door usage restriction scenarios from viewpoint of both passengers and operators in comparison to commuter railway vehicles.

Key words: Light Rail Vehicle, Comfort Evaluation, Passenger Room, Low Floor, Behavior Modeling, Mockup Experiment, Affordance, Simulation

1. Introduction

The Light Rail Transits (LRT) has been remarked as eco- and human-friendly public transportation and newly introduced or renovated from tramways in many cities around the world⁽¹⁾. As Knoflacher acutely pointed out⁽²⁾, human-centered city planning strategies play important roles in urban transportation planning; however, the methodology is not commonly shared among planning engineers, which can be decelerating the reports of following successful LRT cases. From the technical aspects, this is partly because of the difficulty in model space transferability of each successful approach derived from uniqueness of each city, so that simple designing methods for LRT service scenario studies to support the city planning engineers have been anticipated.

As for passenger room design of public transportation, there have been many studies on passenger behavior modeling⁽³⁾⁽⁴⁾⁽⁵⁾ or comfort evaluation⁽⁶⁾⁽⁷⁾ of public transportation; however, no applied studies have ever tried to combine the both approaches to provide engineering methods, except for a study by Suda et al⁽⁸⁾ on railway commuter vehicles.

The purpose of this paper is to provide a general comfort and accessibility evaluation method for space designing of types of Light Rail Vehicles (LRVs) based on ecological modeling of in-vehicle passenger behaviors by extending the existing model for railway commuter vehicles by Suda et al⁽⁸⁾. The model formulas are developed from observation at two types of LRVs in commercial operation and the model parameters are identified by experiments at real LRVs at depot and full-scale mockup at university. The developing model enables numerical comparison of space usage scenarios of LRVs in parallel to

railway commuter vehicles.

2. Formulation of passenger's comfort and accessibility

2.1 Ecological modeling of passenger's behavior

As Gibson, the advocator of ecological psychology, pointed out⁽⁹⁾, behaviors of any living creatures are interactive with their circumstances, so that it is desirable that behavior models of discussing LRV passengers be literal description in behaving order which reflect changes in in-vehicle LRV circumstances interactively caused by passengers. Meanwhile simpler description facilitate intuitive understanding; so that standard situations are selected from observation as modeling targets of this study, and behavior models are developed for average in-vehicle behaviors of passengers under the assumption that all the passengers intend to make the most of in-vehicle space resources, affordance in the word of ecological psychology, of LRV. Thus the boarding and seat-taking behavior of single arriving passengers with sufficient time intervals to select the best seat, and the alighting behavior of half passengers are selected as the modeling targets.

2.2 Structure of LRV evaluation model

Fig.1 Variables of physical evaluation models of comfort and accessibility of LRV
(* : newly introduced variables)

The comfort and accessibility evaluation model⁽⁸⁾ by Suda et al for railway commuter vehicles required room geometry (seat arrangement (size, position, direction) and door positions), line condition (travel time and passenger density) as inputs and produced quantitative evaluation values of comfort in meter scale and accessibility in second scale. These basic models were able to compare types of seat arrangements under a certain operating condition; however this cannot be applied for discussing appropriate service operating conditions or for evaluating floor lowering effects of LRVs to the behavior of passengers. Several new variables are introduced to supplement this model for the evaluation of LRVs, based on the observation of passenger's behaviors and operation conditions of LRVs in commercial operation at two types of LRVs at the Kumamoto municipal transport (Fig.1); The amount of steps at doorway (of room geometry) is needed to highlight the advantage of non-step (often low-floor) LRVs by describing the resistance of extra vertical movement of passengers at conventional LRVs with internal/external steps at passenger doorways, and the door usage type and the fare transaction type (of service operation type) and the distance between doors (of room geometry) are necessary to describe the inconvenience of cases with door usage restriction in boarding and alighting derived from certain fare transaction types, the effect of which is neglected in the cases without door usage restrictions as in railway commuter vehicles (Table1). From the above usage aspects, LRVs are classified as in Table2, where the train length is just a nominal

category to distinguish the discussing two LRVs. The actual forms of these variables will be described in the following chapters.

Table1 Fare transaction types and door usage types of LRVs

Pay Flat Fare to Driver at Boarding from Front Door (e.g. Tokyo Municipal)
Pay Zonal/Stage Fare to Driver at Alighting from Front Door (e.g. Kumamoto Type 9200)
No Internal Payment, Both Doors Available for Boarding/Alighting (Usual Method in Europe)
Pay Zonal/Stage Fare to Driver/Conductor at Alighting from Front/Middle Door (e.g. Kumamoto Type 9700)

Table2 Classification of LRVs from Usage Aspects

Train Length	Steps at Doorway	Door Usage
S : Single Car	S : With Steps	1 : From middle door to front door
L : Linked Train	N : With No Steps	2 : Both doors available
		3 : From front door to middle door

The observed average travel time of inbound line in the off-peak morning at two types of LRVs at Kumamoto municipal transport were 16.1 minutes (42 passengers) at the high-floor LRV (classified as SS1) and 17.0 minutes (67 passengers) at the low-floor LRV (classified as LN2), and the passenger densities ranged from 50% to 90%; thus the standard evaluation conditions for the modeling target in this paper are set as: travel time =15 minutes and passenger density = 50 %.

2.3 Comfort evaluation model

Suda et al⁽⁸⁾ assumed that every passenger sequentially selects the most comfortable seat from all the available seats, and quantitatively described the comfort of seat arrangements of railway commuter vehicles per passenger Ev [m] as linear combination of comfort evaluation value of the path from the boarding door, the seat and the path to the alighting door as follows:

$$Ev = (\sum \max(ev[i][j])) / n \quad (1),$$

where $ev[i][j]$ is the comfort value of seat number j for passenger number i , and n is the total number of passengers. $ev[i][j]$ is composed as linear summation of discomfort value of boarding internal path Ua (<0), alighting internal path Ud (<0) and comfort/discomfort value of sitting seat Cs (>0) or standing seat Us (<0) per travel time, weighted by passenger density η and travel time t with coefficients β and γ to transfer to meter scale, each for sitting seat (ev_1), standing seat (ev_2), and semi-standing seat (ev_3) as follows:

$$ev_1[i][j] = Ua[i][j] + Ud[i][j] + \beta \cdot Cs[i][j] \cdot t[i] \quad (2)$$

$$ev_2[i][j] = Ua[i][j] + Ud[i][j] + \gamma \cdot Us[i][j] \cdot t[i] \quad (3)$$

$$ev_3[i][j] = Ua[i][j] + Ud[i][j] + \gamma \cdot Us[i][j] \cdot t \cdot (1 - p) + \beta \cdot Cs \cdot t[i] \cdot p \quad (4),$$

where the semi-standing seat is a standing seat facing a sitting seat with the probability (p) of later acquiring the sitting seat (here assuming $p=50\%$). Ua and Ud are described as negative summation of walking length from the boarding door (La) or from the alighting door (Ld), and psychological resistance expressed as summation of physical resistance on the aisle per location (phs) with coefficient α to transfer to meter scale as follows:

$$Ua[i][j] = -La[i][j] - \alpha \cdot \sum phs[i][j] \quad (5)$$

$$Ud[i][j] = -Ld[i][j] - \alpha \cdot \sum phs[i][j] \quad (6)$$

At railway commuter vehicles with small gaps between doors, it was allowed to assume that the boarding door and the alighting door are identical and the modeling of Ud was omitted. While at LRVs with large gaps between doors and with door usage restriction in passenger boarding and alighting due to internal fare transaction by the driver, the increase of psychological walking distance and the balance weighting between boarding and alighting must be described, so that Ua and Ud are expressed together as the composite discomfort value of internal walking path in boarding and alighting Uad to be consistent with the formula for railway commuter vehicles as follows:

$$Uad[i][j] = (1 + d) \cdot \{(1 - \varepsilon) \cdot Ua[i][j] + \varepsilon \cdot Ud[i][j]\} \quad (7),$$

where d is the ratio of psychological walking distance to actual physical distance, and ε ($0 < \varepsilon < 1$) is the alighting contribution factor. The ratio d is further simply modeled as linear summation of passenger density ($\eta/100\%$) and distance between doors ($L[m]$) with coefficients A and B :

$$d = A \cdot (\eta - 1) + B \cdot L \quad (8)$$

The psychological resistance in upward/downward passing internal/external steps at passenger doorways is introduced as uniform comfort reduction for each seat from overall comfort evaluation as in (9), just as the extension of walking distance irrespective of d or ε , with number of steps (Nu : number of upward steps, Nd : number of downward steps) multiplied by coefficients (δu and δd) to transfer to meter scale, the values of which for vertical movements has been previously identified as linear function of number of steps from experiments at depot targeting internal steps of double-deck railway commuter vehicles⁽¹⁰⁾:

$$-\delta_u \cdot Nu - \delta_d \cdot Nd \quad (9)$$

Another psychological resistance of path narrowing effects by other standing passengers on the aisles is also introduced as additional walking extension time per location, $narrowPhs$, also multiplied by coefficient α to transfer to meter scale, the value of which for horizontal detours in the aisles was introduced at railway commuter vehicles:

$$-\sum \alpha \cdot narrowPhs \quad (10)$$

Figure 2 illustrates the structure of LRV comfort evaluation formula at two extreme situations of perfect boarding standard ($\varepsilon=0$) and perfect alighting standard ($\varepsilon=1$) for easier comprehension, supposing the case that a passenger selects the best-scored seat among standing seat A nearby the boarding door, standing seat C nearby the alighting door, and sitting seat B between the two doors (closer to the boarding door), where additional psychological resistances at steps or aisles are neglected. The comfort evaluation value of seat number j of passenger i is expressed as a linear function of travel time, with positive gradient $\beta \cdot Cs[i][j]$ for sitting seat or negative gradient $\gamma \cdot Us[i][j]$ for standing seat, and with y-axis of $(1 + d) \cdot Uad[i][j]$, as given with formula from (2) to (7). The bold-outlined seat with best-scored comfort evaluation value at each travel time certainly explains the observed seat-taking behavior of: dominance of standing seat A near the boarding door at

perfect boarding standard and of standing seat *C* near the alighting door at perfect alighting standard both in shorter travel time, and that of sitting seat *B* in longer travel time. The factor $(1+d)$ functions to lower the y-intercept values which is weighted by passenger density and distance between doors as given in formula (8).

Fig.2 Seat-taking behavior explanation by the LRV comfort evaluation model

2.4 Accessibility evaluation model

Suda et al⁽⁸⁾ selected the bottleneck situation of random half passenger alighting at a large transportation transfer node in the line, and modeled the alighting time from the farthest seat (et) which was found proportional to half-passenger alighting time as the accessibility evaluation model:

$$et = Lr / V \cdot \delta + \sum phs \quad (11),$$

where Lr was the actual distance from the seat to the exit door, V was average moving velocity of passengers in free condition, δ was adjusting coefficient.

At LRVs with less transfer volumes than railway commuter vehicles, the situations of half passenger alighting are rarely observed, so that the bottleneck situations are not caused solely by passenger volume and seat arrangement. Moreover, the observation at LRVs in commercial operation revealed that the alighting passengers normally approached the alighting doors before arriving at the alighting transit stop to prepare for the time-consuming fare transactions especially at LRVs with large gap between the doors. This fact requires a different model for explanation of dwell time for transit stops; however we should leave it to other studies and concentrate here on compatible modeling with railway commuter vehicles; thus only the above discussed additional physical resistances for vertical movements at steps of passenger doorway and for horizontal movements of path narrowing in the aisles are newly included in the phs .

3. Parameter identification by experiments

3.1 Seat-taking experiments for comfort evaluation model

To verify the validity of the formulated comfort evaluation model for LRVs through parameter identification of d and ε in the defined comfort evaluation model, a series of seat-taking behaviors are observed at the full-scale LRV mockup at the University of Tokyo to simulate from SN1 to SN3 LRV, where the internal vehicle width and the number of sitting seats per vehicle of which are adjusted to that of the low-floor LRV type 9700 and

the seat arrangement is adjusted to that of conventional LRV type 9200 at the Kumamoto municipal transport, with handrails attached to the standing positions to enhance reality (Fig.3). Each subject was instructed to assume a common travel time and sequentially move from the boarding door to take one of the unoccupied seats (including standing seats) in an

ordered queue with sufficient time interval from the previous subject, so that the order of taken seats can be regarded to describe that of most comfortable unoccupied seats in the LRV. To efficiently simulate different passenger density conditions with the prepared 26 student subjects, full-scale dummies are placed on several seats to compensate for the shortage of subjects.

Fig.3 Full-scale LRV mockup

(Internal length: 10160[mm], internal width:2250[mm], door width (both front, middle):1450[mm], distance between doors (between door edges): 3640[mm], number of sitting seats: 24)

Table3 Conditions of seat taking experiments

No.	Case Classification	Travel Time [min.]	Passenger Density [%]	Note
1	SN1(mockup)	15	90	
2	SN1(mockup)	15	70	
3	SN1(mockup)	15	50	
4	SN1(mockup)	5	50	$\varepsilon = 1$
5	SN2(mockup)	15	50	
6	SN3(mockup)	15	50	$\varepsilon = \text{any}, L=0$

The experimented conditions are designed so that the two parameters (d and ε) are identified from pair comparisons between different line conditions (travel time, passenger density) or service operation types (door usage type) (Table3). At each condition, the parameters are heuristically sought that best describe the averaged seat-taking order of first ten subjects out of 3-time experiments, where the value of d is explored from -1.0 to 1.0 by 0.1 steps and that of ε is explored from 0 to 1 by 0.1 steps.

First solely from the experiment No.4 with short travel time of 5 minutes, where subjects are supposed to follow the perfect

alighting standard ($\varepsilon=1$), the value of d has been explored as $d=-0.3$ (Fig.4). The numbers in the graph show the order of taken seats, where the numbers of mockup experiments is the summed rank of three-time experiments. This means that the simulation at this value of d (Fig.4(b)) has shown best coincidence of seat-taking order up to first five subjects with mockup experiment results (Fig.4(a)). The mean seat-taking orders of first ten subjects

Fig.4 Seat-taking order of mockup experiments and simulation with LRV evaluation model (SN1, $t=5$ min., $\eta=50\%$)

about all the other mockup experiment cases are attached in the Appendix as Fig.8.

Next from the comparison between experiments from No.3 to No.5 with the same values of η and L and thus the same d value as recognized from formula (8), the values of ε has been explored following the above procedure to be $\varepsilon=0.7$ (No.5) and $\varepsilon=0.5$ (No.3). This tendency of larger weight on alighting than on boarding, namely $\varepsilon>0.5$, explains the convergent seat-taking behaviors near the alighting door at actual LRVs in commercial operation.

From experiment No.6 (SN3, $L=0$, $\varepsilon=\text{any}$), boarding and alighting from any door, the value of d has been similarly explored as $d=-0.5$. The parameters at the formula (8) are solved as: $A=1$, $B=0.04$ from the parameters of experiment No.3 and No.6, which shows negligible effect of door usage restriction to the increase in discomfort of internal waling path compared to that of passenger density.

Finally from experiment No.1 to No.3, with the same door usage and travel time, the value of ε has been explored as: $\varepsilon=0.7$ (No.1: $\eta=90\%$), $\varepsilon=0.5$ (No.2: $\eta=70\%$), and $\varepsilon=0.5$ (No.3: $\eta=50\%$), which certainly explains the increase of alighting contribution factor corresponding to the increase of passenger density.

3.2 Alighting experiments for accessibility evaluation model

A series of alighting time of one passenger from the farthest seat from the alighting door et at passenger density 100% are measured at three types of door usage methods (SN1, SN2, SN3) in the end of above seat-taking experiments, both the front and middle door for SN3. To compare the measured time at experiments with simulated alighting time from the accessibility evaluation model for commuter vehicles⁽⁸⁾, *narrowPhs* is calculated to be 1.00 [s]. This additional modeling of path narrowing effect has realized good

Fig.5 Alighting time of one passenger from the farthest seat for accessibility simulation model, with coefficient of determination $R^2=0.81$ (Fig.5).

4. Discussion

From the above procedures, the comfort evaluation formulas of LRVs for sitting seat ($ev1$), standing seat ($ev2$), and semi-standing seat ($ev3$) are given as follows:

$$ev_1[i][j] = Uad[i][j] + \beta \cdot Cs[i][j] \cdot t[i] - \delta_u \cdot Nu - \delta_d \cdot Nd \quad (12)$$

$$ev_2[i][j] = Uad[i][j] + \gamma \cdot Us[i][j] \cdot t[i] - \delta_u \cdot Nu - \delta_d \cdot Nd \quad (13)$$

$$ev_3[i][j] = Uad[i][j] + \gamma \cdot Us[i][j] \cdot t \cdot (1 - p) + \beta \cdot \overline{Cs} \cdot t[i] \cdot p - \delta_u \cdot Nu - \delta_d \cdot Nd \quad (14),$$

where $-\alpha \cdot \sum phs$ is included in the Uad . The comfort evaluation values for commuter railway vehicles are expressed as the cases for $\eta=100\%$, $d=0$, $\varepsilon=\text{any}$, $Nu=Nd=0$; thus the LRV comfort evaluation formulas are compatible with commuter railway vehicles.

Figure 6(a) shows the positions of first ten passengers at the conventional short LRV with two internal steps at the doors (Kumamoto municipal transport type 9200) observed in commercial operation at one-run off-peak hour. Because the exact explanation of seat-taking order is beyond the scope of this simulation model due to variety of passengers in: travel time, composing number of passenger group etc., this comfort evaluation simulator is applied for estimation of not seat-taking order but of seat-taking positions.

The value of ε which best describes the seat-taking positions with the same geometrical conditions of type 9200 LRV is explored to be $\varepsilon=0.7$ (Fig.6(b)), which coincide with the result at experiment No.3. This coincidence certainly supports the validity of the developed comfort evaluation model in explanation of average seat-taking behavior of passengers within the discussed parameter range.

As a case study for application of the developed comfort and accessibility evaluation model, a set of sample service improvement scenarios has been simulated with the developed LRV comfort and accessibility evaluation model, at the condition of travel time $t=15$ minutes and passenger density $\eta=50\%$, under the assumptions of complete alighting standard ($\varepsilon=1$) and no psychological walking distance extension by door usage restriction ($d=0$), to illustrate the exact effects of abolishing 1) internal steps at passenger doorways, 2) door usage restrictions in boarding and alighting, 3) the combination of both 1) and 2) in contrast to railway commuter vehicles. The evaluation results are plotted in a figure with comfort evaluation value in the x-axis[m] and accessibility evaluation value in the y-axis[s], with desirable conditions plotted in right low side (Fig.7).

The low level of comfort and accessibility of high-floor one-car LRV boarding from the middle door and alighting from the front door (SS1) is improved to attain still the level

Fig.6 Seat-taking order of observation and simulation

Fig.7 Simulated comfort and accessibility evaluation values of LRV in comparison with commuter vehicles

of 2-door double-deck railway commuter vehicles (D-AB2p) just by abolishing internal steps at passenger doorways (SN1), and to attain the slightly inferior level to similar-sized 3-door railway commuter vehicles (AL3) by abolishing both the internal steps at passenger doorways and the door usage restriction (SN2). The necessity of abolishing door usage restriction at low-floor two-car LRVs (LN1) to attain the accessibility level of commuter vehicles (LN2) is also indicated. To further exceed the commuter railway vehicles in the service levels of comfort and accessibility from the current LRV (SN2, LN2), the increase of available sitting seats at other-side doorways accompanied by one-way running LRV operation and the decrease of walking distance by the increase of available doors can be proposed.

5. Conclusion

A general comfort and accessibility evaluation model for LRVs in a simple structure, which is virtually able to simulate service improvement scenarios, has been developed from passenger behavior observation at Kumamoto municipal transport and a series of boarding and alighting experiments. The developed model well explains the experiment results in the compatible form with commuter railway vehicles, and has been able to propose service improvement scenarios in contrast with similar-sized commuter railway vehicles.

Among the proposals acquired from the simulation with this developed model, the scenario to abandon the restrictive door usage for the low-floor LRVs has actually been adopted by the Kumamoto municipal transport, and the front door has become available for boarding in commercial operation.

Further scenario studies with this simple-structured physical model will contribute to the widespread of LRT services by promoting human-centered service design in public transportation, by widening the scope of target scenarios (such as: wider range of passenger density, variety of travel time of each passenger) and with user-friendly interfaces of the developed evaluation simulator.

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Appendix

Fig.8 Mockup experiment results
(mean seat-taking order up to first ten subjects)