JOURNAL OF THE FACULTY OF ENGINEERING, THE UNIVERSITY OF TOKYO (B)
Vol. XLI, No. 1 (1991)

Evaluation of Transport Congestion Cost in Commuter Railways and its Applications

By

Hitoshi IEDA

(Received September 25, 1990)

Railway congestion such as seen in the metropolitan area of Tokyo has been a issue to be solved for long. But in spite of the efforts taken so far to increase the traffic capacity of them, the amelioration of railway congestion is still firmly required, and establishing of rational and quantitative evaluation of economic benefits acquired from the projects is more requested to certify their effectiveness and to acquire common understanding upon them. This paper proposes the fundamental theory about the relationship between time consumption and congestion and presents the methods to measure congestion cost and adapted results in some railways. Following these theoretical analysis, the annual economic loss of congestion in commuter railways in Tokyo metropolitan districts is evaluated, and the effectiveness of the recent five multitracking projects comparting to construction cost of improvement is discussed.

Contents

1. Preface

The transport congestion both in railways and in road traffic is one of the most important urban problem in all over the developed or developing countries. Especially railway congestion such as seen in the metropolitant area of Tokyo can hardly be observed in any other cities. But statistically speaking, growth of transport volume is almost 40% in recent twenty years, and the transport capacity has been expanded about two times in this period by multi-tracking or other improvement in every lines. That indicates average load factor (volume/capacity rate; Notice "capacity" includes not only seats but also designed number of standing passengers.) must have been really ameliorated.[1] (Table 1 and Fig. 1) But unfortunately it is also true for commuters in Tokyo that traveler's virtual damage from transport congestion is not being felt so much improved. That is because (1) commuting time has been elongated by sprawling out of urban

Table 1. The Value of Load Factor on Peak Time in Typical Commuter Railway in Tokyo (1986).

Line		Section	Load Factor(%)
JR	Keihin-Tohoku Line	Ueno→Okachimachi	258
	Chuo Line (Rapid)	Shinjuku→Yotsuya	260
	Sobu Line (Rapid)	Shin-Koiwa→Kinshicho	262
	Joban Line (Rapid)	Matsudo→Kita-Senju	271
	Joban Line (Local)	Kameari→Ayase	243
Subway	Ginza Line	Akasakamitsuke→Toranomon	241
	Chiyoda Line	Machiya→Nishi-Nippori	230
Seibu	Ikebukuro Line	Shiinamachi→Ikebukuro	208
Odakyu	Odawara Line	Setagayadaita→Shimokitazawa	208
Tokyu	Shin-tamagawa Line	Ikejiriohashi→Shibuya	226

(Load Factor=Volume/Capacity)

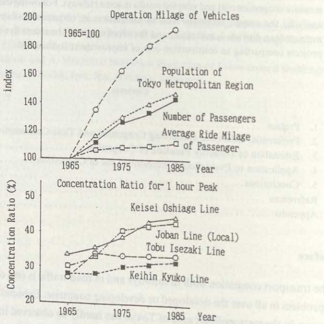

Fig. 1. Capacity and volume of Commuter Railway Transport in Tokyo.

residential area and the effect of improvement was compensated as a whole, (2) concentration rate of transport demand to peak time also grew up by the specialization of land use as commuter's residence in many lines, and (3) Japanese urban citizens became preferring to pursuit more qualified transport amenity. And it can be said that amelioration of railway congestion is still firmly required.

Though many projects of new line construction or multi-tracking were already proposed by the governmental committee responsible for public transport planning of Tokyo and other large cities so that the load factor would be decreased to desirable level (proposed as 150–160%), they have not been satisfactorily carried out because of financial difficulties or lack of common understanding upon construction. Therefore these days, rational and quantitative evaluation of economic benefits acquired from the projects of transportation improvement including those which is aimed at congestion relieving is more and more requested so as to certify their effectiveness and to acquire common understanding upon them.

In this paper, to evaluate the social cost of railway congestion and the effectiveness of congestion relieving projects from above mentioned background, (1) fundamental theory of relation between time consumption and congestion is proposed, (2) method to measure congestion cost and adapted results in some railways are presented, and (3) annual economic loss of congestion in commuter railways in Tokyo metropolitan districts is evaluated and effectiveness of the recent five multi-tracking projects is discussed comparing to construction cost of improvement.

2. Prefecential Behaviour Concerning Congestion and Time Consumption

Transport congestion in road traffic is directly connected to traveler's time loss and increase of fuel consumption, and social cost of congestion is easily evaluated, taking together with time value estimated by so called cost approach or income approach. Congestion tax or tarification theory concerning the optimization of total utility applying marginal cost concept was already proposed and much amount of studies have been done about them.$^{2)}$ But in case of railway transportation, there scarcely occurs any elongation of train's line-haul time according to the increase of transport demand exept for several special cases, because train operation is deterministically scheduled before. As a result, the damage caused by congestion can not generally be observed as the loss of time, but is latent in passengers as some physical or mental stresses. (Fig. 2) These facts make it difficult to evaluate the congestion cost of railways and effectiveness of improving projects.

Now we discuss passenger's preferential behaviour upon combination of time consumption and condition of congestion to make things simple, though they generally take not only time

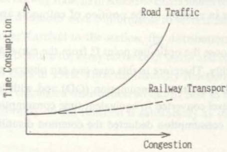

Fig. 2. Time Loss by Congestion.

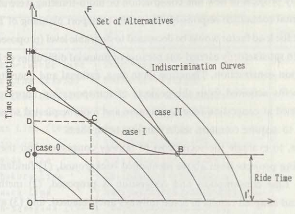

Fig. 3. Preferential Behaviour on Congestion and Time Consumption.

consumption and congestion but also monetary cost or other many service condition into consideration. According to their combination taken, disutility which passenger suffer from transportation alters from high to low. Indiscrimination curves like 1-1' in Fig. 3 indicates group of combinations of time consumption and congestion level that offer same disutility level to passenger. These indiscrimination curves are determined by disutility function which show the level of disutility to every combination of time consumption and congestion level.

Let the ride time from one station to another as 00′. When transport demand is in quite low level (case 0), the set of passenger's alternatives, that is the gathering of feasible combination of congestion level and time consumption, is consisted of only one point 0′. because he has no necessity to consume his time *in vain* and "congestion" is in the best condition. In proportion to increase of transport demand, congestion grows of course, but the set of alternatives also enlarged like the curve AB (case I) in some cases. You can easily comprehend these alternatives, when you image passenger's preferential behaviour of his ride train from a rapid but crowded train or a slow but not so crowded train, or from a train with less waiting time and much crowded or a train with more waiting time but less crowded, or of his boading position from a long (comparing to total time consumption) train. (Condition of congestion and convenience on time consumption in each car varies in relation to the position of entrances and exits in every station.)

Then, travelers are supposed to choose the optimum point C from the curve AB, where they can minimize their transport disutility. Therefore in this case one can observe some kind of modified preferential behaviour with more time consumption (OD) and with less crowd (OE) than point B. Resulted disutility level converted to equivalent time consumption is OG, and congestion cost equivalent to time consumption deducted the common disutility on the case 0 is expressed as O′G.

But in most cases curves which indicate the set of alternatives rises up like curve FB (case II), where it usually needs so much sacrifice of additional time consumption for each passengers to ease congestion, for example in a case on some intermediate station where arrive already much crowded trains. Then the result of their choice reaches a trivial solution, that is, point B. And in this case one can only see the ordinary behaviour with the same time consumption as the case 0 without any special behaviour to ease congestion. Although even in this case, congestion cost should be regarded as O′H irrespective of their real time consumption.

Observations of passenger's choice behaviour in the former case I enable us to estimate the characteristics of user's disutility function concerning time consumption and congestion level.

3. Estimation of Disutility Function of Congestion

In this study, passenger's behaviour in three different circumstances were observed and disutility functions were estimated independently for each case with three different type of model.

3.1 *Microscopic approach to boading position choice*

Passengers always choose their boading position from many cars in a train considering the position of exit of their alighting station and the condition of congestion in every car.[3)] This phenomena can be typically and easily seen when exits of major stations are maldistributed in a train length from some reason. It can be considered that passengers choose their boading position where they can minimize their transport disutility as far as walking time in the boading station from the entrance to platform to the entrance of car does not exceed their time limit decided by their arrival to the entrance of station and the arrival of train. The mathematical model was built to explain such a behaviour on the assumption that disutility caused by congestion was proportion to ride time on train and that total disutility could be calculated from this item added by the total time between their arrival to the entrance of their boading station and the arrival to the exit of alighting station. Then the propabilities of every position selected are described with use of logit model that was adopted considering the distributions of characteristics of passenger's preference to congestion.[4)]

Three railway stations in Keio-Inokasira line in central Tokyo were selected for observation so that the situations were conformable to several theoretical assumptions, and the time series of passenger's arrival to the station, the distribution of their walking speed, the distribution of boading position for every entrance of trains and congestion level of each car were measured in several days in 1986. Then the disutility function of congestion was estimated as follows so that the calculated distribution would fit best to the observed distribution.

Conformity of this function is satisfactory as shown partly in Fig. 4.

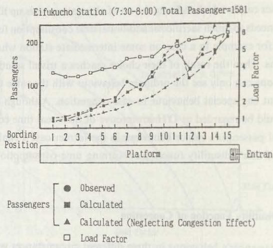

Fig. 4. Observed and Calculated Distribution of Passengers on Platform.

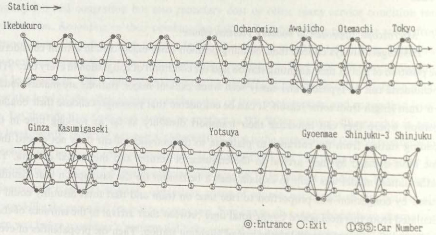

Fig. 5. Marunouchi Line's Network Pattern.

3.2 Macroscopic approach to boading position choice

Above mentioned microscopic approach is precise, but much amount of efforts for observations are required for every station. To avoid this disadvantage the user equilibrium network model was adopted. In this approach the problem of passenger's bahaviour of the choice of boading position is converted as the problem of route choice on some network like shown in Fig. 5. Links on the network are consisted of access links (from every entrance in every station to every position in train), ride links (between every neighbouring station) and egress links (from every position in train to every exit). Link cost function of access and egress links correspond to average walking time for each link. That of ride links are disutility function dependent to link flow including time consumption and congestion. Equilibrium flows in every link can be calculated by the method of Frank and Wolfe if link cost function and traffic volumes between every feasible OD pairs are given. On the contrary link cost function, that is, disutility function, is able to be estimated when link flows and OD pair traffic volumes are observed. This approach is also attractive because of the efficiency that phenomena in many stations are treated simultaneously and connectedly in the model, in spite of the fact that characteristics of passenger's arrival to stations or their variation of walking speed and preference are daringly neglected. The number of boading and alighting passengers from and to 13 stations in Marunouchi line of Tokyo subway network in each train of peak hour about three car positions were measured in 1985, and OD pair volume were calculated and tuned from the result of the Transport Census of Tokyo. Following is the estimated result of disutility function of congestion that maximize the coincidence of calculated and observed link flow.

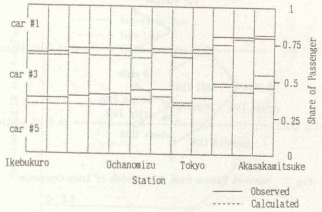

Fig. 6. Results of Observed and Calculated Share of Passenger for Each Car Position.

Fig. 6 shows their agreeable coincidence.

3.3 Train choice approach

Most part of commuters in Tokyo are transported by trains that are well operated with high frequency and with several type of service according to the pattern of stations where trains make stops. It is usual that trains are consisted of at least two kinds, express and normal, with about several minutes of train interval in railways which connect suburban region and central Tokyo. Every commuter is supposed to decide his ride pattern on a given schedule of train operation, considering their transport disutility of ride time, wait time, congestion, transfer and so on.5) The problem to predict transport demand for every train can be also translated into the ploblem to solve user equilibrium flows once when the schedule of train operation is converted into some network pattern like shown in Fig. 7. Each link in the network correspond to its link cost function and the problem can be treated as same as the macroscopic approach to boading position choice.6)

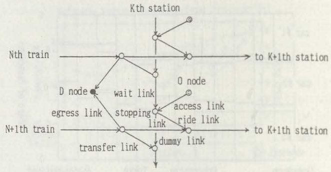

Fig. 7. Network Pattern from the Schedule of Train Operation.

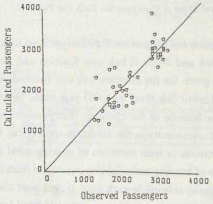

Fig. 8. Observed and Calculated Link Flow.

For the adaptation of this model, Tobu-Tojo line that runs in the north–west suburban region of Tokyo was chosen and link flows, that is, number of passengers on each train between every neighbouring stations were measured on peak time in 1987. The link cost function that was assumed to be linear summation of the items of ride time including congestion, wait time and transfer was estimated, taking together with the data of OD traffics between stations. The following is the part of resulted link cost function that expresses disutility of congestion. Fig. 8 shows suitably fitted relation between calculated flows and observed flows.

Fig. 9 shows the feature of these estimated disutility functions of congestion for unit ride time. The resemblance of these three functions which were estimated independently by rather different model on different condition suggests their validity and transferability. We can see congestion cost for unit ride time is proportional to load factor with exponent about 4, for example, congestion cost for 10 minute ride on a train with the load factor of 200% is equivalent to additional 3 minute time consumption.

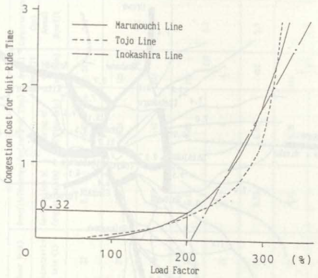

Fig. 9. Estimated Disutility Functions of Congestion (for Unit Ride Time).

4. Application to Evaluation of Economic Loss of Congestion

Economic loss caused by congestion which passengers suffer in commuter railways is able to be evaluated in terms of time by adapting these disutility function of congestion cost, and further more it is also possible to calculate them in monetary dimension by use of so-called time value parameter. In this section there will be shown several results on these loss calculated by adopting the function of Marunouchi line which is the most moderate in three functions acquired and with the use of the recent time value of ¥2,000 for one hour saving (or loss) which was estimated in our modal choice analysis on long distance passenger transport in Japan.[7]

4.1 Congestion loss on railway network in Tokyo

Fig. 10 shows the distribution of annual loss of congestion for 1 km of every railway line in Tokyo metopolitan region in terms of ¥100 million, calculated by the data about the number of passengers, capacity, rate of concentration and cruising speed of trains acquired from the annual statistics on urban transportation in 1985. Total amount of annual loss of congestion in all over the region reaches about ¥60 milliard. Especially in several lines like in the north–east direction, that amounts really over ¥900 million per 1 km line annually, which is equivalent to over ¥13 milliard per 1 km by cumulative present value of 30 years with the discount rate of 7%, and is in easy compensation for multi-tracking construction cost from at least economic standpoint. Precisely speaking, the grasped condition of congestion from these statistics is a mixture of case I and case II already shown in Fig. 3. According to the former case, additional time consumption paid by passengers to avoid congestion should

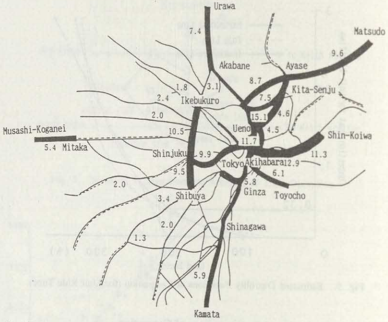

Fig. 10. Evaluated Annual Economic Loss by Railway Congestion for 1 km Line (¥100 million/km).

be considered in calculation. But actually every situation is regarded as on the case II neglecting these effects because of the limitation of such macroscopic statistics. Of course these errors are modified by the fact that the type of case I is rather not predominant case, and that in the case of train choice these effects are involved in the data through average speed of trains. Consequently, as the calculation may be regarded as somewhat underestimation of the influence of congestion taking such cases into account, the results must be more emphasized.

(2) Effectiveness of projects of improvement

Now that the plan of multi-tracking and elongation of train length in five railways in Tokyo were just proposed in 1988, the social benefit acquired from these projects were evaluated from the figures presented by those railway companies. Table 2 shows the result of that. It has become clear that these projects are sufficiently or almost effective compared to their construction cost, and that increase of train speed contributes to the reduction of congestion loss as well as the effect of the amelioration of load factor does.

5. Conclusions

(1) The fundamental theory which explains passenger's preferential behabiour concerning time consumption and congestion was proposed for the condition of commuter

Table 2. Evaluation of Effectiveness of Multi-Tracking Projects in Tokyo.

Line and Section	Construction Cost (¥100 million)	Load Factor (%)		Ride Time/km (min)		Passengers (1 hour Peak)		Benefit/Passenger/km (for Peak Time)		Annual Benefit (¥100 million)	Construction Cost / Annual Benefit
		Present	After Improvement	Present	After Improvement	Number	Concentration Rate (%)	Amelioration of Congestion (min)	Saving of Ride Time (min)		
Tobu Isezaki Line (Kitasenju~Kitakoshigaya)	840	184	161	1.6	1.3	75,000	33	0.20	0.29	261	3.2
Seibu Ikebukuro Line (Ikebukuro~Shakujiikoen)	2538	208	151	1.8	1.4	73,000	27	0.45	0.16	120 } 351	7.2
Seibu Shinjuku Line (Seibu-Shinjuku~Kamishakujii)		191	152	1.9	1.5	60,000	28	0.35	0.40	231	
Keio-Teito Keio Line (The whole line)	632	189	170	1.8	1.7	81,000	25	0.13	0.08	166 } 170	3.7
Keio-Teito Inokashira Line (The whole line)		181	168	1.9	1.9	31,000	22	0.12	0	4	
Odakyu Odawara Line (Shinjuku~Izumitamagawa)	2563	208	166	2.3	1.8	74,000	28	0.51	0.51	452	5.7
Tokyu Toyoko Line (Shibuya~Hiyoshi)	2108	195	162	1.9	1.8	56,000	24	0.30	0.15	144 } 257	8.2
Tokyu Mekama Line (Meguro~Tamagawaen)		171	161	1.9	1.3	51,000	39	0.15	0.58	113	

railways where congestion is not directly converged to loss of time unlike road traffic congestion. Also the concept of congestion cost on these cases was made clear.

(2) To estimate the disutility function of congestion, three types of model and passenger's behaviour were proposed. After the measurement and adaptation of models on several railways in Tokyo, it has clarified that these methods are applicable to actual behaviour of passengers with reasonable validity.

(3) The disutility functions of congestion estimated by the models mostly resemble each other. Roughly speaking, congestion cost for unit ride time is proportional to load factor with exponent about 4. For example congestion cost on 200% load factor reaches about 30% of ride time.

(4) The whole economic loss of railway congestion in Tokyo was evaluated about ¥60 milliard annually by applying the estimated function. The value in some serious lines easily exceed the construction cost of multi-tracking.

(5) The effectiveness of the projects of multi-tracking in some railway lines were also evaluated from the stand point of economic benefit acquired from improvement of congestion, and their validity was proved.

References

1) Ministry of Transport (Japan): Annual Report of Urban Transport (1988).
2) For example: PAPON, F.: Tarification de la congestion et effects redistributifs, TRANSPORT, No. 330 (1988).
3) SZPLETT, D. and S. C. WIRASINGHE: An Investigation of Passenger Interchange and Train Standing Time at LRT Stations i) Alighting, Boading and Platform Distribution of Passengers ii) Estimation of Standing Time, Journal of Advanced Transportation, No. 18–1, pp. 1–24 (1984).
4) MITANI, K., H. IEDA and H. HATAKENAKA: Evaluating Method of Congestion Cost by the Model of Passenger's Boading Behaviour, Infrastructure Planning Review, No. 5, pp. 139–146 (1987).
5) IEDA, H. and Y. MATSUMOTO: Quantitative Evaluation of Seating-Utility in Commuter's Train Choice Behaviour, Proccedings of Japan Society of Civil Engineers, No. 365, pp. 69–78 (1986).
6) IEDA, H., T. AKAMATSU, J. TAKAGI and H. HATAKENAKA: Commuter's Benefit Evaluation of Train Scheduling by Network User Equilibrium Model, Infrastructure Planning Review, No. 6, pp. 177–184 (1988).
7) SHIMOISHI, J. M., H. IEDA and S. TAMAISHI: Stochastic Estimation of the Value of Time on Inter-regional Transportation, Proceedings of Infrastructure Planning, No. 11, pp. 71–77 (1988).

Appendix

Load factor and the density of standing passengers in commuter railway:

Fundamentally speaking, level of crowd on trains congestion should be better expressed by the density of passengers who stand on the floor. However, the value of load factor (volume capacity ratio) was taken in place of that in this paper according to Japanese practical habits.

Fig. A explains the relationship between the density and load factor.

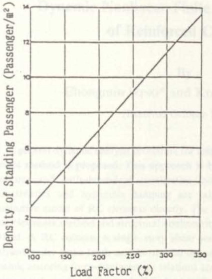

Fig. A. Lord Factor and Density.