ANALYZING THE EFFECTS OF THE ROLLING BLACKOUTS ON RAILWAY SERVICE IN THE TOKYO METROPOLITAN AREA AFTER THE 2011 GREAT EAST JAPAN EARTHQUAKE

Daisuke FUKUDA¹, Ryosuke FUJITA² and Hideki YAGINUMA³

¹Member of JSCE, Associate Professor, Department of Civil Engineering, Tokyo Institute of Technology (Ookayama 2-12-1-M1-11, Meguro-ku, 152-8552 Tokyo, Japan) E-mail: fukuda@plan.cv.titech.ac.jp
²Student Member of JSCE, Department of Civil Engineering, Tokyo Institute of Technology (Ookayama 2-12-1-M1-11, Meguro-ku, 152-8552 Tokyo, Japan) E-mail: r.fujita@plan.cv.titech.ac.jp
³Member of JSCE, Assistant Professor, Department of Civil Engineering, The University of Tokyo (Hongo 7-3-1, Bunkyo-ku, 113-8656 Tokyo, Japan) E-mail: yaginuma@civil.t.u-tokyo.ac.jp

The effects of the rolling blackouts conducted after the 2011 Great East Japan Earthquake, on railway service in the Tokyo Metropolitan Area (TMA) were analyzed in terms of passengers’ generalized traveling costs. We employed the hyperpath-based route assignment model proposed by Spiess and Florian (1989) to compute the costs. Applications to the TMA’s rail network indicated that the effects of the rolling blackouts varied across the areas and days. In particular, passengers from inland areas would have had larger disadvantages while passengers from seaside areas would have received less impact.

Key Words: the 2011 Great East Japan Earthquake, rolling blackouts, railway passenger, travel behavior analysis, route choice behavior, hyperpath

1. INTRODUCTION

The 2011 Great East Japan Earthquake (henceforth “2011GEJQ”) that occurred on March 11 of 2011 damaged the Tohoku Region, which was directly hit by the strong ground motion and the big tsunami and also affected other regions in Japan, which had not been directly damaged. One of the most serious side effects in these regions was the shortage of electric power supply due to the termination of operations of nuclear power plants in the whole Japan. In particular, the Tokyo Metropolitan Area (TMA) was significantly affected by this energy crisis for months just after the earthquake because the terminated nuclear power plants in the east part of Japan Main Island had mainly provided the electric power to the TMA.

Since the TMA is an extensively urbanized and dense area and has more than 30 million population and industrial agglomeration in an approximate span of 70 kilometers, the central government was deeply concerned about the possibility of unexpected electric power outages. At last, the prime minister at that time declared on March 14, 2011 that the “rolling blackouts” would be started and would continue in the area where electric power was supplied by TEPCO (Tokyo Electric Power Co., Inc.). This area included the TMA and rolling blackouts continued for some time to prevent unexpected blackouts. A rolling blackout, which is also referred to as load shedding, is an intentionally engineered electrical power shutdown where electricity delivery is stopped for non-overlapping periods of time over different parts of the region²). This is regarded as a last-resort measure adopted by an electric utility company to avoid a total and unintentional blackout of the power system, which might lead to more severe social and economic loss. In the TMA, the rolling blackouts continued for about three weeks since March 14, 2011 as illustrated in Fig. 1.

Regarding transportation systems in the TMA, urban railway service was mostly affected by the rolling blackouts because most railway business operators in the TMA did not have their own private electric generators and have relied on the electricity provided by electric power providers such as TEPCO. Responding to the possibility of rolling blackouts, railway business operators were obliged to degrade
the level-of-service (LOS) for their train operations and relevant rail facilities in order to save on their consumption of electric power\textsuperscript{1}. The degradation of the LOS was mainly carried out by conducting the following three measures: (1) reduction of the service frequency of train operations; (2) suspension of mutual direct-through operation; and (3) suspension of express/rapid trains. For example, Toyoko Line, which is one of the primary lines in Tokyo Cooperation, had reduced its service frequency to 70–80\% of the normal operations and had only operated local train service during the rolling blackouts\textsuperscript{4}). Since the transport capacity was significantly reduced compared with that during normal conditions, many passengers in the TMA might have suffered from these degradations of the rail services and some of them might have changed their travel decisions such as rail route choice, departure time choice, mode choice and trip cancellation decisions. It would be important to understand and quantify the disutility for passengers caused by these rolling blackouts because we believe that the findings would be useful when considering appropriate urban railway planning or train operations under the possibility of energy crisis, which might happen in the future for some reasons.

With the above-mentioned research motivations, the main purpose of this study is to analyze the effects of the rolling blackouts on railway service in the TMA after the 2011GEJQ from the viewpoints of railway passengers. First, from the perspective of rail business suppliers, we investigate the reduction of railway passengers. First, from the perspective of rail business suppliers, we investigate the reduction of railway passengers. Therefore, the main contribution of this particular study would not be the development of new modeling methodologies but the application of the existing transit assignment method by Spiess and Florian\textsuperscript{1}) for evaluating the rail network degradation in the TMA caused by the 2011GEJQ.

2. DECREASE IN TRAIN SERVICE FREQUENCY DUE TO THE ROLLING BLACKOUTS

In this section, we reveal how the whole urban rail operation in the TMA was affected by the introduction of the rolling blackouts. Since March 14, 2011, each railway business operator had released the latest information about its train operations (e.g., the reduction of service frequency, the suspension of express trains, and the termination of mutual direct-through operations) every day. Because there were no formal database for train operations for the whole TMA rail network, our study team collected the information from the website of railway operators by themselves. This data collection continued until the middle of April 2011 when the rolling blackout was officially stopped. Then we visualized all information about train operation under GIS environment.

Fig. 2 illustrates the outputs of our work on this information collection. In this figure, the degree of service frequency reduction in train operations is categorically visualized with seven different colors for each link of the whole TMA railway network. The situations during morning peak-period in the four typical days are shown: (2a) the start day of the consecutive rolling blackouts; (2b) the day when the government announced the possibility of unintentional blackouts due to the cold weather and recommended it to save energy; (2c) the next day after that cold day and (2d) the typical day after the train operations in

\textsuperscript{1} Actually TEPCO continued to provide electric power to each train operator in TMA even during the period of rolling blackouts, with the strong request from the central government\textsuperscript{3}). Nevertheless, most train operators reduced their LOS fearing that energy shortage might happen.
the TMA after the pattern of the rolling blackouts became almost steady (unchanged) day by day.

We see in Fig. 2a that the service in most rail lines were stopped on March 14, probably because railway operators had not yet fully adopted themselves to the rolling blackouts and had behaved quite “risk-averse” by stopping almost train operations anyway. This was distinct in the surrounding suburbs of the downtown because a lot of red-colored links can be seen there. The number of links where train operations were completely terminated (colored by red lines) was significantly reduced on March 17 (Fig. 2b) but we still see yellow-colored links mainly in the suburbs, which means that the LOS there was almost half of the normal conditions and was not still fully recovered. Just after the central government had warned of the possibility of unintentional blackouts due to energy shortage, the LOS of the whole rail network again became worse on March (Fig. 2c) because each train operator further reduced train service frequencies from that in the previous day. We guess that the actions taken by railway operators became stable since around March 24 because the pattern of the reduction of the LOS in the network had not been changed so much since then. In Fig. 2d, however, the blue-colored links (i.e., normal train operation) mainly belong to the lines operated by East Japan Railway Company, which has its own electric power plants, whereas other private rail operators without power plants had to continue to reduce their service.

Fig. 2 Reduction rate of the service frequency of train operations due to the rolling blackouts for the four typical days (morning peak-period).
3. COMPUTING COST INCREASE FOR RAILWAY PASSENGERS DUE TO THE ROLLING BLACKOUTS

The comprehensive visualization of train operations in the TMA shown in the previous section might be useful for understanding the overall picture of train operation affected by the rolling blackouts. However, it is still unclear how each train passenger incurred costs caused by the reduction of the LOS. In Sections 3 and 4 we analyze and quantify changes in passengers’ traveling costs by employing a modeling methodology of passengers’ route choice behavior.

(1) Hyperpath-based route choice modeling

This study employs a hyperpath-based route choice modeling (henceforth “HBRCM”) initially proposed by Spiess and Florian\(^1\) to evaluate the impact of the rolling blackouts on rail passengers. The generalized traveling cost has been widely used in evaluation of transport project. Among others discrete choice models have been widely applied for modeling travelers’ route choice decisions and for computing the generalized traveling cost\(^6\). Unlike in the case of discrete choice modeling for rail users’ route choice behavior (e.g., Yai et al.\(^7\) for application to the TMA rail passengers), the HBRCM approach allows assigning passenger demand on networks to compute the generalized traveling cost, without explicitly constructing the route choice sets in advance. This would be nice when choice sets may have to be changed due to the change in network performances after the rolling blackouts.

According to the HBRCM, it is possible to simultaneously compute generalized costs and the set of links in the passengers’ optimal strategy (i.e., routes to which the demands are assigned) for any of Origin-Destination pairs in networks. In this study, we quantified and evaluated the disutility caused to travelers by the rolling blackouts with the relative increase (say 150%) in their generalized costs. An illustrative example of quantifying the cost increase with the concept of hyperpath is shown in Fig. 3. There are seven links connecting an origin \(r\) and a destination \(s\) and some of them (i.e., links 1, 2, 3 and 4) are actually utilized for passengers’ traveling in normal situation (a) in Fig. 3. Now we assume that only these four links comprise the possible routes for travelers with the minimum expected cost. This set of links is called “optimal strategy\(^1\)” or “hyperpath\(^8\).” As explained in the preceding subsections, the link usage probabilities (assuming 40% for link 1, 10% for link2, 30% for link 3 and 60% for link 4) and the corresponding generalized cost (assumed to be 300JPY) are simultaneously computed by employing the Spiess and Florian\(^1\) algorithm.

Now let us consider the situation where the train service frequency at link 3 has been reduced due to the rolling blackouts. Then, the hyperpath with the minimum expected cost may be changed. The example (b) shown in Fig. 3 represents the illustrative example in which link 3 is excluded and links 5 and 6 are newly introduced in the hyperpath. Links 5 and 6 are not used in normal situation (a) in Fig. 3 but may be used during the reduction of LOS due to the rolling blackouts because some passengers would have to take long ways around. With these changes in the elements of the hyperpath, let us assume now that the expected cost has also been changed to the new one (assumed to be 450JPY), implying that for this particular example, the relative cost change for this traveler is calculated as 150%.

If we apply discrete choice models (e.g., multinomial logit model or probit model) for modeling route

![Fig.3 An illustrative example to explain how to compute costs caused by the rolling blackouts.](image-url)
choice behavior and compute the minimum expected cost, for example, with the log-sum formula\(^{(9)}\), the pre-definition of the route choice sets of each passenger is necessary. However, it would be difficult to set up appropriate choice sets during the period of the rolling blackouts. The HBRCM, on the contrary, allows the construction of the set of attractive links (i.e., hyperpaths) according to the LOS of the network. This is why we adopted the HBRCM to quantify and evaluate the passenger cost increase caused by the rolling blackouts.

(2) Model formulation

a) Formulation of generalized cost function

The hyperpath with the minimum expected cost is defined as a set of potentially optimal paths from one origin to one destination\(^{(10),(11)}\). The underlying assumptions about passengers’ route choice behavior under the HBRCM are summarized as follows:

(a) passengers have no explicit knowledge about arrival times of each train at each station;
(b) train arrival follows a Poisson distribution (i.e., the corresponding waiting time follows an exponential distribution) and vehicle arrivals across different lines at the same stations or platforms are not synchronized;
(c) passengers randomly arrive at their departing station and always take the first available train; and
(d) passengers look for the set of routes that minimize their total expected travel cost to the destination by repeating en-route switching of links they traverse if necessary.

This study assumes that the information on train operation that is available for passenger is only about the next incoming train when waiting for trains at a certain node. In other words, passengers cannot get information about other lines by using any information resource. This would be an acceptable assumption during the period of the rolling blackouts.

We followed the standard model proposed by Spiess and Florian\(^{(1)}\), which assume fixed demand between any of the origin-destination pairs, no in-vehicle congestion costs, and fixed in-vehicle travel times. A railway network is represented by \( G = (A, I) \) where \( A \) is a set of all links and \( I \) is a set of nodes (stations). The expected generalized cost of hyperpath \( p \), which is expressed as \( g_p \), can be represented as follows:

\[
g_p = \phi \sum_{a \in A_p} \alpha_a t_a + \psi \sum_{i \in I_p} \frac{\beta_i}{F_{ip}}
\]

where

\( I_p \subseteq I \): a set of nodes in hyperpath \( p \),
\( A_p \subseteq A \): a set of attractive links in hyperpath \( p \),
\( t_a \): travel time for link \( a \),
\( F_{ip}(= \sum_{a \in A^+_p} \phi(a)) \): called “combined frequency\(^{(1)}\)” and its inverse is equivalent to an expected waiting time at node \( i \) in hyperpath \( p \),
\( \phi(a) \): service frequency of link \( a \) comprising transit line \( l \),
\( A^+_p \): a set of outgoing links at node \( i \) in hyperpath \( p \),
\( \alpha_a \): a probability of including link \( a \) in hyperpath \( p \),
\( \beta_i \): a probability of including node \( i \) in hyperpath \( p \),
\( \phi \): a marginal value of travel time, and
\( \psi \): a marginal value of waiting time.

The first term of Eq. (1) represents the cost of invehicle time and the second term corresponds to the cost of waiting time at stations. By constructing the set of \( \alpha_a s \) and \( \beta_i s \), a hyperpath \( p \) can be specified.

b) Mathematical optimization problem

Following Bell\(^{(12)}\), the route choice behavior of passengers who seek the hyperpath with the minimum expected generalized cost is modeled as the following constrained optimization problem (the suffix denoting hyperpath \( p \) is omitted for simplification):

\[
\min_{\alpha, \beta} \phi \sum_{a \in A} \alpha_a t_a + \psi \sum_{i \in I} \frac{\beta_i}{F_i}
\]

subject to

\[
\begin{align*}
\sum_{a \in A^+_i} \alpha_a - \sum_{a \in A^-_i} \alpha_a &= g_i \quad i \in I \\
\alpha_a &\leq \phi(a) \times \frac{\beta_i}{F_i} \quad a \in A^+_i, i \in I \\
\alpha_a &\geq 0 \quad a \in A
\end{align*}
\]

The first constraint in (3) represents the flow conservation law for any of origin node \( i \) and for singular cases we set \( g_i = 1 \) if \( i = s \), \( g_i = -1 \) if \( i = r \), and \( g_i = 0 \) otherwise. The second constraint ensures that the usage probability of link \( a \) is proportional to its expected waiting time. The third one represents the non-negativity of probabilities.

Finally, it should be noted that fares are not incorporated into Eq. (1) because the option of including the fare amount directly into the cost function has not yet been explored. Henceforth, we have excluded (complicated) fare principles in the TMA rail network in the modeling framework. Our analysis is constrained by this limitation.

(3) Algorithm for finding the minimum cost hyperpath

For a given pair of origin \( r \) and destination \( s \), an algorithm similar to Dijkstra’s shortest path finding was also proposed by Spiess and Florian\(^{(1)}\). The time complexity of the algorithm is \( O(m^2) \) for each OD pair where \( m \) is the number of nodes. The algorithm is composed of the four main parts. In the procedure, from a destination node \( s \) to all other origins, the minimum cost hyperpath \( \hat{A}^* \) (the solution of the optimization problem (2)) and the expected total generalized cost \( u_i^* \) from each node \( i \in I \) to the destination node \( r \) are computed.

The algorithm is outlined as follows:
[Algorithm of searching hyperpath]
1. (Initialization)
   \[ u_i := \infty, i \in I - \{s\}; \quad u_s := 0; \]
   \[ f_i := 0, i \in I; \]
   \[ V_i := 0, i \in I - \{r\}; \quad V_r = 1; \]
   \[ S := A; \quad A^* := \emptyset; \]

2. (Select the next link)
   If \( S = \emptyset \) then STOP
   otherwise find \( a = (i, j) \in S \), which satisfies
   \[ u_j + t_a \leq u_j + t_{a'}, a' = (i', j') \in S; \]
   \[ S := S - \{a\}; \]

3. (Update the node)
   If \( u_i \geq u_j + t_a \), then
   \[ f_i := f_i + f_{(a)}; \]
   \[ u_i := \sum_{f_{(a)}, f_i} \frac{f_{(a)}}{f_i} (u_j + \phi_{t_a}) + \psi \frac{1}{f_i}; \]
   \[ A^* := A^* + |a|; \]
   go to step 2.

4. (Loading)
   If \( a \in A^* \), then \( V_i := V_i \times \frac{f_{(a)}}{f_r} \) and
   \[ V_j := V_j + \frac{f_{(a)}}{f_i}, \quad \text{otherwise} \]
   \[ f_{(a)} := 0; \]
where \( u_i \) is the expected generalized cost from node \( i \) to the destination and \( f_i \) is combined frequency of all available links at node \( i \).

In step 1 of the algorithm, the node label \( u_i \), that is, the expected generalized cost to reach the destination is set to infinity for all nodes except the destination node for which \( u_i \) is initialized to zero. The auxiliary variable \( f_i \), \( i \in I \) that represents the combined frequencies of all selected links at node \( i \) are initialized to zero. Then, set \( S \) is used to identify the links that have not yet been examined, and set \( A^* \) is used to identify the minimum cost hyperpath. In step 2, the nearest link to the destination is selected among the links that are not yet examined. The cost considered is \( u_j + \phi_{t_a} \), that is, the time from node \( i \) to the destination, not including the waiting time at node \( i \). If this is smaller than the current cost \( u_i \) associated with node \( i \), link \( a \) is added to the minimum cost hyperpath and \( u_i \) and \( f_i \) are updated according to the formulas given in step 3. It is important to note that when \( u_i \) is improved for the first time, we have \( f_i u_i = 0 \times \infty \). To keep the algorithm as compact as possible, we adopt the convention \( 0 \times \infty = 1 \) whenever this case occurs. The repetition between steps 2 and 3 terminates when all links have been checked. In step 4 the link split probabilities are assigned to the network according to the minimum cost hyperpath \( A^* \). This is carried out by assigning to each link \( a \in A^* \) with the proportion to \( f_i \), which means that rail passenger demand incoming into a node is assigned to each outgoing link in proportion to train service frequencies. Please note that all links are processed in reverse topological order.

(4) Procedure for computing relative cost increase due to the rolling blackouts
The procedure for computing relative cost increase due to the rolling blackout is outlined in Fig. 4. For a given pair of origin node station and destination node station, the algorithm to find the minimum cost hyperpath is adopted under both normal situation (i.e., usual train operations) and unusual situation (i.e., operations during the rolling blackouts). Since the absolute value of computed expected generalized costs for OD pairs are fully dependent on their travel distances, we employ the relative change to evaluate the impact of the rolling blackouts.

4. APPLICATIONS AND DISCUSSIONS
This section applies the HBRCM to compute increase in rail passengers’ traveling costs due to the LOS decrease after the rolling blackouts.

(1) Setup of the network and the relevant parameters
The status of the railway transport network during the period of the rolling blackouts is constructed based on a base network previously developed in 2005 by Yaginuma et al.\textsuperscript{13}. The base components of the network (links and nodes) in Yaginuma et al. is the one in 2005 thus we revised the network a little in order to reproduce the actual situation in March 2011. The newly added stations and rail lines are listed in Table 1 (a) and (b).

As for the train service frequencies, we again employed the same database used in Section 2. Consequently, we have the specification of the railway network used in this study as shown in Table 1 (c). However, there are some links with no information about their service frequencies during the rolling blackouts as illustrated in Fig. 2 with the gray-colored legend. Hence we have imputed these missing values of frequencies by applying the reduction rate from normal operation in Table 2. The approximate average numbers of the reduction rate for each date are imputed.

Regarding the value of travel time and the value of waiting time in Eq. (1), we employed the numbers used in Kato et al.\textsuperscript{14} (\( \phi = 35.9 \) JPY/min and \( \psi = 44.6 \) JPY/min).

(2) Computation results of the relative cost increase
We evaluated the increase in passengers’ traveling costs for a given pair of a departing station as an origin node and an alighting station as a destination node. This study particularly focused on several large terminal stations as destinations because it would be more meaningful to evaluate the impact of the rolling
Computing the minimum expected generalized cost:

\[
g_{p,r}^b\]

Compute the relative cost increase:

\[
\text{ratio}_{p,r} = \frac{g_{p,r}^b}{g_{p,r}^a} \times 100(\%)
\]

Visualize the relative cost increase with GIS

Change an origin station node \(r\) and repeat the procedure

Fig. 4 Procedure for computing relative cost increase for a given departing station.

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**Table 1** Settings of railway network.

<table>
<thead>
<tr>
<th>(a) Newly added stations:</th>
<th>Musashikosugi, Nishiomiya, Koshigaya Laketown, Nishifu, Haneda Airport International Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b) Newly added rail lines:</td>
<td><img src="image" alt="Green line of Yokohama City Metro (Nakayama–Hiyoshi)" /> &lt;br&gt; <img src="image" alt="Fukutoshin line of Tokyo Metro (Wakoshi–Shibuya)" /></td>
</tr>
<tr>
<td>(c) Specification of the network:</td>
<td><img src="image" alt="Number of stations (nodes): 1428" /> &lt;br&gt; <img src="image" alt="Number of links: 14607" /> &lt;br&gt; <img src="image" alt="Number of rail lines: 116" /></td>
</tr>
</tbody>
</table>

**Table 2** Criteria for interpolating missing values of train service frequencies.

<table>
<thead>
<tr>
<th>Date (March 2011)</th>
<th>14th</th>
<th>17th</th>
<th>18th</th>
<th>24th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction rate (%)</td>
<td>50</td>
<td>60</td>
<td>65</td>
<td>75</td>
</tr>
</tbody>
</table>

blackouts on larger amount of rail passengers. Hence, Tokyo Central (Tokyo C.), Yokohama and Omiya stations were selected as destinations for this case study. After selecting one of these stations as a destination node, the minimum expected generalized costs were computed for all other stations as origins based on the procedure explained in Section 3. The computation results are summarized in Table 3 and Figs. 5, 6, 7 and 8.

Table 3 presents the frequency distributions of \(\text{ratio}_{p,r}\) (relative cost change as defined in Fig. 4) for each destination station on particular dates. Since there were no observed travel records between some departing stations and each destination station in the Urban Rail Census 2005 in the TMA, the numbers of origin stations considered for each case study had been reduced to the ones shown in the bottom line of Table 3.

Figs. 5, 6, 7 and 8 show the visualization results of the relative cost increases for particular destinations and for particular dates. In these figures, circles are plotted at the location of stations and the destination station is represented by the green circle. The colors of all other stations as origins are determined based on the computation results of the \(\text{ratio}_{p,r}\) with the leg-
end shown in these figures, which correspond to the category already listed in Table 3.

Figs.5 and 6 represent the relative cost increase for the passengers from each station to Tokyo Central for different dates (March 14 and 24). There are many black circles particularly in the surrounding area of the TMA on March 14 (Fig. 5), which means that many train operations were out of service. Though this condition improved on March 24 (Fig. 6), we still see a lot of “red-like” circles implying that the travel cost increased by more than 150% compared with that during normal operations. This would be obvious also from the comparison of the frequency distributions in Table 3. With closer investigations of these figures, we further find the following two typical characteristics: First, the relative costs tend to increase in a concentric fashion from the city center, which means that the further the distance from the center of the TMA (i.e., Tokyo Central Station) is, the larger the relative cost increase is. Second, the relative cost increases at
several stations from where more transfers are needed to arrive at the destination are more distinct than at terminal stations, which might have been caused by the increase in waiting time and which have more serious impact on passengers from farther origins.

We also see from Figs. 7 and 8 and Table 3 that the distribution patterns of relative cost increase when the destination station is changed. Unlike the Tokyo Central Station located in the downtown of the TMA, Yokohama and Omiya Stations are the cores of each subcenter. The origin stations from where more transfers are needed to arrive at Yokohama and Omiya might have been more affected.

(3) Computed hyperpaths

Fig. 9 visualizes the computed hyperpaths from Omiya Station to Yokohama Station for the three particular dates as an example. These results are detailed.
in Tables 4, 5 and 6 with the computed line usage probabilities in the hyperpaths of each date. It would be clear that the hyperpaths for passengers are significantly different across these days because the effects of the rolling blackouts varied day by day.

For example, on March 14 when the impact of the rolling blackout was the most significant, we see that the passengers might have taken the routes such as the Toyoko line of Tokyu Cooperation, which might not be used in normal conditions. This implies that some railway routes included in the optimal strategy under normal conditions might have been removed from the minimum cost hyperpath because of the LOS decrease of the corresponding lines.

5. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This study analyzed the effects of the rolling blackouts, which occurred due to the electric energy crisis that happened after the 2011 Great East Japan Earthquake, on railway transport service in the TMA. In Section 2, we discussed the approaches taken to investigate the actual situation behind the decrease in service levels in the railway network that were mainly caused by the reduction of train service frequencies, suspension of mutual direct-through operations and suspension of express/rapid trains. In Sections 3 and 4, the effects of the LOS decrease from the perspective of passengers' route choice were analyzed in detail by employing the methodology of hyperpath-based route choice modeling. This methodology would be more appropriate than the direct investigation taken in Section 2 because it is possible to directly reflect the changes in the patterns of route choice in the network due to the rolling blackouts. The case studies illustrated in Section 4 revealed that the effects of the rolling blackouts might be var-

![Fig.9](image)

**Fig.9** Computed hyperpaths (Origin: Omiya Station [green], Destination: Yokohama Station [blue]).
ied across the TMA. We found large disparities in the disutility caused by the service degradations: some areas with more alternative rail routes were not so affected but others were disadvantaged more. In particular, it would be seen that passengers from inland areas might have had larger disadvantages, while passengers from seaside areas along Tokyo Bay might have experienced less impact. We believe that the methodologies and the outputs of this study would more or less contribute to future urban railway planning particularly in terms of the robustness of the transportation networks.

More work needs to be done to further enhance methodologies and to make the outputs more persuasive. As for modeling issues, the inclusions of other factors such as in-vehicle congestion, other choice dimensions (trip cancellation, destination choice, mode choice, departure-time choice, and so on) should be incorporated if the actual traffic data during the rolling blackouts are available. The development of the methodology for identifying the critical components of the railway network also would be highly recommended for future research directions.

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REFERENCES


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Table 6 Line usage probabilities in the computed hyperpath (March 24, Omiya–Yokohama).

<table>
<thead>
<tr>
<th>Name of Line</th>
<th>Boarding St.</th>
<th>Alighting St.</th>
<th>Line Usage Prob. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tohoku</td>
<td>Omiya</td>
<td>Ueno</td>
<td>47.1</td>
</tr>
<tr>
<td>Ginza</td>
<td>Ueno</td>
<td>Kanda</td>
<td>22.1</td>
</tr>
<tr>
<td>Keihintohoku</td>
<td>Ueno</td>
<td>Kanda</td>
<td>24.9</td>
</tr>
<tr>
<td>Keihintohoku</td>
<td>Kanda</td>
<td>Tokyo C.</td>
<td>33.7</td>
</tr>
<tr>
<td>Yamanote</td>
<td>Ueno</td>
<td>Kanda</td>
<td>29.8</td>
</tr>
<tr>
<td>Yamanote</td>
<td>Kanda</td>
<td>Tokyo C.</td>
<td>29.8</td>
</tr>
<tr>
<td>Chuo</td>
<td>Kanda</td>
<td>Tokyo C.</td>
<td>7.1</td>
</tr>
<tr>
<td>Saikyo</td>
<td>Omiya</td>
<td>Osaka</td>
<td>29.4</td>
</tr>
<tr>
<td>Yamanote</td>
<td>Osaka</td>
<td>Shinagawa</td>
<td>29.4</td>
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