Direct and indirect effects of new high speed rail service: An empirical analysis using Japanese mobile phone location data

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DIRECT AND INDIRECT EFFECTS OF NEW HIGH SPEED RAIL SERVICE:
AN EMPIRICAL ANALYSIS USING JAPANESE MOBILE PHONE LOCATION DATA

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ABSTRACT

The development of high-speed rail (HSR) is expected to significantly change the long-distance travel structure and transportation patterns. The changes are expected to be not only the increase in the number of tourists who use HSR service (direct effect), but also the change in the regional travel structures by encouraging the growth of several zones as network hubs (indirect effect). In this paper, a methodology to understand the change in the residential - travel destination zone matrix derived from mobile phone location data is proposed. The developed methodology is applied to determine the effect of the Hokuriku HSR on the nationwide long-distance travel patterns. The proposed methodology decomposed the matrix into two meaningful matrices, which can be understood as the direct and indirect effects of HSR. The decomposed results indicate the following three features of the HSR effects: First, the changes before and after the development of the Hokuriku HSR on the residential - travel destination zone matrix are mostly explained by two patterns of change by direct and indirect effect. Second, the direct numerical effects are less significant than the indirect effects. Third, the changes are asymmetric in direction in several zone pairs, because of the indirect effects.

Keywords: High Speed Rail, destination choice, long-distance travel, mobile phone location data
INTRODUCTION

The development of High-Speed Rail (HSR) is expected to significantly change the long-distance travel structure and patterns. For example, the Hokuriku HSR’s Nagano-Kanazawa section (228.4 km, shown as the blue line in Figure 1) has been operating since May 14, 2015. This new HSR service reduced the travel time by railway between Tokyo and Kanazawa from 230 min to 150 min. DBJ (1) reported that because of new HSR service, the cumulative number of overnight travelers to ISK zone, where Kanazawa is located, has increased to 8.2 million per year from 7.7 million.

On the other hand, as the effect of new HSR, we expect not only the increase in the number of tourists to newly connected zones, but also the change in the regional travel structures. For example, Hokuriku HSR is expected to strengthen the “Japan sea side corridor” by encouraging the growth of several base (or hub) cities on the corridor. In order to evaluate this types of effect, it is required to analyze the change of the long-distance travel patterns throughout Japan (the entire origin-destination matrix) and to identify the effect of new HSR on the functions of the cities as network hub. However, the influence of the new HSR on the long-distance travel patterns is still unknown.

Most previous studies to identify the effect of new HSR lines (for example, 2, 3, 4) was not focused on the regional travel structures. They have been limited to the relationships between several zone-pairs or origin zones. Several demand models proposed by Yao and Morikawa (5), Fu et al. (6) and Kato et al. (7) are able to forecast the effect of new HSR on the entire origin-destination matrix. But their forecast results of the long-distance travel patterns depend on the
assumption of the model structure (nest structure or similarity patterns of choicesets). Especially, these models do not incorporate the ‘indirect effects’ on the travel patterns by encouraging the growth of several zones as network hubs.

These limitations of previous study are caused by the difficulty for questionnaire survey to know the exact city-to-city travel pattern of the whole country. On the other hand, mobile phone location data facilitates capturing of volume and time-series changes of nationwide long-distance travel. Mobile phone location data constitutes records of the GPS data or communication data of a mobile networks, for a substantial number of mobile phones at regular time intervals. Thus, it is possible to obtain the population distribution data of a large number of people without being bound by space or time. Therefore, these data are started to applied to capture the spatio-temporal information of long-distance travel (8, 9).

In this paper, a methodology to understand the change in the residential - travel destination zone matrix derived from mobile phone location data is proposed. In addition, the developed methodology is applied to determine the effect of the Hokuriku HSR on the nationwide long-distance travel patterns. The proposed methodology decomposed the matrix into two meaningful matrices, which can be understood as the direct and indirect effects of HSR. The decomposed results indicate the following three features of the HSR effects: First, the changes before and after the development of the Hokuriku HSR on the residential - travel destination zone matrix are mostly explained by two patterns of change by direct and indirect effect. Second, the direct numerical effects are less significant than the indirect effects. Third, the changes are asymmetric in direction in several zone pairs, because of the indirect effects.

The remainder of this paper is organized as follows: First, an explanation of the Japanese mobile phone location data is offered and basic information directly obtained from the data related to Hokuriku HSR is presented. Subsequently, the developed model and decomposition methodology for understanding the change in the residential-travel destination matrix is presented. Based on the decomposed results, the study findings on the effect of the new HSR service is presented.
DATA: “MOBILE SPATIAL STATISTICS”

This section presents the nationwide population distribution data to examine the Hokuriku HSR effects. The data was obtained from the mobile spatial statistics (MSS), which is the aggregated population distribution data estimated by the operations data from the mobile terminal network of NTT DOCOMO. (The detailed estimation methodology is presented in Terada et al. (10)).

This data has three desirable characteristics for viewing HSR effects. First, the very large sample size to estimate the population spatial density (60 million mobile phones served by NTT DOCOMO). This sample size is almost half of the total Japanese population, which means that MSS provides highly accurate population distribution data. The second feature is each contract shows the residential address of the users. This can facilitate estimation of the population of any residential and staying place (travel destination) zone pairs. The third feature is the freedom of temporal information. Each mobile phone communicates with the near base stations at regular intervals (typically: one hour) in order to efficiently connect at any time, and this information is stored for long time. Therefore, the data can be obtained at any time.

In this study, the population in each residential – staying (travel destination) zone pair is analyzed to examine the effect of Hokuriku HSR on the nationwide travel demand. Here, Japan is divided into 50 zones, as shown in Figure 1 (most zones are consistent with prefectures). Consider $Z$ as the all zone set. Hence, the following two matrices ($M_{\text{sc[bef,alt]}}$), obtained from MSS, are compared in this study.

$$M_{\text{bef}} = \frac{\sum_{d=\text{May.1.2014~Feb.28.2015}} Q_{d,t=13:00}}{365},$$

$$M_{\text{aft}} = \frac{\sum_{d=\text{Apr.1.2015~May.31.2015}} Q_{d,t=13:00}}{366},$$

where, $q_{i,j,d,t}$ is the estimated number of people who live in zone $i \in Z$ and stay in zone $j \in Z$ at period $t$ on date $d$. $M_{\text{bef}}$ is the average population density at 13:00 for one year before the beginning of Hokuriku HSR operation, while $M_{\text{aft}}$ is the population density after the beginning of HSR operation. Since 2016 is the leap year, average values are calculated from 366 days, as shown in equation (2). Here, these average values for one year are compared, in order to exclude the influence of seasonal fluctuation and the day of the week.
This section discusses the part of the difference between \( M_{\text{bef.}} \) and \( M_{\text{aft.}} \). Table 1 shows the two features of the travel volume changes in the two major zone pairs. First is the asymmetric change in the TYO – ISK zone pair which is the starting - end zone of the Hokuriku HSR. Although, the number of travelers in both directions (“TYO to ISK” and “ISK to TYO”) increased since the beginning of HSR operation, the increased volume was asymmetric in direction. The number of travelers to ISK from TYO increased by 1,875 (1.6 times), and, the number of traveling to TYO from ISK was increased by only 440 travelers (1.1 times). Second, the number of travelers from OSA to ISK also increased, despite almost no change in the service level in this zone pair. This number increased by 327 travelers (1.1 times), since the beginning of HSR operation, and this increase volume was almost similar to that from ISK to TYO.

**TABLE 1 The Changes in the Average Number of Travelers Before and After the Beginning of HSR Operation**

<table>
<thead>
<tr>
<th>Residential zone</th>
<th>Staying zone at 13:00</th>
<th>( m_{i,j,\text{bef.}} )</th>
<th>( m_{i,j,\text{aft.}} )</th>
<th>( m_{i,j,\text{aft.}} - m_{i,j,\text{bef.}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYO</td>
<td>ISK</td>
<td>3,311</td>
<td>5,186</td>
<td>+1,875</td>
</tr>
<tr>
<td>ISK</td>
<td>TYO</td>
<td>3,452</td>
<td>3,892</td>
<td>+440</td>
</tr>
<tr>
<td>OSA</td>
<td>ISK</td>
<td>3,710</td>
<td>4,037</td>
<td>+327</td>
</tr>
<tr>
<td>ISK</td>
<td>OSA</td>
<td>2,433</td>
<td>2,456</td>
<td>+23</td>
</tr>
</tbody>
</table>
PATTERN DECOMPOSITION OF RESIDENTIAL - STAYING ZONE MATRIX

In this section, the detected differences in travel patterns are analyzed. Accordingly, a methodology to explain the changes in the inter-prefectural distribution matrix, by decomposing the matrix into two types of spatial patterns, referred as “direct effect” and “indirect effect”, is proposed.

Model for Estimating Direct and Indirect Effects

The inter-prefectural distribution matrices $M_{\text{bef},s}$ are analyzed as the result of destination (or staying zone) choice behavior. Assuming the multi-nomial logit model, the probability to stay at zone $j$ in period $s$ for residents of zone $i$ is expressed as follows:

$$p_{i,s}(j) = \frac{\exp(V_{i,j,s})}{\sum_{j \in \mathcal{Z}} \exp(V_{i,j,s})},$$ (4)

where, $V_{i,j,s}$ is the fixed utility at zone $j$ in period $s$ for residents of zone $i$. Then, the difference in fixed utility between zone $j \in \mathcal{Z}$ and residential zone $i$ can be calculated from MSS data $m_{i,j,s}$ by Equation (5):

$$V_{i,j,s} - V_{i,j,s} = \log\left(\frac{p_{i,s}(j)}{p_{i,s}(i)}\right) = \log\left(\frac{m_{i,j,s}}{m_{i,j,s}}\right).$$ (5)

The matrix of fixed utility difference $B_s$ can be denoted as follows.

$$B_s = \begin{pmatrix}
    b_{11,s} & \cdots & b_{1j,s} & \cdots \\
    \vdots & \ddots & \vdots & \ddots \\
    b_{i1,s} & \cdots & b_{ij,s} & \cdots \\
    \vdots & \ddots & \vdots & \ddots 
\end{pmatrix} = \begin{pmatrix}
    0 & \cdots & V_{i,j,s} - V_{i,j,s} & \cdots \\
    \vdots & \ddots & \vdots & \ddots \\
    V_{i,j,s} - V_{i,j,s} & \cdots & 0 & \ddots \\
    \vdots & \ddots & \vdots & \ddots 
\end{pmatrix}.$$ (6)

Figure 2 shows the following two features of the matrix $B_{\text{bef}}$. First, the values close to the diagonal element are large, and the values far from the diagonal element are small. In this figure, spatially close zones are located near to each other. Therefore, this feature means that travelers basically choose near place as the travel destination. Second, the log ratio of travel destination TYO and OSA are exceptionally large for almost all residential zones. Thus, TYO and OSA are exceptionally chosen by high ratio of travelers, regardless of their residential locations.
FIGURE 2 Calculated difference of fixed utilities $B_{bef}$ (period: “Before the beginning of HSR operation”)

In this paper, the change in matrices $B_s$ is decomposed into three simple components:

$$B_{aft} - B_{bef} = D_{diff} + C_{diff} + E_{diff}.$$  (7)

$E_{diff}$ is the residual matrix. $C_{diff}$ is assumed to be the symmetric matrix which satisfies the condition that all-diagonal elements are equal to zero as follows:

$$C_{diff} = \begin{bmatrix} 0 & c_{1,2,diff} & c_{1,3,diff} & \cdots \\ c_{1,2,diff} & 0 & c_{2,3,diff} \\ c_{1,3,diff} & c_{2,3,diff} & 0 \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}.$$  (8)

And $D_{diff}$ is assumed to satisfy the two following conditions: all-diagonal elements are equal to zero, and all off-diagonal elements in the same column are equal. This matrix is written as follows:

$$D_{diff} = \begin{bmatrix} 0 & d_{2,diff} & d_{3,diff} & \cdots \\ d_{1,diff} & 0 & d_{3,diff} \\ d_{1,diff} & d_{2,diff} & 0 \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}.$$  (9)

Here, each of the elements $(c_{i,j,diff}, d_{j,diff})$ in matrix $(C_{diff}, D_{diff})$ refer to the changes of fixed utility in different spatial patterns, as shown in Figure 3. $c_{i,j,diff}$, are defined in each zone pair $(i, j)$ and equal in both directions, as expressed in Equation (8). These patterns are similar to the change in travel service qualities (fare, required time, frequency of operation, etc.) which are “directly” changed.
by the new HSR service. For example, Hokuriku HSR reduced the 80 min travel time between TYO and ISK. This service improvement is beneficial for all travelers between TYO and ISK in both directions as described in Figure 3(a).

\[ d_{j,diff} \] are defined in each destination zone \( j \in Z \), and equal to all residential zones \( i \in Z \), as described Figure 3(b). This spatial pattern can be considered as a centripetal force of zone \( j \), and this is similar to the utility change caused by the construction of new attractive facilities, such as amusement parks. When building new HSRs, there is a potential to change the pattern via improvement of the value of zone as the destination (ex. through accumulation of business facilities). As a result of this effect, the behavior of people who do not directly use the HSR service also changes. Therefore, in this paper, the effect in \( D_{diff} \) is referred to as an indirect effect, compared to the direct effect in \( C_{diff} \).

These indirect effects were not considered in the studies by Yao and Morikawa (5) and Fu et al. (6), because the pattern of \( D_{diff} \) was described by socio-economic factors such as zone population and economic scale. Thus, the relationship between the existence of HSR services and socio-economic factors were not described in their models. In this paper, both the direct and indirect effects of Hokuriku HSR are estimated based on the MSS data, and the significance of the direct and indirect effects are compared.

**FIGURE 3** Two decomposed patterns of change

**Estimation Methodology**

By rewriting the matrices \((B_{aft} - B_{bef})\), \(D_{diff} \), \(C_{diff} \), and \(E_{diff} \) as vectors, Equation (7) can be rewritten as follow:

\[ b_{diff} = K(d_{diff}) + e_{diff} \quad . \quad (10) \]

where, \( b_{diff} \) = \( \begin{pmatrix} b_{1,2, aft} - b_{1,2, bef} \\ b_{1,3, aft} - b_{1,3, bef} \\ \vdots \\ b_{50,49, aft} - b_{50,49, bef} \end{pmatrix} \), \( d_{diff} \) = \( \begin{pmatrix} d_{1,diff} \\ \vdots \\ d_{50,diff} \end{pmatrix} \), \( c_{diff} \) = \( \begin{pmatrix} c_{1,2,diff} \\ \vdots \\ c_{50,49,diff} \end{pmatrix} \), \( e_{diff} \) = \( \begin{pmatrix} e_{1,2,diff} \\ \vdots \\ e_{50,49,diff} \end{pmatrix} \).

These vectors are composed of non-diagonal components of matrices \((B_{aft} - B_{bef})\), \(D_{diff} \), \(C_{diff} \), and \(E_{diff} \) . Further, \( K \) is the binary matrix satisfying Equations (8) – (10).

Then, the \((d_{* bef} , c_{* bef})\) minimize the residual sum of squares \( \sum_{(i,j)} (\epsilon_{i,j,diff})^2 \) are estimated. Here, Equation (7) can be rewritten as follow:
Therefore, there exists a vector $a \neq 0$, which satisfies Equation (12):

$$K(d_{\text{diff}} + e \epsilon_{\text{diff}}) = K\left(d_{\text{diff}} + e\right), \quad \forall e \in \mathbb{R}.$$  \hspace{1cm} \text{(12)}

This means that $K$ is the rank-deficient matrix and we cannot estimate unique $(d_{\text{bef}}, c_{\text{bef}})$ only minimizing the residual sum of squares.

In this paper, $(d_{\text{bef}}, c_{\text{bef}})$ are estimated by following two step calculations. In the first step, we consider the vector $z$ defined as follows:

$$Lz = \left[d_{\text{diff}} - d_{i,j,\text{diff}} a\right], \quad \text{where} \quad L = \begin{pmatrix} 1 & 1 & \ldots & 1 \\ 0 & 0 & \ldots & 0 \end{pmatrix}.$$  \hspace{1cm} \text{(13)}

Then, using Equations (12) - (13), Equation (10) can be rewritten as follow:

$$b_{\text{diff}} = KLz + \epsilon_{\text{diff}},$$  \hspace{1cm} \text{(14)}

Here, $[L'K'KL]$ is the regular matrix, therefore the $z^*$ which minimize the residual sum of squares can be estimated by following equations:

$$z^* = \arg\min(z^{'\epsilon_{\text{diff}}'}\epsilon_{\text{diff}}) = [L'K'KL]^{-1}L'K'b_{\text{diff}},$$  \hspace{1cm} \text{(15)}

In second step, we estimate unique $(d_{\text{bef}}^*, c_{\text{bef}}^*)$ from following equation:

$$\begin{pmatrix} d_{\text{diff}}^* \\ c_{\text{diff}}^* \end{pmatrix} = \begin{pmatrix} 0 \\ z^* \end{pmatrix} + e^* a.$$  \hspace{1cm} \text{(16)}

Hence, in order to determine $e^*$, it is assumed that most components of $c_{\text{bef}}^*$ are close to zero. This assumption is reasonable because there were no major changes in travel service quality in most zone pairs, excluding pairs related with the Hokuriku HSR. Then, $e^*$ is estimated as follows:

$$e^* = \arg\min \sum_{(i,j)} |e_{i,j,\text{diff}}^*|.$$  \hspace{1cm} \text{(17)}

Finally, $(d_{\text{bef}}^*, c_{\text{bef}}^*)$ can be estimated using Equation (15), (16) and (17).
Estimated Decomposed Results

Figure 4 shows the estimated results of $D^*_{\text{diff}}$, $C^*_{\text{diff}}$. Figure 4(a) indicates that $c_{i,j,\text{diff}}$ are increased in the zone-pair which are connected by new HSR (red blocks in Figure 4(a); Kanto – ISK, TYM which are directly connected by the Hokuriku HSR). In the other words, the new HSR increased the number of travelers between Kanto and Hokuriku areas (ISK, TYM zones). This change is directly anticipated because of the time reduction effect of the new HSR service.

Figure 4(b) indicates that the indirect effect $d^*_{j,\text{diff}}$ was increased in the ISK zone. As discussed in the previous section, these changes are similar in all residential zones including OSA zone, which is in the opposite direction to the new HSR line. On the other hand, asymmetric effect was detected in on direction, in the TYO – ISK pair.

In order to confirm the validity of this decomposition, $(B_{\text{bef}} - B_{\text{bef}})$ and $(D^*_{\text{diff}} + C^*_{\text{diff}})$ are compared, as shown in Figure 5. Figure 5(a) illustrates $(B_{\text{bef}} - B_{\text{bef}})$ calculated from MSS data directly, while Figure 5(b) shows $(D^*_{\text{diff}} + C^*_{\text{diff}})$, which are the estimated components in this study. The comparison between Figure 5(a) and (b) indicates that $(D^*_{\text{diff}} + C^*_{\text{diff}})$ succeed in reproducing most of the features of $(B_{\text{bef}} - B_{\text{bef}})$. In the other words, most changes that occurred before and after the beginning of the new HSR service were patterns of $C^*_{\text{diff}}$ and $D^*_{\text{diff}}$. 

**FIGURE 4** Two decomposed matrices.
Direct vs. Indirect Effects of the New HSR

In this section, the amount of direct effect of $C_{\text{diff}}$ and indirect effect of $D_{\text{diff}}$ in Hokuriku HSR are compared. First, the change volume by both effects $n_{i,j,\text{both}}$ (residential and staying zone pair: $(i, j) \in Z \times Z$) can be calculated using the following equation:

\[
n_{i,j,\text{both}} = \text{POP}_i \sum_{j \in Z} \frac{\exp\left(b_{i,j,\text{bef}} + c_{i,j,\text{diff}} + d_{j,\text{diff}}\right)}{\sum_{j \in Z} \exp\left(b_{i,j,\text{bef}} + c_{i,j,\text{diff}} + d_{j,\text{diff}}\right)} - m_{i,j,\text{bef}},
\]

(16)

where $\text{POP}_i$ is population of zone $i \in Z$, which is equal to $\sum_{j \in Z} m_{i,j,\text{bef}}$. Second, the amount of change by only the direct effect $n_{i,j,\text{Direct}}$ (residential and staying zone pair: $(i, j) \in Z \times Z$) can be calculated using the following equation:

\[
n_{i,j,\text{Direct}} = \text{POP}_i \sum_{j \in Z} \frac{\exp\left(b_{i,j,\text{bef}} + c_{i,j,\text{diff}}\right)}{\sum_{j \in Z} \exp\left(b_{i,j,\text{bef}} + c_{i,j,\text{diff}}\right)} - m_{i,j,\text{bef}}.
\]

(17)

This $n_{i,j,\text{Direct}}$ indicates the amount of change before and after the Hokuriku HSR, without the indirect effect $D_{\text{diff}}$.

Table 2 lists part of estimated results of $n_{i,j,\text{Both}}$ and $n_{i,j,\text{Direct}}$. The following features of direct and indirect effects of Hokuriku HSR can be recognized. First, the increase volume of travelers to ISK from TYO due to the direct effect is smaller than the volume by “both” effects. The ratio of the direct effect to the total of both effects was only 34%. This is attributed to the large increase in value of the zone as travel destination (indirect effect) in the ISK zone seen in Figure 4(b). On the other hand, in the reverse direction (traveler to TYO from ISK), the direct effect accounts for majority of the increase, because the value of TYO zone as travel destination was not increased. Hence, the direct effects are almost similar in both directions of the zone pair. Therefore, the total increase amount was asymmetric between directions.
of travel because of the difference in the indirect effects. Furthermore, in the result of the total increase of travel volume to the ISK zone, the direct effect was very limited, and 93% of the increase was due to the indirect effect. This reflects the increase in inflow from other zones connected by the new HSR service, such as OSA. Accordingly, when the changes before and after the beginning of Hokuriku HSR operation are compared, it is found that the indirect pattern effects, which are described in Figure 3(b), were more significant than the direct pattern effects.

**TABLE 2** Estimated Direct and Indirect Effects of the Hokuriku HSR

<table>
<thead>
<tr>
<th>Residential zone</th>
<th>Staying zone at 13:00</th>
<th>(1) Direct effect only</th>
<th>(2) Direct + indirect effects</th>
<th>(1) / (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYO</td>
<td>ISK</td>
<td>+551</td>
<td>+1,617</td>
<td>0.34</td>
</tr>
<tr>
<td>ISK</td>
<td>TYO</td>
<td>+583</td>
<td>+647</td>
<td>0.90</td>
</tr>
<tr>
<td>46 zones*</td>
<td>ISK</td>
<td>+555</td>
<td>+8,097</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*‘46 zones’ means all zones except four zones in Hokuriku regions (Nigata, Toyama, Ishikawa and Fukui).

**SUMMARY**

In this study the direct and indirect effects of Hokuriku HSR on the residential - travel destination matrix data are analyzed. The matrix was decomposed into two matrices corresponding to direct and indirect effects, in order to understand the matrix difference. The decomposed results indicate the following three features of the HSR effect: First, the change before and after the beginning of the Hokuriku HSR operation in the residential - travel destination matrix are mostly explained by two change patterns (direct and indirect effects). Second, the direct numerical effects are smaller than in-direct effects on the travel volume. Third, the changes are asymmetric on the flows for several zone pairs because of indirect effects. The current study findings reveal the importance of predicting the indirect effects, while forecasting the effects of the new HSR lines. However, most long-distance travel demand models are similar to those developed by Yao and Morikawa (5) and Fu et al. (6), which cannot predict these indirect effects. Therefore, in order to understand the value of the HSR services for the national-scale travel structure or patterns, and to estimate the benefits of the new HSR services, it is necessary to model and incorporate the indirect effect of new HSR service. For modeling the indirect effects, it is required to compare the indirect effects of several HSR services. Moreover, it may be important to discuss the long-term and short-term effects of the service, because the indirect effects are expected to reflect long-term changes, such as the future economic development of the region (location of companies). The focus of this paper is only on the short-term effect (1 year). However, the long-term effects can also be discussed by applying a similar methodology to long-term data.

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