Construction of Method for Comprehensive Priority Assessment of Road Maintenance Sections Using Network DEA

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Abstract: In this paper, we construct a structural model of multiple main factors influencing road section traffic flow and safety, which could not be taken into account using conventional DEA. In this model, road sections are compared in terms of traffic flow and safety, and Network DEA is used to assess comprehensively the maintenance priority on the basis of these two parameters. In addition, the priority assessment of road maintenance sections was tested, taking 64 traffic census section locations from Sapporo City's densely inhabited district as a model case. From these results, we found that the maintenance priority becomes clear in cases where multiple factors are considered, and the usefulness of Network DEA is validated through the comparison of analysis results from conventional DEA and the proposed model.

Keywords: Network DEA, priority assessment, traffic flow, safety

1. INTRODUCTION

The increasing financial restrictions placed on road maintenance projects in recent years, such as the reallocation of road-designated financial resources to general revenue, are expected to become even more severe in the future. To carry out all road maintenance projects adequately under such circumstances, it is important to determine the necessity and maintenance effectiveness of projects objectively, as well as to assess the maintenance priority of all such projects.

Road maintenance projects are assessed using indicators such as traffic flow, safety, pleasantness, convenience, economic efficiency and environmental impact, and a maintenance plan is devised accordingly. To assess the road traffic condition in particular, it is necessary to look objectively at separate road sections from a macroscopic point of view. However, within such an assessment, traffic flow and safety are the indicators of greatest concern for both road
management and users, as they describe fundamental road functions

Until now, assessing traffic flow usually has usually entailed assessing the traffic indicators of congestion level, traffic volume and travel speed. As a comparative indicator for assessing basic road function, the congestion level, which primarily compares road traffic volume within a certain time period to this time period's standard measure, is an important indicator for considering the priority of road maintenance sections. For assessing safety, the rate of fatal and injury accidents, and the rate of fatal accidents, are used; the priority of maintenance is then decided accordingly. As a result, road sections and locations are selected on the basis of difference in these indicators and comprehensive prioritization is difficult.

Therefore, in the present paper, we focus on the structure of the basic road functions of traffic flow and safety, using a Network Data Envelopment Analysis (DEA) model that assesses management efficiency. Traffic flow and safety are not assessed separately; instead, the goal is to construct a comprehensive method for assessing the priority of road maintenance sections, taking into account both of these indicators.

Existing research on the prioritization of road maintenance can be largely divided into two areas, one being the traffic network optimization model (Tamura et al., 1994) and the other being the synthesis of multiple assessment indicators (Ando et al., 2002). As our aim here is to use the DEA commonly used in solving multi-indicator type assessment problems in order to assess the priority of road maintenance sections, the present work can be grouped into the latter research area.

Assessment of maintenance priority using DEA, in our previous work of traffic capacity (Takada et al., 2009), was performed by using a priority assessment method that takes traffic flow as a measurement item, but does not comprehensively assess multiple indicators.

In the present work, we construct a structural model of road sections, taking into account traffic flow and safety, with a focus on the main factors influencing both of them. This structural model is characterized by the use of Network DEA to assess road sections comprehensively rather than separately and thus can be used to determine maintenance priority.

2. OVERVIEW OF THE DEA MODEL

2.1 Basic Concept of DEA

If the activity of a project is viewed as the process of converting resource inputs into benefit outputs, output/input comparison is useful for measuring efficiency, and the efficiency for the conversion process is measured as a ratio. When assessing management efficiency in particular, the use of expense and revenue comparison is widespread, but efficiency assessment using ratio scale with multiple input/output data is not simple. Solving such multi-indicator type assessment problems is a key advantage of DEA.

Using DEA to evaluate a decision making unit (DMU), we find that DMU-A produces the highest output from the lowest input, and thus judge it as most efficient. We can then plot a straight line connecting DMU-A and the origin, which is called the efficiency frontier. The efficiency frontier indicates the best DMU performance, and other DMUs can be assessed by
taking the efficiency frontier as a standard. The efficiency value of DMU-A is set as 1 and the other DMUs are assessed in relation to DMU-A. Therefore, one characteristic of DEA is the possibility of finding available improvements for inefficient DMUs, because efficiency assessment using DEA is a relative evaluation using the most efficient DMU as the evaluation standard.

2.2 The CCR Model
The most basic model in DEA is the Charnes–Cooper–Rhodes (CCR) model (Charnes et al., 1978). For DMU\(_j\) (\(j = 1,..., n\)), the input values are \(x_{1j}, x_{2j},..., x_{mj}\) and the output values are \(y_{1j}, y_{2j},..., y_{sj}\), and the efficiency of any assessment target DMU\(_o\) is given by Eqs. (1)–(4).

Objective function: \[
\max \theta = \frac{u_1y_{1o} + u_2y_{2o} + \cdots + u_sy_{so}}{v_1x_{1o} + v_2x_{2o} + \cdots + v_mx_{mo}} \tag{1}
\]

Constraints equation: \[
\frac{u_1y_{1j} + \cdots + u_sy_{sj}}{v_1x_{1j} + \cdots + v_mx_{mj}} \leq 1 \quad (j = 1,...,n) \tag{2}
\]

Input weight: \(v_1, v_2,\cdots, v_m \geq 0\) \hspace{1cm} (3)

Output weight: \(u_1, u_2,\cdots, u_s \geq 0\) \hspace{1cm} (4)

For the optimal solution \((v^*, u^*)\) and the objective value \(\theta^*\), the following statements can be made.

i. If \(\theta^* = 1\), then DMU\(_o\) is D-efficient.

ii. If \(\theta^* < 1\), then DMU\(_o\) is D-inefficient.

The CCR model further defines Activity \((x, y)\) as a function of input \(x \in R^m\) and output \(y \in R^s\), and if the sum of the activity is defined as the potential production sum \(P\), we can assume that for Activity \((x, y)\) that includes \(P\) and gives Activity \((kx, ky)\) when multiplied by \(k\), the scale of the return is constant.

2.3 Applying the Network DEA model
Because conventional DEA does not consider the internal structure of DMUs, but rather uses only the DMU’s input and output parameters, it is sometimes called a black-box model. However, the traffic flow and safety of road sections are governed by various factors that are interconnected in a complex way. Therefore, when assessing the efficiency of road sections, it is necessary to use an assessment method that considers the internal structure rather than a black-box model that uses only input and output parameters separately.

Here, we use a Network DEA model, which is capable of considering the relation between factors. It constructs a structural model of the various main factors connected to the traffic flow and safety of road sections in order to perform an assessment.
2.4 Basic framework of Network DEA

In this section, we introduce Network DEA model referring to its production possibility set, efficiency and projection.

We employ the following notations for describing Network DEA.

\[ n : \# \text{ of DMUs} \]
\[ K : \# \text{ of divisions} \]
\[ mk : \# \text{ of inputs to Division } k \]
\[ rk : \# \text{ of outputs from Division } k \]

\[ D : \text{ The set of divisions in the model. The divisions are numbered from 1 to } K. \]
\[ S : \text{ The set of divisions which have no incoming links, i.e. starting divisions} \]
\[ T : \text{ The set of divisions which have no outgoing links, i.e. terminal divisions} \]
\[ (k,h) : \text{ The link (intermediate product) from Division } k \text{ to Division } h \]

\[ T_{(k,h)} : \# \text{ of items in Link } (k,h) \]
\[ L : \text{ The set of links} \]

\[ P_k = \{ p \mid (p,k) \in L \} \text{ (antecessor)} \]
\[ F_k = \{ q \mid (k,q) \in L \} \text{ (successor)} \]

\[ x_j^k \in \mathbb{R}_{+}^{m_k} : \text{ Input resources to DMU}_j \text{ at Division } k \ (k=1,K,K) \]
\[ y_j^k \in \mathbb{R}_{+}^{r_k} : \text{ Output resources to DMU}_j \text{ at Division } k \ (k=1,K,K) \]
\[ z_j^{(k,h)} \in \mathbb{R}_{+}^{I_{(k,h)}} : \text{ Linking input resources to } \text{ DMU}_j \text{ at Division } h \text{ from Division } k \ ((k,h) \in L) \]

\[ = \text{ Linking output products from DMU}_j \text{ at Division } k \text{ to Division } h \ ((k,h) \in L) \]

where \( j \) denotes \( j \)-th DMU \((j=1,K,n)\).

We assume

\[ z_j^{(k,h)} = 0 (\forall j,h \in S) : \text{ No linking inputs to starting divisions and} \]

\[ z_j^{(k,h)} = 0 (\forall j,k \in T) : \text{ No linking Outputs from terminal divisions.} \]  \hspace{1cm} (5)

The production possibility set \( \{(x_j^k, y_j^k, z_j^{(p,k)}, z_j^{(k,q)})\} \) is defined by

\[ x_j^k \geq \sum_{j=1}^{n} x_j^{k,j} \ (k=1,K,K) \]
\[ y_j^k \geq \sum_{j=1}^{n} y_j^{k,j} \ (k=1,K,K) \]
\[ z_j^{(p,k)} = \sum_{j=1}^{n} z_j^{(p,k),j} (\forall (p,k)) \ (\text{as inputs to } k) \]
\[ z_j^{(p,k)} = \sum_{j=1}^{n} z_j^{(p,k),j} (\forall (p,k)) \ (\text{as Outputs from } p) \]
\[ z_j^{(k,q)} = \sum_{j=1}^{n} z_j^{(k,q),j} (\forall (k,q)) \ (\text{as Inputs to } q) \]  \hspace{1cm} (6)
\[ z^{(k,q)} = \sum_{j=1}^{n} z_j^{(k,q)} x_j^{(k,q)} \] (as Outputs from \( k \))

\[ \sum_{j=1}^{n} \lambda_j^k = 1(\forall(k), \lambda_j^k \geq 0(\forall j,k) ) , \]

where \( \lambda^k \in R^m_+ \) is the intensity vector corresponding to Division \( k = 1, K \).

We notice that the above model assumes the variable returns-to-scale (VRS) for production. However, if we neglect the last constraint \( \sum_{j=1}^{n} \lambda_j^k = 1(\forall(k) \) we can deal with the constant returns-to-scale (CRS) case.

DMUo \((o=1, K, n)\) can be represented by

\[
\begin{align*}
x_o^k &= x^k + s_o^{k-} \quad (k=1, K, K) \\
y_o^k &= y^k + s_o^{k+} \quad (k=1, K, K) \\
e^k &= 1 \quad (k=1, K, K) \\
\lambda^k &\geq 0, s_o^{k-} \geq 0, s_o^{k+} \geq 0 \quad (\forall k)
\end{align*}
\]

Where

\[
X^k = (x_1^k, K, x_n^k) \in R^m_k \times n
\]

\[
Y^k = (y_1^k, K, y_n^k) \in R^n_k \times n .
\]

As regard to the linking constraints, we have several options of which we present two possible cases.

(a) The “fixed” link value case.
The linking activities are kept unchanged:

\[
\begin{align*}
z_o^{(k,h)} &= Z^{(k,h)} \lambda^h \quad (\forall(k,h)) \\
z_o^{(k,h)} &= Z^{(k,h)} \lambda^h . \quad (\forall(k,h))
\end{align*}
\]

(b) The “free” link value case.
The linking activities are freely determined while keeping continuity between input and output:

\[
Z^{(k,h)} \lambda^h = Z^{(k,h)} \lambda^k . \quad (\forall(k,h))
\]

Where

\[
Z^{(k,h)} = (Z_1^{(k,h)}, K, Z_n^{(k,h)}) \in R^{f(k,h)}
\]

2.5 Input–oriented efficiency \( \theta_o^* \)
As the weighted mean of divisional input efficiencies, we have

\[
\begin{align*}
\theta_o^* &= \min \sum_{k=1}^{K} w_k \left[ 1 - \frac{1}{m_k} \left( \sum_{m=1}^{m_k} \frac{s_{i0}^m}{s_{i0}^k} \right) \right] \\
&\quad \text{with } \sum_{k=1}^{K} w_k = 1, w_k \geq 0(\forall k) \quad \text{and subject to (7), (9a) or (9b)},
\end{align*}
\]
Definition 1 (Input-oriented divisional efficiency)
Using the optimal input slacks $s_{o}^{-k}$, we define the input-oriented divisional efficiency by

$$
\theta_{k} = 1 - \frac{1}{m_{k}} \left( \sum_{t=1}^{m_{k}} \frac{s_{o}^{-k}}{x_{io}^{k}} \right) \quad (k = 1, K, K)
$$

(12)

If $\theta_{k} = 1$, then the DMUo is called input-efficient for the division $k$.

Definition 2 (Input-oriented overall efficiency)
We call $\theta_{o}^{*}$ the overall input-efficiency of DMUo. If $\theta_{o}^{*}$, it is called overall input-efficient.

We notice that the above divisional efficiency score is not always uniquely determined. The overall input-oriented efficiency score is the weighted arithmetic mean of the divisional scores.

$$
\theta_{o}^{*} = \sum_{k=1}^{K} w_{k} \theta_{k}
$$

(13)

3. D-EFFICIENCY VALUE DEFINITION AND INPUT/OUTPUT ITEM SELECTION

3.1 Input/Output Item Selection for Traffic Flow
Regarding the input/output items for assessing traffic flow, we focus on the main factors that are strongly related to the road section service level indicators of congestion level and travel speed. For selecting input items, peak time traffic volume, traffic signal intersection density and large vehicle percentage are selected as input items in terms of traffic capacity. Traffic signal intersection density is a parameter that strongly affects travel speed in road sections and tends to be a bottleneck that causes decreasing of traffic capacity. Large vehicle percentage also causes decreasing of traffic capacity, thereby is selected as input item. Other factors, such as extreme gradient and road width, may cause decreasing of traffic capacity. However, this study focuses on the priority assessment of the road maintenance for national highways in urban central areas where there are no extreme gradient and road width. Therefore those factors are not selected as input items. However, for little input and large output to become efficient, the inverse of travel speed is used. In other words, to assess traffic flow, road sections are taken as DMUs producing congestion and traffic jams. The D-efficient value calculated by Network DEA then becomes an indicator for comparatively assessing sections with high congestion level and low travel speed despite low peak traffic volume [vehicles/h], low traffic signal intersection density [points/km] and low large vehicle percentage [%]. Sections with a high D-efficient value are defined as having high maintenance priority. In addition, regarding fluidity, the expression that sections with a high congestion level and low travel speed are efficient is easily misunderstood and therefore replaced by the concept of congestion rate.

3.2 Safety Input/Output Item Selection
For input/output items assessing safety, factors that are highly relevant to the number of accidents are selected, namely, congestion level, intersection density and traffic volume. Regarding the congestion level, previous studies have found a tendency for the accident rate to rise in accordance with the congestion level, together with an increase in congestion level being accompanied by a tendency of the rate of rear-end collision accidents to increase. Regarding intersection density, the danger of accidents involving pedestrians and bicycles, as
well as accidents involving vehicles turning right and colliding with vehicles traveling straight from the opposite direction rises in intersections with traffic signals. In intersections without traffic signals, the danger of side-impact accidents exists in addition to the same types of accidents seen at intersections with traffic signals. Intersection density is thought to be strongly related to the occurrence of accidents. Because an increase in accident risk can be predicted from high road section traffic volume itself, we select congestion level, intersection density [points/km] and daily traffic volume [vehicles/day] as input items and traffic accident numbers [number/km] as output items. In other words, in regards to safety, road sections are seen as DMUs producing traffic accidents. The D-efficient value calculated by Network DEA then becomes an indicator for comparatively assessing sections with high traffic accident numbers, which efficiently produce accidents despite low congestion level, low intersection density and low daily traffic volume. Sections with a high D-efficient value are defined as having high maintenance priority. In addition, the term "efficient" regarding safety is easily misunderstood and therefore replaced by the concept of risk percentage.

3.3 Construction of Proposed Network DEA Model
As the conventional DEA model does not take into account internal DMU structure for assessment indicators, D-efficient values are calculated independently. As a result, when an output parameter becomes an input parameter in different aspects, even within the same DMU, the optimal value varies among aspects and continuity is not preserved, even though the parameter does not change. In Network DEA on the other hand, only one optimal value is calculated from the relationships among different aspects, and the parameters linking the aspects are called linked parameters.

In this paper traffic flow and safety are taken as two aspects, and by the selection of congestion level as a linked (shared) parameter, the assessment takes the internal structure of road sections into account.

![Figure 1 Model structure of conventional DEA and Network DEA](image-url)
4. COMPREHENSIVE ASSESSMENT OF ROAD TRAFFIC CENSUS SECTION

4.1 State of Road Congestion and Accident Occurrence in Sapporo City

Currently nine national road routes are present within Sapporo City, Hokkaido, Japan. On these routes, congestion is severe, and there are sections where many accidents occur. To date, many road reforms have been proposed to improve this condition. As can be seen in Figure 2, which shows Sapporo City's congestion level and traffic accident rate, road sections with a congestion level of 1.0 or more constitute around 80% of the total of 83 sections, while chronically congested sections with a congestion level of 1.75 or more constitute around 10%. A fatal accident rate of 100 or more accidents per hundred million vehicle-kilometers can be found for greater than 90% of all road sections, and a fatal accident rate of 300 or more accidents per hundred million vehicle–kilometers can be found for around 20% of road sections. Sapporo City is therefore a city containing many road sections with a high frequency of accidents.

Figure 2 Ratio of congestion level and fatal accident rate for Sapporo City census sections
4.2 Selection of Target Sections for Analysis
Aiming to facilitate the improvement of congestion and the decrease of accidents in Sapporo City, this paper used national roads within the densely inhabited district of Sapporo City as the target model case. Toward this end, 64 sections of 8 national roads were selected as analysis targets from the 2005 road traffic census results. Input/output items were also taken from the 2005 road traffic census results.

![Figure 3 Analysis target sections](image)

4.3 Network DEA Analysis Results
Results of the Network DEA census section analysis are shown in Table 1 and Fig. 4.
For traffic flow, a total of 11 sections with a congestion rate of 1.0 were found: two city center sections on national road Route 36, two suburb sections on Route 231, two suburb sections on Route 274, one city center section on Route 275 and four suburb sections on Route 453. The two city center sections on Route 36 had the lowest travel speed of less than 10 km/h, even though the peak traffic volume on these two sections was low. The two suburb sections on Route 274 had a high congestion level and a low travel speed of around 10 km/h, even though their traffic signal intersection density was the lowest of all sections.

Looking at the average congestion rate by route, Route 453 showed the highest congestion rate. Travel speed was comparatively low on these sections, even though peak time traffic volume and large vehicle percentage were low.

For safety, a total of eight sections with a risk rate of 1.0 were found: three city center sections on Route 36, two suburb sections on Route 230, one suburb section on Route 274, one suburb section on Route 275 and one suburb section on Route 453. Section 1021 of Route 36 had the highest number of accidents, even though the daily traffic volume and congestion...
level were low. Looking at the average risk rate by route, Route 36 showed the highest risk rate. The number of accidents was high on these sections, even though the daily traffic volume was low. For the city center sections, accidents involving pedestrians and bicycles can be expected.

For comprehensive assessment of congestion and risk rate, a total of five sections with a combined rate of 1.0 were found: two city center sections on Route 36, one suburb section on Route 274, one city center section on Route 275 and one suburb section on route 453. These five sections have highest maintenance priority if assessed with consideration of the congestion rate and risk rate.

![Analysis target results](image)

Figure 4 Analysis target results
Table 1 Network DEA analysis results

<table>
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<tr>
<th>Section number</th>
<th>Score Rank</th>
<th>Score Rank</th>
<th>Score Rank</th>
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<td>R36 average</td>
<td>0.735 0.794 0.616</td>
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5. COMPARISON OF CONVENTIONAL DEA AND NETWORK DEA MODELS

To verify the validity of the Network DEA model used in this study, we next conduct a comparison with conventional DEA model. The congestion level, which was used as a linked parameter combining congestion rate and risk rate in the Network DEA model, was used as an input/output parameter in the conventional model. The analysis was performed using the CCR model and the results were compared.

From the comparison results for the congestion rate, the conventional DEA model finds 19 sections showing a congestion rate of 1.0, which is a greater number than the 11 sections found using the Network DEA model. Here, the conventional DEA model shows the weakness that the number of DMUs assessed as D-efficient rises with the increasing in input/output parameters. Looking at the rank variation, we find that the Network DEA model shows the same results for sections with a congestion rate of 1.0 as the conventional DEA model, but in the Network DEA model results Section 1013 of Route 12 and Section 1030 of Route 230 are respectively assigned a low rank of 59 and 62 out of the 64 sections. This result
differs greatly from the results obtained using the conventional model. This can be attributed to the fact that the conventional model does not take the internal structure into account and performs assessments independently, leading to the results being influenced by the size of one indicator, in this case, the congestion level. Likewise, looking at the risk rate assessment, the conventional model finds an increased number of ten sections with a risk rate of 1.0. In the case of Section 1049 of Route 231 there was a large difference in rank, and because the congestion level was the lowest out of the 64 sections, this influenced the assessment. Since the conventional model is easily influenced by a single extreme parameter value, in cases such as road sections with many main factors used in the assessment, the Network DEA model that takes into account the relation between factors is thought to be appropriate.

### Table 2 Comparison of conventional DEA model and Network DEA analysis results

<table>
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<tr>
<th>DMU</th>
<th>Traditional DEA congestion rate</th>
<th>Network DEA congestion rate</th>
<th>Rank variation</th>
<th>Output</th>
<th>Linked parameter (Network DEA)</th>
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<th>Input</th>
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<th>Intersection density</th>
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6. CONCLUSIONS

For road maintenance projects under tightening budget restrictions and for meeting the existing need for efficient and effective public utilities that take into account regional characteristics, a method for assessing the priority of all projects is necessary. However, for assessing road maintenance priority, no method handling many assessment indicators in a unified way has been developed before now.

Therefore, in order to assess the traffic flow and safety of road sections comparatively, we have constructed a structural model of the many factors influencing the traffic flow and safety of road sections, which the conventional DEA cannot take into account. To do this we used the Network DEA model to devise a comprehensive maintenance priority assessment method that takes both of these factors into consideration.

In addition, taking 64 places from the road section census in Sapporo City as a model case, we validated the road maintenance section priority assessment. As a result, a total of 5 sections in the city center and suburbs of Sapporo City with high maintenance priority were clearly identified by considering multiple factors. Furthermore, analysis results of conventional DEA and the proposed method were compared, and the validity of using the Network DEA for projects such road section maintenance, which should assessed using multiple factors, was confirmed.

As a future task, we plan to investigate the subjective opinions of road users and managers in order to verify the validity of the calculated results.

Here, we took the total accident count as an output parameter of safety; going forward, we would like to collect data on similar accident types, reestablishing the input parameter based on their relevance and then performing a detailed analysis. We also plan to perform assessment from the perspective of road networks, applying the advantages of Network DEA by including indicators such as convenience in the analysis.

REFERENCES


