Study on the Degree of the Network Connectivity of Expressways Operated in the Closed-type Toll Collection System

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Abstract: The Korea Expressway Corporation collects tolls in all expressways in its charge under the Toll Road Act establishing user pay principle, cost recovery method, and integrated-profit system as legal bases for collecting tolls. However, the act does not clearly stipulate the methodology how to measure the connectivity in terms of transportation, which is one of requirements for the adaptation of integrated-profit system, so that there have been lots of arguments on collecting tolls on the expressways. Thus, this research effort developed a transportation-connectivity index to estimate the degree of the connectivity of expressways in terms of physical linkage and actual usage. The index was validated using TCS and Hi-Pass data collected from expressways operated under the closed-type toll collection system. Conclusively, the connectivity indexes of the subject expressways in use are over 2.0 in general, which mean all the subject expressways are physically well connected and multiple expressway routes are frequently and simultaneously used.

Key Words: Expressway, connectivity, Toll Collection System, Hi-Pass, Toll Road Act

1. INTRODUCTION

In Korea, the Toll Road Act was enacted and promulgated for the first time in 1963. And the first toll road that stretched in the distance of 23.6km from Seoul to Suwon was put into service in December 1968. Thus far, tireless efforts have been made to expand the expressway network in Korea with much achievement. As of October 2009, the expressways operated by the Korea Expressway Corporation (KEC) included 27 routes stretching in the total distance of 3,481km across the nation.¹

¹ Source: web site of the Korea Expressway Corporation  
(http://www.ex.co.kr/portal/opn/mng/ mng/pub3/cor_opn_mng_pub03.jsp)
In Korea, tolls are collected from for drivers who use toll roads, based on the user pays principle, the cost recovery method, which aims at recovering the total construction-maintenance cost, and the integrated profit system, which are stipulated in the Toll Road Act. Furthermore, as the structure of tolls for expressways operated by KEC has changed over time. Tolls in the two-part tariff system that consists of the basic fee and the traveling fee are charged by vehicle types based on the three aforementioned principles, currently (Korea Development Institute, 2008).

However, it is true that there have been many controversies on the toll system for expressways operated by KEC. Examples of ongoing controversies include which one is desirable between the integrated profit system and the independent profit system, whether the current two-part tariff system is reasonable or not, whether the difference in tariff is reasonable between the expressways managed by KEC and the other private expressways or not, and whether the current tariff system ensures regional equity or not.

In addition, one of the requirements for the integrated profit system, stipulated in the Article 18 of the Toll Road Act, is "transportation connectivity." But the issue has been raised that the integrated profit system does not specify the requirement of transportation connectivity. On the issue of the requirements for the integrated profit system, the court stated in a positive way that "there is no reason to say that the expressways of the 12 routes nationwide (as of 1991) managed by the defendant (KEC) do not have the transportation connectivity" and continued to state that "there seems to a special reason for the integrated toll collection in consideration of the current status of the expressways and the future plan for transportation improvement" (refer to the Seoul High Court 91-1-5336) (Korea Development Institute, 2008).

In order to examine the "transportation connectivity," which is one of the requirements for the integrated profit system stipulated in the Article 18 of the Toll Road Act, the purpose of this study is to develop the index to measure the "transportation connectivity" for the expressways in use, and to quantify the degree of the transportation connectivity by each expressway route.

2. DISCUSSIONS ON PREVIOUS STUDIES

2.1 Previous Studies in Korea
Kwon et al. (2006) developed the standards for identifying inefficient road investment. The study was initiated to make efficient investments on principal national roads including expressways and national highways. To this end, the superficial similarity, the functional similarity and the timeliness of two or more routes running parallel were analyzed to determine whether investing the both routes is reasonable or not in economic point of view. For the analysis of functional similarity, the long distance trip rate similarity and the trip distribution similarity for any parallel routes were analyzed to quantify the similarity of travel behavior on the routes. In the study, however, the physical connectivity of the two routes was not examined. Therefore, it is considered that the results of the study are not suitable as an index that indicates the degree of transportation connectivity that is required by the Toll Road Act.

Han et al. (2005) used the analytic hierarchy process (AHP) to determine investment priorities of the ASEAN Highway Network Project that aimed at expanding economic exchanges through physical connection within the territory of the Association of South East Asian Nations (ASEAN).
The study conducted by Han et al. offered how to prioritize the investment of each road section using the Analytic Hierarchy Process (AHP) instead of a B/C analysis, which required too much information hard to acquire because too many road axes (road groups) of the investment targets were scattered around. Therefore, Han et al. applied AHP structured with AADTs, average construction costs, regional equity, interests of governments, and road connectivity shown in the equation below.

\[ \sum_{od} \frac{w^{od}(i,j)}{W^{od}_{ij}} \]  

(1)

Where,  
\[ W^{od}_{ij} = \text{Total sum of the weights that routes connecting each zone pair (od) generate in the node } j. \]
\[ w^{od}(i,j) = \text{Weights that routes connecting each zone pair (od) generate in the link (i,j)}. \]

The "road connectivity" suggested in the study was developed to express the importance that each route of investment targets has compared to the total road network. In Equation (1), the weights are the path selection probabilities of each road section in the entire network based on the Dial’s algorithms, which is a famous traffic assignment algorithm (Dial, 1971; The Korea Transport Institute, 2003). Consequently, it can be unreasonable to use the "road connectivity" as an index that shows the degree of transportation connectivity required by the Toll Road Act due to the lack of the consideration on the physical connectivity of roads.

2.2 Previous Studies in Foreign Countries

Also in Japan, the Article 19 of the Act on Special Measures for Road Maintenance (Special Case for Toll Collection by Toll Road Operators) stipulates that a "close relation among roads in terms of transportation (hereafter, close relation)" is required for single road operator to collect tolls on the group of roads as an integrated-profit system. The criteria for determining the "close relation" are as follows. The first is the case where drivers should simultaneously use two or more roads at their trips. For example, at least a half of the traffic volume on a road should come via at least one of other roads which are physically connected within the group. The second is the case where two or more roads in the group should have the functional interchangeability for drivers with the same origin and destination. For example, in the case of two roads, drivers who have the same origin and destination should be able to use evenly either road. In addition, when one of the two roads becomes unusable, at least a half of drivers who used to use the unusable road should be able to transfer to the other road. The last is the case where two or more roads are connected (or expected to be connected in less than two years). In this case, the "close relation" can be acknowledged regardless of the two aforementioned conditions.

2.3 Findings

There have been many controversies on the issue of "transportation connectivity" stipulated in the Toll Road Act. In spite of such controversies, there have been no specific and clear methodology on "transportation connectivity" in Korea. Japan also has a similar act that has the article about "transportation connectivity." And the Japanese act suggests the relatively specific criteria for the transportation connectivity. As a result, it is required to develop criteria or index to quantify the degree of transportation connectivity of the expressway routes in Korea.
3. METHODOLOGY

3.1 Conceptual Definition of "Transportation Connectivity"
Currently, it is difficult to verify the legal ground for specific definition of "transportation connectivity," which is one of the requirements for the integrated profit system stipulated in the Article 18 of the Toll Road Act. In terms of traffic engineering, however, there may be three types of approaches to quantify the transportation connectivity. The first is to consider physical aspect. This means developing and quantifying an index that can express physical interconnection between expressway routes. But this approach has such a limitation that only the connection of routes is simply used to measure the degree of transportation connectivity. The second is to develop and quantify an index in consideration of operators and operation characteristics by expressway routes. But this approach is reckoned to be inappropriate for examining if the integrated profit system can be applied to routes of the expressways operated by the single operator (i.e., KEC) even though the approach is suitable for expressing the degree of transportation connectivity of all expressways across the nation. The last is to develop and quantify an index by considering travel behavior of drivers who use expressways. This approach is considered to be relatively advantageous to ensure the validity compared to the two approaches mentioned above because it can be used to analyze the relation between the expressway routes in the viewpoint of drivers who use the expressways.

Conclusively, an index will be developed to quantify the degree of transportation connectivity of expressways in consideration of physical connection between the expressway routes and travel behavior of drivers who use expressways in this study. The index will be suggested based on the actual expressway usage data.

3.2 Determining the Methodology for Analysis of the Degree of Transportation Connectivity
In order to define the degree of transportation connectivity of expressways in consideration of physical connection between expressway routes and travel behavior of drivers who use expressways, the easiest way is to quantify the degree of cross-utilization between the expressway routes by tracing the individual travel paths taken by drivers. This concept can be schematized as shown in Figure 1. The case 1 in the figure shows a trip entering and exiting through the tollgates located on Expressway Route I. In this case, the trip has no relation with any other expressway routes but Expressway Route I. The case 2 shows a trip entering the tollgate located on Expressway Route I, taking Route I and Route J, and then exiting using the tollgate located on Expressway Route J. In this case of trip, it can be said that Expressway Routes I and J are physically connected and have a relation with each other in terms of travel behavior. The case 3 illustrates the highest connectivity because the three expressway routes, including Expressway Routes I, J, and K, are involved in a trip together.
The "expressway transportation connectivity index," which will be suggested in this study based on the concept mentioned above, is the coefficient that shows the degree that a driver who uses a specific route of expressway utilizes other routes of expressway simultaneously. The transportation connectivity index for the section of the expressway route can be defined in the equation as follows.

\[
TT_i^a = \frac{\sum_r \sum_s f_t^a \delta^a \gamma^a}{\sum_r \sum_s f_t^a \delta^a}
\]

Where, \( TT_i^a \) = Transportation connectivity index for the section \( a \) of the expressway route \( i \)

\( f_t^a \) = Traffic volume of the path between the tollgates \( r \) and \( s \)

\( \delta^a \) = 1 if the section \( a \) is included in the path between the tollgates \( r \) and \( s \), or 0 if not

\( \gamma^a \) = Number of the expressway routes included in the path between the tollgates \( r \) and \( s \) on the basis of the section \( a \)

In this case, the final transportation connectivity of the expressway route can be calculated by using the traffic volume-weighted average value for the sections that are included in the route.
The meaning of the equation above can be explained in the examples as follows. When all of the vehicles running on the section $a$ of the expressway route $i$ use only the expressway route $i$, the expressway transportation connectivity index for the section $a$ is 1.0. If 50% of the vehicles running on the section $a$ use only the expressway route $i$ while the remaining 50% of them use the routes $i$ and $j$ simultaneously, the transportation connectivity index is 1.5. Here, the transportation connectivity index of 1.5 means that the index meets the first requirement for “close relation” that is stipulated in the Act on Special Measures for Road Maintenance of Japan. In addition, if the transportation connectivity index is 1.0, it can be said that there is no relation in terms of transportation connectivity. In other words, if the expressway transportation connectivity index is higher than 1.0, it can be said that there is a relation in terms of network connection and utilization.

3.3 Limitations on the Methodology

In order to apply the method mentioned above to the expressways operated by KEC, it should be able to trace individual trips from its entrance tollgate to its exit tollgate by identify the entire path of the trip. However, there are two technical limitations in applying such a methodology. First, the methodology can be applied only to a section of the expressways that are operated in the closed-type toll collection system. Application of the methodology requires identifying entrance tollgate and exit tollgate of each trip. In case of sections on expressways operated in the closed-type toll collection system, the Toll Collection System (TCS) and Hi-Pass\(^2\) data can be used to identify entrance tollgate and exit tollgate. However, in case of the section operated in the open-type toll collection system, the toll is collected based on the assumption that a driver uses the minimum distance passing through the tollgate, which is located on the main lanes of expressways. Therefore, it is impossible to precisely identify the entrance tollgate and the exit tollgate that an individual vehicle passes through. Second, in case of the expressways operated in the closed-type toll collection system, it is impossible to verify the travel path of an individual vehicle even though it is possible to identify the entrance tollgate and the exit tollgate. As a result, if there are multiple alternative paths between the entrance and exit tollgates on the expressway network, it is unable to precisely identify the travel path of an individual vehicle using the Toll Collection System (TCS) and Hi-Pass data. And it is difficult to obtain precise data required to apply the aforementioned equation. Consequently, there is no other option but to assume the minimum distance traffic assignment in order to apply the equation. For reference, such minimum distance assignment principle is equally applied to the calculation of expressway toll. However, KEC has started to install road side units (RSU) which can read Hi-Pass identification numbers of vehicles passing the coverage of the RSU, through the entire expressways including major interchanges and junctions. Based on the data from RSUs, the exact paths of sufficient sample vehicles may be identified sooner and later. It should be noted that the usage of the Hi-Pass in Korea has reached 50% as of year 2010.

\[^2\] Hi-Pass is the name of the electronic toll collection system (ETCS) used in Korea
4. ANALYSIS RESULTS

4.1 Analysis Data
In order to calculate the transportation connectivity index defined in the previous chapter, the traffic assignment was conducted by using the yearly origin-destination traffic volume between tollgates generated by TCS throughout the year 2006 for the expressways operated in the closed-type toll collection system, and the minimum distance data between the tollgates, and the all-or-nothing traffic assignment which was intended to find the shortest-distance path between the tollgates. For analysis, all types of vehicles (type 1, 2, 3, 4, and 5 and lower compact car) were examined when they passed through tollgates on the expressways operated in the closed-type toll collection system.

The total of 21 expressway routes was used for analysis as shown in Table 1. Among the routes, the Cheonan-Nonsan Expressway and the Busan-Daegu Expressway are not operated by KEC. The reason for including the two private expressways for analysis is that it is difficult to separate them physically from other routes since they are connected with routes of the expressways operated by KEC.

4.2 Analysis Results
Table 1 shows the values of transportation connectivity index by each expressway that are calculated by using the TCS and Hi-Pass data on the expressway routes operated in the closed-type toll collection system in 2006.

<table>
<thead>
<tr>
<th>Name of Expressway Route</th>
<th>Transportation Connectivity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyeongbu Expressway</td>
<td>2.39</td>
</tr>
<tr>
<td>Namhae Expressway</td>
<td>2.32</td>
</tr>
<tr>
<td>88 Olympic Expressway</td>
<td>4.27</td>
</tr>
<tr>
<td>Gochang-Damyang Expressway</td>
<td>2.85</td>
</tr>
<tr>
<td>Seohaean Expressway</td>
<td>2.10</td>
</tr>
<tr>
<td>Ulsan Expressway</td>
<td>2.91</td>
</tr>
<tr>
<td>Iksan-Pohang Expressway</td>
<td>2.53</td>
</tr>
<tr>
<td>Honam Expressway</td>
<td>3.00</td>
</tr>
<tr>
<td>Jungbu Expressway (including the second Jungbu Expressway)</td>
<td>2.93</td>
</tr>
<tr>
<td>Pyeongtaek-Eumseong Expressway</td>
<td>3.71</td>
</tr>
<tr>
<td>Jungbu Naeryuk Expressway</td>
<td>3.33</td>
</tr>
<tr>
<td>Yeongdong Expressway</td>
<td>2.21</td>
</tr>
<tr>
<td>Jungang Expressway</td>
<td>2.36</td>
</tr>
<tr>
<td>Donghae Expressway</td>
<td>2.00</td>
</tr>
<tr>
<td>Masan North Expressway</td>
<td>2.85</td>
</tr>
<tr>
<td>Branch Line of the Second Namhae Expressway</td>
<td>1.92</td>
</tr>
<tr>
<td>Branch Line of Honam Expressway (including the Cheonan-Nonsan Expressway)</td>
<td>3.32</td>
</tr>
<tr>
<td>Daejeon Southern Ring Expressway</td>
<td>3.74</td>
</tr>
<tr>
<td>Jungbu Expressway (Daejeon-Tongyeong Expressway)</td>
<td>4.07</td>
</tr>
<tr>
<td>Branch Line of Jungbu Naeryuk Expressway (Guma Expressway)</td>
<td>3.10</td>
</tr>
<tr>
<td>Jungang Expressway (Samnak-Daejong) and Branch Line of Jungang Expressway (including Busan-Daegu Expressway)</td>
<td>2.66</td>
</tr>
</tbody>
</table>
As shown in Table 1, all of the transportation connectivity indexes are higher than 1.0, which means that most of the expressway routes were connected through the network, and the cross traffic was frequent. The expressway route that showed the lowest transportation connectivity index was the branch line of the Namhae Expressway with 1.92. On the contrary, the expressway that showed the highest index was the 88 Olympic Expressway with 4.27. In this case, the low index means the high rate of short distance traffic volume as drivers use only the expressway route while the high index indicates the high rate of vehicles that use the expressway route to approach other expressways.

5. Conclusion and Future Studies

The analysis of "transportation connectivity" of the expressway network in Korea, which is one of the legal requirements for the integrated profit system, showed that the transportation connectivity index was higher than 2.0 for most of the expressways, which means that the expressways were interconnected through the network and that the cross traffic was frequent. Consequently, it can be inferred that the 21 expressway routes included for analysis were physically connected through one network and that there was a ground to say that the routes had the relation with one another in terms of use behavior.

However, this study focused only on the expressways operated by the KEC. In order to apply the method suggested in this study to sections on expressways operated in the open-type toll collection system, it is possible to use the method of conducting the origin-destination (O-D) survey for interchanges and junctions on the expressways or the method with the traffic assignment model by utilizing the network and the O-D provided by the Korea Transportation Database (KTDB) (Korea Development Institute, 2008). However, there exist the limitations that the first approach requires a high cost and a long time while the second may cause a problem on the degree of reflecting the results of using the traffic assignment model in a reality.

Another study topic is to identify individual travel paths of the closed section of route and materialize the transportation connectivity index. This is due to the reality that the number of paths available increases as expressway routes have continued to expanded. This can be solved by weighting and expanding the probability of path selection for the sample vehicles that were obtained by installing the automatic vehicle identification (AVI) system that uses the Hi-Pass system at junctions of major expressways that may have alternative path. However, to this end, it is required to install Hi-Pass antennas at many points, which is troublesome.

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