Prediction of Travel Time of Fire Service using Kriging and Weighted-sum Technique

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Abstract: The accessibility of city fire services is an important indicator for evaluating fire services and optimizing fire resource allocation. For firefighting, rescue, and first-aid activities, it is recommended that the time from fire vehicles leaving the garage to arrive at the scene is less than 5 minutes. Therefore, the travel time of fire services is one of the main concerns for many researchers. This study assumes that changing the urban environment affects the travel time of fire services. Therefore, in this study, weights were applied over the years to predict the travel time of fire service by using the kriging technique. As a result of the case study, temporal factors (elapsed year, term of travel time, and time spent) did not significantly affect travel time prediction accuracy using the kriging technique. As observed in previous studies, it is confirmed that the prediction accuracy is high because it is less affected by traffic-related factors at short travel distances. The results of this study contribute to the development of spatial analysis techniques to improve the accuracy of travel-time prediction.

Keywords: Fire service, Travel time, Kriging, Weighted sum

1. Introduction

If a fire continues without abatement of the combustion phenomenon in its early stages, the surrounding temperature rises rapidly, and the combustion spreads instantly. After 5 minutes, heat and combustible gas accumulate owing to convection and radiation phenomena; when a certain temperature is reached, instantaneous explosive combustion proceeds and the entire building is engulfed in flames[1]. When the fire reaches its peak stage, the amount of carbon monoxide accumulated inside the building increases rapidly, reducing the survival probability of a rescued person. Therefore, the recommended time between fire vehicles leaving the garage and arriving at the scene for extinguishing, rescue, and first-aid operations is less than five minutes. However, the arrival time at the fire site is delayed due to traffic congestion and parking problems, resulting in frequent large-scale fires[2]. In general, the travel time of fire vehicles is affected by land-use behavior (residential, commercial, industrial, etc.), road grade, number of lanes, road traffic characteristics such as one-way and exclusive bus lanes, and environmental characteristics such as the day of the week, time zone, and weather[3].

The fire risk assessment of buildings is affected by the fire prevention and protection measures for individual buildings, evacuation measures, and fire department responses. The occupants of buildings where the fire department's travel time prediction indicates that it will be difficult for firefighters to arrive within the golden time should strengthen fire prevention, protection, and evacuation measures to reduce fire risk.

Therefore, the travel time of firefighting services has been a primary concern for many researchers, and various prediction methods have been proposed. Because the physical and social processes of urban systems are spatial in nature, the data that describe them include spatial autocorrelations (proximity-based interdependencies on variables) that must be accounted for[4]. This study intends to predict fire service travel time using kriging, a spatial interpolation technique. This study assumes that changing the urban environment affects the travel time of fire services. Therefore, the weights were applied to the data by year. Daegu City, one of the largest cities in Korea, was selected as the research target, and fire service data (19,663 cases) from 2005 to 2014 were analyzed to predict the travel time of fire services.
2. Literature Review

2.1 Travel time prediction of emergency services

Various emergency services, including firefighting (emergency medical care, rescue, police, etc.), must be guaranteed to be as short and stable as possible to facilitate quick response[5]. When time is expended in the process of performing a mission, various rights (exceeding the speed limit, ignoring traffic signals, giving priority, etc.) are granted to enable quick responses[6]. Table 1 shows previous studies on the travel time of emergency services. In many studies[7-9] using geographic information system (GIS) network analysis, service areas were analyzed by applying the approximate travel speed. Shahparvari et al.[10] utilized the ratio of road density to travel time to account for variability in speed on the streets. Piórkowski[11] presented two versions of a method for displaying maps for ambulance coverage of areas and ambulances' probable travel times. They presented static (reachable positions at 15-20 min) and dynamic (for monitoring under normal conditions or in the event of a crisis) versions.

Another study[12-18] predicted travel time by applying parametric (e.g., linear regression, time series models, dynamic traffic assignment models, and Kalman filtering techniques) or nonparametric (e.g., neural network models, simulation models, Bayesian models, and support vector regression) methods.

In the field of spatial analysis, geospatial interpolation and regression tools have been used with a focus on the spatial autocorrelation of urban spatial data[19-22]. In addition, a study[23] was conducted to analyze the spatiotemporal accessibility of emergency services.

Table 1. Previous Studies on the Travel Time of Emergency Services

<table>
<thead>
<tr>
<th>Approach</th>
<th>Previous Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic or Stochastic Travel Time</td>
<td>[7-11]</td>
</tr>
<tr>
<td>Parametric or Nonparametric Methods</td>
<td>[12-18]</td>
</tr>
<tr>
<td>Geospatial Analysis</td>
<td>[19-23]</td>
</tr>
</tbody>
</table>

2.2 Kriging method

The spatial interpolation of low-density observation data causes an error at the point where data are not obtained, which negatively affects the accuracy of the analysis. Data obtained from high-density observation points can reduce the error rate in spatial interpolation; however, this is an inefficient method that increases the time and cost[24].

In addition, interpolation and extrapolation, which are estimation methods based on weights or the least-squares method, help construct a certain relationship by collecting independent elements without considering the correlation between the data used to form a relationship. Therefore, the problem with these methods is that the intrinsic characteristics between neighboring points are not reflected[25].

To solve this problem, several techniques, such as inverse distance weighting, local trend surface models, triangulated irregular networks, and kriging, have been studied in relation to spatial interpolation. Among them, ordinary kriging interpolation, proposed by Matheron in 1973, is an interpolation method that uses a weighted linear combination that minimizes the error variance[26].

Kriging is a statistical analysis method that applies the best linear unbiased estimator (BLUE). Estimated values are obtained from the correlation according to the linear combination of the surrounding data; the variance of the error is minimized, and the residual error is 0, so it has high accuracy[25,27].

Previous studies on predicting traffic data using the kriging technique include those by Crosby et al.[4], Ozbay and Yildirimoglu[28], Zou et al.[29], and Yang et al.[30].
3. Methods

This study focuses on assigning different weights to the temporal elements of data to increase the accuracy of predicting the travel time of a fire brigade using the kriging technique. In other words, the changing urban environment was assumed to affect the travel time of the fire service, and weights were applied to the data by year. Daegu City, a representative metropolis in Korea, was selected as the study site, and fire response data for 10 years (2005-2014) were collected. Data for eight years (2005-2012) were set as input values, and the accuracy of the analysis results was measured based on data for the remaining two years (2013-2014).

The weights given to the input values differed according to the year section and were divided into four cases.

① Case 1: Analyze eight years of data simultaneously.
② Case 2: After dividing the data into two sets of four years each, kriging analysis was performed, followed by overlapping analysis by assigning a high weight to the latest layer.
③ Case 3: After dividing the data into four sets for two years each and performing kriging analysis, a high weight was assigned to the most recent layer to perform overlapping analysis.
④ Case 4: After performing the kriging analysis by dividing the data into eight sets for one year each, a high weight is assigned to the most recent layer, and overlapping analysis is performed.

The flow of research for this study is shown in Figure 1.

![Figure 1. The flow of research for this study.](image)

The area of Daegu-si was 883.54 km². There were eight fire departments at the study site (119 rescue teams in 12 locations, 119 first-aid teams in eight locations, 119 safety centers in 49 locations, and 119 local teams in one location). Point data generated using the geocoding of real-time active fire data were obtained from the fire department. Figure 2 shows the locations of the fire sites within the study site.

In the 10-year period (2005-2014) within the study site, the total number of fire calls was 19,663, as shown in Figure 3; 13,809 cases required less than 5 min of travel time from the fire department to the scene, accounting for 70% of all such cases. In the case of arrival times of more than 5 minutes and less than 10 minutes, there were 4,874 cases, accounting for 24.78% of all such cases. The average travel time was 4 min 50 s (4.84 minutes), and it took up to 57 min 19 seconds (57.32 minutes).

Grades were classified based on the weight of the travel time of fire trucks. The Jenks natural break classification method was used to classify the grades into five and then supplement it to minimize the average deviation of the travel time of fire trucks within the target site and maximize the dispersion between each grade. In this study, if the travel time was less than 3 minutes, it was classified as 1st grade; if it was 3 minutes or more and less than 7 minutes, it was classified as 2nd grade; and if it exceeded 20 minutes, it was classified as 5th grade. Table 2 lists the classification criteria for fire response travel time used in this study. In the case of accuracy verification, actual
data and errors can be analyzed; however, in this study, the matching ratio (accuracy) was analyzed by comparing the grades of the predicted and actual data based on the grade of the fire emergency travel time.

![Figure 2. Distribution of fire response for 10 years (2005-2014) within the study site.](image)

Table 2. Grade Classification Criteria for Travel Time for 10 Years (2005-2014)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Natural Breaks (Jenks)</th>
<th>This Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Grade</td>
<td>0.000000-3.833333</td>
<td>0.000000-3.000000</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Grade</td>
<td>3.833334-6.600000</td>
<td>3.000001-7.000000</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; Grade</td>
<td>6.600001-11.666667</td>
<td>7.000001-10.000000</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; Grade</td>
<td>11.666668-22.166667</td>
<td>10.000001-20.000000</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; Grade</td>
<td>22.166668-56.366667</td>
<td>20.000001-56.366667</td>
</tr>
</tbody>
</table>

![Figure 3. Travel time statistics.](image)
4. Results

4.1 Accuracy result based on weight application according to case

Figure 4 shows the results of the kriging and weighted-sum analyses. These are based on the classification of fire-response travel time for eight years (2005-2012), as presented in Table 3.

A comparison of the analysis results with the grade of the fire-response travel time for two years (2013-2014), as presented in Table 4, revealed that the proportion (accuracy) of the predicted and actual values was 64.94%-66.09%. Although the accuracy differs slightly depending on the case, it is concluded that the application of a large weight to the data of the recent year does not significantly affect the accuracy.

![Figure 4](image-url)

**Figure 4.** Results of kriging and weighted-sum analyses: (a) case 1, (b) case 2, (c) case 3, and (d) case 4.
Table 3. Criteria for Applying Weights for Weighted-sum Analysis

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>8-year Period</td>
<td>2007-2014</td>
</tr>
<tr>
<td>Case 2</td>
<td>4-year Period</td>
<td>2007-2010</td>
</tr>
<tr>
<td>Case 3</td>
<td>2-year Period</td>
<td>2007-2008</td>
</tr>
<tr>
<td>Case 4</td>
<td>1-year Period</td>
<td>2007</td>
</tr>
</tbody>
</table>

Table 4. Comparison of Actual Travel Time and Predicted Results

<table>
<thead>
<tr>
<th>Classification</th>
<th>Number of Matches / Total</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>2,271/3,497</td>
<td>64.94%</td>
</tr>
<tr>
<td>Case 2</td>
<td>2,327/3,521</td>
<td>66.09%</td>
</tr>
<tr>
<td>Case 3</td>
<td>2,353/3,543</td>
<td>66.41%</td>
</tr>
<tr>
<td>Case 4</td>
<td>2,328/3,544</td>
<td>65.69%</td>
</tr>
</tbody>
</table>

4.2 Accuracy results according to travel time (grade) classification

Analysis of the prediction accuracy according to travel time (grade) revealed that the 1st and 2nd grades showed high accuracy, whereas the 3rd-5th grades showed low accuracy. In this study, grades were classified according to travel time; hence, it was inferred that travel time prediction using the kriging technique applies to fire cases with relatively short travel times.

![Figure 5. Accuracy results by grade and case.](image)

4.3 Accuracy results according to time spent (0-23 hour) classification

Accuracy of prediction according to time spent changes in a "W" pattern. In this case study, the 7-8 o'clock interval yielded the lowest prediction accuracy. The period with the highest prediction accuracy was the 0-1 o'clock interval.
5. Discussion

The occurrence of a fire is probabilistic; such an event can occur anytime and anywhere, and the state of the fire site is diverse. Therefore, the arrival of a fire brigade within the golden time is crucial; accordingly, various attempts have been made to predict the travel time, but this field is still challenging. "Travel time estimation and forecasting rely on data on vehicles (flows, speeds, queues, densities, etc.) on transportation networks, which are collected either manually (through questionnaires, surveys, census, or even standing at street corners and counting vehicles) or by installing sensors (hardware and software)" [6].

In this study, weights were applied over the years to predict the travel time of fire service by using the kriging technique. However, as described in Section 4, the weight applied to the data of the most recent year did not significantly affect the accuracy of the measurement results. Traffic and route selection significantly affect the travel time of fire vehicles, making their prediction difficult. In this study, the changing urban environment was assumed to affect the travel time of the fire service, and weights were applied to the data by year. However, at the study site, there were no urban environmental changes (e.g., fire emergency vehicle priority signal system) that could significantly affect the travel time of the fire service. Therefore, it is inferred that applying weight to the data by year does not significantly affect the research results.

In the case of Korea, the fire emergency vehicle priority signal system is being actively applied in some areas (e.g., Gyeonggi-do, Ulsan, etc.), and its effectiveness has been verified. According to J. H. Kim and H. J. Lee [31], an analysis of the pilot operation cases in April 2017 revealed that the average fire response time was shortened by 3 min 50 s. In this case, it is concluded that the weight application considerably influences a fire service's travel-time prediction.

Analysis of the prediction accuracy according to travel time (grade) revealed that the accuracy was high in the section with a relatively short travel time. According to Chen et al. [21], under moderate accessibility conditions, fire accidents are most affected by traffic congestion. In this study, the prediction accuracy changed according to time in the W-pattern. Because this case study simply analyzed the spatial autocorrelation of the fire point and travel time, the prediction accuracy was not high. However, according to Chen et al. [21], the accessibility of fire departments exhibits a W-pattern over time. Accessibility is lower during rush hour than at other times, and the rate of decrease in the accessibility of fire departments during rush hour is greater in urban areas than in suburban areas. Therefore, to improve the accuracy of travel time prediction, it is necessary to consider the spatial classification of cities, the distribution of roads (density and connectivity of roads), and the amount of traffic according to the time spent.

Travel time prediction of emergency services is highly related to the location-allocation problem of emergency facilities. From this point of view, the fact that the study did not analyze travel time by the fire department is the study's limitation. In future research, it is recommended to analyze and predict travel time by the fire department.
6. Conclusions

Continuous monitoring and improvement of information on the travel time of various emergency services are necessary to ensure the safety of a city, owing to the dynamic nature of the urban environment. Recently, it has become possible to collect data related to various environments and processes that can affect the travel time of fire vehicles. Therefore, research on big spatiotemporal data related to urban systems' physical and social processes and fire response data is attracting attention. In particular, in the case of firefighting services, data collection and prediction of travel time of firefighting services are important for solving the problem of optimization of firefighting resource allocation to reduce property damage and casualties.

This study attempted to predict the travel time of fire vehicles in terms of spatial autocorrelation of city data. A case study using kriging and weighted-sum methods confirmed that the prediction accuracy was not high. Considering the results of related studies comprehensively, to increase the accuracy of travel time prediction, it is necessary to consider not only the traffic volume according to the time spent but also the spatial classification of the city, distribution of roads (road density and connectivity), and changes in the spatiotemporal urban environment.

Author Contributions


Conflicts of Interest

The authors declare no conflict of interest.

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