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Research article

The Impedance of East Jakarta Road Network to Estimate Fire Station Service Areas

Jarot Mulyo Semedi, Mohammad Raditia Pradana*, Dhavani Ardyas Putera, Nurul Sri Rahatiningtyas

Department of Geography, Faculty of Mathematic and Natural Sciences, Universitas Indonesia, Depok 16424, Indonesia

*) Correspondence: mohammad.raditia@ui.ac.id

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Abstract

Urban fires, prevalent in densely populated areas, pose significant risks by increasing deaths and injuries. Fire departments must navigate challenging access routes to manage these incidents effectively. This study analyzes the service coverage of fire stations in East Jakarta, considering road network, width, speed, and travel time. The study utilizes secondary data from the DKI Jakarta Provincial Fire and Rescue Service, road network data from local government sources, and traffic data from Google Maps. Additionally, a field survey was conducted to validate road conditions and accessibility. Using graph theory-based network analysis, the study assesses connectivity, flows, directions, and destinations to determine the coverage extent. The optimal route, defined by road class, width, and condition, exhibits the lowest impedance. Google Maps' estimated travel times, incorporating traffic conditions, are used to assess travel times, with a 5-minute travel time set as the standard barrier for coverage. Results reveal that the current service coverage of East Jakarta fire stations is only 66.57%. This disparity indicates an inadequate number of fire stations relative to their required service areas. The findings underscore the need for strategic placement of additional fire stations and potential improvements in road infrastructure to enhance response times. Traffic dynamics often affect travel times, demonstrating that shorter distances do not always result in faster arrivals according to real-time data.

Keywords: connectivity; fire; impedance; network analysis; service area.

1. Introduction

Fire is defined as fire that cannot be controlled and is caused by three elements, namely oxygen as a burning agent, fuel or material, and heat or flame source (National Fire Protection Association, 2021; Rahadian *et al.*, 2022). In terms of disasters, fire incidents are in a Fire dominant position in increasing mortality and loss rates (Alkış *et al.*, 2021; Challands, 2010; Rahadian *et al.*, 2022). Losses from fire can include death and injury, building damage, disruption of community activities, and environmental pollution (Yu *et al.*, 2020). Fires in urban areas or urban fires are any fires that occur in densely populated urban areas and residential buildings, represent the majority of fire station services, and have significant economic and social impacts (Balasubramani *et al.*, 2016; Bispo *et al.*, 2023).

Fire has played a pivotal role in human history, from its discovery by early humans to its modern-day management (Dong *et al.*, 2018; Noori *et al.*, 2023). Throughout civilizations, fire has been both a vital tool for cooking and warmth and a destructive force requiring careful control (Rodrigues *et al.*, 2014). As societies have evolved, so too have our methods for handling fire-related incidents. However, as urban areas continue to expand, the challenge of managing fires in densely populated settings grows more complex (Ardiansyah *et al.*, 2019; Fire Fighter Nation, 2015; Zhang *et al.*, 2020). Today, understanding the causes and impacts of fires is essential for developing effective strategies to protect lives and property.

In 2020, the City of East Jakarta had 349 fire incidents throughout the year with various levels of damage and loss (DKI Jakarta Provincial Fire and Rescue Service, 2021). These figures indicate that the city of East Jakarta experiences fire incidents almost every day. For example, the Gembrong Market fire in East Jakarta took 4 hours and 43 minutes to extinguish using 26 fire trucks and 130 personnel. The estimated loss resulting from the fire incident was 400 burned buildings (Hardiantoro, 2022). From this information, starting from the causes and consequences, it is reflected that the fire incident in DKI Jakarta represents fires in urban areas.

Previous studies have extensively explored the service areas of fire stations to enhance emergency response efficiency. For instance, Balasubramani *et al.* (2016) and Davoodi (2019) analyzed the spatial distribution of fire stations and their response times in urban settings, emphasizing the importance of optimal locations for minimizing response time. Similarly, Dong *et al.* (2018) utilized GIS-based network analysis to determine the most effective routes for fire trucks, considering traffic conditions and road network configurations. Yu *et al.* (2020) employed GIS tools to map fire station coverage and response times, emphasizing the importance of strategic placement and route optimization.

Our study adopts these previous methodologies but focuses more on evaluating fire station service areas at the sub-district level in East Jakarta. Unlike earlier research, which assumed uniform road network conditions, our approach emphasizes the accessibility of firefighting vehicles on the dynamic road network. By incorporating real-time traffic data, we aim to provide a more detailed assessment of service area coverage and identify potential improvements in fire station response strategies based on specific sub-district conditions.

Extinguishing efforts, or in this case, the suppression stage, are key in containing the spread of the fire, such as response action from fire department personnel to the location of the incident (KC & Corcoran, 2017; Liu *et al.*, 2019). The fire department's response to fires is based on the assumption that the earlier a fire occurs, the less impact it will have on people and property (Challands, 2010; Erden & Coşkun, 2010; Liu *et al.*, 2021). This also depends on road conditions, such as travel time and traffic jams, which determine the impedance from the fire station to the fire location (Xu *et al.*, 2021). The service area of the fire station is the starting point for personnel to get to the fire location using efficient routes (Tali *et al.*, 2020; Zainal *et al.*, 2022). This research focuses on how the fire station reaches the surrounding area and how the impedance of fire fighting personnel gets to the fire location based on a road network whose travel time is dynamic at all times.

This study aims to assess the efficiency of the existing fire station service area coverage in East Jakarta, examine the correlation between the number of fire stations and service area coverage, and explore the possibility of adjusting travel times in response to real-time traffic conditions to improve the efficiency of fire response. By focusing on the fire station's reach to surrounding areas, the relationship between the number of fire stations and service area coverage, and the impact of dynamic travel times, this research seeks to develop a comprehensive understanding of the factors influencing fire response times in East Jakarta.

2. Research Methods

2.1. Study area

The study area for this research is East Jakarta City, DKI Jakarta Province. The city of East Jakarta consists of 10 sub-districts, which have a total area of 188.03 km^2. The population density in East Jakarta City reaches 16,401 people/km^{2,} with Matraman District being ranked first as the district with the most dense population in East Jakarta City (BPS Kota Jakarta Timur, 2023).

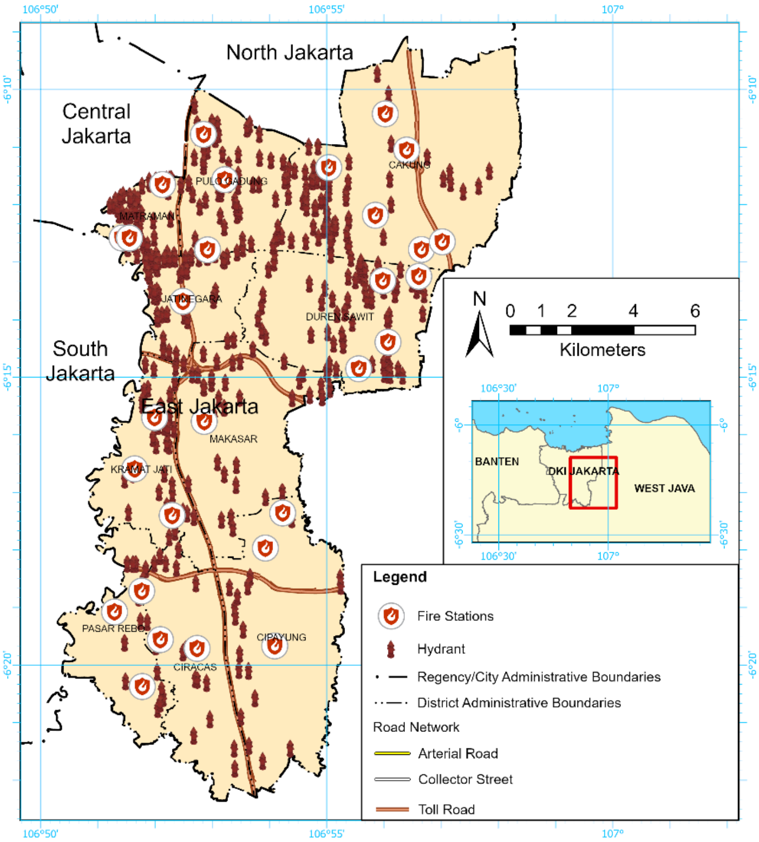

Figure 1. Study area.

There are 10 Fire Management Areas (WMK) in East Jakarta with a technical travel distance of 7.5 km or 15 minutes from the fire station. However, in practice, the division of WMK isased on sub-districts, especially in DKI Jakarta Province (Minister of Public Works of the Republic of Indonesia, 2009). Fire protection infrastructure to overcome this is present, such as 30 fire stations and 424 hydrants located in East Jakarta City (Figure 1).

These fire protection facilities are strategically positioned to minimize response times and maximize accessibility to densely populated areas, where the risk of fire incidents is higher. The presence of a sufficient number of fire stations and hydrants reflects the proactive approach of local authorities in mitigating fire risks and safeguarding the welfare of residents (Alkış *et al.*, 2021).

2.2. Variable and data

The data used in this research is spatial data which includes research variables, namely fire station locations, road networks, Fire Management Areas (WMK), and historical fire events (Table 1). The table provides an overview of various variables relevant to fire management and emergency response within East Jakarta City. Firstly, it includes data on the locations of fire stations, represented by their latitude and longitude coordinates, sourced from the East Jakarta City Fire Management and Rescue Sub-Department. This information is crucial for understanding the spatial distribution of fire stations across the city, facilitating effective deployment and coordination during emergency situations. Additionally, the table presents data on road networks, including the classification of road network classes in East Jakarta City sourced from OpenStreetMap. This classification encompasses factors such as the average width of each road network class, speed limits for each road class, aiding in assessing the accessibility and navigability of routes for fire vehicles. Furthermore, it provides insights into Fire Management Areas (WMK), delineated by the East Jakarta City Fire Management Area shapefile, offering a geographical framework for organizing and managing fire response efforts within specific zones. The table also includes information on historical fire events, serving as a sample dataset of past incidents in East Jakarta, essential for analyzing patterns and trends to inform future prevention and response strategies. Lastly, the table incorporates data on travel time dynamics, including estimated travel time based on traffic conditions sourced from Google Maps, which is instrumental in optimizing route planning and resource allocation for timely and efficient emergency response operations. Overall, the table aggregates diverse datasets crucial for enhancing fire management and emergency response capabilities in East Jakarta City.

Table 1. List of variables and data.

No	Variable	Data description	Source
1	Fire station locations	Location coordinates of fire stations in East Jakarta City (latitude and longitude coordinate)	East Jakarta City Fire Management and Rescue Sub-Department
2	Road networks	Classification of road network classes in East Jakarta City The average width of each road network class classification Speed limits for each road class	OpenStreetMap
3	Fire Management Areas (WMK)	East Jakarta City Fire Management Area (shapefile)	East Jakarta City Fire Management and Rescue Sub-Department
4	Historical fire occurance	Sample of fire incidents in East Jakarta	
5	Travel time dynamics	Estimated travel time based on traffic conditions	Google Maps

2.3. Analysis process

The analysis process in this research includes processing processes for the spatial data used (Figure 2). The processing and analysis process includes data preparation processes, database creation, network analysis, and calculating travel time estimates based on traffic dynamics. The process starts from preparing road network data which includes class, width and average speed using a topology process (Table 2 & 3). Apart from that, fire station location data will be included in the network dataset along with the results of the existing road network topology. Next, network analysis was carried out in the form of a service area with a time impedance input of 5 minutes. This will result in two classes of areas that cover 5 minutes and those that don't. This coverage will be analyzed according to WMK as the unit of analysis. These results will be compared with the estimated travel time from Google Maps. The output of this process is carried out to estimate fire fighter travel time based on traffic dynamics.

Service areas in a general context are spatial partitions which are an important issue in determining service area boundaries that have high efficiency values (Balasubramani *et al.*, 2016; Yu *et al.*, 2020). To obtain this coverage, the considerations used can be distance, time and connectivity

(Baihaqi *et al.*, 2019; Wan Jusoh *et al.*, 2023). Therefore, in obtaining the coverage area or range of fire posts based on the road network, network analysis with service area types is used. The analysis process ensures a comprehensive understanding of fire station service areas, the impact of road network characteristics on fire response times, and the dynamic nature of travel times based on real-time traffic conditions.

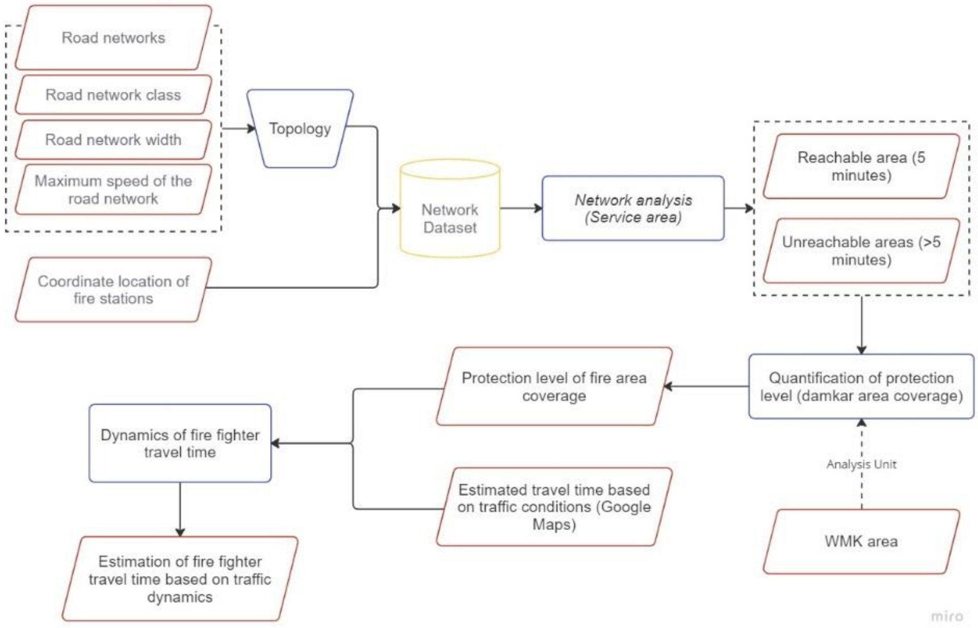

Figure 2. Research process flow.

Network Analysis:

1. **Service Area Analysis**: Perform a network analysis to determine the service areas of fire stations with a time impedance input of 5 minutes. This analysis helps identify areas within 5 minutes of a fire station and those beyond this threshold.
2. **Coverage Analysis**: Compare the 5-minute service area coverage with WMK boundaries to assess the effectiveness of fire station distribution in covering the population.

This process involves using geographic information system (GIS) tools to model and visualize the service areas, highlighting gaps in coverage and areas needing improved access.

Travel Time Estimation:

1. **Traffic Dynamics:** Integrate real-time traffic data from Google Maps to estimate travel times under various traffic conditions. This step is crucial for understanding how dynamic traffic conditions affect fire response times.
2. **Comparative Analysis:** Compare the travel time estimates from the network analysis with real-time traffic data to identify discrepancies and validate the model. This comparison helps ensure that the travel time estimates are realistic and applicable in practical scenarios.

Statistical Analysis:

Regression Analysis: Use regression analysis to evaluate the relationship between the number of fire stations and the service area coverage, on Equation 1. This helps determine whether increasing the number of fire stations leads to better coverage.

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \quad (1)$$

Y_i: Service area coverage for WMK i, X_i: Number of fire stations in WMK i, β_0: Intercept (constant term), β_1: Slope coefficient (indicates the change in service area coverage for each additional fire station), and ϵ_i: Error term (captures random variability).

Correlation: Identify the strength of the relationship between the number of fire stations in each WMK and the size of the service area, in Equation 2.

$$r = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2 \sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \quad (2)$$

$\bar{X}$: Mean of X (number of fire stations), $\bar{Y}$: Mean of Y (service area coverage), interpretation of r :

$r = +1$: Perfect positive correlation

$r = -1$: Perfect negative correlation

$r = 0$: No correlation

Table 2. Firefighting vehicle accessibility based on road width.

The width of the road	Accessibility of fire fighter vehicles
<5.5 meter	Can't access
≥5.5 meter	Can access

Table 3. Maximum speed based on road classes.

Road class	Maximum speed (km/hour)
Arterial road	80
Collector road	80
Neighborhood road	30
Local road	30
Toll road	100

Source: Minister of Transportation Regulation of the Republic of Indonesia Number PM 111 Year 2015 concerning Procedures for Determining Speed Limits (Minister of Transportation of the Republic of Indonesia, 2015).

3. Results and Discussion

3.1. Service area coverage

Service area coverage from network analysis confirms that all fire stations cannot cover all areas of East Jakarta City (Figure 3). The area covered by fire stations is 123.19 Ha (66.57%) and not covered is 61.85 Ha (33.43) (Table 4). Only about a third of the area of East Jakarta City is covered by fire stations during the critical time of 5 minutes. If we look at the research analysis unit, namely WMK, we get various numbers. The Pulo Gadung district area was fully covered by fire extinguishers for 5 minutes (Figure 4). This is very different from Cipayung District, where only 22.35% of the area is covered by fire stations within 5 minutes. There are also two WMKs or other districts with critical fire post coverage areas, namely Cakung and Pasar Rebo. Other WMKs with coverage above 70% consist of 7 WMKs or other districts. Therefore, this analysis produces 3 WMKs or sub-districts that are worrying about handling fires. This critical WMK raises the question of whether having more fire stations in an area can increase the service area coverage of fire stations?

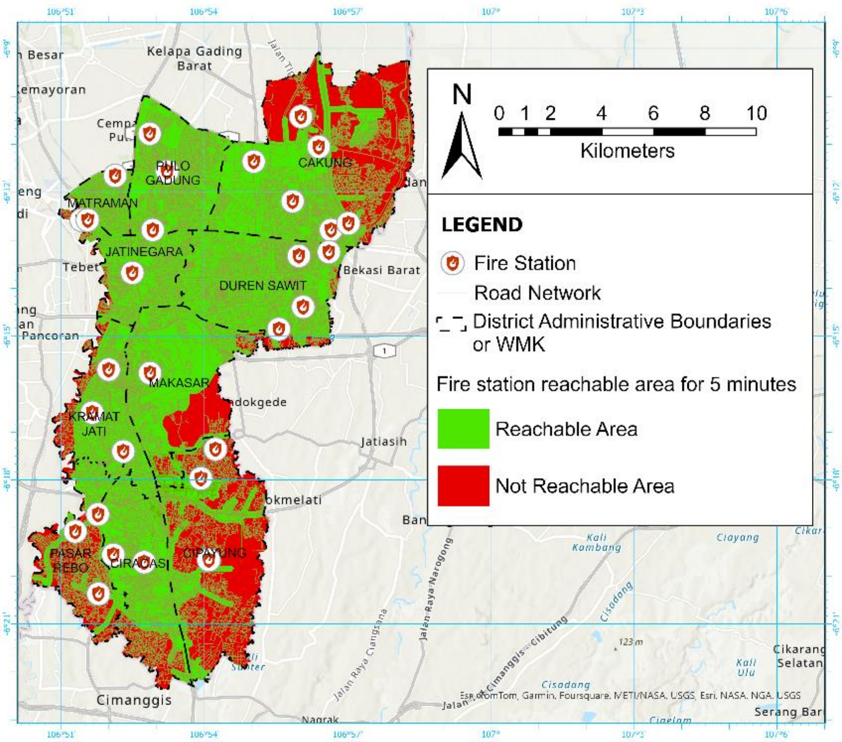

Figure 3. Fire station reachability map for 5 minutes.

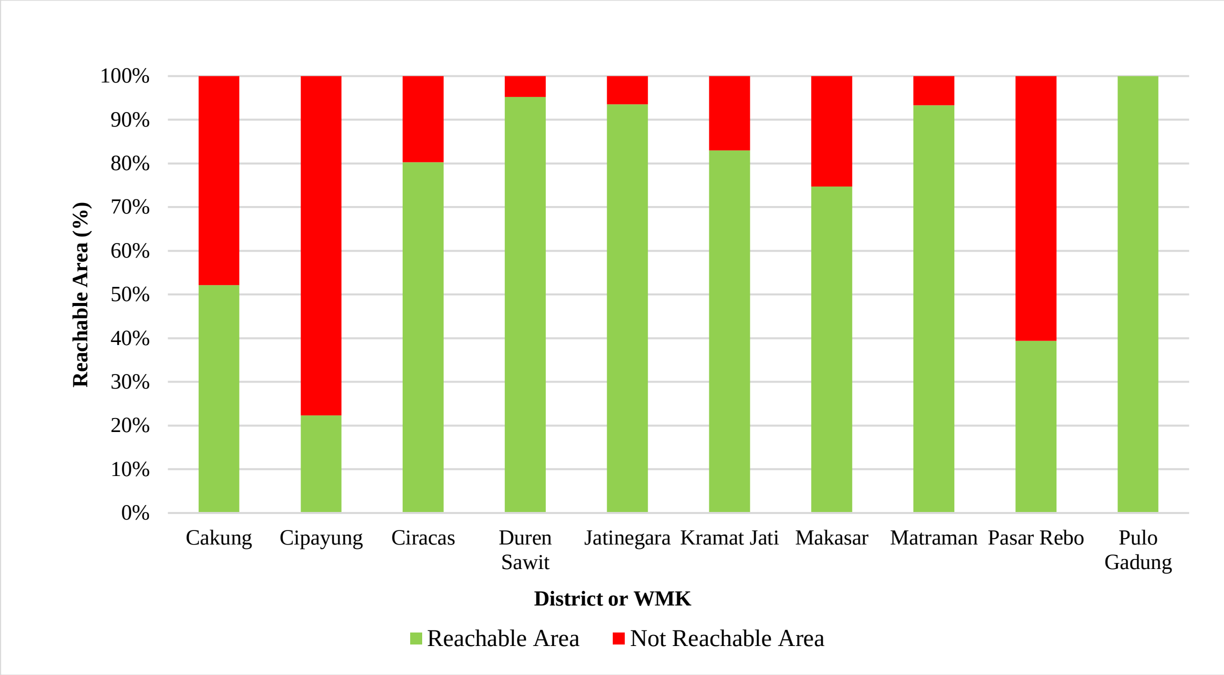

Figure 4. Percentage of reachable areas per WMK or district.

Table 4. Fire stations coverage service area in East Jakarta.

	Reachable	Not Reachable
Hectares	123.5	61.85
Percent (%)	66.57	33.43

3.2. More fire station, more coverage area?

Fire stations have a central role in handling fires. Response times, locations and extinguishing actions are regulated in applicable regulations such as Minister of Public Works Regulation 20/PRT/M/2009 concerning Technical Guidelines for Fire Protection Management in Urban Areas which includes fire stations accessibility and technical Fire Management Areas (WMK) established (Minister of Public Works of the Republic of Indonesia, 2009). However, the basic and general question is "Will more fire stations provide a wider range of fire handling within the range of response times?". The answer can be seen in the figure 5 which provides information on the distribution of the relationship between the number of fire stations and the size of the fire service area per sub-district. It can be seen that the distribution has a random pattern and is certainly not linear. WMK Cakung with the highest number of fire stations, namely 6, only has a service area of around 50%. In contrast, WMK Jatinegara only has 1 fire station with a service area above 90%. WMK Pulo Gadung, which has 100% service area coverage, only has three fire stations. Others, WMK Cipayung with the same number of fire stations only have the lowest coverage.

An analysis was conducted to examine the relationship between the number of fire stations and the reachable area percentage across 10 districts in East Jakarta City. A Pearson correlation test revealed a weak negative correlation ($r = -0.2751$, $p = 0.4416$) between these variables, indicating no statistically significant linear relationship. Linear regression analysis further supported this finding, with a negative slope (-4.5997) and a low R-squared value (0.0757), suggesting that only about 7.57% of the variance in reachable area can be explained by the number of fire stations. The scatter plot visually confirms the lack of a clear linear trend, with districts like Pulo Gadung achieving 100% coverage with just 3 fire stations, while Cakung, with 6 stations, only reaches 52.15% coverage. These results align with the original observation that the relationship between fire station numbers and coverage area is not linear. Factors such as district size, road network connectivity, spatial distribution of fire stations, and traffic dynamics likely play significant roles in determining effective coverage. This analysis underscores the complexity of fire service planning and suggests that simply increasing the number of fire stations may not necessarily lead to improved coverage without considering other critical factors.

Other factors certainly influence why these cases arise. These factors can include area per area, road network connectivity which includes road restrictions and their suitability for operating fire engines, and spatial factors such as location that influence the impedance of the fire station itself (Lee *et al.*, 2021; Wagistina *et al.*, 2022). This factor is a static factor which does not change over time. However, another factor that is close to reality in the real world is traffic dynamics which of course influences the travel time from fire station personnel to the fire location.

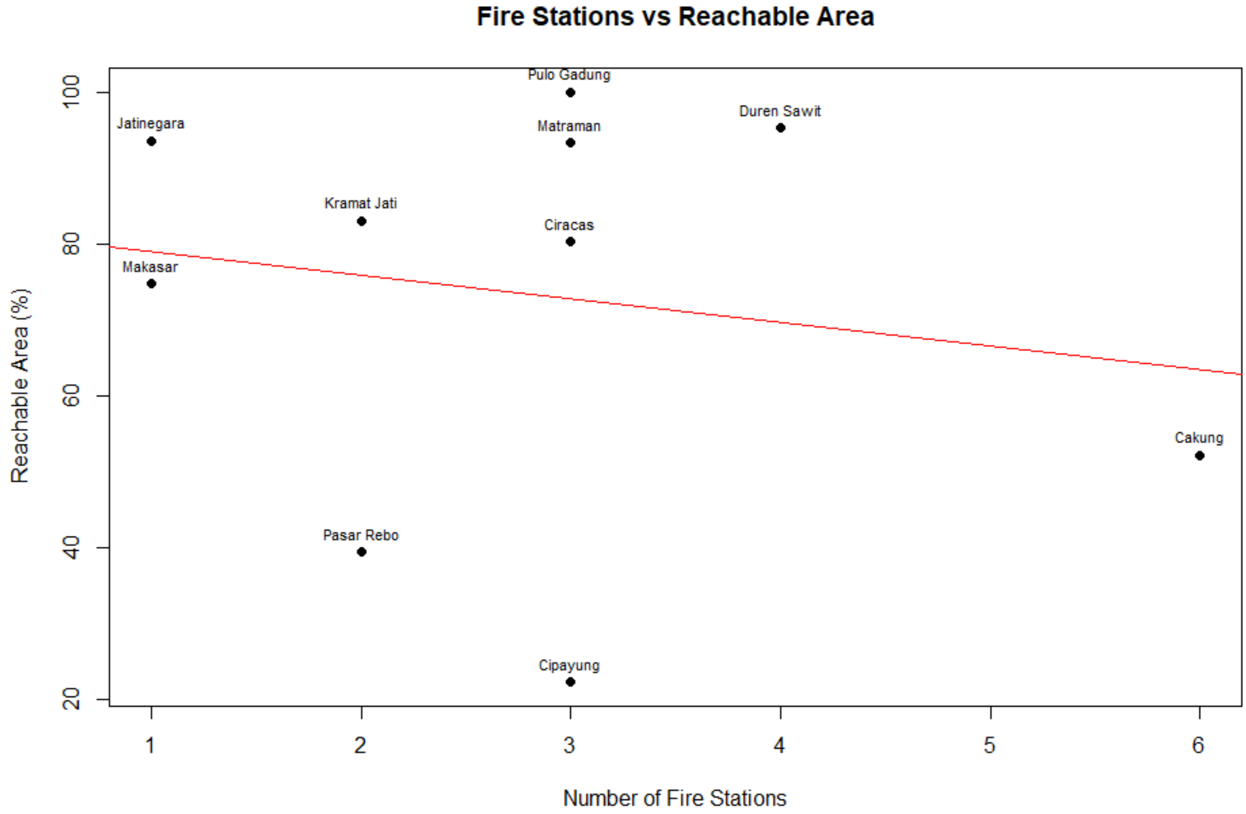

Figure 5. Distribution of reachable areas with number of fire stations per WMK or district.

3.3. Study case: Travel time dynamic

In this research case study, two fire cases were taken in East Jakarta City. The two cases were a fire incident at Gembrong Market, Jatinegara District on April 24 2023 (Hardiantoro, 2022) and a fire incident on the Duren Sawit District Ring Road on May 30 2023 (Putra, 2023). The difference in fire cases is the accessibility, especially the main road network of the two incidents, Gembrong Market is on a major road (Figure 6a) and the incident on the Ring Road is a small road (Figure 6b) which of course has different accessibility. In this case study we also use the two closest fire stations each from the two locations obtained from Google Maps (Figures 7a – 7d). The resulting travel time estimate is visible in the figure which shows the dynamics of travel time between the nearest fire post and the location of the fire incident as well as the travel distance sourced from Google Maps (Figure 7).

Travel time estimation results sourced from Google Maps provide dynamic traffic conditions. The time division is divided into three, namely morning (08.00 AM), afternoon (12.00 AM), and afternoon (04.00 PM). These three times are of course meant to represent three conditions of time. Morning represents traffic conditions in starting activities (going to work, school, etc.), afternoon represents traffic conditions in activities such as work, school, and other economic activities, and afternoon represents traffic conditions in ending activities (coming home from work, school, etc.). The results obtained show that these dynamics are described in a matter of minutes. However, minutes are considered important when it comes to blackout activities, where time is critical.

The discussion that emerged from these results (Figure 8) was that fire fighter personnel from the fire station arrived at the fire location predominantly in more than 5 minutes, which according to the standard 5 minutes is the maximum time for fire fighter personnel to arrive at the fire location. The road to the large Gembrong Market shows its characteristics if you compare the travel time for Matraman Fire Service Station – Gembrong Market with a distance of 3.4 km and Keleder Fire Station – Lingkar Duren Sawit Road with a distance of 2.7 km. It can be seen that longer distances can have lower travel times if we look at this case. The accessibility factor is that the road to Gembrong Market is on a large road, while the fire incident at Lingkar Duren Sawit Road has low accessibility with a smaller road, automatically the speed of fire fighting vehicles can be reduced.

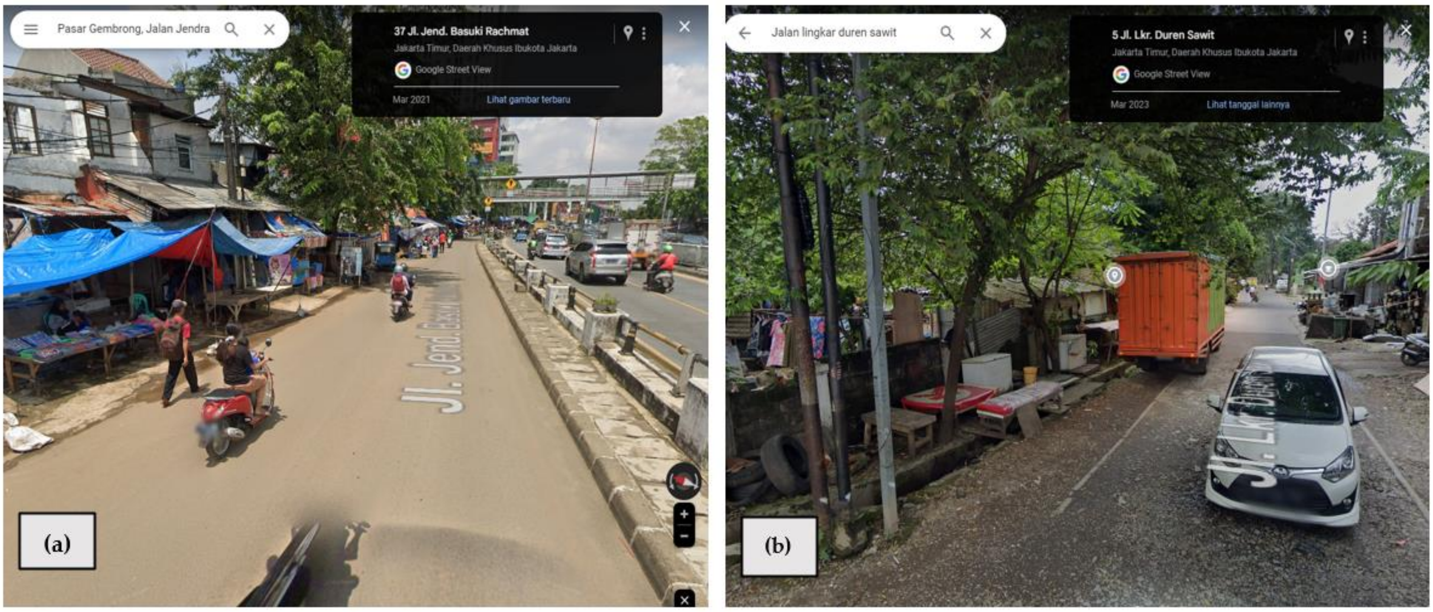

Figure 6. (a). Gembrong Market road condition, (b). Lingkar Duren Sawit road condition.

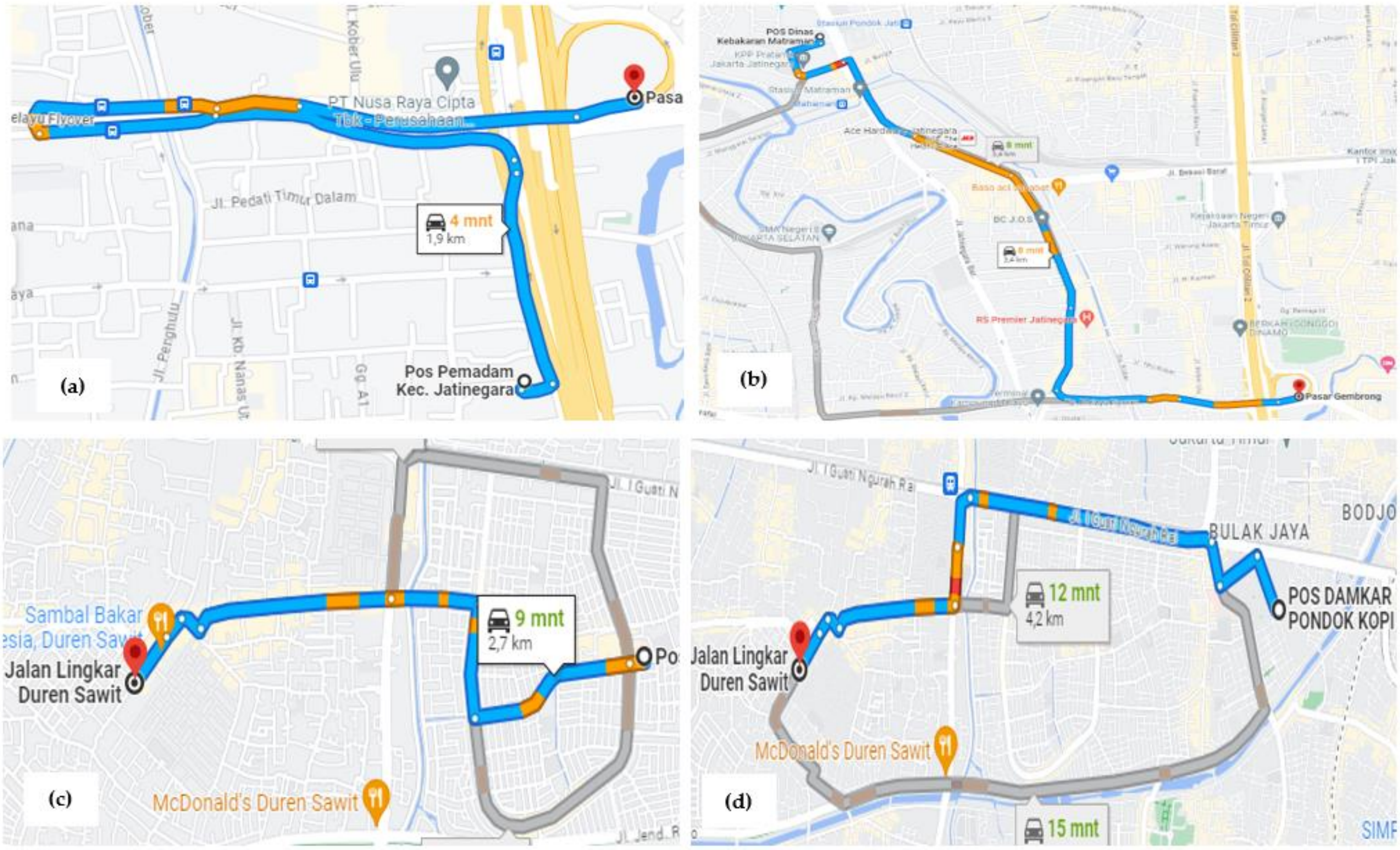

Figure 7. (a) Jatinegara District Fire Station – Gembrong Martket (1.9 km), (b) Matraman Fire Service Station – Gembrong Market (3.4 km), (c) Kelender Fire Station - Lingkar Duren Sawit Road (2.7 km), and (d) Pondok Kopi Fire Station - Lingkar Duren Sawit Road (4.2 km).

However, another case that is contrary to the previous case is that the travel time for Jatinegara District Fire Station - Pasar Gembrong (1.9 km) and Pondok Kopi Fire Station - Lingkar Duren Sawit Road (4.2 km) shows linear condition (Figure 8). The longer the distance, the higher the travel time. These things indicate that traffic dynamics do not run linearly, especially travel time and distance considering traffic conditions such as vehicle volume, vehicle speed on the road, and connectivity. Impedance (travel time) from one place to another certainly cannot be separated from these factors which are static (travel distance) and dynamic (traffic conditions).

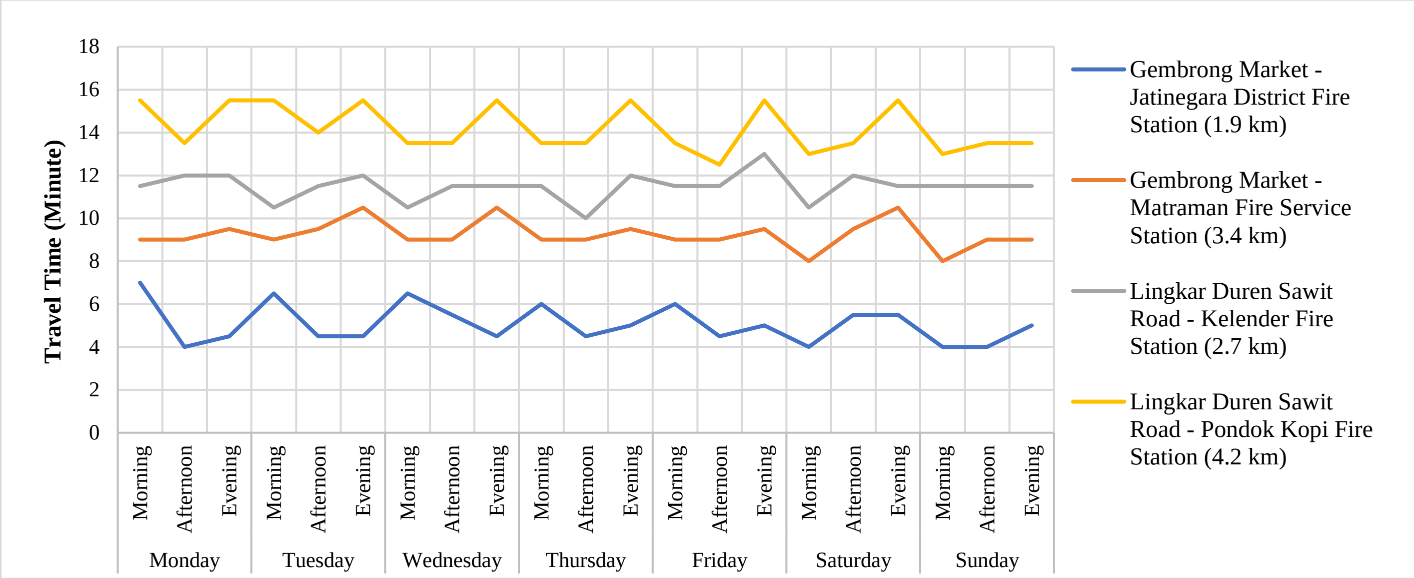

Figure 8. Dynamics of travel time from the fire station to the incident location.

3.4. Discussion

This study provides a comprehensive understanding of fire station service coverage and the challenges faced in East Jakarta City. Previous research has emphasized the critical role of fire stations in emergency response (Lestari *et al.*, 2022; Zainal *et al.*, 2022). The findings highlight significant deficiencies, with only 66.57% of the area reachable within the critical 5-minute response time, indicating vulnerabilities in emergency preparedness linked to road network connectivity and the expansive geographical area covered by each fire station.

Lestari *et al.* (2022) achieved over 90% coverage on a small island despite minimal road infrastructure, leveraging narrow land areas and specialized hose lengths. Similarly, Zainal *et al.* (2022) demonstrated high coverage using small vehicles on narrow roads. In contrast, the methodology of this study imposes limitations to ensure accessibility for all types of fire-fighting vehicles, accommodating the widest fire truck widths compatible with road conditions. These comparisons underscore the need for tailored approaches to address diverse geographical and infrastructural challenges effectively.

Furthermore, the analysis reveals significant variations in coverage among East Jakarta's subdistricts, indicating areas with both robust service and critical gaps during peak response times. Understanding these disparities is crucial for identifying high-risk areas and optimizing resource allocation to mitigate potential threats (Tali *et al.*, 2020). Interestingly, the research challenges the assumption that increasing the number of fire stations linearly expands coverage. The study found a non-linear relationship between station quantity and service area size, highlighting the significant influence of road network connectivity, traffic dynamics, and spatial characteristics on response times (Wan Jusoh *et al.*, 2023; Widyantoro & Santosa, 2021).

The study faces certain limitations due to the availability and accuracy of data related to road conditions and traffic dynamics. These factors are crucial as they directly impact the response times of fire stations. The study relies on existing data, which may not always capture the real-time variability of traffic conditions in East Jakarta City. For instance, traffic patterns can fluctuate throughout the day and across different days of the week, affecting how quickly fire stations can respond to emergencies. Moreover, the accuracy of road condition data can influence the accessibility of fire-fighting vehicles, which is essential for determining the effective coverage area of each fire station. These limitations imply that the findings and conclusions drawn from the study are based on the assumptions made from available data rather than real-time, dynamic conditions on the ground.

4. Conclusion

The conclusions from this research are divided into several important things. The important thing is that all fire stations do not fully cover the service area coverage in East Jakarta City. If we trace it to the unit of analysis used, it is per district or WMK, in this case some gaps can be seen between several WMKs. There are variations in service area coverage between WMKs which cannot be said to be directly proportional to the number of fire stations in each WMK. Traffic dynamics also need to be considered in terms of quick response from firefighters to the location of the fire inci dent. Traffic dynamics affect the travel time for fire personnel to get to the

fire location, which is a critical condition. In the case studied, travel time and travel distance do not run linearly, where random conditions influence traffic conditions. It is hoped that further research can fill the gap in this research by being able to map the fire station service area dynamically or according to traffic conditions in a fraction of time, so that the impedance of the fire station service area can be drawn to the surrounding area in a specific time period.

Highlighting challenges in emergency preparedness linked to road network connectivity and fire station coverage. To address these findings, future efforts should prioritize incorporating real-time traffic data to better understand and respond to dynamic traffic conditions impacting response times. Additionally, considering factors such as population growth, urban development trends, and seasonal traffic variations in emergency response planning can optimize resource allocation and enhance service coverage across different sub-districts. Implementing predictive modeling based on historical data and growth projections would further guide strategic decisions on fire station placement and resource distribution, ensuring more effective emergency response capabilities in East Jakarta City.

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Author Contributions

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Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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