Selecting The Best Route for Aerial Ladder Truck to Speed Up Response Time in High-Rise Buildings Located in Unprotected and High Fire Risk Areas

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Abstract— **Fire outbreaks on high-rise buildings require specific techniques and equipment; one of such equipment is aerial ladder trucks. Firefighters in aerial ladder trucks must ideally arrive at the location of the fire within the ideal response time constraint in the context of fire emergency management to minimize collateral damage, be it of human lives or properties. This study aims to discover the best route traversable by aerial ladder trucks to achieve the ideal response time should a fire occur in high-rise buildings, particularly stated buildings located within unprotected and high fire risk areas in Sidoarjo Regency. The best routes were selected through a simulation using the closest facility in GIS Network Analyst based on proximal distance and travel time. The study results show that the aerial ladder trucks can traverse the recommended routes to the high-rise buildings within the ideal response time. However, the majority of these results only occur during off-peak hours. Hence, the addition of new fire stations, whose locations are within 5 km of the high-rise buildings, and the improvement or addition of street networks as an alternative to increase the fulfillment of the ideal response time of aerial ladder trucks, especially during peak hours, are recommended.**

Keywords— **Closest Facility, Fire, GIS Network Analyst, High-Rise Building, Response Time.**

I. INTRODUCTION

Sidoarjo Regency constitutes part of the metropolitan area of Surabaya or commonly known as the GKS metropolitan area (*Gerbangkertosusilo*), situated within East Java Province, Indonesia. The location of Sidoarjo Regency is geographically bordering Surabaya City, acting as both the capital province and center of urban activity in the GKS metropolitan area (see Figure 1). Its location's strategic value and supporting role to Surabaya City have pushed rapid physical urban changes. Undeveloped lands, previously functioning as farmlands and inland fishing grounds, were converted into residences, shopping centers, warehouses, and industrial areas **Error! Reference source not found.**. As a result, secondary and tertiary economic sectors currently become the backbone of the Sidoarjo Regency's economy [2].

The rapid development experienced by the regency has made it the second densest city in the GKS metropolitan area after Surabaya City. According to the Central Bureau of Statistics, the total population had reached 2.2 million with a population density of 3,173 people/km^2 [3]. However, the dwindling availability of vacant land and increase in land prices, which demand more efficient and effective land use, led to developers constructing more high-rise buildings in the past few years.
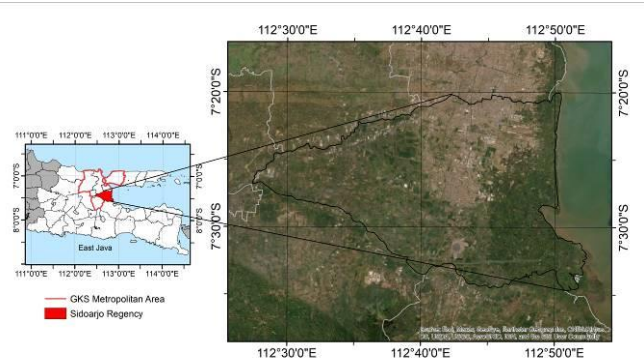

Figure 1. Location of Sidoarjo Regency on East Java Province.

There are various usages of high-rise buildings in Sidoarjo Regency, ranging from apartments and hotels to higher education facilities. When further examined, their locations are mostly dispersed within the city center and the border between Sidoarjo Regency and Surabaya City. At this point, problems started to arise. Based on data from the Sidoarjo Regency Fire Department, 2019 had the most fire incidents during the last four years, with up to 421 incidents. Most of the fire incidents occurred in the city center of Sidoarjo Regency.

On the other hand, according to the Fire Protection System Master Plan for Sidoarjo Regency Year 2020 (RISPK 2020), most high-rise buildings are located beyond the service coverage area of aerial ladder trucks. Such circumstances indicate that firefighters are unlikely to reach the site in an ideal response time if a fire occurs in any of the facilities mentioned above. In retrospect, the response time rate in fire emergency management plays a vital role in minimizing collateral damages, be it of human lives and properties [4]–[8].

Fire management on high-rise buildings requires different or specific techniques and equipment by the inability of standard equipment to reach buildings above 75 feet (± 6 stories) [9]. Internal fire protection systems installed inside the buildings will be insufficient in removing fire-related threats in a fire outbreak, such as flame and smoke puffs capable of spreading at a frantic rate due to the stack effect [10]. During an evacuation towards a safe refuge, the situation is exacerbated by the intense heat, paranoia, and toxic fumes, which further endangers the safety of the evacuees [11]–[13]. Hence, firefighters must arrive quickly with the necessary instruments, one of them being aerial ladder trucks, on fire outbreaks in high-rise buildings to extinguish what would otherwise be unreachable fire hotspots

for standard equipment.

By considering the importance of speed in responding to a fire outbreak, this study aims to discover the best route traversable by aerial ladder trucks to achieve an ideal response time should a fire occur in a high-rise building. The best routes were selected through the closest facility solver approach in the GIS Network Analyst by considering two main factors consisting of the proximity of the high-rise building to five existing fire stations and the travel time required to reach it. In addition, this study established 15 minutes as the baseline of the ideal response time. This decision was under the applied standard based on the Decree of Indonesia's Ministry of Public Works and Housing (*Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat*) No. 20/PRT/M/2009. It reflects that there is no universally agreed ideal response time because it depends on the urban setting and the availability of resources, respectively [8]. Therefore, each area possesses a varying degree of the response time difference, ranging from 4 to 25 minutes [14]–[15], [10], [16]–[20].

High-rise buildings that become the foci of the study refer to buildings with more than five stories, located within the high fire risk zone and beyond the service coverage area of fire stations. The underlying reasons behind the limitation of the building floor relate to the skyline and fire management. On the one hand, building structures with more than five stories protrude beyond the skyline more than other buildings in the Sidoarjo Regency. On the other hand, specific techniques and equipment are required for building structures with more than five stories [9], [21].

II. METHODOLOGY

A. Field Observation

We conducted field observations to identify the distribution of high-rise buildings and fire stations in the Sidoarjo Regency. From a technical standpoint, we utilized satellite imagery as an aiding tool to determine the coordinates of the locations. The result of the coordinates was processed in GIS to produce a distribution map of high-rise buildings and fire stations. For the high-rise buildings, we also reviewed the characteristics of state buildings and formulated the information in a table.

B. Overlay Analysis

We performed overlay analysis to determine the status of the high-rise buildings concerning the high fire risk zones. The previous map (distribution map of high-rise buildings) was overlaid with the increased fire risk zone map obtained from the Fire Protection System Master Plan (RISPK) for Sidoarjo Regency Year 2020. The outcome of the overlay exhibited the status of the stated buildings, whether they are zoned in low-, medium- or high-risk fire areas.

C. Network Analysis

Network analysis is a commonly-used approach to solve transportation problems, including but not limited to finding the closest facilities to a particular location, discovering optimal service areas, calculating multi-point vehicle routing, performing location-allocation, conducting time-independent analysis, and creating an origin-destination (OD) cost matrix [22]–[23]. In this study, we used one of the layers in GIS

Network Analyst, which is the closest facility solver, to determine the best routes traversable by aerial ladder trucks towards their respective high-rise buildings in a fire outbreak by considering two main factors; the proximity of the high-rise building to five existing fire stations and the travel time required to reach said high-rise building.

We utilized three principal network datasets covering: 1) data on the distribution of fire stations; 2) data on the distribution of high-rise buildings; and 3) street networks. The distribution of fire stations depicted the location of five existing fire stations distributed in Buduran, Krian, Porong, Candi, and Waru District. On the other hand, the distribution of high-rise buildings contained the location of multi-story buildings within the high fire risk zone and situated beyond the service coverage areas of stated fire stations. Finally, the street networks showed road segments traversable by aerial ladder trucks with the following criteria:

1. Road dimensions

A particular road segment must possess a minimum width of 5 meters to cater to aerial ladder trucks' maneuvers with average dimensions of 12 meters long, 2.5 meters wide, and 3.9 meters tall. The dimensions of the aerial ladder truck are the smallest in sizes based on the average aerial ladder truck suppliers in Indonesia, which is adjusted to the condition of the road network in the Sidoarjo Regency (Figure 2). The selection of the stated road segments utilized the street network data provided by the Department of Transportation of Sidoarjo Regency (*Dinas Perhubungan Kabupaten Sidoarjo*).
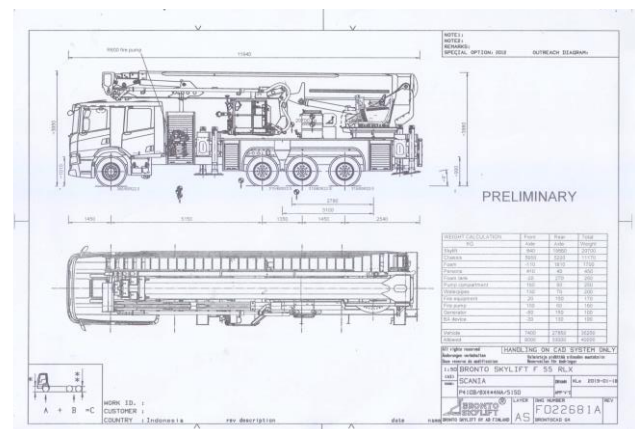

Figure 2. The specifications technical drawing of aerial ladder truck type 55 m (height above 40 m and below 60 m)

2. Traffic barriers

Road segments must be vacant of any traffic barriers potentially hindering the mobilization of aerial ladder trucks. Examples of the obstacles include but are not limited to upper barriers (viaducts and tree branches) and lower barriers (road bottlenecks, crossroads/road junctions (signaled or non-signaled), and railroad crossings) [24]–[26]. We utilized Google Street View to identify upper and lower barriers, where field observations eventually verify stated barriers.

After having selected segments of the street network traversable by aerial ladder trucks, the time required by stated trucks to navigate each part of the road (line-per-line) was counted. The time measurement was categorized during peak hours and off-peak hours, considering traffic density

significantly affects travel duration [27]–[28]. Next, the travel time in each road segment was calculated through Google Maps, which has taken the real-time trip, actual traffic conditions, and network structure (the presence of signaled or non-signaled crossroads/road junctions) into account of the required time. The calculation of peak hour travel time was comprised of three major time divisions: 07.00-09.00, 11.00-13.00, and 16.00-18.00 for two weeks throughout October 2020, whereas the calculation of off-peak hour travel time was conducted randomly out of the peak hours. The results of the measures were then averaged to determine the baseline standard of travel time required to navigate each road segment.

Three of the stated network datasets were analyzed using the closest facility available in the GIS Network Analyst feature. In the analysis setting, the unit of distance was set to a meter to offer more straightforward data interpretation after conversion to a kilometer. Furthermore, the selected travel management setting (*travel from*) was the facility to the incident with the limitation of only two nearest fire stations to be considered in the simulation of one high-rise building. The output of the analysis was in the form of a recommendation of the two best routes traversable by aerial ladder trucks from the nearest two fire stations to the location of the high-rise buildings. We would select the best route out of the two recommended routes by comparing the distance and travel time.

III. RESULTS AND DISCUSSIONS

A. Distribution and Characteristics of High-Rise Buildings

The result of the field observation indicated that there are seven high-rise buildings in Sidoarjo Regency functioning as apartments, hotels, and universities. Out of all of the high-rise buildings, Tamansari Prospero Apartment was visibly seen as the tallest building, with its structure being comprised of 29 stories. It had been built in 2015 on top of 1.2 hectares of land by one of the state-owned enterprises, Wika Bangunan Gedung [29]. The apartment's location is situated in the residential area of Kahuripan Nirwana, which was historically built to relocate the disaster victims of Lapindo Sidoarjo. The distribution and characteristics of high-rise buildings in Sidoarjo Regency are shown in Figure 2 and Table 1, respectively.

Table 1. The characteristics of high-rise buildings in Sidoarjo Regency

No.	Name of Buildings	Functions	Locations (District)	Number of Floors
1	Tamansari Prospero	Apartment	Buduran	29
2	Muhammadiyah University (Campus 1)	University	Sidoarjo	23
3	Luminor Sidoarjo	Hotel	Sidoarjo	7
4	Fave Hotel Sidoarjo	Hotel	Sidoarjo	7
5	Premier Place	Hotel	Gedangan	6
6	Swiss-Belinn Airport	Hotel	Gedangan	6
7	Neo+	Hotel	Waru	7

High-rise buildings in Sidoarjo Regency are predominantly dispersed in a corridor pattern. The first corridor resides within the main road to Juanda International Airport. All of the high-rise buildings in the stated corridor function as hotels provided to support the activities of aerial travel passengers. Meanwhile, the second corridor is around the national road,

one of the main connectors between two metropolitan areas: GKS and Malang Raya. This corridor is a non-toll road frequently crossed by motorized vehicle riders from the southern regions, such as Malang, Pasuruan, Batu, and others. The rest of the high-rise buildings are scattered throughout the downtown area of Sidoarjo Regency.

The majority of high-rise buildings in Sidoarjo Regency were built by private sectors. As a result, the Government of Sidoarjo Regency only possesses one 4-story structure named Public Service Mall, operating as a one-stop service since 2019.

B. Status of High-Rise Buildings Within Fire Risk Zones and Service Coverage Areas of Aerial Ladder Trucks

The result of overlay analysis between the distribution of high-rise buildings and fire risk zones (Figure 3) illustrated that all of the existing high-rise buildings in Sidoarjo Regency are situated within a high-fire risk zone. It was mainly caused by the sheer height of building density and fire frequency in the surrounding area. According to the fire outbreak statistics during 2015-2019, the most significant number of outbreaks happened in Sidoarjo, Krian, Waru, and Buduran District, where most of the high-rise buildings are located.
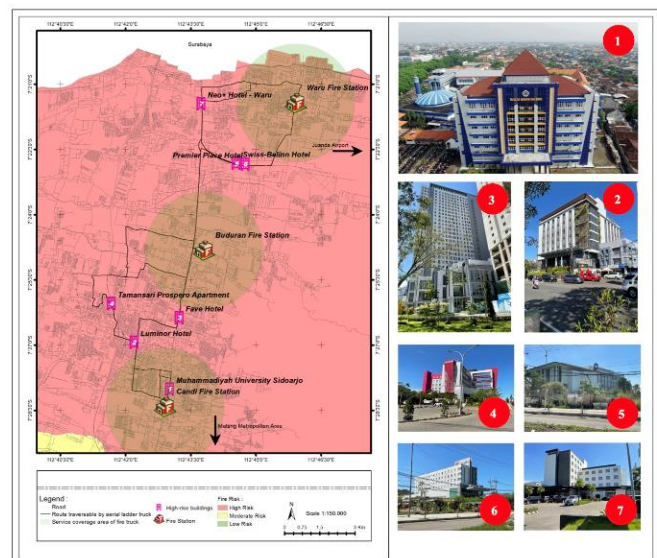

Figure 3. Overlay of high-rise buildings distribution, service coverage areas of an aerial ladder truck, and fire risk zone map.

In addition to being prone to fire outbreaks, most of the high-rise buildings in Sidoarjo Regency are also located in areas unprotected by the service coverage areas of aerial ladder trucks. Out of 7 buildings, Muhammadiyah University (Campus 1) is the only high-rise building within the service coverage area of aerial ladder trucks, with less than 1 km of distance to Candi Fire Station. This result indicated that the only building where firefighters may reach the target within the ideal response time during a fire outbreak is only Muhammadiyah University.

C. Selection of the Best Route Traversable by Aerial Ladder Trucks Towards the Building Location

This stage of analysis was started by identifying routes traversable by aerial ladder trucks in Sidoarjo Regency. Preliminary results based on the criteria above suggested that not all road segments were eligible due to the insufficiency of

road width and presence of traffic barriers. Most of the selected street networks possessed a minimum Right of Way (ROW) of 5 meters. The next step was continued by measuring travel time for each road segment chosen, both during peak and off-peak hours, through Google Maps.

The closest facility solver analysis output depicted only three fire stations near the high-rise buildings: Buduran, Candi, and Waru Fire Station. When further examined, Luminor Hotel, Fave Hotel, and Tamansari Prospero Apartment are close with Candi and Buduran fire station compared to three other fire stations. In contrast, Premier Place Hotel, Swiss-Belinn Airport Hotel, and Neo+ Hotel are closer to Waru and Buduran Fire Station. In addition, the study results suggest that there is only one different route option traversable by aerial ladder trucks during peak and off-peak hours identified from the simulation of Waru Fire Station to Neo+ Hotel. On the other hand, the rest of the simulations follow the same routes, both during peak and off-peak hours, due to the low number of possible ways which fulfilled the criteria. The closest facility solver analysis and travel time measurement results are presented in the following figures (Figure 4, 5, 6, 7, 8, and 9) and table (Table 2), respectively.
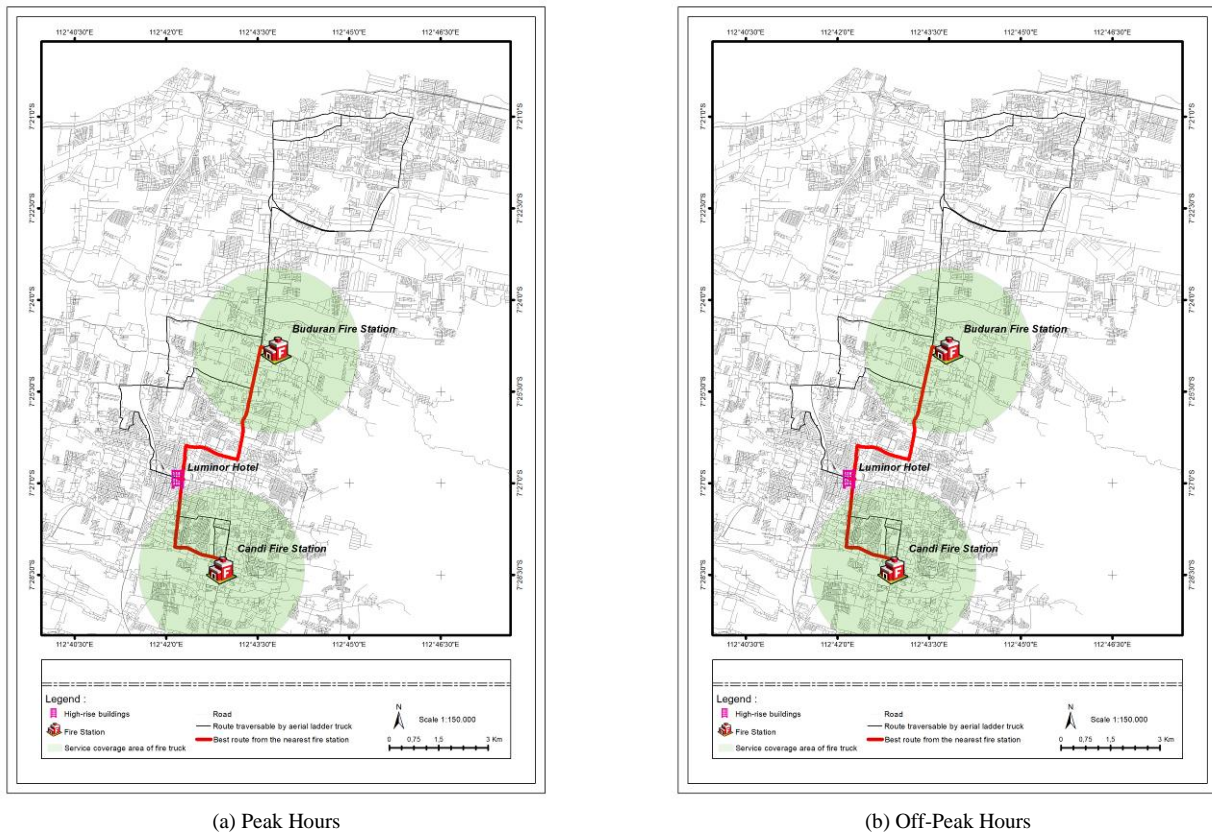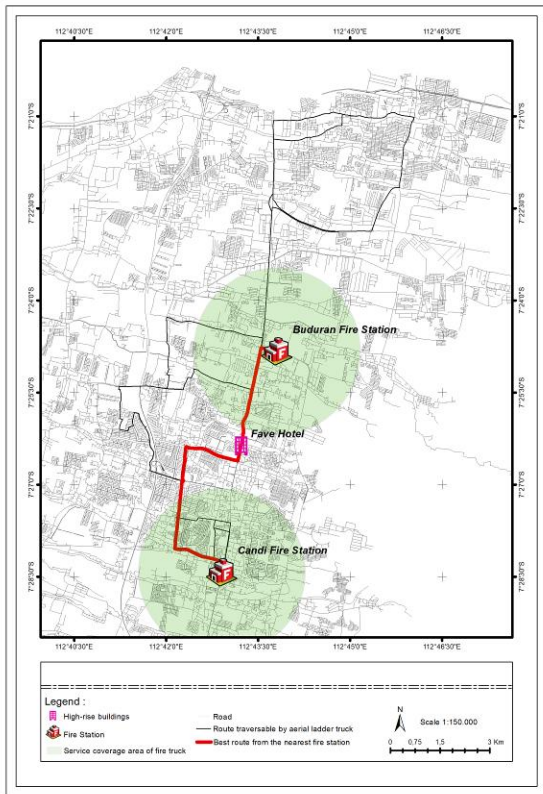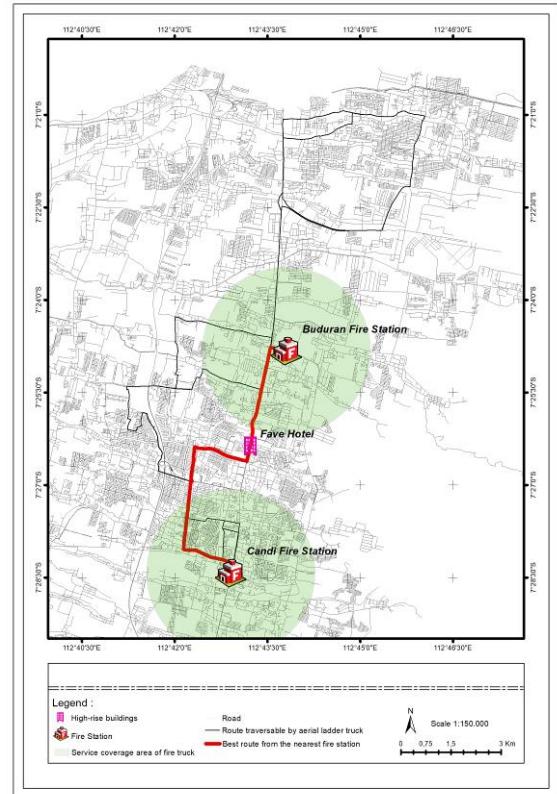

(a) Peak Hours

(b) Off-Peak Hours

Figure 4. Selection of two routes traversable by aerial ladder trucks from fire stations to Luminor Hotel.
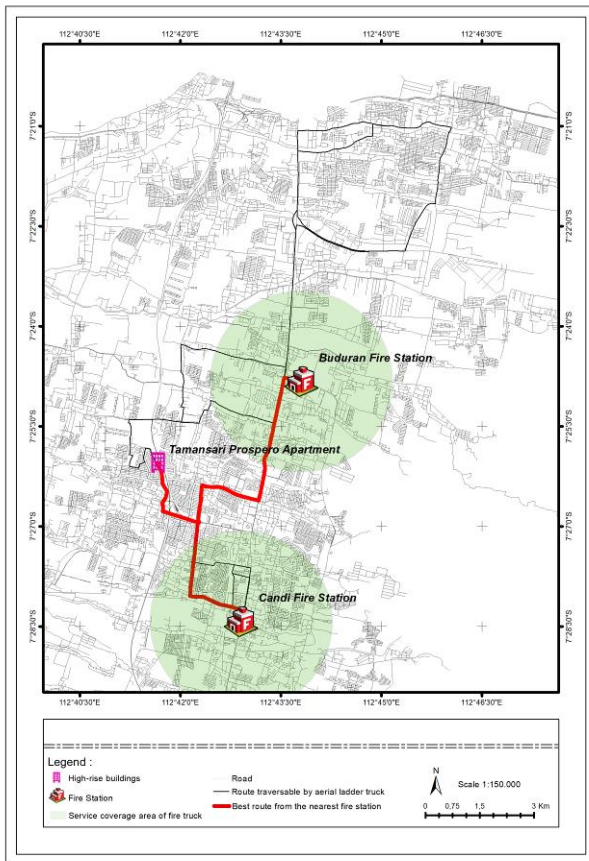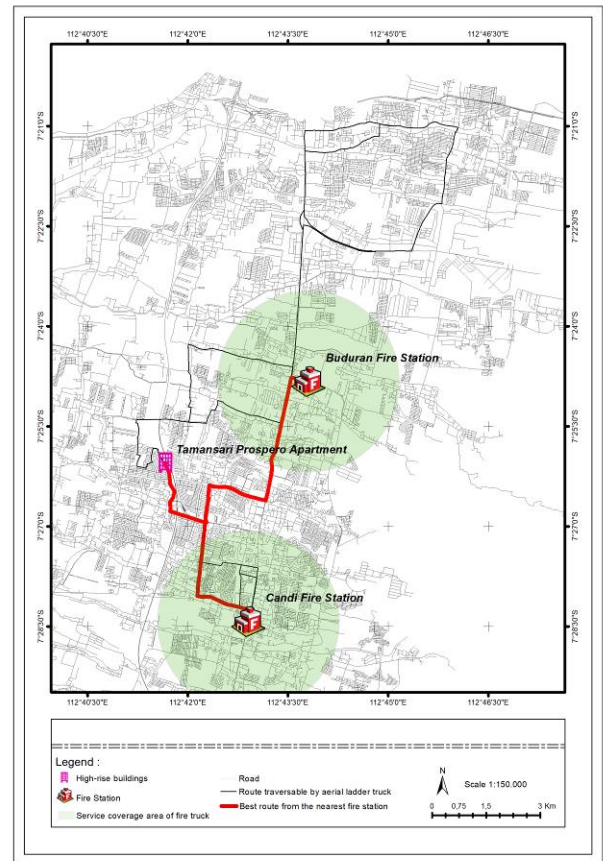
| (a) Peak Hours | (b) Off-Peak Hours |

Figure 5. Selection of two routes traversable by aerial ladder trucks from fire stations to Fave Hotel.
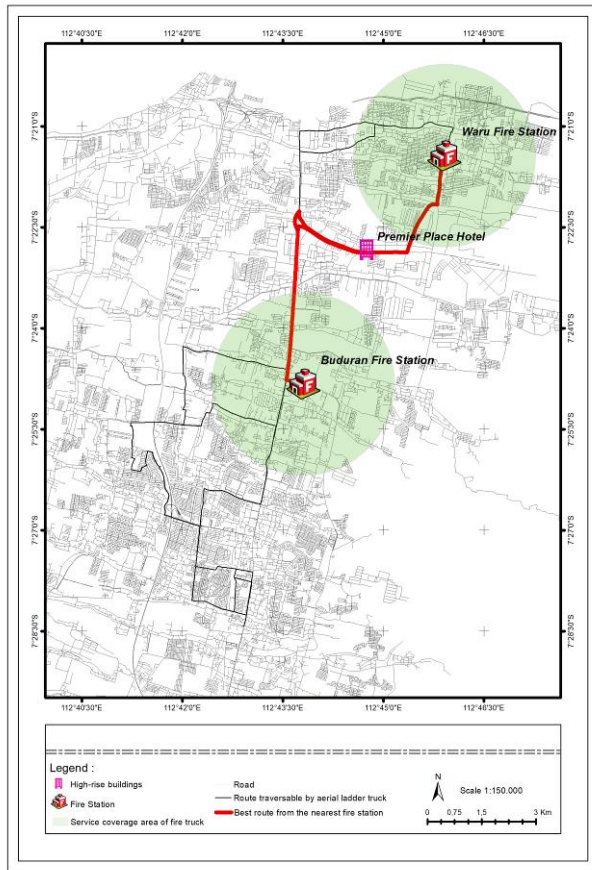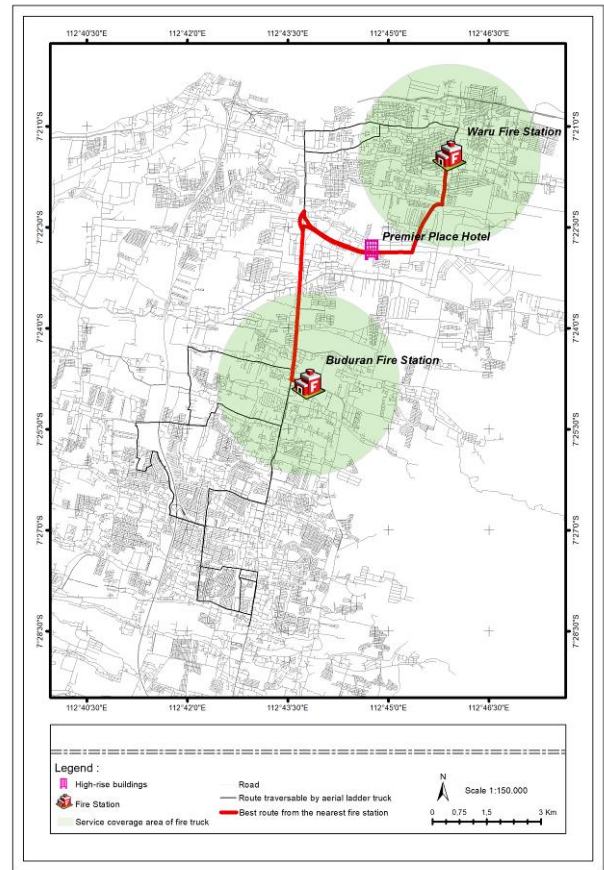

| (a) Peak Hours | (b) Off-Peak Hours |

Figure 6. Selection of two routes traversable by aerial ladder trucks from fire stations to Tamansari Prospero Apartment.
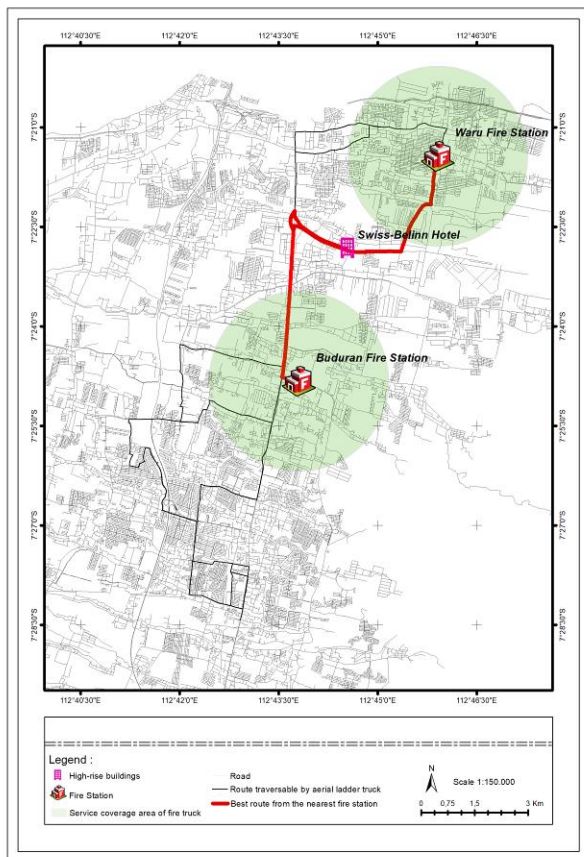
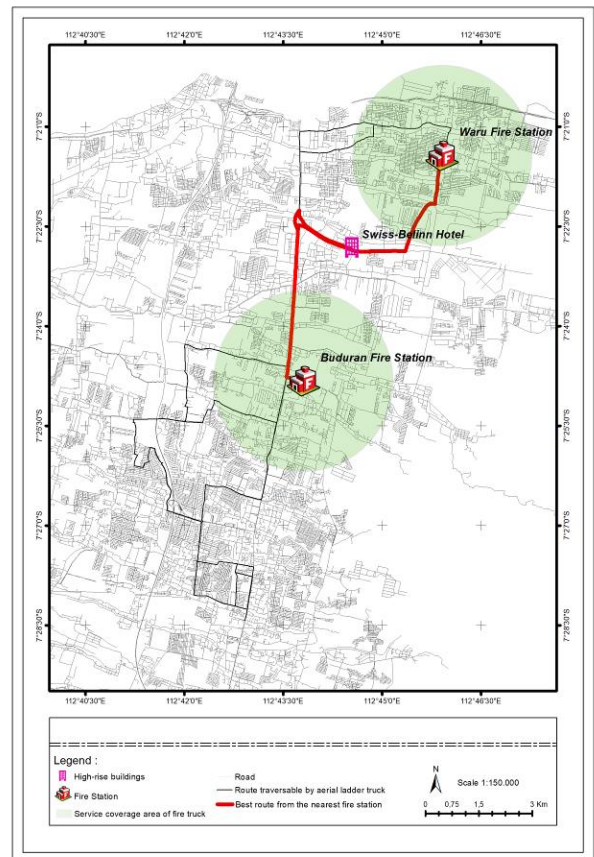(a) Peak Hours   (b) Off-Peak Hours

Figure 7. Selection of two routes traversable by aerial ladder trucks from fire stations to Premier Place Hotel.

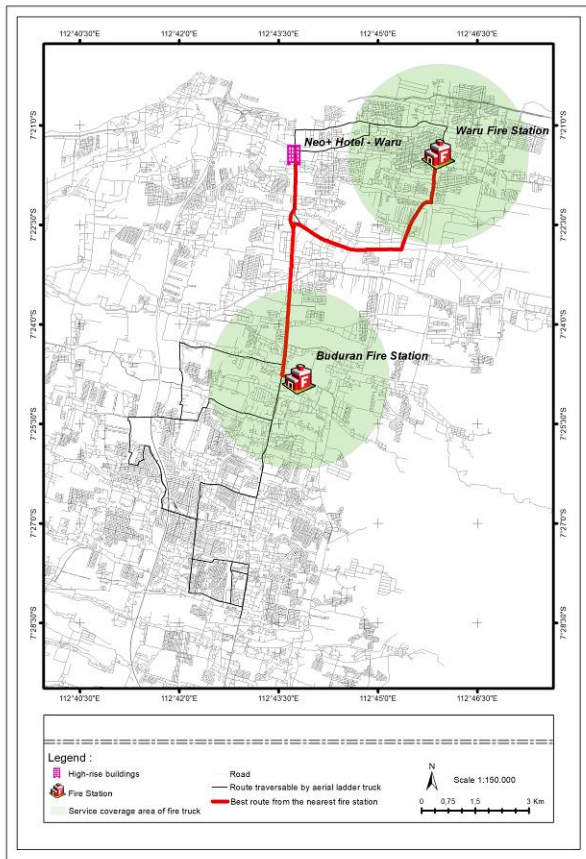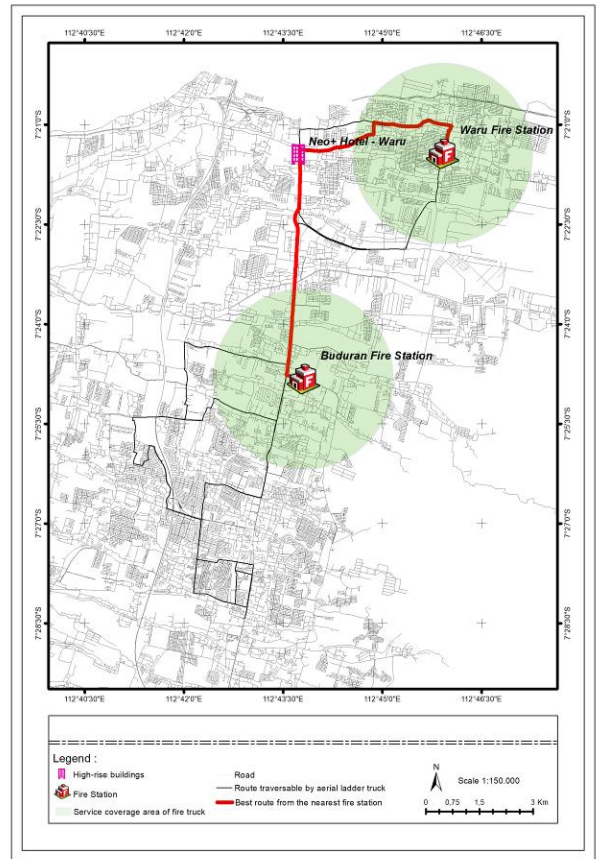(a) Peak Hours   (b) Off-Peak Hours

Figure 8. Selection of two routes traversable by aerial ladder trucks from fire stations to Swiss-Belinn Airport Hotel.

(a) Peak Hours   (b) Off-Peak Hours

Figure 9. Selection of two routes traversable by aerial ladder trucks from fire stations to Neo+ Hotel.

Table 2.
The best route recommended based on proximal distance and travel time

No.	Direction/Itinerary	Distance (km)	Route	Travel Time (minutes)	
				Peak Hours	Off-Peak Hours
1	Candi Fire Station - Luminor Hotel	4.07	Jalan Raya Candi → Gatot Subroto → Raya Tenggulunan → Raya Sumokali → Lingkar Barat → Raya Taman Pinang Indah → Pahlawan	**10.93**	**8.16**
	Buduran Fire Station - Luminor Hotel	6.82	Jalan Lingkar Timur → Raya Buduran → Mayjen Sungkono → Pagerwojo → Raya Ponti → Pahlawan	18.35	13.52
2	Candi Fire Station - Fave Hotel	7.12	Jalan Raya Candi → Raya Tenggulunan → Raya Sumokali → Lingkar Barat → Raya Taman Pinang Indah → Pahlawan → Thamrin → Ahmad Yani → Jenggolo	18.56	13.79
	Buduran fire station - Fave Hotel	3.51	Jalan Lingkar Timur → Raya Buduran → Jenggolo	**10.04**	**7.41**
3	Candi Fire Station - Tamansari Prospero Apartment	6.41	Jalan Raya Candi → Raya Tenggulunan → Raya Sumokali → Lingkar Barat → Raya Taman Pinang Indah → Pahlawan → Jati Raya → Kahuripan Raya	19.57	**14.56**
	Buduran Fire Station - Tamansari Prospero Apartment	9.16	Jalan Lingkar Timur → Raya Buduran → Jenggolo → Mayjen Sungkono → Pagerwojo → Raya Ponti → Pahlawan → Jati Raya → Kahuripan Raya	26.99	19.91
4	Waru Fire Station - Premier Place Hotel	9.23	Jalan Raya Tropodo → Raya Pabean → Raya Bypass Juanda → Raya Bandara Juanda	20.05	14.62
	Buduran Fire Station - Premier Place Hotel	7.50	Jalan Lingkar Timur → Raya Tebel → Ahmad Yani → Letjen S Parman → Raya Waru → Raya Bandara Juanda	19.99	**13.78**
5	Waru Fire Station - Swiss-Belinn Airport Hotel	8.82	Jalan Raya Tropodo → Raya Pabean → Raya By pass Juanda → Raya Bandara Juanda	18.98	13.83
	Buduran Fire Station - Swiss-Belinn Airport Hotel	7.08	Jalan Lingkar Timur → Raya Tebel → Ahmad Yani → Letjen S Parman → Raya Waru → Raya Bandara Juanda	18.92	**12.99**
6	Waru Fire Station - Neo+ Hotel	8.40	**Peak hours** Jalan Raya Tropodo → Raya Pabean → Raya By pass Juanda → Raya Bandara Juanda → Raya Waru **Off-peak hours** Jalan Raya Tropodo → Letjen Suprapto → Raya Wadung Asri → Raya Berbek → Brigjen Katamso → Raya Waru	16.94	12.54
	Buduran Fire Station - Neo+ Hotel	6.67	Jalan Lingkar Timur → Raya Tebel → Ahmad Yani → Letjen S Parman → Raya Waru	16.87	**11.79**

Legend:

　　　　　 : The recommendation of the best route based on proximal distance and travel time

Concerning travel time measurement, Table 2 also presented the recommended best route for aerial ladder trucks based on the consideration of proximal distance and travel time. For instance, Candi Fire Station responded more aptly to fire outbreaks happening in Luminor Hotel compared to Buduran Fire Station due to nearer space and faster travel time between the fire station and the hotel. Therefore, by utilizing the recommended route in the table above, firefighters may arrive at the Luminor Hotel with the aerial ladder truck in less than 11 minutes during peak hours and slightly beyond 8 minutes during off-peak hours.

Based on Table 2, Waru Fire Station is not recommended to handle any fire on high-rise buildings located on the southern side of Sidoarjo Regency. The presence of this fire station does not possess enough efficiency when compared with Buduran Fire Station. In addition, if a fire happens at either Premier Place Hotel, Swiss-Belinn Airport Hotel, or Neo+ Hotel, aerial ladder trucks from Waru Fire Station would arrive later than that of Buduran Fire Station, both during peak and off-peak hours.

The analyses also revealed several recommended routes that fulfill the ideal response time suggested by the paper. Where other buildings only meet the perfect response time on off-peak hours, Luminor Hotel and Fave Hotel become the only high-rise buildings traversable by aerial ladder trucks with sufficient travel time below 15 minutes on both peaks and off-peak hours. Regardless of how promising it may be shown, this result still raises a particular concern on account of the average trip requiring over 10 minutes. In addition, the target time may be unfulfilled when, in practice, firefighters

would need around 5 minutes of pre-departure preparation from personnel, vehicle, and equipment, as well as post-arrival preparation, such as installing water pumps, positioning of aerial ladders, and further engagement of fire.

As discovered through this study, the proximal distance between fire stations and high-rise buildings significantly influences the required travel time. Aerial ladder trucks may arrive on the location of the high-rise buildings in less than 11 minutes on both peak and off-peak hours when the distance is less than 5 km (see Fig. 10). This situation indicates that based on the current assessment in Sidoarjo Regency, the local government is recommended to set the service coverage area of aerial ladder fire trucks to 5 km to ensure the ideal response time is met.
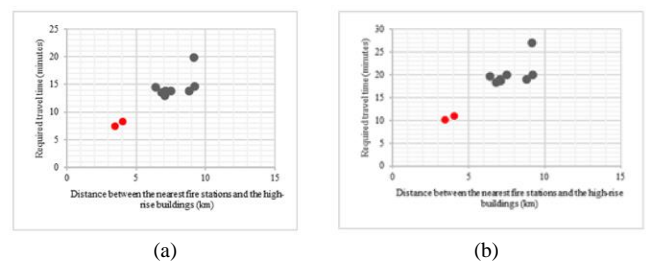

(a)　　　　　　　　(b)

Figure 10. Comparison of distance and travel time during (a) off-peak hours and (b) peak hours.

IV. CONCLUSION

The study results recommend the best route traversable by aerial ladder trucks to several high-rise buildings in Sidoarjo Regency in the fastest time possible during a fire outbreak.

Some of the recommendations are within the suggested ideal response time according to the Decree of Indonesia's Ministry of Public Works and Housing No. 20/PRT/M/2009. However, the study also proves that the targeted response time is still beyond reach during peak hours despite the results. Using the recommended routes, the average time required to arrive at stated locations is above 16 minutes. This failure to meet the response time should the distance between the high-rise buildings and the nearest fire stations be more than 5 km.

There are at least two alternative actions to improve the response time. The first action would be to establish new fire stations around high-rise buildings on further consideration that the maximum service coverage area of aerial ladder trucks be 5 km. The second action would be to add selectable routes traversable by aerial ladder trucks to stated high-rise buildings by improving the quality of the road or adding new street networks. This intervention is especially essential considering that there is only one traversable route available for aerial ladder trucks to pass through, further complicating the firefighters should any barriers occur, such as road incidents, physical road maintenance (underground pipes, road paving, etc.), and other events.

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