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Tesis

Optimization of Emergency Routes in Gas Centers: Evaluation and Effective Strategies

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Optimization of Emergency Routes in Gas Centers: Evaluation and Effective Strategies

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Abstract In this study, emergency routes were evaluated and optimized for the El Tambo 198 Fire Company in Huancayo, Peru, using geospatial data and infrastructure analysis. Twenty-six routes to different supply taps were analyzed. Thus, the purpose of the study was to evaluate the operational effectiveness of emergency routes in case of explosions. For this purpose, QGIS and ArcGIS were used to map the road network, critical facilities, and risk zones, classified into three levels: severe (zone A), moderate (zone B), and mild (zone C). The network analysis identified the most effective emergency routes, considering factors such as speed limits and traffic congestion. Detailed maps of optimal routes were created for each gas center and restrictions were established to minimize congestion in high-risk areas. These were adjusted to the speed regulations of the National Traffic Regulations and simulated emergency vehicle traffic, prioritizing access to hospitals and fire stations. The results showed variable response times between 1.1 and 6.8 minutes, highlighting the importance of proximity to gas facilities. Shorter routes, such as to the PetroPERÚ Tap (San Pedro), allowed for a quick response, while longer routes showed the need for improved road infrastructure. The research underscores the importance of inter-agency collaboration and strategic planning to optimize emergency response, as well as ongoing training and road maintenance.

Keywords Supply Taps, Disaster Risk Management, Geographic Information Systems, Strategic Planning, Critical Infrastructure

1. Introduction

Today, the hazards associated with the operation of service establishments, including gas stations and chemical manufacturing plants, are a growing concern in the areas of safety and emergency management. These establishments are involved in the storage and handling of hazardous materials, such as flammable gases and toxic chemicals, which can pose a significant risk of causing catastrophes if incidents such as fires or explosions occur [1]. This threat is exacerbated by the increasing urban density and the proximity of these facilities to residential areas, which increases the potential consequences of any incident [2].

Numerous cases underline the seriousness of industrial mishaps. For example, the incident at the Repsol refinery in Puerto Llano (Spain) in 2003 exemplified how an explosion can cause a major conflagration due to deficiencies in the management of hazardous chemical materials. Its containment lasted 48 hours, culminating in the tragic loss of eight lives and considerable material devastation [3]. This underscores the critical need to implement strict safety protocols and meticulously crafted emergency response strategies.

A notably significant incident is the catastrophe that occurred at the Flixborough petrochemical plant in

England in 1974. This event, considered one of the most catastrophic in the history of the chemical industry, occurred as a result of the explosion of a vapor cloud in the caprolactam manufacturing units [4]. The rupture of interconnecting piping between the reactors, along with technical and engineering miscalculations, culminated in the discharge of a flammable cloud of cyclohexane that detonated and resulted in 28 deaths, 36 critical injuries and the destruction of infrastructure within a 600-meter radius [5].

In the Peruvian context, incidents involving explosives at service establishments, while infrequent on a large scale, have manifested themselves with profoundly damaging consequences. A notable example is the catastrophic event that occurred in Villa El Salvador in 2020, in which a liquefied petroleum gas (LPG) leak from a tanker vehicle precipitated an explosion that resulted in the loss of 34 lives and inflicted serious injuries on 28 people, as well as extensive material devastation [6]. This incident highlights significant shortcomings in safety protocols and clarifies the imperative need for improved emergency response frameworks.

These cases make it clear that the deployment of geographic information systems (GIS) and network analysis methodologies can be instrumental in enhancing emergency response capabilities [7]. Research in China has demonstrated the effectiveness of GIS in the strategic planning of evacuation routes and management of industrial calamities, significantly reducing the duration of response and enhancing the safety of affected communities [8]. The analytical approach formulated by [9] to assess the vulnerability of transportation networks has proven to be critical in orchestrating more effective responses to both natural disasters and industrial mishaps.

In this sense, industrial accidents can be characterized as incidents that cause damage to infrastructure, the environment and the surrounding population, as demonstrated by numerous academic researches around the world. For example, [10] conducted an analysis demonstrating that chemical incidents can cause significant human and property damage, and emphasized the need for rapid and effective response strategies to alleviate the impact of such incidents.

Strategic planning of emergency routes represents one of the most effective measures for managing the ramifications of explosions at service facilities [11]. This process involves not only designing frameworks that facilitate the rapid evacuation of affected populations, but also establishing optimal access routes for emergency responders, including firefighters, law enforcement and medical teams [12] [13]. The integration of advanced technological tools, such as network analysis through ArcGIS, has become increasingly important to optimize these routes and minimize response times [9] [14].

In this context, this research focuses on the Mantaro valley, specifically in the district of El Tambo in Peru, which is characterized by a high number of gas centers, where risk assessment and emergency route planning are essential to protect the population and mitigate damages. Consequently, the main objective was to determine the optimal emergency routes in response to possible explosion scenarios at gas facilities in the area, using network analysis tools that take into account existing road restrictions.

2. Materials and Methods

2.1. Study Area

This investigation was carried out in the lower region of the Tambo district, located within the province of Huancayo, in the department of Junín (Peru), covering an area of 2033.66 hectares. This region is distinguished by a high population density and a notable aggregation of service establishments (gas centers), which increases susceptibility to explosion incidents (figure 1).

El Tambo district is located at 12°03'48" south latitude and 75°12'27" west longitude. This particular area was chosen because of its growing development within the fuel commercialization sector, specifically with regard to the gas centers and service stations operating nearby. Examining the environmental impact and operational efficiency of these facilities is essential to understanding their influence on the local ecosystem and their contribution to the energy supply for the population.

The demarcation of the study area was conducted through a methodical digitization process that utilized web mapping services (WMS) in conjunction with geographic information systems to accurately delineate the spatial distribution of gas facilities and infrastructural attributes of district roads. This methodological framework facilitated an in-depth examination of the ramifications of an explosion, as well as the strategic planning of evacuation protocols and relevant access routes to emergency response units [15].

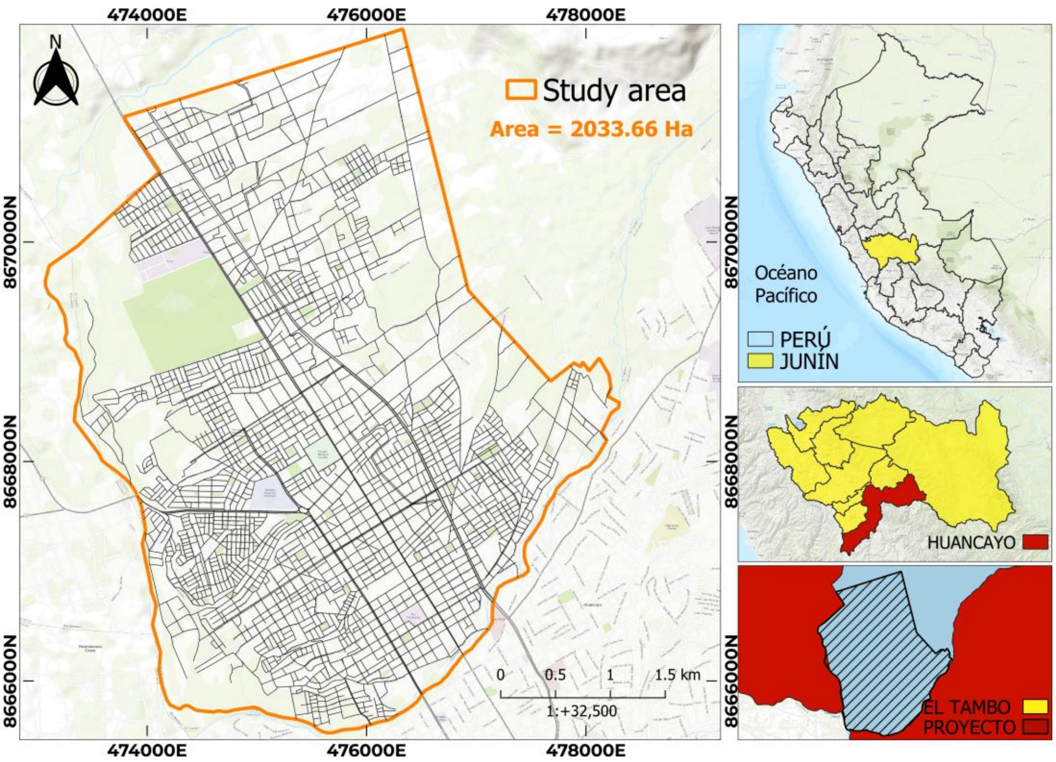

Figure 1. Location of the study area

2.2. Network Analysis

The project methodology began with systematic data collection followed by a comprehensive network analysis to determine the most efficient emergency routes. This procedural framework was executed using QGIS software, which allowed for the integration of various optimization algorithms through specific plugins. The optimization process employed Dijkstra's algorithm, available in QGIS, to calculate the shortest paths for emergency response routes.

The process began with the installation of the QuickMapServices and OSMDownloader plug-ins in the QGIS environment. These tools facilitated the obtaining and visualization of fundamental maps and OpenStreetMap (OSM) data, focusing on the designated study area, specifically the district of El Tambo. Subsequently, the OSMDownloader add-on was used to collect data pertinent to the area of interest, which was then integrated into the QGIS project as vector layers covering the road network and points of interest.

After activating the OSM Standard plugin in QGIS, the downloaded vector layers were incorporated into the project framework. The development of the node and road layers was carried out using the editing tools available in QGIS, establishing new fields within the attribute table, including node ID, initial and terminal nodes, and modifying the road layer to incorporate attributes such as road classification, hierarchy, traffic direction, and speed limitations. Supplemental layers covering gas stations, fire departments, and urban blocks were digitized to include all essential facilities in the study area.

An analysis of the impact zones resulting from potential blasts was then carried out using the Multiring Buffer add-on, which facilitated the creation of zones of influence at different distances and classified the areas according to the severity of the expected impact (zone A, zone B, and zone C).

With this data, blocks that could be affected and roads that would be restricted were identified, which is critical to mitigate the spread of incidents and improve emergency response capabilities. Efforts were made to rectify topological inaccuracies within the road network through the application of the QGIS topology tool, ensuring data integrity for accurate analysis. This corrective process involved the removal of extraneous intersections, pseudonodes, and dangling nodes that could undermine the accuracy of the analytical results. The execution of this analysis culminated in the identification of optimal emergency routes for each gas hub according to predetermined criteria, resulting in the generation of route maps that visually delineate preferred and prohibited routes, along with summary tables detailing routes, travel times, distances, and imposed restrictions.

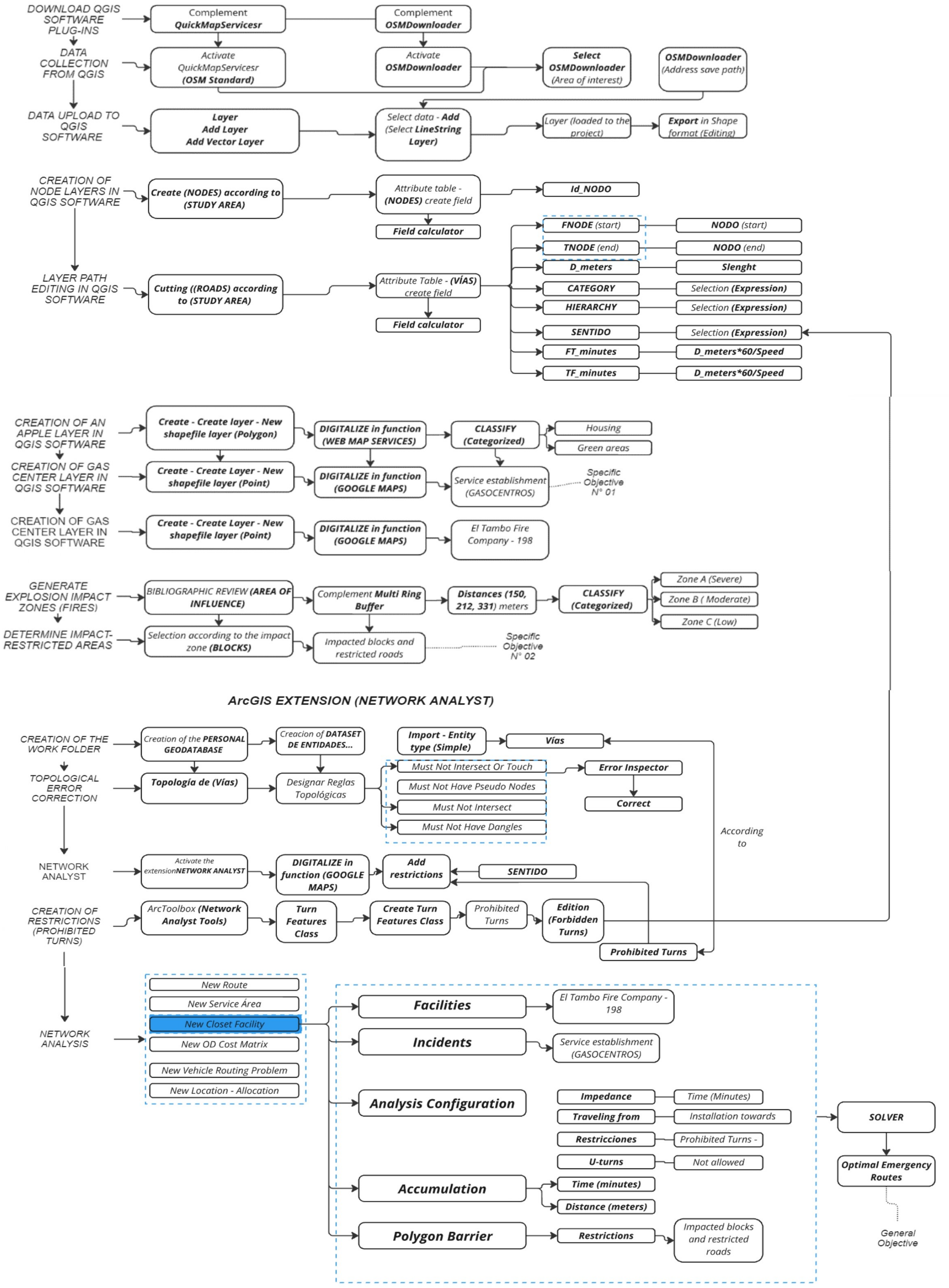

Figure 2. Outline of the Process of Analysis and Planning of Emergency Routes in El Tambo

2.3. Maximum and Minimum Speed Limits in an Urban Area

In this section, ArcGIS software, extended with the Network Analyst extension, was used to design strategies and simulate optimal emergency routes, using data sets meticulously structured to accurately represent the road network within the study area, including specific attributes such as rotation time (0.084 units, corresponding to approximately 5 seconds). The coordinate reference system used was SRC WGS 89/UTM zone 18S (EPSG:32718), ensuring geospatial accuracy.

A fundamental component of the analysis consisted of incorporating current regulations, as described in the National Traffic Regulation, promulgated by SUPREME DECREE No. 016-2009, which establishes in its articles 162 and 165 the maximum and minimum prescribed speed limits allowed in urban contexts. These speed limitations were essential for the configuration of the road model (figure 2).

Each of the aforementioned categories was systematically represented using the mathematical formulations outlined in Table 1, which clarify the correlation between distance traveled in meters and elapsed time, thus gauging the speed allowed for each specific road category. Therefore, the methodological framework was oriented towards the identification and evaluation of optimal routes to deal with unforeseen emergency situations, particularly with regard to explosive incidents occurring at gas facilities located in the district of El Tambo.

In addition, the simulation of emergency scenarios was integrated, taking into account the complementary provisions of the National Traffic Regulations, specifically articles 66 and 125, paragraph C, which give priority to emergency vehicles. These regulations ensure that ambulances, firefighters and other emergency response units have unequivocal priority on designated routes. In addition, the safety protocols articulated in Article 280 were incorporated, which oblige the National Police and the General Fire Department to adopt the necessary measures to alleviate damages in emergency situations [16].

Table 1. Hierarchy of speed limits

Category	Hierarchy	Maximum speed (km/h)	Expression	Minimum speed (km/h)	Expression
Via Expresa	1	80	[Distance (meters)]*60/80000	40	[Distance (meters)]*60/40000
Avenues	2	60	[Distance (meters)]*60/60000	30	[Distance (meters)]*60/30000
Streets	3	40	[Distance (meters)]*60/40000	20	[Distance (meters)]*60/20000
Tatters	4	40	[Distance (meters)]*60/40000	20	[Distance (meters)]*60/20000
School zone	-	30	[Distance (meters)]*60/30000	15	[Distance (meters)]*60/15000
Hospital area	-	30	[Distance (meters)]*60/30000	15	[Distance (meters)]*60/15000

3. Results and Discussion

The cartographic representation produced (Figure 3) provides a detailed description of the most effective emergency routes within the El Tambo district, taking into account the spatial distribution of gas facilities and impact zones in the event of an explosion. This assessment is essential for designing rapid and effective responses to hazardous scenarios.

The map delineates the risk areas into three distinct classifications; Zone A (Severe) is marked in red and encompasses the areas with the highest probability of severe damage. These are located in the immediate vicinity of gas centers, where the consequences of an explosion would be devastating and it is crucial to have well-planned emergency routes that allow for quick and efficient evacuation to minimize risks and ensure the safety of residents. Meanwhile, Zone B (Moderate), represented in orange, includes areas that are close to gas centers, but not in the immediate vicinity. Although the risk of damage is lower compared to Zone A, the consequences could still be significant. The response should be rapid, but the priority is lower compared to severely affected areas.

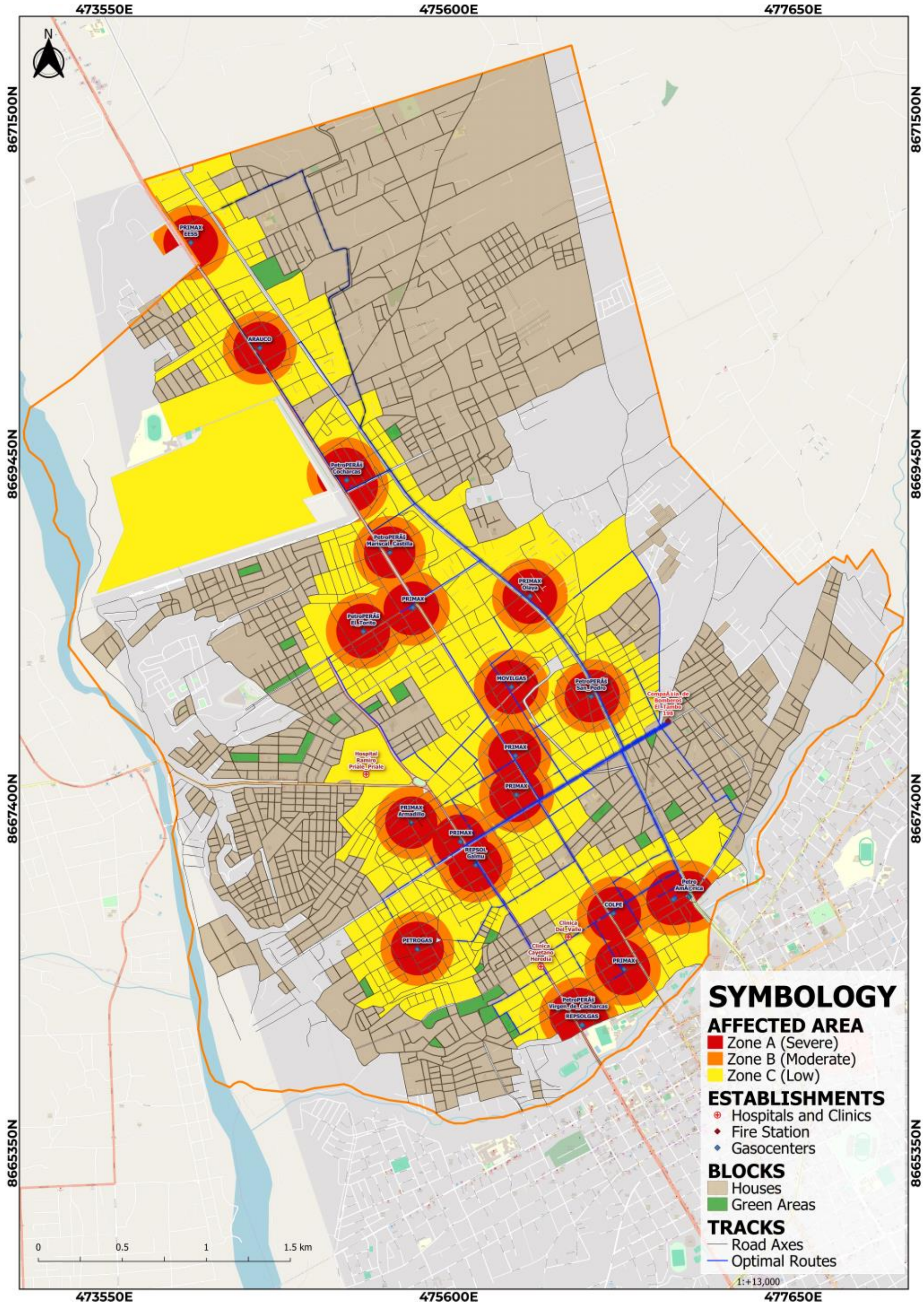

Figure 3. Map of Emergency Roads and Impact Zones in El Tambo

It is important to note that emergency route planning and crisis preparedness remain essential. Finally, Zone C (Mild), shown in yellow, covers the areas farthest away from the gas centers. Although the risk of damage is the lowest in these zones, an adequate contingency plan is still required. In these areas, traffic management and evacuation route planning are necessary to avoid congestion and ensure effective emergency response.

3.1. Optimal Emergency Routes

The blue lines on the map indicate the most favorable emergency routes and the more intense they are, the greater the utilization during a crisis. They were selected for their ability to accommodate significant volumes of traffic and for their direct connections to high-risk areas, which also means that they are comparatively faster and safer.

3.2. Key Intersections and Choke Points

Analysis of the map reveals several key intersections where emergency vehicle traffic is likely to be concentrated. It is of utmost importance that these intersections remain unobstructed to ensure uninterrupted passage for emergency vehicles. In addition, planning should take into account potential congestion points, particularly in the vicinity of hospitals and clinics, which may be designated as evacuation centers. The map also marks the location of hospitals, clinics, fire stations and gas facilities, each of which is critical to an effective emergency response.

3.3. Restriction of Areas and Roads

Based on the results of the analysis, it was decided to impose restrictions on access to specific regions and roads to mitigate traffic congestion in high-risk areas during emergencies. These restrictions served to channel emergency traffic along safer routes, thereby reducing the likelihood of emergency vehicles becoming trapped in dangerous or congested locations.

3.4 Optimal Routes Per Facility

Table 2 serves as a fundamental tool for the strategic formulation of expeditious emergency response protocols within the El Tambo jurisdiction. This table delineates and enhances the pathways linking El Tambo Fire Company 198 to several critical locations, particularly gas facilities, which represent a potential hazard due to the combustible characteristics of the fuels they contain.

Table 2. Fire Company 198 Response Times and Distances to Gas Installations in El Tambo

Installation	Incident	Time	Distance	Route description
El Tambo Fire Company 198	TAP REPSOL (Galmu) - TAP PRIMAX	2.7 min	1180.8 m	P. José Carlos Mariátegui
		4.2 min	1839.2 m	P. José Carlos Mariátegui, A. Mariscal Castilla, A La Victoria, A. Huancavelica
		4.0 min	1634.9 m	P. José Carlos Mariátegui, A, Mariscal Castilla, J Aguirre Morales, J. Junín
El Tambo Fire Company 198	TAP PRIMAX (Olaya)	3.2 min	1612.3 m	P. José Carlos Mariátegui, J. Cajatambo, A. Los Ángeles, A. Progreso
		2.7 min	1076.1 m	P. José Carlos Mariátegui, A. Ferrocarril
		4.7 min	1916.3 m	P. José Carlos Mariátegui, J. Santa Isabel, A. Tahuantinsuyo, A. Progreso, A. Grau, J Atalaya
El Tambo Fire Company 198	TAP PRIMAX (EESS)	8.3 min	4657.7 m	P. José Carlos Mariátegui, A. Ferrocarril, A. La Esperanza, A. Mariscal Castilla.
		9.4 min	5235.5 m	P. José Carlos Mariátegui, A. Ferrocarril, A. Tahuantinsuyo, A Miguel Grau
El Tambo Fire Company 198	TAP PRIMAX (Armadillo)	3.8 min	1657.3 m	P. José Carlos Mariátegui, J. Junin, J Aguirre Morales
		3.8 min	1684.8 m	P. José Carlos Mariátegui, J. Panamá
El Tambo Fire Company 198	TAP PRIMAX	4.1 min	2056.6 m	P. José Carlos Mariátegui, A. Ferrocarril, A. Evitamiento
		4.3 min	2009.2 m	P. José Carlos Mariátegui, A. Mariscal Castilla
El Tambo Fire Company 198	TAP PRIMAX	2.4 min	983.0 m	P. José Carlos Mariátegui, A. Mariscal Castilla
		2.4 min	879.5 m	P. José Carlos Mariátegui, Calle Tahuantinsuyo
El Tambo Fire Company 198	TAP PRIMAX	2.1 min	825.4 m	P. José Carlos Mariátegui, J. Santa Isabel, J. Faustino Quispe
		2.6 min	1026.5 m	P. José Carlos Mariátegui, A. Grau, J. Ricardo Palma,A. Mariscal Castilla

Table 2 continued

El Tambo Fire Company 198	TAP PRIMAX	4.0 min	1689.0 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Parra del Riego, J. Santa Isabel
		5.1 min	2150.5 m	P. José Carlos Mariátegui, J. Parra del Riego, J. Libertad
El Tambo Fire Company 198	TAP PetroPERÚ (Virgen de Cocharcas) - TAP REPSOLGAS	5.0 min	2178.0 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Parra del Riego, J. Arequipa, A. 13 de Noviembre
		5.1 min	2361.6 m	P. José Carlos Mariátegui, A. Huancavelica
		6.8 min	3072.1 m	P. José Carlos Mariátegui, A. Huancavelica, J. Trujillo, J. Los Minerales, A. Alejandro Deústua, J. Calcita, A. 13 de Noviembre
El Tambo Fire Company 198	TAP PetroPERÚ (Villa Rica de Oropesa)	5.1 min	2632.2 m	P. José Carlos Mariátegui, A. Ferrocarril, A. La Esperanza
		5.4 min	2708.8 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Julio Llanos, A. Mariscal Castilla
El Tambo Fire Company 198	TAP PetroPERÚ (San Pedro)	1.5 min	485.4 m	P. José Carlos Mariátegui, J. Inca Ripac, A. Jorge Chávez
		1.1 min	409.3 m	P. José Carlos Mariátegui, A. Ferrocarril
		3.2 min	1208.4 m	P. José Carlos Mariátegui, J. Santa Isabel, A. Jorge Chávez
El Tambo Fire Company 198	TAP PetroPERÚ - Mariscal Castilla	4.7 min	2475.9 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Julio Llanos
		4.7 min	2386.8 m	P. José Carlos Mariátegui, A. Ferrocarril, A. La Esperanza
El Tambo Fire Company 198	TAP PetroPERÚ (Gotari) - TAP PetroAmérica	3.6 min	1251.2 m	P. José Carlos Mariátegui, J. Inca Ripac, Prolongación Sebastián Lorente, J. Amauta, J. Las Begonias, J. Trujillo
		3.9 min	1598.7 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Antonio Lovato, J. Santa Isabel
		2.5 min	1032.5 m	P. José Carlos Mariátegui, A. Ferrocarril
El Tambo Fire Company 198	TAP PetroPERÚ - (El Torito)	5.0 min	2404.3 m	P. José Carlos Mariátegui, A. Ferrocarril, A. Evitamiento
		6.8 min	2990.1 m	P. José Carlos Mariátegui, A. Mariscal Castilla, A. Julio Sumar, J. Alexander Flemino, J. Rebagliati, A. Huancavelica, A. Evitamiento Norte
El Tambo Fire Company 198	TAP PETROGAS	5.1 min	2242.0 m	P. José Carlos Mariátegui, A. Huancavelica, A. La Victoria, A. Circuito Los Héroes, A. Las Colina
		4.8 min	2122.9 m	P. José Carlos Mariátegui, J. Los Bosques
El Tambo Fire Company 198	TAP MOVILGAS	2.9 min	1132.8 m	P. José Carlos Mariátegui, J. Santa Isabel
		4.4 min	1883.2 m	P. José Carlos Mariátegui, A Mariscal Castilla, J. Aguirre Morales, J. Moquegua, J. Jorge Chaves, A. Melchor Gonzales, A. Julio Sumar
El Tambo Fire Company 198	TAP COLPE	5.3 min	2489.4 m	P. José Carlos Mariátegui, A. Huancavelica, J. Parra de Riego
		3.5 min	1472.7 m	P. José Carlos Mariátegui, A. Mariscal Castilla
		3.3 min	1405.1 m	P. José Carlos Mariátegui, A. Ferrocarril, J. Chiclayo
El Tambo Fire Company 198	TAP ARAUCO	6.7 min	3647.5 m	P. José Carlos Mariátegui, A. Ferrocarril, A. La Esperanza, A. Mariscal Castilla
		6.8 min	3556.3 m	P. José Carlos Mariátegui, A. Ferrocarril, A. Universitaria

4. Conclusions

The evaluation of emergency routes to the taps from the El Tambo 198 Fire Company showed variable efficiency in response times, ranging from 1.5 to 6.8 minutes, depending on the distance and road conditions to each tap. The proximity of taps such as the PetroPERÚ Tap (San Pedro), only 485.4 m away, highlights the importance of having accessible water sources to reduce emergency response times. However, the variability in travel times and the dispersion of the taps identify critical areas where road infrastructure needs improvement and the installation of new supply points should be considered.

The application of operational research methods, such as linear programming and network analysis, in combination with GIS technology, allowed for modeling the most efficient routes and optimizing emergency response. Collaboration between public and private entities, along with strategic planning based on these analyses, is essential to ensure community safety. Additionally, community training and periodic maintenance of these routes are crucial for ensuring an effective and efficient response in emergency situations.

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