GIS-Based Network Analysis for the Roads Network of the Greater Cairo Area

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Abstract

In a crowded city like Grater Cairo Region (GCR), Egypt, finding a desired location becomes a difficult task, especially in emergency situations. The main criteria of any emergency response system (ERS) are its readiness to solve the immediate emergency situation such as fire emergency response, police station emergency response, healthcare emergency response system, etc. The main purpose of this paper is to provide an enhanced network analysis that uses the capabilities of Geographic Information System (GIS) to identify the best route from the location of an incident for any healthcare service providers in the Greater Cairo metropolitan area. The results obtained in this paper showed that the best route travel time is much better than the shortest route travel time by 22%. In emergency situations, it is essential to reach the location of an incident as fast as possible to rescue people life. So, based on the obtained results, this paper recommended that the GIS best route algorithm is better than the shortest route algorithm in emergency situations especially in a crowded city like GCR.

1 Introduction

Geographic Information System (GIS) technology is one of the hottest research tools in the world recently and one of the fastest growing high technology of monitoring. It has been proven to be valid and efficient to solve real-life problems, such as responding and resolving emergency situations [1]. A geographic information system is a computerized system that is designed to capture, store, manipulate, analyze, manage, visualize, and present all types of geographical data associated with geographical locations [2]. GIS can bring all that data together quickly and enable users to analyze and visualize information in an efficient way. It has been used in several fields such as transportation management, emergency services, gas station mapping, and healthcare planning [2]. The shortest path between two vertices "s" and "t" in a network is defined as the directed simple path from "s" to "t" with the property that no other such path has a lower weight [8]. Most applications solve the shortest path problem based on the distance as a weight. In this paper, we used the time parameter instead of the distance which calculated the path between two points that takes minimum time based on one or more parameters other than the distance. Examples of these parameters are road width, average speed, waiting time, etc. In emergency situations, the best path is preferred, that it takes the minimum time to reach a destination which helps to save people life. The main objective of this research is to find the best path and representing this valuable spatial information to end-users in an efficient way using GIS software. Most of shortest path algorithms (Dijkstra's shortest path algorithm, Euler's algorithm, etc.) are finding the shortest path that has only the least distance between a source node and a destination node. Applying one of these algorithms on GIS software that resolve emergency situations is not suitable for real road network because it considers only the length of the path to find the shortest one and does not consider other real-time traffic information (i.e. Road width, speed limit, surface condition, turn restrictions, etc.) which should be defined to identify more realistic routes.

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The road network of the Greater Cairo region was taken as a case study to apply the proposed enhanced method.

2 Related Works

In [2], the authors tried to solve the problem of finding a specialized hospital and its shortest path to reach in Aurangabad city, Maharashtra State, India. They used the ArcGIS software and Dijkstra's algorithm that provide the shortest path from one location to another for finding the nearest location of the hospitals from user's location. The calculations of the shortest path were based on road distances; traffic congestion and state of the roads were not considered.

In [3], the authors developed a GIS based application for healthcare emergency response system services to manage healthcare in the ALMOKATAM Zone in the south of Cairo, Egypt. The optimal route was modeled based on the distance to the closest healthcare service providers. The system integrated data acquisition from databases and plotted the location-based features of satellite image through a web base interface which gives access to all different tasks by different end users to be a decision maker or policy makers in system management. They didn't consider any factor other than the distance.

In [4], the authors discussed the shortest path analysis based on Dijkstra's algorithm and implemented an emergency response system based on GIS. They also integrated GIS, web services, and Asynchronous JavaScript and XML (Ajax) technologies and provided a web-based application for finding the best routes from specialized response team stations locations and incident locations. Their proposed system provided the optimal route depending on the distance of route without considering road conditions and traffic congestion.

In [5], the authors developed a desktop-based emergency response system for emergency readiness and management through GIS in Delhi, India. The main objective of this application was to provide immediate response to any incident or accident. A detailed transportation network was maintained and integrated with real-time traffic data provided by NAVTEQ in India. The near real-time traffic information was used to analyze suitable routes to the incident location by avoiding highly congested routes and therefore reducing the response time. Using GIS capabilities, various analyses were performed such as finding the shortest route using Origin–Destination (OD) cost matrix, network analysis, proximity analysis, and buffer analysis.

In [6], the authors established a GIS based fire emergency response service in Kumasi Metropolis, Ghana where the Ghana National Fire Service (GNFS) can identify the optimal route from its location of any fire incident. The optimal route was modeled based on the travel distance, travel time, the slope of the roads and the delays in travel times.

In [7], the authors provided a study that depicted the preliminary results for a decision support tool to model network congestion routing and provide an alternative route during rush hours in emergency cases. The system predicts traffic flow and barriers during rush hours and suggests the alternative route to reach hospitals at the time of emergency. The authors used ArcGIS 9.3 network analyst tool and Dijkstra's algorithm for performing shortest path analysis. The main objective of this study was to find the best route from the nearest hospital ambulance to the incident location and from the incident location to the nearest hospital with alternate routes.

In [8], the authors proposed an optimized version of the shortest path based on the Dijkstra's Algorithm. In the optimized version, the starting node is changed with the searching process, and uses the stack structure to maintain it, in order not to revisit the nodes. This improved the searching efficiency to the shortest path practically. But this system was also considering only the length of the path and did not consider other real-time traffic information.

3 Methodology

In this research, the flowchart of the proposed enhanced roads network analysis methodology using GIS software is shown in Figure 1. Six stages of the process have been applied, beginning with collecting and preparing the data that will be used in the analysis (the study area base map, road network data, healthcare service provider data, and historical traffic data), then Geo-referencing the base map of the study area. Following this is the creation of a Geo-database that will store the prepared data. Then building both the network topology and the network dataset. Finally, the network analysis process has been applied to the road network of the Greater Cairo Region (GCR).

3.1 Data Preparation

This phase includes downloading the study area base map, preparing the road network data, downloading the healthcare service provider's data, and preparing the historical traffic data.

The study area is the Greater Cairo metropolitan area. It is extended from 30° 11′ 10″ N and 31° 27′ 50″ E. Greater Cairo is the largest metropolitan area in Egypt, and the largest urban area in Africa and the world's 16th largest metropolitan area. It consists of Cairo Governorate, parts of Giza Governorate, and parts of Qaliobia Governorate, with a total population estimated at 20,500,000; and its area is about 1,709 km2; as well as its density is 10,400/km2 [9]. Cairo is the capital of Egypt and it is a vibrant city. It is associated with Ancient Egypt, as the famous Giza pyramid complex and the ancient city of Memphis are located in its geographical area. It is located near the Nile Delta [10].

The base map of Greater Cairo was downloaded from OpenStreetMap (OSM). OSM can be accessed as an ArcGIS Online Service that provides free read-only access to OpenStreetMap as a base map for GIS work in ESRI products such as ArcGIS Desktop It is shown in Figure 2

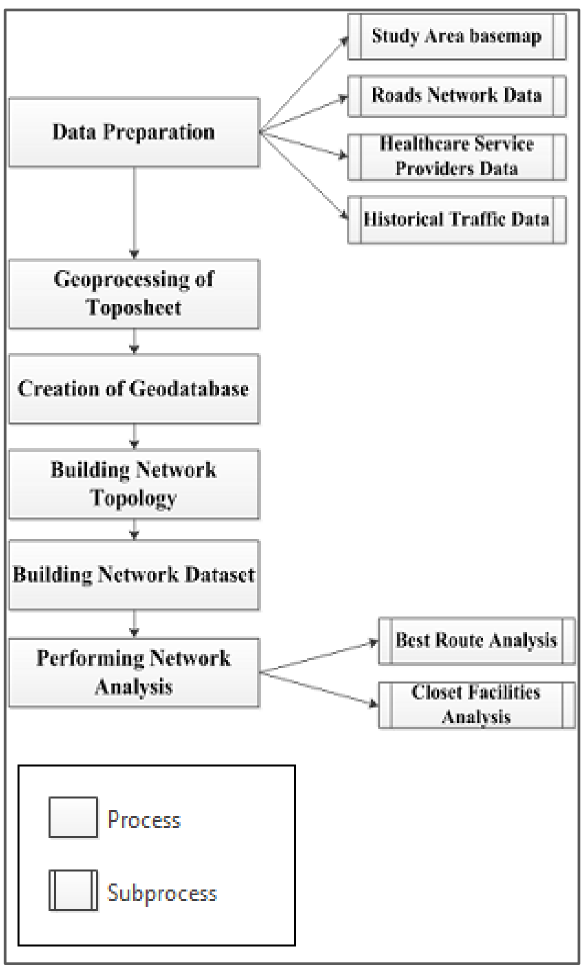

Figure 1: Enhanced Network Analysis Process Flow Diagram

The Greater Cairo road network data were downloaded using the ArcGIS Online Service as shown in Figure 3. The data contain an attribute (Meters) to store the length of each road segment in the roads network, an attribute (Direction) to store the direction of each segment, and two fields (TF_Minutes and FT_Minutes) to store the time required to travel over each road segment in minutes in both directions, and an attribute (Name) to store the name of each road segment. The healthcare service providers' data were downloaded from the OpenStreetMap. The data contain an attribute (Name) to store the name of each healthcare service provider, and another attribute (Type) to store the type of this healthcare service provider.

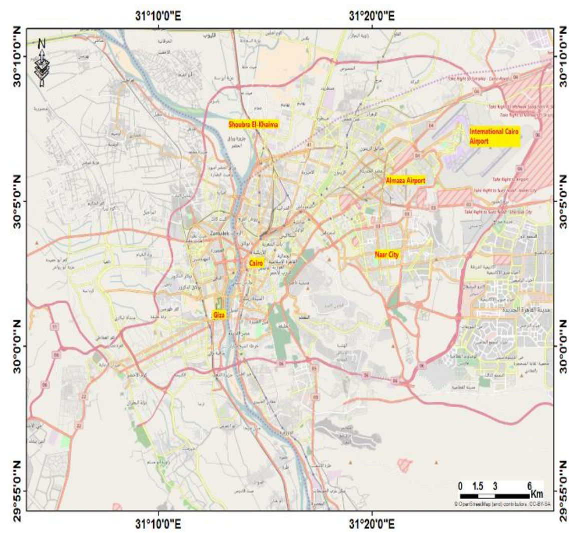

Figure 2: Base Map of Greater Cairo (from OSM).

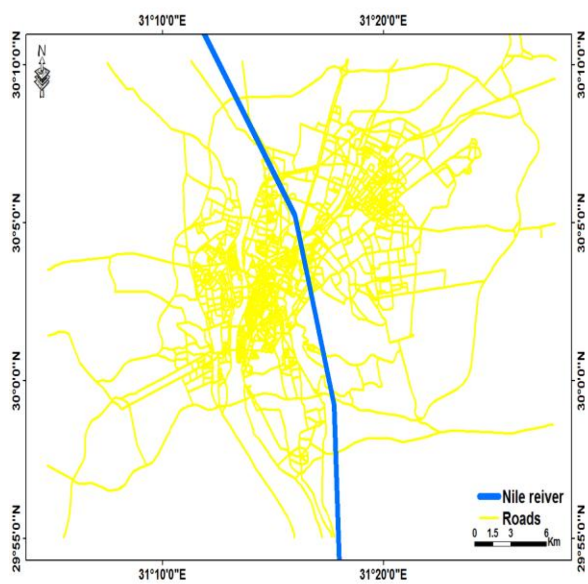

Figure 3: The Greater Cairo Roads Network

The last step in the data preparation phase is the preparation of the road network traffic data. Traffic data are given information about how travel speeds on specific road segments change over time. In network analysis, traffic is important because it affects travel times, which in turn affect results. If we don't account for traffic routing from one location to another, the expected travel and arrival times could be far from accurate. Another reason to account for traffic is that it gives the routing opportunities that avoiding the slower, more congested roads, which saves time. Traffic data can be stored using two different models: historical and live traffic. In this paper, traffic data were stored as historical traffic data.

The historical traffic data were modeled based on the idea that travel speeds follow a weeklong pattern. Thus, the travel speeds of a given road segment at a certain time of a day of a week are expected to be similar to those of the same road segment at the same time of the same day in another week. The expected speeds are usually determined by averaging multiple observations over some time span, such as a year. Also, the historical traffic data were created according to the ArcGIS Network Analyst specifications.

3.2 Geo-processing of Toposheet

In this phase, a Geo-referencing process for the downloaded roads network data is being performed. The Geo-referencing process allows the registration of the digitized top sheet on the earth's surface [2]. It is considered a very critical stage as it affects the accuracy of the road network data.

3.3 Creation of Geo-database

The Geo-database is the native data structure used in ArcGIS and is the fundamental data format used for both editing and management of the data. A Geo-database can be personal, file, or enterprise. In this proposed method, a personal Geo-database has been created using ARCGIS. A personal Geo-database is a database that can store, query, and manage both spatial and non-spatial data. It will contain the data of healthcare service providers, road network, and traffic tables. The road network data and the healthcare service providers' data were discussed earlier in the methodology. DailyProfiles and Streets_DailyProfiles tables were used to store traffic information. The "DailyProfiles" table is used to store the speed profiles for each day of the week (Table1). The times of the day are split into time intervals, or time slices (one hour) of equal duration.

Table 1: Daily Profiles Table Structure

Field	**Data Type**	**Notes**
Object ID	Long	Unique identifier for each record in the table.
SpeedFactor_0000 to SpeedFactor_2300	Double	Represent free-flow scale factor at different times of the day.

The Streets_DailyProfiles join table identifies road features, their free-flow travel speeds, and their related traffic profiles for each day of the week (Table2).

Table 2: Streets_DailyProfiles Table Structure

Field	Data Type	Notes
Object ID	Long	Unique identifier for each record in the table.
EdgeFCID	Long	Identifies the feature class that the street feature is stored in.
EdgeFID	Long	Identifies the road feature.
EdgeFrmPos And EdgeToPos	Double	Work together to identify the direction of travel (0 since the beginning of the road, 1 for the opposite end)
BaseSpeedKPH	Double	Represents the free-flow speed
Profile_1	Short	Represents the traffic for Sunday
Profile_2	Short	Represents the traffic for Monday
Profile_3	Short	Represents the traffic for Tuesday
Profile_4	Short	Represents the traffic for a Wednesday
Profile_5	Short	Represents the traffic for Thursday

Profile_6	Short	Represents the traffic for Friday
Profile_7	Short	Represents the traffic for a Saturday

3.4 Building Network Topology

To get good analysis and results, it is necessary to build a topology of the road network to discover whatever errors in the data and correcting them. This was performed by applying some topology rules such as ensuring that there are no dangles in the road network and the roads do not intersect or overlap with themselves.

3.5 Building Network Dataset

After correcting the road network errors, it is ready for being used in building the network dataset that will be used in the network analysis. To create a network dataset that renders traffic data, we need a Geo-database that contains a line feature class, and the two traffic data table created earlier. The line feature class will represent the road network and must be stored in a feature dataset. The traffic tables will represent the traffic data and its relationship with the road network. The network dataset is well suited to model the transportation network. It consists of a set of edges that represent the links over which agents will travel, and a set of junctions that connect edges and facilitate navigation from one edge to another. The Network analyst extension was used in ArcGIS for Desktop to create the network dataset shown in Figure 4.

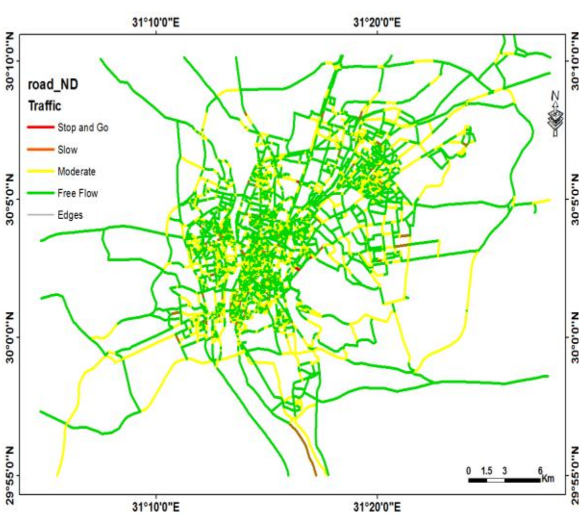

Figure 4: Network Dataset Renders Traffic Results

3.6 Performing Network Analysis

The road network analysis has been implemented using ArcGIS Network Analyst Extension. It is a powerful extension of ArcGIS that provides network-based spatial analysis, including route analysis, travel directions, closest facility analysis, and service area analysis [2]. It enables users to dynamically model realistic roads network factors, such as turn restrictions, speed limits, and traffic conditions at different times of the day. The ArcGIS Network Analyst Extension uses the standard Dijkstra's algorithm to calculate the least accumulated cost between the destination node and every other node in the network. Two types of network analyses were applied; the best route analysis, and the closet facilities analysis.

3.6.1 Best Route Analysis

The best route analysis generates the best route between two locations based on travel time which depends on the traffic conditions available on the network at a particular time of a day. The network analyst extension makes it is easy to set the best rote analysis parameters, such as the travel time that will be used as an impedance factor, the start time of traveling which produce different results based on the day profile selected, the restrictions on the analysis, such as the road directions (unidirectional or bidirectional), and the ability to ignore invalid network locations that may cause the analysis to fail.

After adjusting the best route analysis settings, we chose the start location and the end location, and then using the best route solver tool to generate the best route between these two locations. Figure 5 shows the best route between a start location (Location 1) and end location (Location 2).

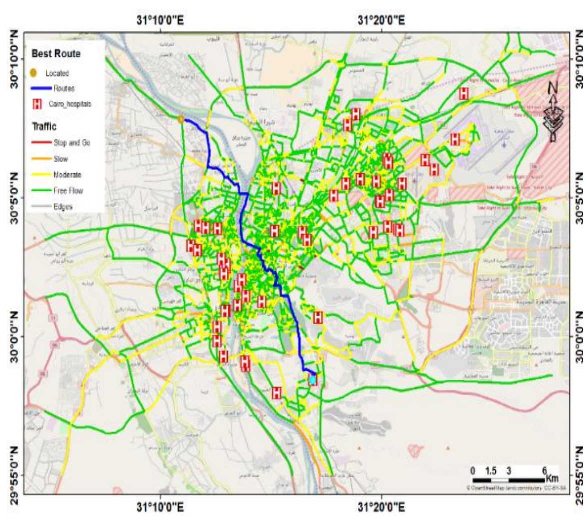

Figure 5: The Best Route Result

The directions window of the previous analysis is shown in Figure 6.

3.6.2 Closet Facilities Analysis

The closet facilities analysis finds the closest facilities that can be reached in a specific period from an incident location based on travel time and traffic information available. This helps in emergency situations to know the closest facilities that can be reached from the incident location, which in turns reduces time, effort, resources and saving people life [3]. The network analysis extension makes it is easy to set the analysis parameters for the closet facilities analysis, such as the impedance factor in the analysis, the start time, the period to reach the closet facilities, the number of facilities to find, and the directions of travel (from incident to the facility or from the facility to the incident). Then, by using the network analyst extension solver, the closest facilities to the location of an incident can be found as shown in Figure 7. The directions window of the previous analysis is shown in Figure 8.

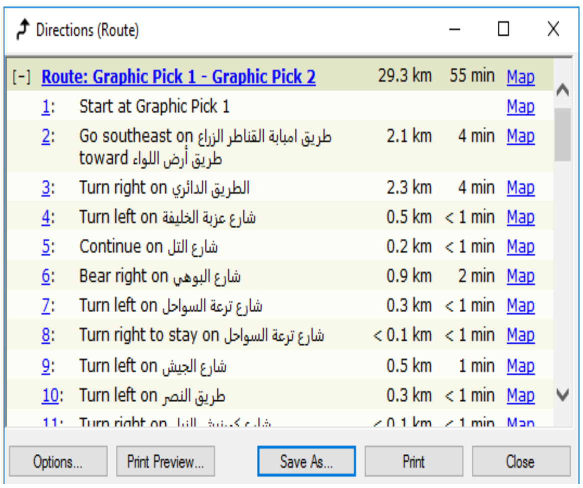

Figure 6: The Best Route Directions Result

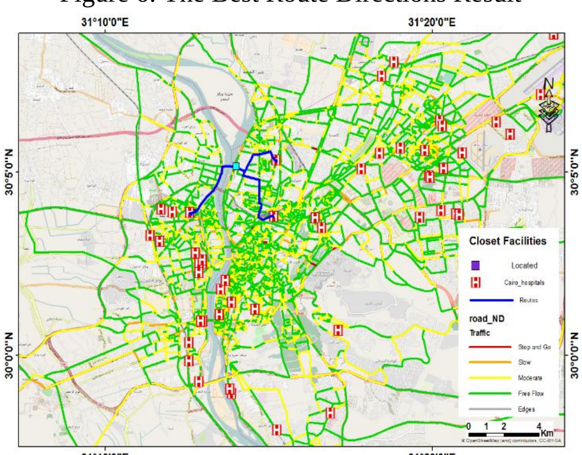

Figure 7: The Closet Facilities Analysis Result

4 Results and Discussion

In this paper, we provide analysis and comparison of the results of the network analysis using two different methods. To navigate from one location to another, either the route with the least length (shortest route) will be selected, or the route with the least travel time (best route) will be selected depending on the impedance factor you choose to solve for. Figure 9 shows the shortest route between a source location (The Autostrad Road, El-Maadi, Cairo, Egypt) and a destination location (The Ring Road, New El-Marg, Cairo, Egypt). In this analysis, the road length has been chosen as the impedance factor, the start time of travelling to be 3:00 PM which is the evening rush hour traffic on the road network in the Greater Cairo area.

The distance of the route obtained from the shortest route analysis represents the accumulated lengths of the road segments over which agents will travel. In a similar manner, the total time of the route obtained from the shortest route analysis represents the accumulated time in minutes for each route segment over which agents will travel. The shortest route results can be represented graphically as shown in Figure 10.

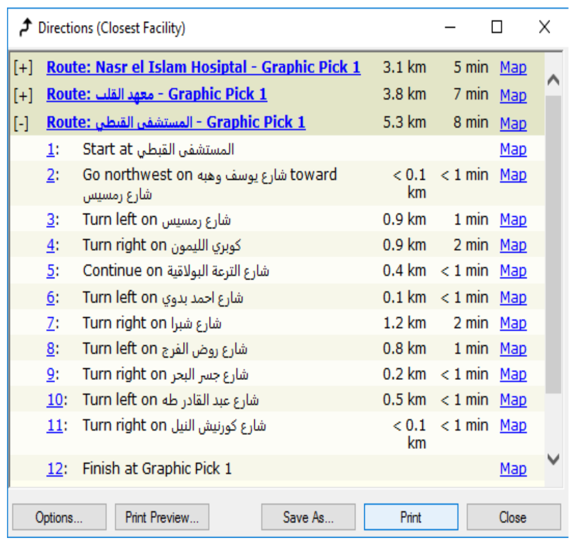

Figure 8: The Closet Facilities Directions Result

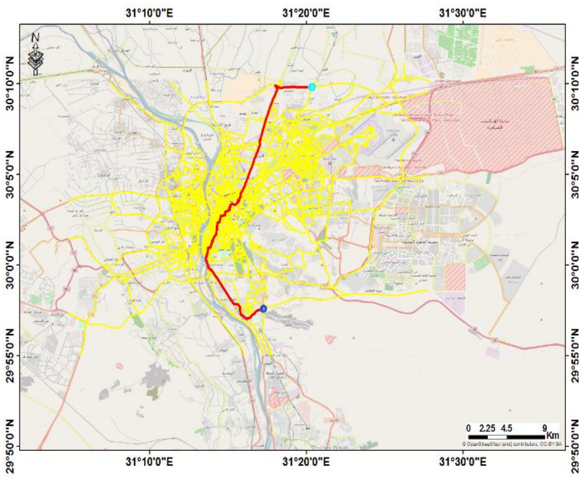

Figure 9: The Shortest Route Analysis Results

Figure 11 displays the best route between the same two locations. In this analysis, we have chosen the road's travel time as the impedance factor, and this analysis was performed at the same time and over the 7 days of the week as the shortest route analysis. The best route results can be represented graphically as shown in Figure 12. We have repeated the two analyses for the same two locations in 7 days from Saturday to Friday, at the same time and calculated the total distance (in KM) and the average travel time (in Minutes) for the two obtained roads as shown in Table 3.

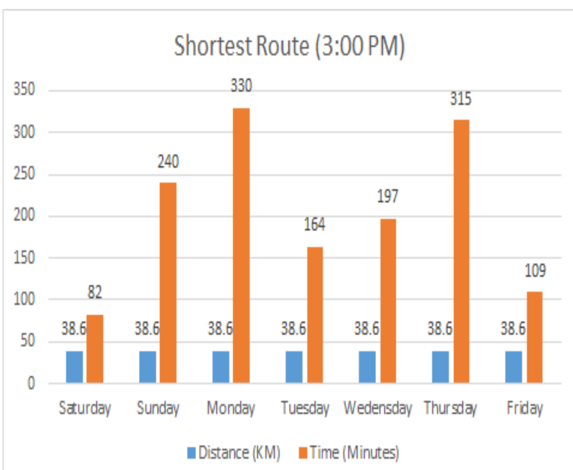

Figure 10: The Shortest Route Analysis at 3:00 PM within the Week Days.

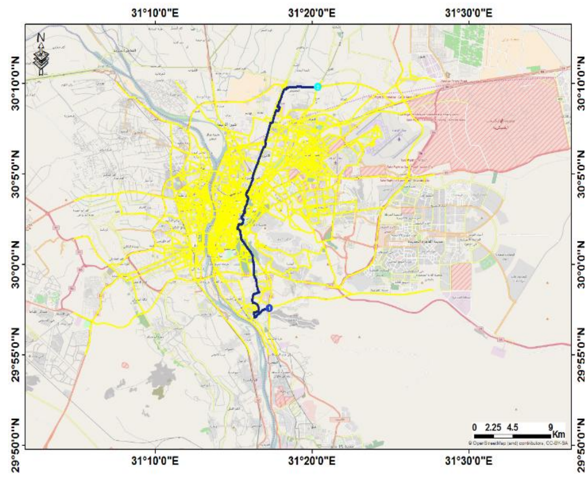

Figure 11: The Best Route Analysis Results

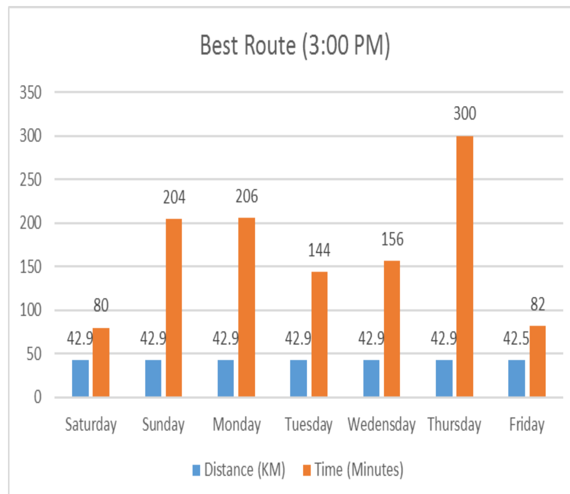

Figure 12: The Best Route Analysis at 3:00 PM within the Week Days.

Table 3: Times and Lengths of the Best and the Shortest Route Analyses

Day	**Shortest Route**		**Best Route**	
	Length	**Time**	**Length**	**Time**
Saturday	38.6	82	42.9	80
Sunday	38.6	240	42.9	204
Monday	38.6	330	42.9	206
Tuesday	38.6	164	42.9	144
Wednesday	38.6	197	42.9	156
Thursday	38.6	315	42.9	300
Friday	38.6	109	42.5	82
Avg Time		**205.29**		**167.43**

To give an evidence for the superiority of the best route on the shortest route, we have performed the previous analysis at different periods for each day in the week on a time slice of 120 minutes starting at 8:00 AM and ending at 12:00 AM for both the shortest route and the best route. We excluded the periods from 1:00 AM to 7:00 AM from the calculations as it will not give us any differences between the shortest route and the best route because in these periods there are no traffic jam on the road network. The average travel time in minutes for each analysis was calculated and recorded as shown in Table 4.

Table 4: The Average Travel Times (in minutes) for both the Shortest and the Best Route Analysis Methods for each Time Slice.

Time	Shortest Route	Best Route	Difference (%)
8:00 AM	133	120	11 %
10:00 AM	98	83	18 %
12:00 PM	108	81	33 %
2:00 PM	193	170	14 %
4:00 PM	184	164	12 %
6:00 PM	143	126	14 %
8:00 PM	105	93	13 %
10:00 PM	92	81	14 %
12:00AM	92	54	70 %

The obtained results can be represented graphically as shown in Figure 13. The superiority percentage (SP) is a measure for the preference of one alternative over another alternative. In our case, it gives an indication for the preference of the best route over the shortest route. The superiority percentage for the best route travel time was calculated according to the following formula:

$$SP = [((\sum_{i=1}^{9} \frac{SRTi}{BRTi}) - 1)/9] * 100$$

Such that:

SP = Superiority Percentage

SRT = Shortest Route Time

BRT = Best Route Time

Substituting the values of SRT and BRT from Table 4 in the previous formula, we get:

SP = 22 %

Which means that the best route travel time is much better than the shortest route travel time by 22%.

In emergency cases, it is essential to reach the location of an incident as fast as possible to rescue people life. So, according to the superiority percentage, the best route is more suitable for being used in emergency situations than the shortest route.

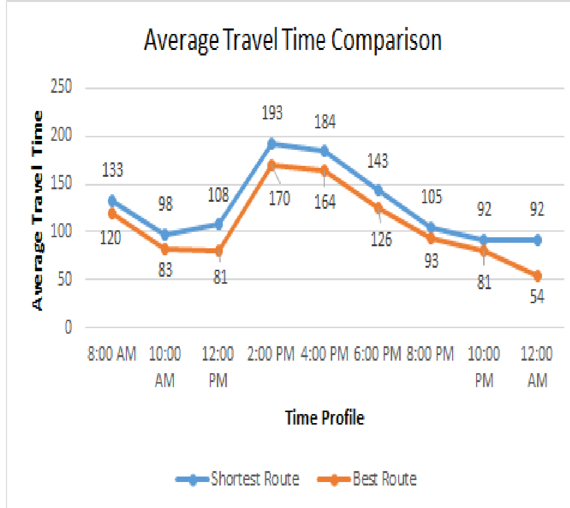

Figure 13: Average Travel Time Comparison between the Shortest and the Best Route Methods

5 Conclusion and Future Work

In this paper, an enhanced GIS-based network analysis was implemented and applied to the Greater Cairo road network. It focuses on finding the best route between two locations on the road network and finding the nearest healthcare service providers to an incident location based on the travel time. Also, the proposed method integrates historical traffic data to be used in the analysis, which in turn produces more accurate results that are suitable for realistic road networks. The Dijkstra best routing algorithm built into the ARCGIS software is the best method for the network analysis, especially in the crowded city such as Cairo city. This algorithm can preserve the travel time with 20% to 22%, depending on the travel distances. In the future work, we suggest to use live traffic data when it is available instead of historical traffic data and consider other factors such as road width, road state, road type, and time delay on the road to get realistic results. Also, we plan to enhance the Dijkstra routing algorithm used by the ArcGIS network analysis extension to improve its performance.

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