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MLRS and Dynamic Segmentation for Traffic Congestion Management

Amr H. Ali*

Benha University

Email: amrhali@feng.bu.edu.eg

Abstract

Geomatics techniques is applied in many directions as a decision support tool, one of them is the organization and management of transportation. Traffic congestion is a serious problem, where the road behavior is influencing on people economically as well as intellectually/ Transportation networks are a specialized type of graph that models the logical and topological information in the real world. The road network includes multi-linear reference system (MLRS) based model that focuses on network topological analysis. It involves the collection of traffic data that describe the characteristics and geometry of road network, vehicle counts, speed, flow rates, density in order to define the congestion situation. The objective of this research is to integrate the rules of graph theory MLRS and dynamic segmentation (DS) to examine the significance of historical traffic information gathered through Geographic Information Systems (GIS) for solving the dynamic path analysis. This guides vehicles through the urban road network using the optimal path taking into account the traffic conditions on the roads that change over the time.

Keywords: Multi-linear referencing systems; dynamic segmentation; GIS; congestion management; and dynamic network.

1. Introduction

The trend of modernization leads to the population sprawl and urbanization that requires increasing in transportation means. This causes the increasing number of vehicles that reflects on traffic movements and cause traffic congestions [1]. The solution can be achieved using an effective system in terms of large quantities of data, mathematical handling, spatial visualization, and management to simplify the decision-making process [2].

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* Corresponding author.

Like many developing countries, Cairo the capital of Egypt is suffering from traffic congestion due to rapid population density and exceeding number of motorized vehicles. It is ranked as the 42nd most crowded city in the world, with around 12 Million populations and a density of about 1540/sq. km [3]. Furthermore, over 1.2 million vehicles are registered in Greater Cairo only, with an annual incremental rate of 10% [4]. This volume of traffic congestion in Cairo which is experienced almost every day actually costs the government about 8 billion USD annually, which represents about 4% of the total Gross Domestic Product of Egypt [5]. Many studies applied globally, confirmed that the posted speed limit, geometric design in terms of median width and edge length had a significant impact on free-flow speed on urban streets [6,7].

Moreover, [8,9] present an analysis of the traffic characteristics of urban network and multi-lane highway respectively. The results show how the capacity in terms of road geometry and traffic characteristics affects the computation of Level of services (LOS).

In this research we are focusing on applying the Geomatics principles to manage the traffic congestion in urban area, where we will tackle the theories of graphs, MLRS modeling and temporal DS for traffic management using GIS tools to analyze huge historical traffic data. These will examine the congestion situation and suggest optimum dynamic path analysis to mitigate this congestion. Downtown area is chosen for our case study as it suffers from major traffic jams, where most of the ministries, governmental institutions, banks, and local or private companies are located.

2. Background

Models of graph theory are usually denoted to the real world problems. It applies the mathematical combinatoric linear-algebraic and the visualization symbolizes in graphs form. A road network can be represented by weighted directed graph, G (N, A) with real valued weights or lengths assigned to each edge. N is a set of nodes, while A is a set of unordered pairs of distinct nodes [10]. See Fig. (1).

This network models represent topological information of a network, such as connectivity of edges and nodes, their direction and weight, etc. Road network models include a mechanism of determining locations along linear features as MLRS. A location of unknown points is a distance along a route from a known point of reference. All linear referencing methods consist of an ordered and directed, set of edges coded conventionally, where no attributes are assigned to linear referencing methods. Events are linearly reference data that occur along network edges. The object database design modeling illustrated in Fig. 2 [11].

Events may be point or line event. Point events occur at precise position on a route such as accident, bus stops, etc. Line events break up a linear feature as highways into edges so that each one corresponds to an event value such as pavement conditions. These linear features may have attributes that frequently changed, so that to reveal these changes; it is required to split and / or merge these features. This can be achieved by using DS as a method of locating events on the fly. DS is a special type of line analysis where, edges are divided dynamically and temporarily for the analysis. It efficiently manages heterogeneous attributes along linear system without breaking them. This technique affords that multiple sets of attributes can be associated with any portion of an existing linear feature that segmented dynamically and temporarily for the analysis and to store multiple attributes. For example, Fig. 3 represents the same edge with different subdivision based on lane number, surface material, speed limit, and pavement quality. Every time these attributes change, the road will need to be further subdivided [12].

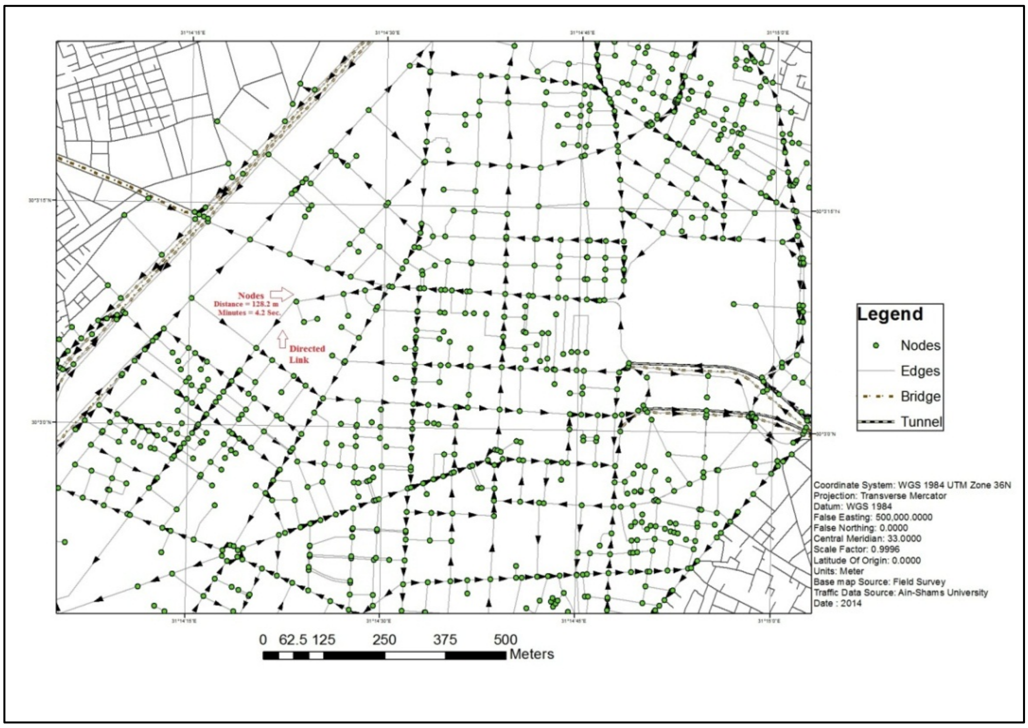


Figure 1: Road network representation

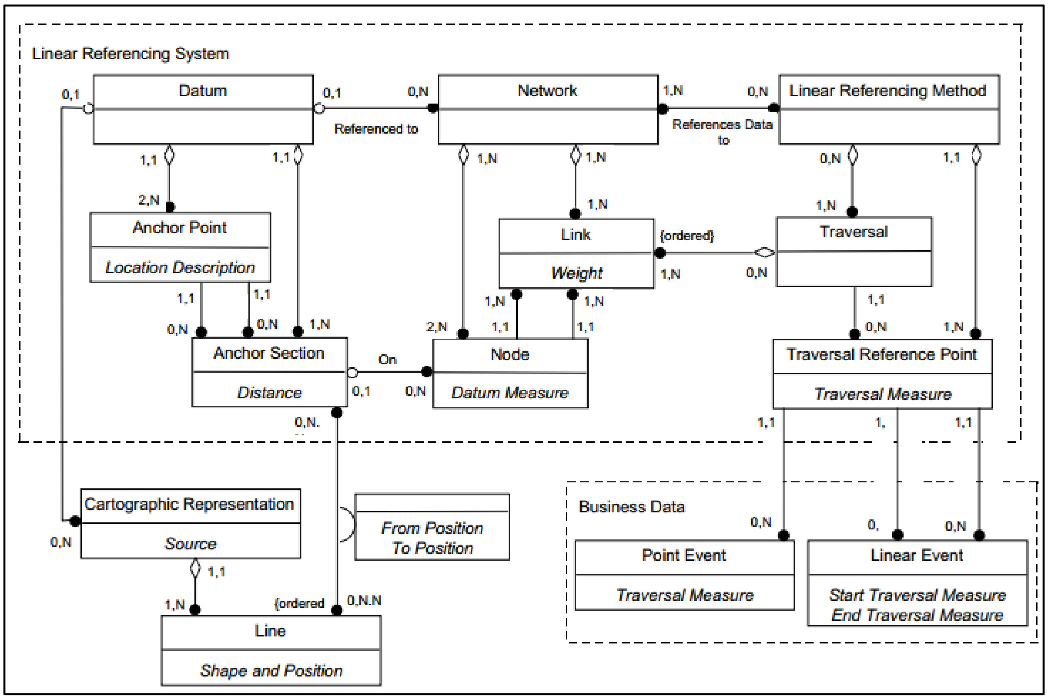


Figure 2: Linear Reference System Object Model

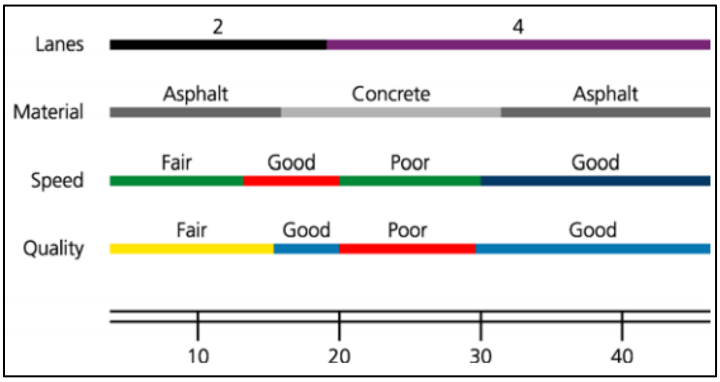


Figure 3: Storing multiple sets of attributes for one feature

3. Methodology

Generally, many factors cause traffic congestions, such as traffic flow, road geometry, road incidence such as bad road construction, traffic incidence..,etc. Therefore, several traffic congestions indexes can provide information for traffic situation [13].

This study proposes a method for solving the dynamic path analysis for the urban road network taking into account the temporal traffic conditions by integrating the principles of Geomatics in terms of graph theory, MLRS and DS. This method is composed of three main stages. The general model of the work flow for this research is presented as in Fig. 4.

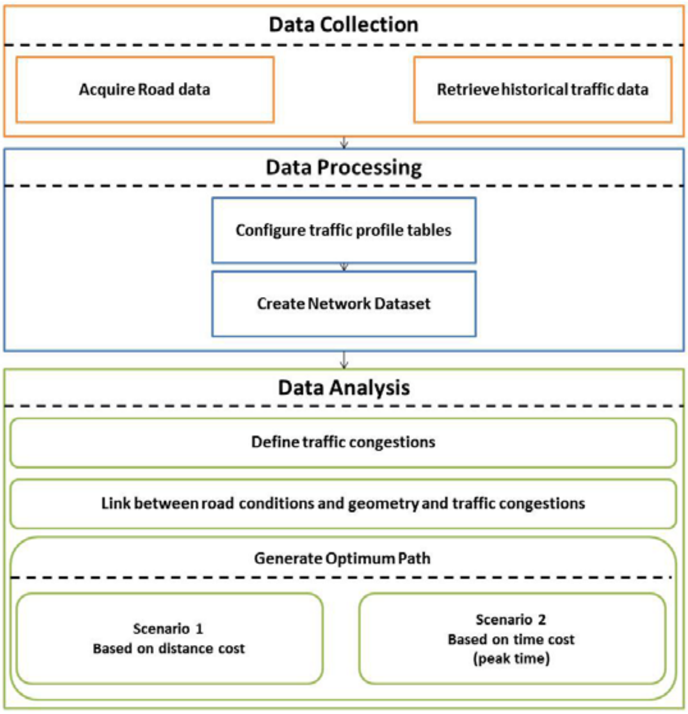


Figure 4: Conceptual workflow for the proposed Methodology

Stage (1) is the data collection stage, where both the road characteristics and traffic data are acquired. Generally, there are two main methods; one is collecting information from fixed locations on cross roads using equipped sensors, while the other is collecting information from moving vehicle mounted by onboard GPS devices [14].

Stage (2) represents the processing stage that is applied to configure the traffic profile tables, and then to model the traffic enabled network that consider both MLRS modeling and the related DS based on road features such as pavement condition, number of lanes, …etc.

Stage (3) is the data analysis, where we apply the congestion index to define the network situation, and then edge between the road characteristics and congestion level.

This can lead us to the spatial analysis of finding optimal path between two specific locations in a network where its traffic congestion changes continuously.

3.1. Congestion Index determination

This section explains the applied mathematical model for defining the congestion index. For such a reason, the required data are divided into two main types; road characteristics and traffic volume data. Road geometric data include lane width, number of lanes, and pavement width. Traffic volume data has three main characteristics intensity, density, and means speed.

The traffic flow “q” as represented in Eq. 1 is the average number of vehicles passing a cross section of a road (V) in a unit of time (T).

$$q = \frac{V}{T} \tag{1}$$

Similarly, Eq. 2 formulates the density (K), which is the number of vehicles (m) per a unit of road length (X) at a given moment.

$$K = \frac{m}{X} \tag{2}$$

If the traffic flow is a stationary and homogeneous, then the following relationship is valid as expressed in Eq.4.

$$q = K * u \tag{3}$$

The capacity of a road depends on various design factors such as lane widths and intersection configurations. Several studies have shown that other factors (such as weather and ambient conditions) also influence the capacity significantly.

Also, the capacity of the road is highly influenced by the behavior of the drivers. [15]. Optimal performance values are shown in nest two tables. [16]

Table (1) shows the speed, flow and density of traffic under each Level of Service (LOS) rating.

Table 1: Typical Roadway Speed, Flow and Density Relationships

Level of Services	**Speed Range (mph)**	**Flow Range (veh. / hour / lane)**	**Density Range (veh. / mile)**
A	> 60	< 700	< 12
B	57 – 60	700 – 1100	12 – 20
C	54 – 57	1100 – 1550	20 – 30
D	46 – 54	1550 – 1850	30 – 42
E	30 – 46	1850 – 2000	42 - 67
F	< 30	UNSTABLE	> 67

Depending on that, each road edge can be categorized into one of five congestion levels, as summarized in table (2).

Table 2: Standard Congestion Level

	Extreme	**Severe**	**Heavy**	**Moderate**	**Free flow**
Arterial					
Avg. Daily Traffic Per Lane	> 10000	8501 – 10000	7000 – 8500	5001 – 7000	< 5500
Avg. Vehicle Speed (mph)	21	23	27	30	35

Based on the comparison between traffic count data, road intensity calculation and local knowledge, five grades of congestion level were proposed for evaluation of congestion in the current situation as shown in Fig. 5.

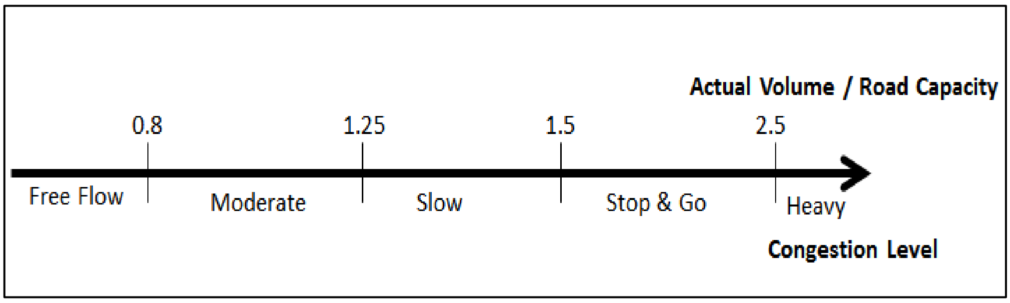


Figure 5: Congestion Levels

3.2. Generating optimum path analysis

The algorithmic core problems that underlie the intelligent transportation system (ITS) application is a special case of finding optimum path from specified source node in road network to a specified destination node. The prerequisites data to this function is the vector road network layer. Recalling, it represented by a directed multi-graph. Let G (N, A) be a directed graph whose edges are weighted by a function. We interpret the weights as the edge lengths, where the length of the path is the sum of weights of its edges. The problem lies in finding a path of minimum length from a given source S to a given destination D.

Dijkstra's algorithm is the one of the most commonly used route finding algorithm for solving the optimum path. It is based on the concept of graph theory and algorithmic techniques such as dynamic programming, partitioning, tree searching, recursion, and geometric method (nearest neighbor problem) [17].

The modified Dijkstra's algorithm takes into account the dynamic changing parameters such as traffic congestion, where the travel time changes or varies with respect to time. In contrast, travel time is considered dynamic due to traffic volume, and historical traffic data applied to a network. Dynamic variables like weights are time-varying travel that derived from historical traffic data. The network analysis will reflect actual traffic conditions occurring at various times during the day when time-dependent variables are incorporated [18].

So, the real-time traffic information is used effectively for achieving an optimal path within a stochastic transportation network and the preliminary analysis of the real-life traffic flow. Equation 4 proposes the following relationships of the varying parameters with the weight associated with each edge: 1) The weight (Wij) is directly proportional to the traffic congestion (Tij) between two nodes i and j, 2) The weight (Wij) is directly proportional to the distance (Dij) between two nodes i and j, and 3) The weight (Wij) is inversely proportional to the vehicle speed (Vij) between two nodes i and j. Hence, the weight (Wij) assigned to an edge connecting node i and j by Eq. 4 [19]:

$$W_{ij} = \frac{D_{ij}T_{ij}}{S_{ij}} \tag{4}$$

3.3. Traffic database model

The traffic database model integrates traffic and spatial data, where the database design model represents the characteristics of traffic flows within an urban system as shown in Fig 6. It integrates the temporal and spatial dimensions of a traffic system using a homogeneous database representation. The main network entities used for the management of incoming traffic data are as follows: nodes that represent an intersection within the network, road segments that describes a part of the physical network between two nodes and incoming edges which represent a lane that arrives at a node. [20].

3.4. Traffic data visualization

Finally, one of the most important tools is the visualization process in order to integrate the spatial and dynamic temporary to provide complementary perspectives. Animations allow users to browse through the temporal traffic states to enrich the user perception of traffic data through time.

A multi-dimensional approach of the visualization of the dynamic data improves the user perception of traffic data through time and act as an exploration tool that can be used to identify traffic patterns in space and time. [21].

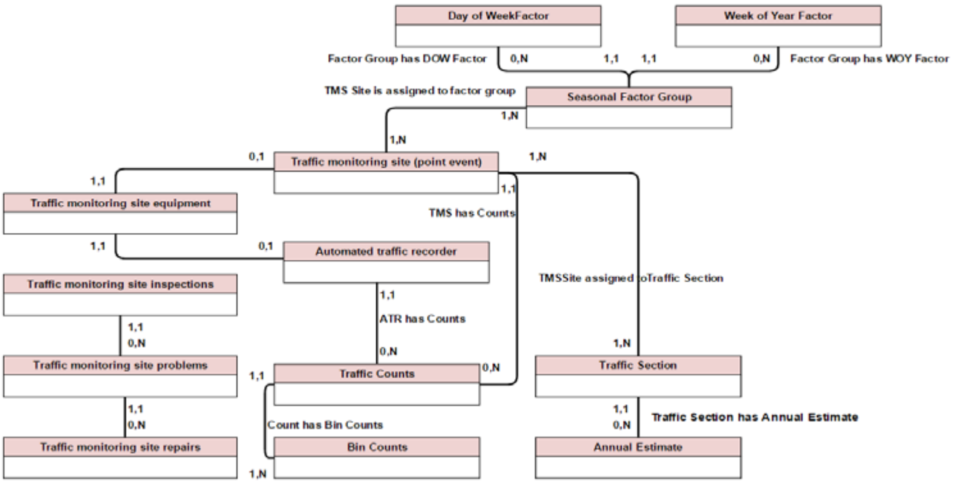


Figure 6: Traffic Data Model

4. Case study

This research focuses on the urban street of the downtown area, Cairo, Egypt, which represents a typical example of an urban area with traffic congestion hotspots. The applied map is prepared by field survey at a scale of 1:5000 and contains the major natural and man-made features. See Fig. 7.

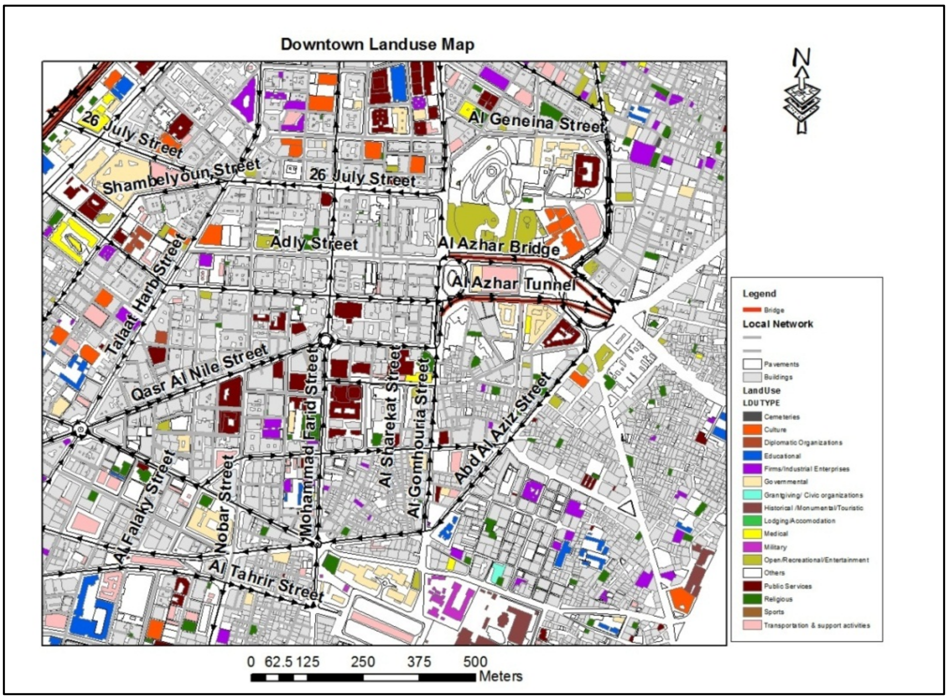


Figure 7: Land use map of downtown area

The total traffic data collection was conducted by the Central Traffic Department in Cairo by using automatic sensors that count vehicles per lane of the typical edge of the road.

The preliminary selection was based a congested day, where the data is observed on Monday (working day) for 24 hours. The collected data is provided every 15 minutes.

During all data collection periods, the weather was clear and the pavement was dry and generally, in a good condition. Based on this count, the peak hour of the typical working day is selected for further analysis. Statistics of the traffic data that represent the number of lanes, lane width, curb lane, pavement width, average daily traffic, flow rate and density. It is based on both the descriptive statistics and the robust statistics calculations.

Mean error (average, or arithmetic mean) is the best estimator of the measured value and it is given by the sum of the values in the distribution divided by the number of edges:

$$Mean = \frac{1}{n}\sum_{i=1}^{n} |\mathrm{Value}_i| \quad (5)$$

Where the term Value represents any of the above mentioned traffic data; and n is the number of edges.

The mean error value is defined by the standard deviation σ that is given by:

$$\hat{\sigma} = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(\mathrm{Value}_i - \hat{\mu})^2} \quad (6)$$

Where $\hat{\mu}$ is the mean error value [22]. Table 3 represents the summary statistics of the values of these data.

Table 3: Statistical analysis of the traffic data

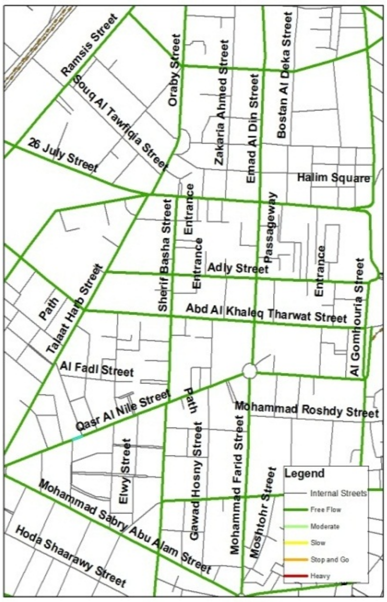
	Min.	Max.	Avg.	SD
Lane Width (m)	3	3	3	0
Pavement width (m)	1.5	5	2.63	0.829
No. of Lane	2	5	2.95	0.72
Curb Lane width (m)	3	3	3	0
Average Daily Traffic	1580	31050	10881	5320.7
Flow rate (vehicles / hr.)	1	1635	148.9	199.9
Density	1	40.8	1.94	4.05

In total, 28 road edges represent the major roads within the study area and are suffering from severe traffic congestion in the current situation have been selected for evaluation.

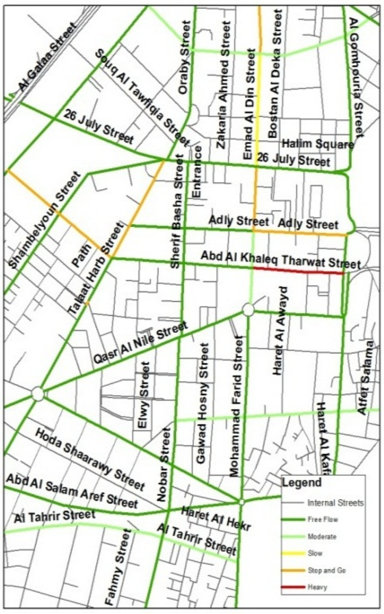
5. Results and Analysis

The congestion index is calculated for the whole streets network, and then the network dataset including the historical traffic information is created.

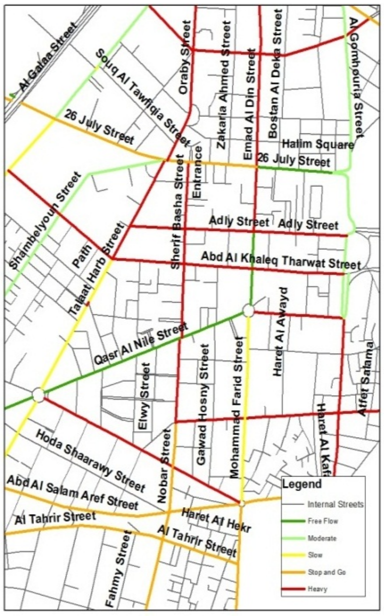
The five congestion levels are applied to classify the data each two hours. Fig. 8 (a,b,c,d,e,f,g,h,I,j,k,l) shows the results of applied congestion index model in the study area that emphasizes the traffic data situation every two hours.



(a) 2 AM -4 AM



(b) 4 AM -6 AM



(c) 6 AM -8 AM

(d) 8 AM-10 AM

(e) 10 AM-12 AM

(f)12 PM-2 PM

(g) 2 PM-4 PM (h) 4 PM-6 PM (i) 6 PM-8 PM

(j) 8 PM-10 PM (k) 10 PM-12 PM (l) 12 PM-2 AM

Figure 8: Downtown Cairo Traffic Data Changes on Week Day

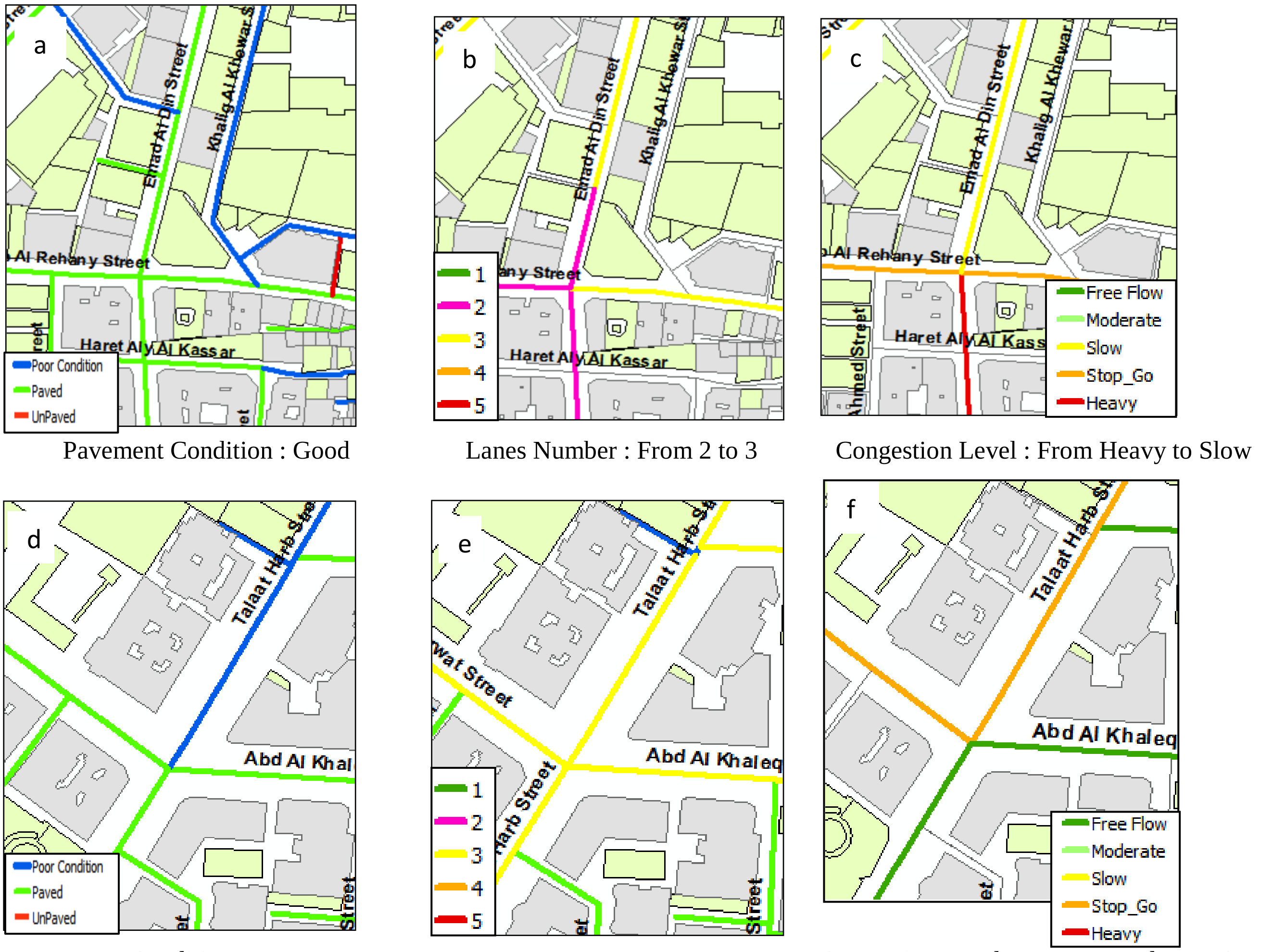
In general, the above figures show that downtown is congested almost all of the day and even at the expected peace time (early morning and late night where there is a moderate congestion level at few roads).

The peak hours can be divided into 3 periods as the morning peak hours (between 6 am and 10 am), afternoon peak hours (between 12 pm and 4 pm) and the evening peak hour (between 8 pm and 10 pm.).

Table 4 illustrates the road KM covered per each congestion level that signifies the traffic count for each peak period.

Table 4: Congestion Level Index KM Covered per each level

Index Class	KM/Class				
	6am-8am	**8am-10am**	**12pm-2pm**	**2pm-4pm**	**8pm-10pm**
Free Flow	1.5	0.0	0.0	0.0	2.8
Moderate	6.0	3.8	1.8	1.0	5.9
Slow	2.3	1.5	3.0	7.7	2.4
Stop & Go	5.6	6.5	12.5	8.5	3.6
Heavy	6.2	9.7	4.3	4.4	6.8



Pavement Condition : Good

Lanes Number : From 2 to 3

Congestion Level : From Heavy to Slow

Pavement Condition : From Poor to Good

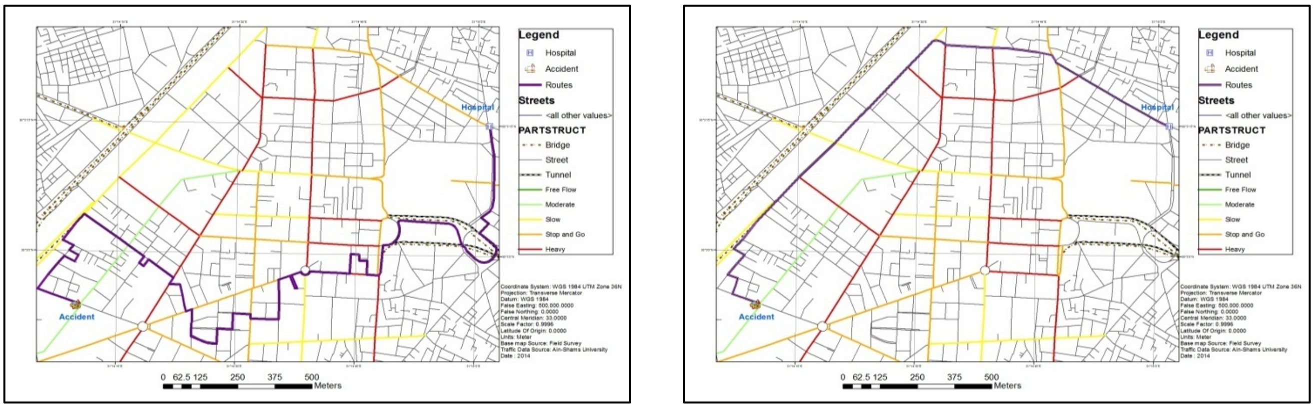
Lanes Number : 2

Congestion Level : From Free Flow to Stop & Go

Figure 9: Street of mixed congestion levels

The output is accepted in most of the street edges; however, some streets represent mixed levels. For example Emad Al Din Street denotes a mixed result between heavy and slow traffic levels. As shown in Fig. 9 (a,b,c) the pavement condition of the two parts are the same; while the number of lanes changes from three lanes to two lanes and this could explain the occurred traffic behavior change. Another case that also has different congestion levels between free flow and stop & Go is Talaat Harb Street, but here the reason may return to the change in pavement condition from Good to Poor Paved street. See Fig. 9 (d,e,f).

As mentioned before, the choice of the routing can depend on distance, time, velocity, etc…... Here, the assumption is to generate two routing examples between vehicle accident location selected from the event layer of crash data to the nearest hospital. Figure 10 shows scenarios 1 and 2 of routing solution. The first one is depending on the time-varying factor of the historical traffic data; while the second one is based on the shortest distance. Routing based on weight attributes derived from historical travel-time data and applied to network edges should assist emergency response vehicles to avoid congested areas. Recalling, Monday was selected as weekday traffic and time from 2 PM to 4 PM exemplifies the most peak hours.



(a) Routing Scenario 1 Depend on Time (02 PM-04 PM)

(b) Routing Scenario 2 Depend on Distance

Figure 10: Example of Routing Scenarios

According to the results, the total distance of route scenario 1 (Fig. 10, a) is 3.60 KM with travel time 3 minutes. This value is based on the time impedance. When observing scenario 2 result (Fig. 10, b), which is based on distance weight, the accumulated value of the distance is 2.19 KM with travel time 5 minutes. It indicates that Route scenario 2 has a shorter distance than Route scenario 1, but it has a longer travel time. It has demonstrated that the travel times and routes generated within a dynamic network are still considered as more realistic than the ones in a static network environment.

6. Conclusions

The Multi-linear referencing system data models, dynamic segmentation based on graph theory provides a framework to integrate temporal traffic data for satisfying the need of traffic congestion management.

A congestion index model is used to define the congestion levels through five defined levels. Through dynamic segmentation, we can integrate different linear attributes such as pavement condition, number of lanes and congestions level.

Downtown study area is selected for assessment, where this paper concluded that there is a traffic congestion problem at this area with high expectation for expansion in future. This is due to many factors that reflect on the traffic flow, such as the existing dynamic activities that affect the traffic flow especially in the peak hours, the increase of vehicles numbers in relation to the capacity of roads and the variation of the street widths.

Analysis and temporal visualization functions can support a graphical view of traffic conditions by using visual and animated cartographical capabilities to improve the potential of the traffic management systems.

The integration of temporal traffic data enriches the optimum path analysis, where the results agree with the expectations. The distance impedance generated the shortest path regardless the travel time. However, historical traffic data generate the best or most optimal path illustrating how a dynamic network is preferred over a static network when applied to the emergency response routing.

According to the fact that gathered data for the case study that represents the down town area is not comprehensive, another important dynamic variables is desired to enhance the analysis; such as the seasonal weather conditions, slope, annual daily traffic (ADT), peak hourly volume (PHV), driver behavior, parking area reflection etc. Also, other regions with other behavior are needed to test the influence of the implemented GIS tools in this research.

It is recommended to improve the road network management and the subsequent analysis by taking into consideration the incorporating of other factors to define the model traffic congestion. Furthermore, to expand the routing function through the fusion of real-time or live traffic data. More investigations are required to generate semi-automatic model using weighted index values based on the network classes.

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