A GIS-based Traffic Control Strategy Planning at Urban Intersections

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Summary
For having better and up to date traffic information access, spatio-temporal GIS for transportation (TGIS-T) needs to interact with the intelligent transport systems (ITS). Advanced traffic management systems (ATMS) is one of the components of the ITS and predicts traffic congestion and provides real time traffic information and optimal control strategies for freeways and arterials. ATMS needs automatic acquisition of traffic information such as traffic volume using different detectors. In fact, the ideal condition for ATMS is the one in which all urban intersections are equipped with these detectors, however, it would not be possible in short time. So, the urban intersection degree of importance recognition in order to consider the priority as well as planning for detectors installation is one of the main traffic control designers' challenges.
In this paper, an approach has been proposed and implemented to measure each intersection degree of importance, considering the impact of other network intersections using GIS capabilities, dynamic traffic modeling and space syntax theory.
Tests of each intersection degree of importance for a part of North-West of Tehran urban traffic network are conducted and the results verified the efficiency of the proposed method and support our strategy.
Key words:
TGIS-T, ATMS, Space Syntax theory, Network analysis ere the part of 4-5 keywords.

1. Introduction

Decisions are often evaluated on the basis of quality of the processes behind. It is in this context that geospatial information system (GIS) and spatial decision support system (SDSS) increasingly are being used to generate alternatives to aid decision-makers in their deliberations [1].
Among so many implementations of GIS, a GIS application for Transportation (GIS-T) has become an outstanding one [2]. It is possible to state unequivocally that GIS-T represents one of the most important application areas of GIS technology [2].
For having better and up to date traffic information access, GIS-T needs to interact with the intelligent transport systems (ITS). Advanced traffic management systems (ATMS) is one of the components of the ITS which predicts traffic congestion and provides real time control strategies for freeways and arterials [3]. As one important component of ATMS, traffic control systems respond to changing traffic conditions to control ramp flows to improve the efficiency of freeways, to maintain priorities for high-occupancy vehicles and to coordinate signal timing strategies across regional arterial network. By ATMS-produced information utilization, advanced traveler information systems (ATIS), the other component of the ITS assists travelers with planning, perception, analysis and decision making to improve the convenience, safety and efficiency of travel [3]. ATIS is currently being developed to improve the safety and efficiency of automobile travel. In conjunction with ATIS and ATMS, advanced public transportation systems (APTS) is another important component of ITS. APTS applies advanced navigation, information and communication technologies that most benefit public transportation [3].
According to the above information, it is supposed that ATIS and APTS need cooperating with ATMS, furthermore, ATMS needs automatic acquisition of traffic information such as traffic volume by using different detectors.
In fact, the ideal condition for ATMS is the one in which all urban intersections would be equipped with these detectors but it would not be possible in short time. So, the urban intersection degree of importance recognition in order to consider the priority as well as planning for detectors installation is one of the main traffic control designers' challenge [4]. Practically, choosing an intersection for detectors' installation is done by comparing local traffic statistics regardless of the effect of other network intersections on the proposed intersection in different times a day [5, 6].
In one hand, this selection method may reach to a fruitful result but it is time and money consuming. In the other hand, if we installed the detectors on the intersection(s) that were effective on the selected intersection for installing detectors as well as considering some controlling strategies, the congestion of the chosen intersection could be reduced definitely.

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In this paper, an approach has been proposed and implemented to measure each intersection's degree of importance, considering the impacts of other network intersections using GIS capabilities, dynamic traffic modeling and space syntax theory.
In section 2, the proposed strategy is exhibited. In section 3, the proposed method is represented. Experiments are exhibited in section 4 and finally the results are introduced in section 5.

2. Strategy

Geospatial Information System (GIS) is widely used to support the spatially related decisions and provides an integrated and flexible set of tools for analyzing large volume of geospatial data and services. To achieve full GIS functionalities, they must have capabilities to store and retrieve, manipulate and represent data [7].
In many applications, GIS tends to show a static situation of the world called a snapshot [8]. However, recent developments in time-dependent data from historical to real time data capture, such as transportation lead to many new potential applications for spatio-temporal systems [9]. Enhancing the spatio-temporal capabilities of geospatial information systems in transportation applications is an issue that has been received much attention recently and it is led to the development of a GIS branch called spatio-temporal GIS for transportation (TGIS-T). These information systems manage not only spatial and aspatial components of geospatial transportation entities, but also consider their temporal characteristics [7].
GIS-T components can be obtained from extension of common GIS components. These components are temporal data management, analysis and visualization [7]. It is obvious that spatio-temporal analyses are based on existing spatio-temporal databases and therefore, most past efforts to add temporal capabilities to geospatial information systems have been undertaken to spatio-temporal databases and modeling. Time-stamping and event or process based spatio-temporal data modeling are some of the results in this area [10]. On the other hand, temporal visualization is not a pure geospatial information (GI) related problem and the results of the other data visualization and representation efforts, such as animation, 3D and multimedia representations can also be used for representation of spatio-temporal data [7].
Space syntax is a set of theories and tools used for spatial morphological analysis with particular applications in urban science [11, 12]. It has been widely used for pedestrian modeling[13], crime analysis [14], traffic pollution control [15], and way-finding processes [16]. As the space syntax theory is based on the graph theory principles, the design and implementation of space syntax spatial analyses is possible through GIS analytical capabilities.
Accordingly, some of the Jiang's researches could be considered [11, 12, 17, 18, 19].
Among Jiang's researches, [17] seems to be more justified in terms of integrating space syntax with GIS. One of the shortcomings of the previous researches on the integration of GIS and space syntax is to consider specific problems. This research intends to provide a comprehensive approach for GIS and space syntax integration.
By proposing an innovative approach on the basis of TGIS capabilities, dynamic traffic modeling and space syntax theory, this paper has come up to measure each intersection degree of importance, considering the impacts of other network intersections.

3. The Proposed Method

In this section, the specific approaches used for computing the importance of each urban intersection are introduced.

3.1 Algorithm

Figure 1 shows the workflow of the proposed algorithm.

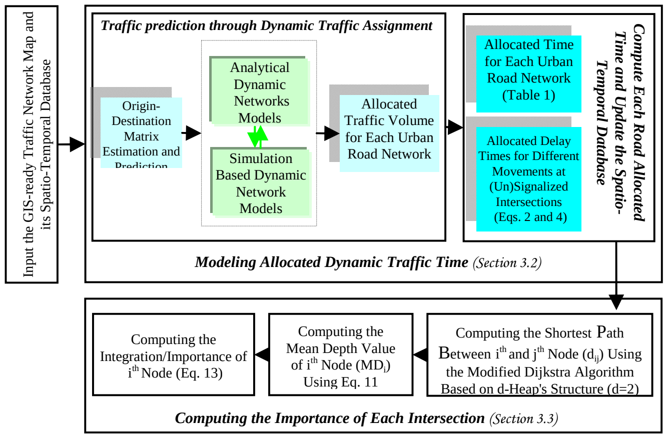

Fig. 1 The workflow of the proposed method to achieve each intersection degree of importance

3.2 Modeling allocated dynamic traffic time

The proposed approach used for modeling allocated dynamic traffic time shown in Figure 1, is explained as follow.

3.2.1 Travel time-volume functions

An effective approach to model transportation network congestion is through equilibrium analysis [20, 21, 22]. The equilibrium approach captures the relationship between users' travel decisions and network performance. Adjustments occur between users' decisions and network performance until a balance pattern is achieved. This pattern is network equilibrium in the sense that each traveler has no further incentive to change their route choices. Empirical evidence, albeit limited in scope, supports the existence of network equilibrium.

The basic model of congested network equilibria is the user optimal (UO) [3]. This principle states that, at network equilibrium, no traveler can reduce his or her travel costs by unilaterally changing routes. Alternatively, all used routes between an origin-destination (O-D) pair have the same, minimal cost and no unused route has a lower cost [22]. Effective algorithms exist that solve for the network flows that correspond to the UO pattern [21].

The standard UO approach is oriented towards long term infrastructure planning and policy. Since it assumes a 'steady-state' equilibrium, it cannot capture detailed temporal and spatial dynamics. However, these dynamics are especially important for capturing congestion patterns and properties that affect routing and schedule within and through urban areas.

Several dynamic network flow models are available [23]. However, many have strong computational and data requirements. A typical formulation treats the network as a dynamic system whose flow is the solution of an optimal control problem. In addition to a substantial computational platform, this requires continuous-time monitoring and control of flows in the network. This may be reasonable for applications such as intelligent transportation systems (ITS).

Since we are designing a pragmatic dynamic congestion module as part of a broader logical analysis system, we have selected a more tractable modeling strategy. The dynamic user optimal (DUO) approach is a discrete-time dynamic flow model [24]. Although it cannot capture continuous-time patterns, it can provide flow dynamics to a fine level of temporal resolution. This finite resolution is sufficient for solving urban routing problems. The DUO principle states that, at network equilibrium, no traveler who departed during the same time interval can reduce his or her travel costs by unilaterally changing routes. Alternatively, all used routes between an O-D pair have the same, minimal cost and no unused route has a lower cost for travelers that departed during the same time interval. These conditions are a temporal generalization of the UO conditions: UO is a special case of a DUO with one long analysis time period [24].

Dynamic traffic assignment (DTA) is a solution algorithm for solving the DUO problem [24]. The DTA is a heuristic algorithm that generates approximate solution of DUO conditions. Interfacing the DTA procedure with a GIS enhances its functionality for conducting analysis. The GIS provides effective decision support through its database management capabilities, graphical user interfaces and cartographic visualization of complex spatial and temporal congestion patterns and the resulting optimal paths [9]. GIS also allows the analyst to change the road network to reflect failure or capacity reduction due to unplanned disruptions.

Road type	V_0 ***(Km/h)***	***Function***
Exp. Way with a negative slope	90	$t = 0.67\left[1+0.15(\frac{v}{390w})^4\right]$
Exp. Way without a slope	80	$t = 0.75\left[1+0.15(\frac{v}{350w})^4\right]$
Exp. Way with a positive slope	70	$t = 0.86\left[1+0.15(\frac{v}{330w})^4\right]$
Major arterial (outside the central district)	60	$t = 1.00\left[1+0.15(\frac{v}{310w})^4\right]$
Major arterial (inside the central district)	60	$t = 1.00\left[1+0.15(\frac{v}{250w})^4\right]$
Minor arterial	50	$t = 1.20\left[1+0.15(\frac{v}{240w})^4\right]$
Collector-Feeder	*40*	$t = 1.50\left[1+0.15(\frac{v}{200w})^4\right]$
Local access	40	$t = 1.50\left[1+0.15(\frac{v}{150w})^4\right]$

Modeling speed and time: DTA forecasts traffic volume for each urban road network using speed and time assignments of each road using Bureau of Public Roads (BPR) functions defined for each road (link) type [3]. The standard "BPR" performance functions relate capacity, current volume and free-flow traversal speed to estimate travel speed as a function of current flow [25]:

$$\frac{1}{V} = \frac{1}{V_0}\left[1+\beta(\frac{v}{Q})^n\right] \tag{1}$$

where:
V = link travel speed (Km/h)
V_0 = link free-flow travel speed (Km/h)
v = link flow rate (vehicles per time interval)
Q = steady state link capacity (vehicles per time interval)
β , n = empirical parameters

Some metropolitan planning organizations have estimated the required empirical parameters for their local areas. In Iran β and n are estimated as 0.15 and 4, respectively [26]. Since these parameters are related to different functional urban road types (in terms of posted speed limits), they provide reasonable results without the expense of calibrating the flow cost functions for each study area. However, they cannot capture regional or local differences in driver behaviors. Table 1 shows the travel time-volume function for different road types of urban traffic network in Iran.

Table 1: Travel time-volume function for different road types [26]

3.2.2 The delay function of intersection with traffic light (signalized intersection)

The average delay time for passing through signalized intersections is presented as Eq. 2 [27]:

$$d = \frac{(c-g)^2}{2*c(1-\frac{v}{w*s})} + a*(\frac{v}{Q})^b \qquad (2)$$

where:

- d: the average delay per vehicle for passing the intersection (per second)
- c: the cycle time (per second)
- g: the green time length for a particular cycle for a needed movement (per second)
- v: the total traffic volume in the street having traffic light (car equivalent per hour)
- s: the rate of the saturation flow for 1 meter of width (car equivalent per hour)
- w: the width of the street having traffic light (per meter)
- Q: the practical capacity of the street having traffic light (car equivalent per hour) and

$$Q = \frac{g}{c} * s \qquad (3)$$

- a: the constant value for various movements in one intersection (Table 2)
- b: the constant value equals to 2

Table 2: Different "a" values for various movements in one intersection [27]

Movement type	*a*
Turn right movement	*32*
Straight movement	*29*
Turn left movement	*36*

3.2.3 The delay function of intersections without traffic light (unsignalized intersection)

The average delay time for passing through one intersection with a flashing traffic light, a square, and a regular intersection is calculated using Eq. 4 [28]:

$$d = d_f * m * \left[3.5 + 4*(\frac{v}{w*Q})^2\right] \qquad (4)$$

where:

- d: the average delay per vehicle for passing intersection (seconds)
- d_f: the coefficient delay for the entering street with no traffic light

  d_f shows the right of way effect for each entering in comparison with other intersection entrances. d_f for an entering with the right of way is always smaller than that for an entering with no right of way (Table 3).

- *m:* the movement degree of difficulty coefficient in which

  $$m = m_1 * m_2 \qquad (5)$$

  m_1*:* the number of legal and effective movements in an intersection

$$m_1 = NEL*NExL-NTNU-NFM-NLM \qquad (6)$$

NEL: the number of entrance links to an intersection
NExL: the number of exit links from an intersection
NTNU: the number of two direction links with no U-turn
NFM: the number of forbidden movement in an intersection
NLM: the number of legal movements

m_2*:* the ratio of the number of entrances to exits

$$m_2 = \min\{\frac{1+\text{the number of entrances}}{1+\text{the number of exits}}, 1.2\} \qquad (7)$$

- w: the width of the street having traffic light (per meter)
- Q: the practical capacity of the street having traffic light (car equivalent per hour)
- v: the total traffic volume in the street having traffic light (car equivalent per hour)

Table 3: Different "df" values regarding various right of way situation [28]

An entering street situation	d_f
An entering street with no right of way	$\frac{1}{2}$
An entering major/minor arterial street having right of way	$\frac{1}{4}$
An entering Exp. Way having right of way	$\frac{1}{6}$

3.3 Computing the importance of each intersection

As stated in section 2, space syntax is a set of theories and tools used for spatial morphological analysis with particular applications in urban science [11, 12]. As the space syntax theory is based on the graph theory principles, the design and implementation of space syntax spatial analyses is possible through GIS analytical capabilities.

In following, first we point the different steps in space syntax with GIS integration based on the researches undertaken by Jinag, then we elaborate the existing problems in some parts, and finally we represent a proper solution for the mentioned problems.

Based on the Jiang's researches [11, 12, 17, 18, 19], the main steps in integrating space syntax with GIS are briefly mentioned in preprocessing and processing steps. The steps 1 and 2 represent prepossessing steps and step 3 belongs to processing step:

1. Spatial decomposition of spatial configuration into elementary units of analysis: bounded spaces, convex spaces and axial lines [12].
2. Representing derived analysis units and their connections as a connectivity graph in which its nodes and links are respectively the analysis units and their connections. Jiang et al. [12] illustrate three different representations for a connectivity graph depending on the degree of linearity in environment including axial line, convex and grid representations [12]. Axial line representation is used for structural representation of street network [17]. In this structure a street network is represented using a graph where named streets are represented as nodes and street intersections as links of the graph (Figure 2).

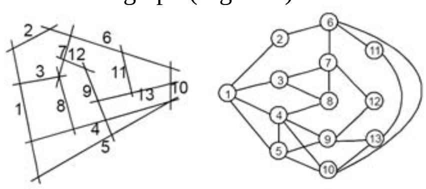

Fig. 2 Axial line representaion [12]

3. Deriving the graphs morphologic properties: connectivity, control value, depth, and integrability. These are defined as follow [12]:

- The connectivity value is the number of immediate neighbors of nodes (Eq. 8).

$$C_i = k \tag{8}$$

where C_i = Connectivity of i^{th} node

k = Immediate neighbours

- The control value of a node expresses the degree to which the node controls access to its immediate neighbors, taking into account the number of alternative connections of these neighbors (Eq. 9).

$$ctrl_i = \sum_{j=1}^{k} \frac{1}{C_j} \tag{9}$$

where

$ctrl_i$ = Control value of i^{th} node

k = Connected nodes to i^{th} node

C_j = Connectivity of j^{th} node

- The depth value is the smallest number of steps from a node to the others. It is defined as total depth and mean depth values (Eqs. 10 and 11).

$$D_i = \sum_{j=1}^{n} d_{ij} \tag{10}$$

$$MD_i = D_i/(n-1) \tag{11}$$

where D_i =Total depth value of i^{th} node

d_{ij} = shortest path between i^{th} and j^{th} node

n = Number of nodes

MD_i =Mean depth value of i^{th} node

- Integration/importance value is the degree to which a node (i.e., street in Jiang's researches based on the step 2) is integrated or segregated from the system. Based on the step 2, a node is known to be more integrated if all the other nodes can be reached after traversing a small number of intervening nodes and less integrated if the necessary number of intermediate nodes increases. The integration of a node is measured similar to relative asymmetry as the average depth of the node to all other nodes (Eqs. 12 and 13).

$$RA_i = 2(MD_i - 1)/(n-2) \quad (12)$$

$$I_i = 1/RA_i \quad (13)$$

where

RA_i =Relative asymmetry value of i^{th} node.

I_i = integration of i^{th} node

In steps 1 and 2, Jiang et al. suggested an axial line for solving the urban street network structure, which it seems the best usage of this structure is for the model-based generalization [12, 17]. It led them for using the Breadth First Traverse algorithm for finding the shortest path between two nodes to such an extent that the above definition of a more/less integrated node is affected by using this algorithm. But the Breadth First Traverse algorithm should be used for recognizing the shortest number of edges between two nodes. It is clear that when all the graph edge lengths are equal with each other, the Breadth First Traverse algorithm utilization has the same result as the shortest distance algorithm like Dijkstra [29] and of course it would not happen in urban street network practically.

It could be said that the axial line method proposed in step 2 causes all the results in step 3 would be unrealistic. Because urban problems like the problem under investigation need to calculate the shortest path between two intersections by considering the travel time needed to pass a road as well as an intersection. So instead of using step 2, after geometric and topological errors elimination, the urban traffic network graph was used in a way that every node and edge in step 3 represents an intersection and a road, respectively. Accordingly, a node is called to be more integrated if all the other nodes can be reached after traversing a small cost (travel time in the problem under investigation) and vice versa.

The most important element in step 3 is dij calculation. One of the key factors in dij calculation is to be cautious about the possible need for optimizing one criterion in order to calculate the shortest path between the two nodes. For instance, if it is supposed that a node is more integrated in a graph or less integrated; one question is posed that “how could the importance of a node (intersection) in an urban traffic network dependent on different values of a criterion e.g., the travel time of each street during a day, be calculated?”

So, the integration/importance of a node is different according to different values calculated by the proposed method in section 3.2 for travel time during a day based on the different calculated dij. Accordingly, the solution for dij is classified in single criterion shortest path problems (SSP) which is one of the branches of shortest path problems in GIS network analyses [30]. In this paper, we used the modified Dijkstra's algorithm based on d-Heap's structure with d=2 for dij calculation. This algorithm is capable of memory cost management in large networks [29].

4. Experiments

The proposed methods were implemented by ArcGIS utilization and customization. ArcGIS has a feature in architectural design, which enables it to be developed by COM programming in any visual environment.

To evaluate the performance of the outlined method, we performed experiments using actual road maps of a part of the North-West of Tehran urban traffic network at a scale of 1:2000. Table 4 shows the characteristics of the maps used in the experiments, where the nodes correspond to the intersections. In addition, each result given up was performed on Intel® Core™ 2 Duo CPU T7300 (2 and 1.99 GHz) with 2 GB of RAM.

Table 4: Characteristics of the map used

	Number of links	***Number of nodes***
Map	5121	4389

Based on Figure 1, the integration value for every urban traffic network node (intersection) during four times a day is calculated (Figures 3 to 6) and is classified in 4 classes by the equal interval classification approach. According to the figures, the more the integration, the more node importance will be.

Based on the figures (3 to 6) the degree of importance of the intersections (Equation 13) is different regarding to dijs' inequality during a particular time a day. The different dijs' inequality is the result of dynamic allocated time for passing each link (road) and node (intersection) during a particular time a day (section 3.2). Now it is the best time to plan and to install detectors according to achieved importance of each intersection during a particular time a day. So, all intersections with the degree of importance more than 39.842 could be the suitable place for installing traffic detectors.

Among the figures (3 to 6), Figure 3 needs the most detectors installation which shows the highest requirement of imposing traffic control strategies from 6:30 to 7:30 p.m. In Figures 7 and 8, we compare selected places for installing detectors (places with integration more than 39.842 achieved from proposed method from 6:30 to 7:30 p.m.) and the current detectors installed by Tehran Traffic Control Center without using the proposed method, respectively. Although, there are some similar detectors in the same place according to the above-mentioned ways, there are actually some differences which determine the significance of the proposed method for recognizing the exact place of detectors installation by considering the lowest cost and time in advance.

Fig. 3 The integration/importance value for each node form 6:30 to 7:30 p.m. on a typical Saturday

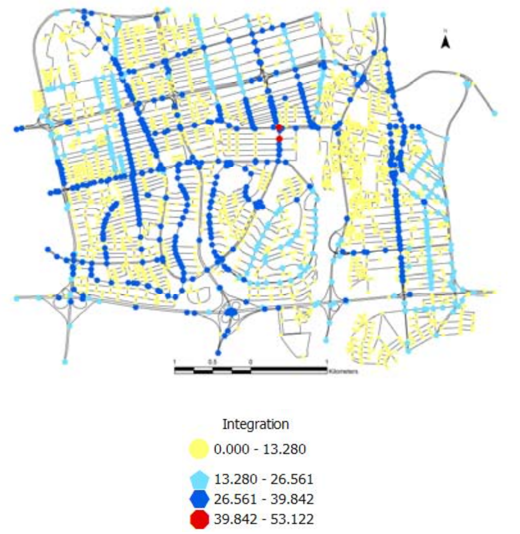

Fig. 4 The integration/importance value for each node from 7:30 to 8:30 p.m. on a typical Saturday

Fig. 5 The integration/importance value for each node from 8:30 to 9:30 p.m. on a typical Saturday

Fig. 6 The integration/importance value for each node from 9:30 to 10:30 p.m. on a typical Saturday

Figure 7: The selected intersections for installing traffic detectors based on the integration values more than 39.842 form 6:30 to 7:30 p.m. on a typical Saturday

Figure 8: The traffic detectors installed by Tehran Traffic Control Center

5. Conclusions

For having better and up to date traffic information access, spatio-temporal GIS for transportation (TGIS-T) needs to interact with the intelligent transport systems (ITS). Advanced traffic management systems (ATMS) is one component of the ITS and predicts traffic congestion and provides real time traffic information and optimal control strategies for freeways and arterials. ATMS needs automatic acquisition of traffic information such as traffic volume by using different detectors.

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In this paper, a unique approach has been designed and implemented to measure each intersection degree of importance, considering the related impacts of the other network intersections using the GIS capabilities, dynamic traffic modeling and space syntax theory.

So, dynamic traffic modeling is used for calculating allocated dynamic traffic time for passing from each link and intersection. These allocated dynamic traffic times are also saved in the spatio-temporal traffic network data base in order to analyze the shortest path between two nodes in GIS. Finally, the degree of importance of each network node in a particular time a day was calculated by integration of both space syntax theory and GIS. The results show the efficiency of the algorithm and support our analyses.

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