Spatio-temporal Analysis and Visualisation of Incident Induced Traffic Congestion Using Real Time Online Routing Information

A Case Study of Fremantle South, Perth, Western Australia

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***Abstract*— Traffic congestion triggered by incidents is extremely challenging because of its random occurrence. Incident Induced Traffic Congestion (IITC) usually refers to a form of non-recurrent congestion, which can be measured based on travel time variation after an incident has occurred. This study aims to analyze the spatio-temporal pattern of travel time variation induced by incidents using a case study of Fremantle South, Western Australia. The travel time data and information were collected from the TOMTOM® online routing system through TOMTOM® API. Around ninety-nine origin-destination (O-D) pairs were generated and geocoded to collect travel time information in three different periods, i.e., morning peak (7:00 am to 9:00 am), evening peak (4:00 pm to 6:00 pm) and off peak (1:00 am to 3:00 am) for six months from March 15, 2016 until September 15, 2016. Simultaneously, around 1047 records of incident location information have been collected in the vicinity of the study area. To understand the road network performance, travel time variation and delay were estimated using the Travel Time Index (TTI) measure. The spatial and temporal pattern of travel time variations were analyzed and visualized using specialized geo-spatial tools and techniques. The paper displays the spatial and temporal pattern of IITC in different circumstances that can be used for better traffic management and planning. An attempt will be made to generate various IITC scenarios using Geographic Information System (GIS) tools and techniques. These scenarios may be used for further research to understand the behaviour of road networks due to the occurrence of incidents for the development of congestion mitigation strategies.**

Keywords- Incident Induced Traffic Congestion (IITC); Online Routing, Travel Time delay; Spatio-temporal Data Analysis; Data visualization; GIS.

I. INTRODUCTION

At present, ensuring proper planning and management of the transport sector is a universal issue. Besides, an emerging challenge for transport planning is to mitigate traffic congestion in a sustainable way. There is no concrete definition of congestion. Congestion can be defined as the travel time delay from the origin to destination during peak hours [1]. Factors, such as, high travel demand, low supply of road network and incidents on roads may lead to traffic congestion or travel delay. Different agencies and researchers tend to define incidents in a different way. According to the Traffic Incident Management Handbook, the term “incident” can be defined as occurrence of any non-recurring event that reduces the roadway capacity or abnormally increases highway demand [2]. Congestion caused by incidents is usually defined as non-recurrent congestion, which can be measured based on travel time variation in a certain location. Hence, location and time of incident, and travel time variation are two significant factors to measure the spatio-temporal distribution of IITC. Four general aspects to measure congestion are duration, extent, intensity and reliability [3].

To measure congestion a real-time travel information system is becoming a significant objective. Global Navigation Satellite System (GNSS) technologies such as Global Positioning System (GPS) floating car data, GPS probe vehicle (moving vehicle equipped with vehicle tracker) or cell phone tracking are worthy methods for collection of non-stationary spatial data such as real time traffic flow and travel time information along the road network. Google API and TOMTOM API are two widely known Web-data-portal techniques that have been developed with the integration of GPS equipped floating car data. GPS floating car data is a potential source to collect data without using any vehicle detection technique [4]. A very few studies have been carried out to understand traffic congestion features using empirical data on traffic states from Web portal information [5].

Previous studies suggest that Travel Rate Index (TRI) [6], Congestion Index (CI) [7]-[11], Travel Time Index (TTI) [12] [13] and Speed Performance Index (SPI) [14] are the most widely used indices to quantify congestion and IITC. Among them, TTI has the benefit of assessing traffic congestion from a spatio-temporal perspective and it contains both recurring and incident circumstances encountered by urban travelers. Space and travel time variation are two significant features to measure congestion caused by incidents, which are indispensable elements for effective congestion and incident management [15]. On the other hand, incident information helps to generate different congestion scenarios based on random events that help identify route choice behaviour during incidents induced congestion [16]. Beforehand, most studies were focused to identify the major areas of concern due to incidents or crashes; thus, additional study is required to identify areas of concern through emphasis on non-recurrent traffic congestion.

Appropriate tools and techniques need to be identified to analyze and visualize IITC by considering the domains of space and time. Previously, several methods have been used to visualize and analyze spatio-temporal data on traffic congestion and incidents through human computer interaction. For instance, different graphical, cartographic and GIS tools such as, spider plots or radar graphs, line plots, scatter plots, box plot, QQ plot, Theme River, Comap, Self-organizing Map (SOM), contour map, pencil icons, spatial autocorrelation, spatio-temporal interpolation, cluster analysis etc. (), are widely used techniques to analyze, illustrate and visualize spatio-temporal information effectively [10] [17]-[22].

This study aims to analyze the spatio-temporal patterns of travel time fluctuation due to incident induced traffic congestion (IITC) in Fremantle South, Perth, Western Australia from real time traffic information to generate different IITC scenarios. Later, the generated scenarios (based on travel time variation) will be used to develop congestion mitigation strategies. The core hypothesis of this study is that, random events are the cause of non-recurrent congestion. The specific objectives of the study are as follows:

- Identify appropriate measures for IITC;
- Identify proper techniques to visualize and illustrate the spatio-temporal pattern of IITC;
- Evaluate and implement the techniques using a case study area.

Two major research questions were developed to fulfil the objectives:

- What is the appropriate measure to identify IITC pattern?
- Which visualization tools and techniques can be used to illustrate the information?

This paper consists of four main sections with a list of references. Section one (I) reflects the study background and target of this study. Section two (II) contains the materials and method including the study area delineation, data collection and pre-processing and detail about the approaches for data analysis and visualization of the outcomes. The study outcomes are highlighted in the results and discussion section. The study outcomes are highlighted in the results and discussion section (III). Finally, conclusions are drawn in section four (IV) based on study findings to address the research questions and to provide further research direction.

II. MATERIALS AND METHOD

The study outcomes will be generated by following a sequential approach. The spatio-temporal pattern of traffic delay has been estimated using TTI and demonstrated in a GIS environment using ArcGIS 10.4 e to generate various incidents induced congestion scenarios. To analyze the study data and visualize the outcomes ArcGIS 10.4 and MS Excel Analysis ToolPak-VBA have been used. Figure 1 demonstrates the conceptual framework for linking IITC data from a spatio-temporal perspective.

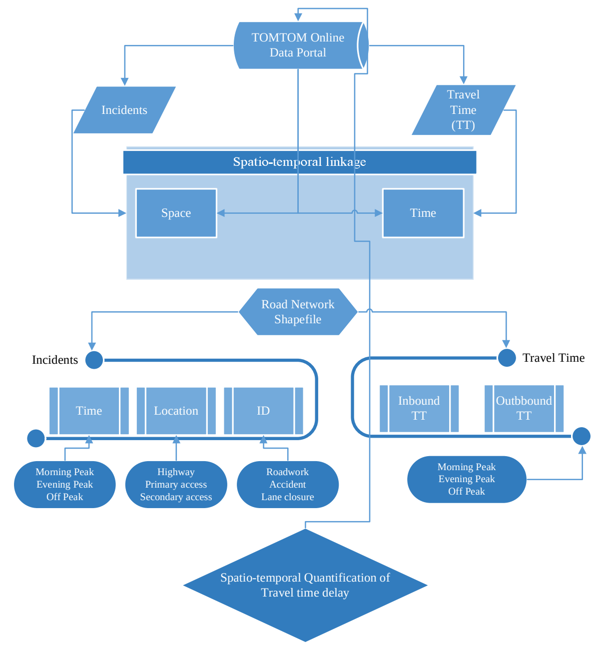

Figure 1. Conceptual framework of spatio-temporal analysis of IITC data

A. *Study Area Deliniation*

The Fremantle City Centre is a historical and touristic place in Western Australia. The market place or city centre (destination point) includes but is not limited to East Street, Queen Victoria Street/Adelaide Street, Market Street/South Terrace, Parry Street, Ord Street and the connecting roads. Queen Victoria Street and Adelaide Street are two major corridors inside the study area. This corridor is a busy link connecting Fremantle to Perth CBD and the surrounding suburbs. Canning Highway and South Street form the northern and southern study boundaries and eastern and western boundaries are Carrington Street, Mews Road and Cliff Street. The study area boundary and the location of Origin-Destination (O-D) points are shown in Figure 2.

B. *Data Collection and Pre-processing*

All the data and information were collected based on two major parameters of this study, i.e., travel time and records of incidents in the study area. The travel time information was collected from TOMTOM online routing system (TOMTOM® API) generated from GPS floating car data [23]. Around ninety-nine (99) O-D pairs were generated and geocoded to collect location specific data in two periods, i.e., morning (7:00 am-9:00 am) and evening (4:00 pm-6:00 pm) peak in each 15-minute interval. However, to get accurate real time information during free flow condition another time span at midnight from 01:00 am to 3:00 am travel time information was also collected.

The information was cross-checked with data collected from Google API. Travel time (TT) data were segregated as morning and evening peak, mid-day and late night hours from the original data set (from March 15, 2016 until September 15, 2016).

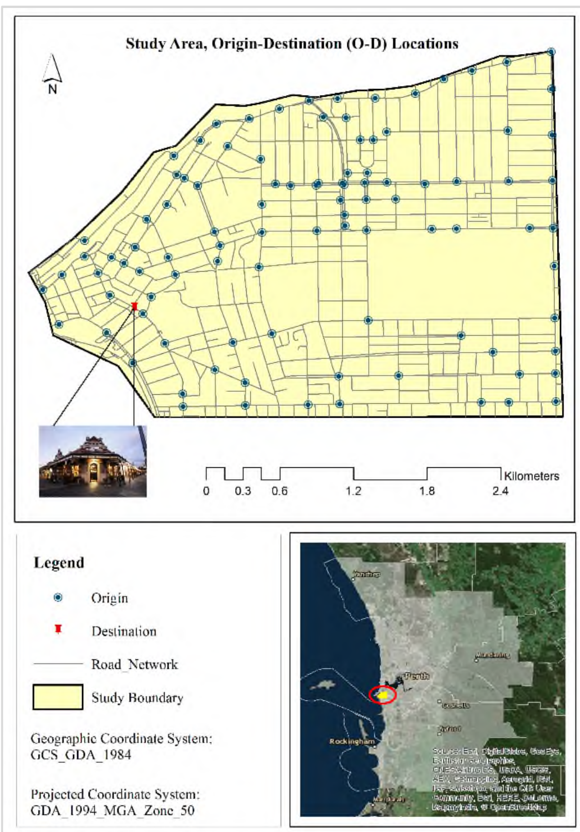

Figure 2. Study area boundary with Origin-Destination loaction, Fremantle, Perth

For the case of incidents, a bounding box was created within the vicinity of the study area and around 1047 records of incidents data were collected from the TOMTOM Traffic™ (the Online Traffic Incidents API). Finally, 747 records were identified after normalizing and overlaying the data with the study boundary. All the record were aggregated based on time and location during the analysis stage such as mean travel time during morning and evening peak, segment wise incident count per month etc. The road network data set was collected from Main Roads, Western Australia.

C. Data Analysis and Visualization

This section describes the spatio-temporal data analysis process, in addition to the illustration of study outcomes explained in the following sections.

1) Explore the General Pattern of Congestion

Exploratory analysis of spatial data, including statistical analysis and data visualization, were considered to generate the outcomes as the two major spatio-temporal data analysis techniques [24]. The average travel time (ATT) was calculated using an excel query and pivot table for each O-D (origin to destination) location during morning and evening peaks. The peak hour delay was measured using TTI based on average travel time during peak hour and free flow travel time. TTI was computed from Equation (1) [12]:

$$TTI = PTT/FFTT \qquad (1)$$

Where, TTI is the Travel Time Index, PTT is the actual travel time during peak hours and FFTT is the free flow travel time for the same O-D location.

Average TTI for each O-D pair was calculated based on morning and evening peak hours and free flow conditions. In addition, the average TTI for the total peak hour was estimated. This outcome reveals the general pattern of congestion through a line diagram.

Next, the road network was segmented according to location of O-D points using *network analyst* tool in ArcGIS. Then the segment wise travel time was calculated by subtracting the TT value of each O-D pair (location A) from O-D pair (location B) followed by a sequential location of travel time for each origin towards the destination. A model was developed in GIS to iterate the process 40 times to get TT value of all road segments. This outcome will be used to calculate segment wise delay that will demonstrate the spatio-temporal pattern of congestion in general (work in progress).

2) Mapping the Location of Incident

To define a unique ID for each incident, the find *identical tool* in ArcGIS was used to identify duplicate record of incidents. Then summary statistics were calculated to determine the maximum count of each incident and joined with the main data file. To define the projection of all the data sets, geographic coordinate system GDA 1994 was used and MGA Zone 50 was used as the projected coordinate system. The incident point data set was plotted and mapped in ArcGIS to visualize the location of incidents using the spatial analysis toolkit. Temporal patterns of incidents were analyzed using spider graphs and doughnut charts in MS Excel.

As the work is currently in progress, another subsequent initiative will be taken to identify incident hotspots using spatial analysis tools such as *Kernel Density Estimation* and *Ordinary Kriging* methods.

3) Calculate Incident Frequency

Around 683 incidents were identified through overlay analysis in ArcGIS by considering spatial joins between the two attributes, i.e., incidents and road segments. The incident rate in each segment was calculated using the frequency method for six months records, shown in Equation (2):

$$Loc_i = N_i/(L_i * T) \qquad (2)$$

Where, Loc_i is the incident rate at location i. N_i is the number of incidents identified at a certain location i over the period of T (total duration of recorded incidents) and L_i is the length of segment in metres.

A total of 131 days from the survey were identified (excluding public holidays and weekends). Total hours were then calculated by multiplying total days with the total recorded hours per day. In this study, six hours per day of data were recorded (2-hour morning peak, 2-hour evening peak and 2-hour off peak) with a total of around 786 hours.

4) Identify the IITC Affected Road Segment, Is Congestion Associated with an Incident or Not?

This section analyses and identifies major congested areas based on average TTI and incident rate per hour along the road network segments. Here, the association between TTI and the average incident rate from the previous calculation was explored. Both attributes from two different datasets were linked using the *spatial join* tool in ArcGIS. Then, the rate of incidents per segment were evaluated using the value of TTI. Later, a correlation analysis will be conducted between the number of incidents per segment or incident frequency and the average TTI per segment as further research.

5) Spatial-temporal Pattern of IITC

The spatio-temporal pattern of IITC for a major roadway was illustrated based on TTI of a specific day (with incident). The outcome was visualized through map and tables as shown in results and discussion section.

III. RESULTS AND DISCUSSION

A. General Pattern of Congestion

To understand the behaviour of road networks from a spatio-temporal perspective, the general pattern of congestion was analyzed without incidents. Here the travel time data was separated from the days with incidents. Then average TTI was calculated to estimate delay for each O-D pair. That provides a notion of re-current delay along the road network. Figure 3 illustrates the average travel time variations in morning peak (Avg_TT_Mor), evening peak (Avg_TT_Eve,), free flow average (AVG_FF) and average for whole peak hour travel time (AVG_Peak) in each O-D pair.

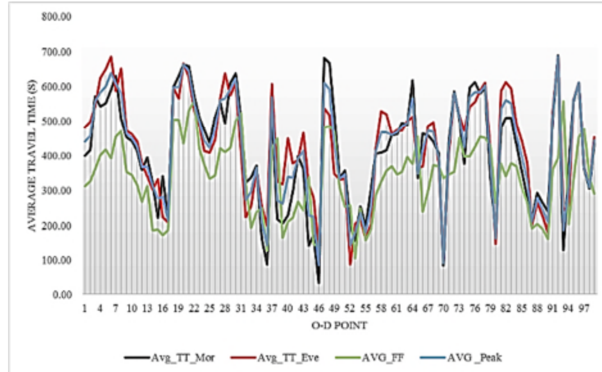

Figure 3. Average travel time variation (morning peak, evening peak and Free flow) per O-D pair;

According to the O-D point analysis, morning peak-hour travel times for pairs 1, 2, 5, 27, 83 and 85 are much higher than evening peak-hour travel times. Alternatively, pairs 37, 46, 52, 70 and 94 have minimum travel times both for the morning and evening peak hours that are lower than the free flow condition. This may happen due to a high rate of speeding by drivers.

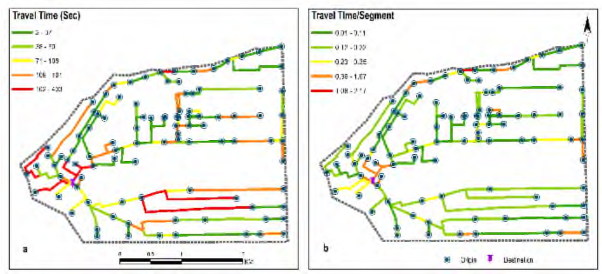

Figure 4. Travel time pattern in morning peak, 7:00 am along the road netwrok generated from *netwrok analyst* (a), normalized travel time for each road segmnet (b).

Morning peak-hour travel time was estimated for each road segment to explore the spatial pattern of congestion without incidents. Figure 4 (a) in the left side shows the distribution of travel time based on segment length (if the length is maximum then the value of TT was also maximum). Then the values were normalized with the lengths of road segments to get logical values of TT as shown in figure 4 (b). The north-west part of the study area near Canning highway was identified as mostly congested during peak periods.

B. Incident Distribution

The spatio-temporal distribution of incidents was analyzed using ArcGIS 10.4 and MS Excel Power Pivot. Figure 5 represents the locations of incidents based on category along the road network.

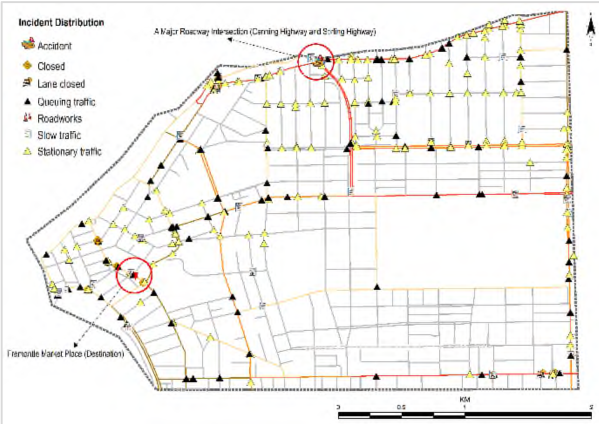

Figure 5. Spatial distribution of incidents based on categories

From the spatial distribution of incidents, only one record of an accident was found close to the Canning Highway and Stirling Highway intersection, which is a major intersection (Figure 5).

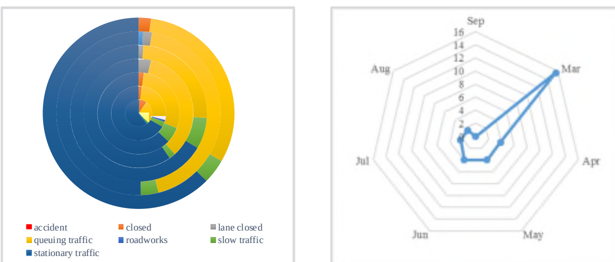

Figure 6. (a) Temporal distrbution of incident per month (March to September, 2016), (b) Amount of incidents overlay with road segments per month

Figure 6 illustrates the temporal pattern of incidents before and after overlay with the road segments. Most of the incidents generated stationary and queuing traffic. A very few number of (only two) accidents were reported in August 2016 over the whole study period, while a high number of incidents (how many) were found in March 2016

C. Incident Frequency

The hourly rate of incident per segment was calculated to measure the magnitude of incidents per segment along the whole road networks.

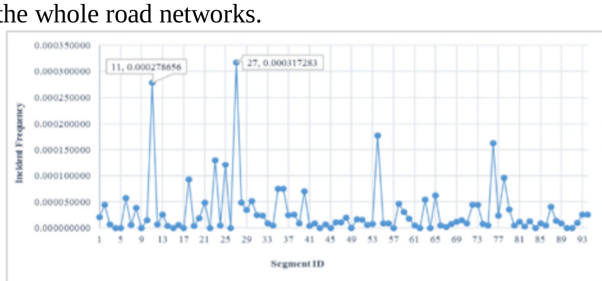

Figure 7. Incident rate per hour in each segment

Figure 7 describes the rate of incidents for each road segment. The maximum incident frequency rate were 0.0003 and 0.0002 near Staton Road to Stirling Highway and Queen Victoria Street to High Street (segments 11 and 27) respectively. This outcome will be used to select the date and location of incident for the next step of analysis.

D. Major Incident Induced Congested Road Segment

To identify a major congested road segment, travel time for a typical day was tested. Among the seven categories of incidents, an accident time of occurrence and location were selected to examine the impact on travel time for selected segments near the accident location. Hence, the evening peak hour TTI on Wednesday 17 August 2016 was analyzed to explore the spatio-temporal pattern of congestion, where the time of accident was recorded as 4:30 pm. From the result, segments 94 and 27 were identified as the most affected road section due to incident (accident).

E. Spatio-temporal Pattern of IITC

To explore the spatio-temporal pattern of congestion for road segments, the delay has been measured using the estimated average value of TTI during peak hours (morning peak, evening peak and total peak periods) as shown in Figure 8.

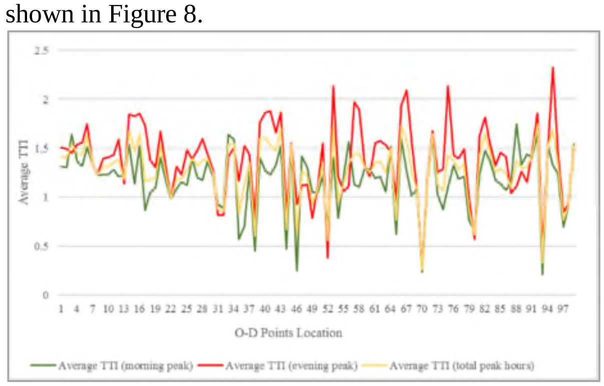

Figure 8. Estimated TTI value during Morning, evening and total peak periods

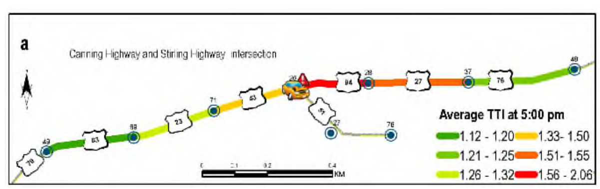

Figure 9. Spatial pattern of IITC during incindent at segment 43, 23, 63 at u/s and at 94, 27, 76 d/s

Figure 9 displays the pattern of congestion based on a single incident on 17 August near the Canning highway and Stirling highway intersection (segments 43, 23, and 63 in u/s and segment 94, 27 and 76 in d/s) during evening peak hour (5:00 pm) on 17 August 2016. Logically, upstream (u/s) segments close to the accident should be more impacted than u/s locations further away. Also, the nearest downstream (d/s) segments should have more impact due to incidents than those further away.

TABLE I. TTI VALUE OF U/S O-D POINTS TO AN ACCIDENT

Date (17/08/2016)	Average TTI Values (u/s segments)		
Time	O-D 69	O-D 71	O-D 26
16:00	1.13	1.32	1.50
16:15	1.13	1.32	1.50
16:30	1.12	1.31	1.49
16:45	1.12	1.31	1.49
17:00	1.12	1.30	1.48
17:15	1.11	1.29	1.46
17:30	1.10	1.28	1.45
17:45	1.09	1.27	1.43
18:00	1.07	1.25	1.41

TABLE II. TTI VALUE OF D/S O-D POINTS FROM AN ACCIDENT

Date (17/08/2016)	TTI Values (d/s segments)		
Time	O-D 28	O-D 37	O-D 48
16:00	1.71	1.52	1.22
16:15	1.70	1.52	1.22
16:30	1.71	1.52	1.23
16:45	1.69	1.51	1.21
17:00	2.06	1.51	1.20
17:15	1.67	1.50	1.19
17:30	1.66	1.49	1.18
17:45	1.65	1.48	1.17
18:00	1.63	1.47	1.16

Tables I illustrates the temporal pattern of IITC, where the closest u/s segment 43 (O-D point 71in u/s and O-D point 26 in d/s) was affected more than more distant u/s segments. Similarly, Table II illustrates how closer d/s segments 94 (O-D point 26 to O-D point 28) was affected more than more distant d/s segments. Next affected road segment in the d/s was 27.

IV. CONCLUSION AND FUTURE WORK

This study is part of an ongoing research program. The method will be used to further develop the research work. The aim of this paper was to explore and illustrate the spatio-temporal pattern of incident induced traffic congestion (IITC) on the road network using online traffic data. The study was designed to answer two research questions:

- What is the appropriate measure to identify IITC pattern?
- Which visualization tools and techniques can be used to illustrate the information?

This study attempts to explore appropriate tools and techniques to visualize and illustrate IITC that will be helpful for policy makers and the non-scientific community to understand congestion patterns along the road network. Travel time variation caused by incidents (vehicle crashes) were identified as the primary feature to define IITC. TTI has been identified as a useful index to measure the duration and extent of IITC. ArcGIS Network Analyst and Excel Analysis ToolPak-VBA are very useful tools to analysis and illustration of spatio-temporal data and outcomes.

From the preliminary analysis of incident and travel time data, segments 43 and 94 were found to be two major congested road sections due to an incident (accident). The preliminary assumption of this study was that random incidents are the cause of non-recurrent delay, and the results in Figure 9 and Tables I and II support the conclusion. This study attempts to explore suitable tools and techniques to visualize and illustrate IITC that will be helpful for the policy makers and non-scientific community to understand the congestion pattern along the road network.

The relationships between different spatial data attributes will be explored as further research work. To identify and evaluate the outcome of major congested road segment a correlation analysis will be carried out between two data parameter, i.e., travel time index and incident frequency rate based on space and time. In addition, the major area of concern or significant incident induced congested road segment will be identified using ArcGIS Network Analyst tool.

A major limitation of this study is the lack of data, especially information of travel demand and volume. To get robust results on incidents at least one-year of data should be used. Further research needs to develop more refined approaches to measure the spatial temporal dynamics of incident induced congestion.

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