PAPER • OPEN ACCESS

A Method of Identifying Critical Road Segment: A Case Study of Peninsular Malaysia Road Network

To cite this article: Amir A. Redzuan *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **479** 012003

IOP Conf. Series: Earth and Environmental Science **479** (2020) 012003 doi:10.1088/1755-1315/479/1/012003

A Method of Identifying Critical Road Segment: A Case Study of Peninsular Malaysia Road Network

Amir A. Redzuan*[1], Aznah Nor Anuar[1], Rozana Zakaria[2], Eeydzah Aminudin[2,3], Norbazlan M. Yusof[4], and Amirul Hakim Jamil[5]

[1] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[2] School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.
[3] Construction Research Centre, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[4] PLUS Berhad, Persada PLUS, Subang Interchange,KM15, New Klang Valley Expressway, 47301 Petaling Jaya, Selangor, Malaysia
[5] Department of Architecture, Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

.
*Corresponding author e-mail: redzuanamir03@gmail.com

Abstract. The resiliency of transportation infrastructures has been a major concern for the continuity of road services. In order to assess these issues, road network analysis is crucial to investigate the functioning of the existing road network and pinpoint each critical road segment. This enables early preparation for road operators and planners to focus on the road segment user most dependent on of which will be impacted most in case of disruption. This paper aims to introduce a method integrating different network analyses using a combination of three measures namely road segment length, betweenness centrality, and road density to identify critical road segments. The result shows the relationship between the different modes proposed with respect to the topological data implemented and concluded as the critical value of each road segment. This paper also includes the application of the methodology in a national scale region of Peninsular Malaysia road network.

1. Introduction

The resiliency of transportation infrastructures has been a major concern for the continuity of road services. Recently, disasters causing road disruption events had issued an interruption in social mobility resulting in an extensive loss such as severe congestion, cut-off of two distinct locations and isolation of towns in suburb areas [1, 2]. Roads as a component of critical infrastructure, are physical facilities providing consistent services for the functioning of society and economy [1]. Degradation of this infrastructure for an extended time will significantly impact the well-being of a nation [3]. Roads are among many other critical infrastructures vulnerable to disruption from either natural or man-made disasters due to its long-spanning and coverage in all sorts of terrain [4]. Increased in these vulnerable areas have called for road operators and planners to navigate the current structure of the road network and identify critical links for advance preparation by planning proper management strategy beforehand [5, 6].

IOP Conf. Series: Earth and Environmental Science **479** (2020) 012003 doi:10.1088/1755-1315/479/1/012003

Degradation of an important link significantly disables any movement of the affected area, furthermore causing cascading failures to other parts of the connected link [7]. Various methods were developed by researchers to encapsulate the definition of critical road networks with a common purpose of identifying the most crucial link within a boundary area. Within the context of road network topology, one may identify a specific location to be more sensitive to changes comparing others in a study of a critical network.

Static network connectivity analysis based on a topological model is the conventional way to quantify the criticality of existing road networks [6, 8]. Therefore, this paper aims to introduce a method to measure critical road networks using a combination of three technique namely road segment length, betweenness centrality, and road density. Different modes and models of the road network are proposed to calculate the critical value of each road segment. Through this means, this paper describes the process of analyzing the existing road network by explaining the concept definition of a critical road network, the methodology proposed in a detailed manner and its implementation on a macro scale region. The experiment covers the main network of Peninsular Malaysia consisting of the expressway, federal road and state road linking major cities and areas. The result presents critical road network mapping for the concern of road operators in mitigating future disturbance.

1.1. Critical Link in Road Network

Critical network analysis is developed to better understand the network structure under operation. Critical, vulnerable, reliable and sensitive are the few common terms in network analysis referring to a study on important links of a network. Hence, one may find that components creating a network (link and nodes) have different sensitivity values with respect to its position. Disturbance to a critical link of a network significantly results in degradation of connectivity itself, increase in time and cost of travel, rise in user dissatisfaction and maximize vehicles on road capacity [9]. Most authors incorporate dynamic traffic-related information for more reliable results [6]. A link geographically important may be considered as a critical link but it does not consider the probability of link failure [1]. Augmented definitions of a critical network may consider time-varying origin-destination (OD) as well as travel demand for shortest paths computation.

In examining a critical portion of a network, two noticeable approaches are done through topological assessment on an existing network or by disabling links to evaluate the severity of network failure. The first approach is usually delivered along with a street connecting mechanism to capture the characteristics of road network topology before analyzing. The second type usually refers to the reliability study of a network, using a probabilistic approach to link failure. The greater the damage the more reliable the link. Both are accepted as critical link analyses. However, this paper focuses on the first approach as an initial step in identifying critical road segments. Hence, in this study, three sets of road network analyses has been proposed using different techniques. Each technique represents a unique set of data of which require standardize leverage process for integration. For example, the first technique (segment length) represents road design and property data. The second technique (betweenness centrality) represents centrality measure data. The third technique (road density) represents data involving population attributes of the region.

1.2. Centrality Measure

In the field of space syntax, a study on special configuration and design relative to social effect, centrality measure is a popular way to analyze street networks [10]. Axial analysis such as an axial model to represent road segment is a fundamental component to syntax analysis [11]. In analyzing large-scale network, an issue made mandatory are to identify the critical element in a network. Through a topological viewpoint, these elements can be assessed by the relevance of the location of nodes and axis with respect to the given network performance [12]. Centrality measure is a standard procedure appropriate for this purpose relying only on the topological information. The three classic centrality measure are degree centrality (connectivity), closeness centrality (integration) and betweenness centrality (choices). Degree and closeness centrality are based on the idea of nodes being near to other nodes. Betweenness centrality is based on the idea of a node located between all other nodes in a network [13].

Other recently developed centrality measures are information centrality, eigen-vector centrality, page rank centrality, flow betweenness, the rush index, delta centrality, harmonic centrality, and Katz centrality just to name a few [14]. It must be mentioned that this research only used betweenness centrality for experimental purposes in Section 3. Traditionally, betweenness is the best choice for traffic network analysis purposes as it expresses the number of intersection needs to be crossed for each node on the shortest paths connecting them [6, 15]. From this experiment, betweenness is observed to have high correlative value with Malaysia's expressway. However, the argument that this value predicts the car flow of a street is still ongoing [10].

Many techniques are developed by authors to capture the characteristics of road network topology. James Sullivan et al. and Ayse Ozbil both explained their way of developing a road segment model [16, 17]. Fangxia Zhao et al. and Daisuke Watanabe adopted a relative neighborhood graph as a network connecting mechanism [18, 19]. Shuangming Zhao et al. modeled three modes of road network considering both the topological and geometrical characteristics and evaluate them by centrality measure to find its correlation [20]. Xiaolin Xia studied the comparison between topologic and angular analyses based on three kinds of urban street representation models: natural streets, axial lines and axial segments [21]. Alasdair Turner demonstrates angular segment analysis on road-center line segments constructed from Ordnance Survey land-line data [11].

2. Methodology

2.1. Framework

This section proposes an assessment of critical road networks using a combination of different methods. The proposed framework is shown in Figure 1 followed by a detailed description of the implementation process. The overall procedure comprises of three steps; modeling the primary road network, calculating the road network and analyzing the critical network. Then, it elaborates on the process of developing the three models.

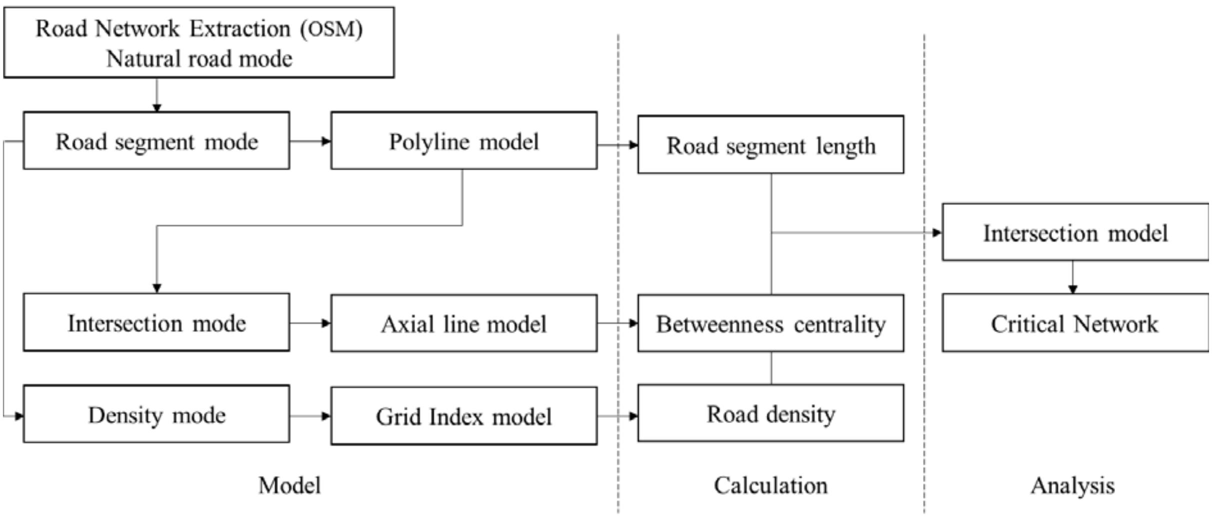


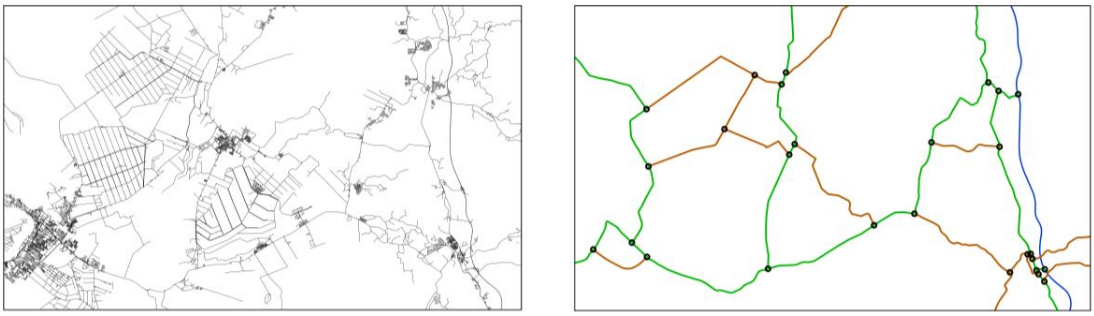
Figure 1. Proposed Framework

Step 1) Modeling the road networks
The road network of the study area is extracted from OpenStreetMap (OSM) in the form of individual street lines. Each streets in Malaysia belongs in a category of road classes according to the Public Work Department (JKR) list, namely; Expressway, Highway, Primary Road, Secondary Road and Minor Road. This study limits the scope by filtering the main network only consisting of Expressway, Highway and Primary Road. The studied network is then modeled according to three different modes, in section; *2.2 Polyline model for road segment mode, 2.3 Axial line model for intersection mode* and *2.4 Grid index model for density mode.* The output of this step is topological matrixes for three different modes.

Step 2) Calculation of the road network
This step involves the calculation of the street length, betweenness centrality, and road density. The calculation is referring to the process of achieving value for every line segment from each model developed. The first model, the polyline model, allows calculating each street length using ArcGIS. This process is explained in *Section 2.2*. The second model, axial line model consisting of only axial line and nodes representing road segment, allowing the betweenness centrality to be calculated in DepthmapX. This process is explained in *Section 2.3*. The third model, grid index, is the summed of road length in each grid of 5 kilometers square created in ArcMap and inserted to each road segment as its value. This process is explained in *Section 2.4*.

Step 3) Analyzing the critical network
The critical network in this study is achieved through the integration of the three modes. The intersection model developed allows value from each model to merge in a single identity. This reading offers a dynamic input by choice of a user on the weightage of the three modes. However, the result discusses are based on an assumption on equal distribution of weightage for the three integrated modes. The range of value is presented in graphic mapping in Section 4.

2.2 Polyline model for road segment mode
Intersections are represented as nodes, usually take the form of a point element in the map and the road segment connections between intersections are represented as edges. In a network assessment, edges connecting two nodes ostensibly have uniform characteristics [17]. To mention a few most considered are class, length, direction, capacity, speed and number of lanes. Intersections are the key to traffic analysis and the detection of insufficient traffic capacity which is the main cause of traffic congestion [20]. From the OSM road network shown in Figure 2 (a), we select only the primary road and modeled the network for each road segment to be a single identity.



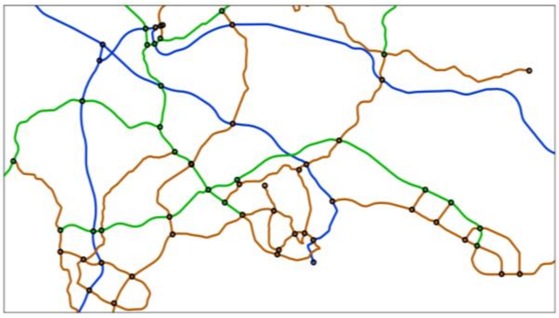
(a) OSM street line (b) Road segment mode

Figure 2. Polyline model for road segment mode

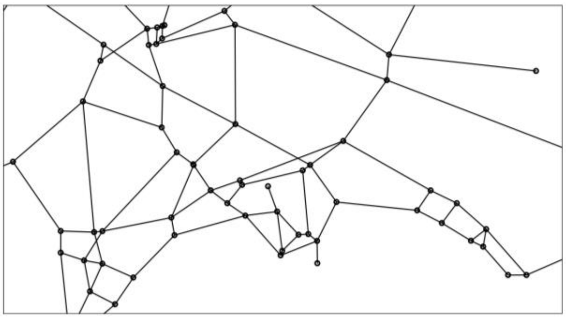
In computer graphics, this term is called polyline, the continuous line composed of one or more line segments. Figure 2 (b) shows the product of the polyline model assigning each line with a unique identity. The only characteristic it has in this stage are the classes it belong to either expressway (blue), federal road (green) and state road (brown).

2.3. Axial line model for betweenness centrality

Intersection mode preserves the nodes from a network and modified the connecting polyline into axial lines. The polyline, as traced from satellite imagery, carries detailed property of the actual road segment such as positioning and length. Axial lines are made to represent the existing road segment to serve as a direct relationship of every connecting pair of nodes. The significant purpose of developing the axial line model is to allow the processing of centrality measures using designated software. Figure 3 (a) shows a sample portion of a road network in road segment mode simplified into intersection mode by an axial line model in Figure 3 (b).



(a) Road segment mode



(b) Axial line model b

Figure 3. Axial line model for intersection mode

We use graph theory for this study, an undirected graph G = (N, E) to model the road network. Graph G is a set of nodes and edges, in which N is the set of all nodes, representing research units in the road network, and E is the set of all edges connecting two nodes in N [20]. The betweenness centrality C_B is defined by assuming that path travels from nodes to nodes are along the shortest path. If n_{jk} is the number of path linking two nodes j and k, and $n_{jk}(i)$ is the number of path linking the two nodes j and k that contain node i, the betweenness centrality of node i can be defined as [8, 13]:

$$C_B(i) = \sum_{j \neq i \neq k \in G} \frac{n_{jk}(i)}{n_{jk}}$$

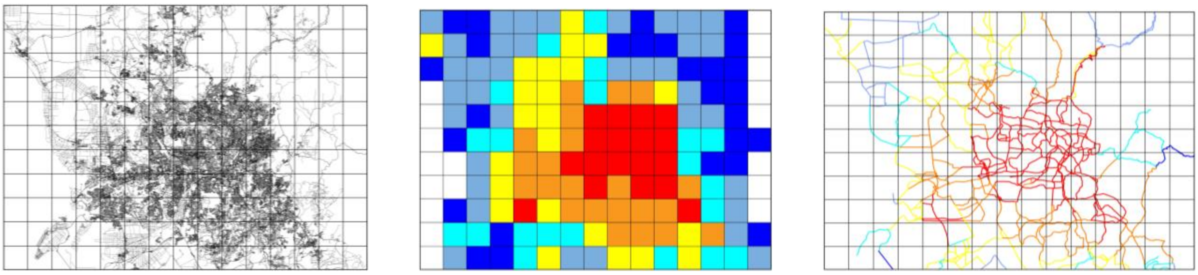
2.4. Grid index model for density mode

Degree centrality, a type of centrality measure, suggests a network strength to be on a global scale while density represents network strength on a regional scale. This density mode is the preferred method as opposed to the degree centrality of having a center as the highest value. Road density is defined as the ratio of the length of the total road network to a nation's boundary [22]. However, this model proposed road length in a grid index. In this process, we took account of the entire existing road vector dataset available in OSM, as in Figure 4(a), to calculate the road density. To calculate the road length per area requires a uniform division of area throughout the network. Unlike the most popular method of area division among studies that apply district boundary [23], we define density area by producing a raster layer of square grid measuring in square kilometer (5 x 5 km). Division by district boundary for this study is irrelevant as the result is biased toward responsible authority instead of equally dividing for spatial analysis.

This method calculates the density of linear features in the neighborhood of each output raster cell. Density D, is calculated in units of length per unit of area. Each raster cell are drawn to summed the line figure, and the total is divided by the grid's area.The corresponding population field values is V, thus:

$$D = (L * V)/A$$

If a population field other than NONE is used, the length of the line is considered to be its actual length times the value of the population field for that line. The distribution of grid value for this experiment is arranged in six colors for visual purposes with red being the highest. By having density mode, a critical area is designated to a grid of higher value as indicated in Figure 4(b). The higher density indicates the more population is exposed to the impact of road disruption in case of an emergency. The value of road density in each grid, became the value of every road segment in contact with the grid of higher value, as shown in Figure 4(c).



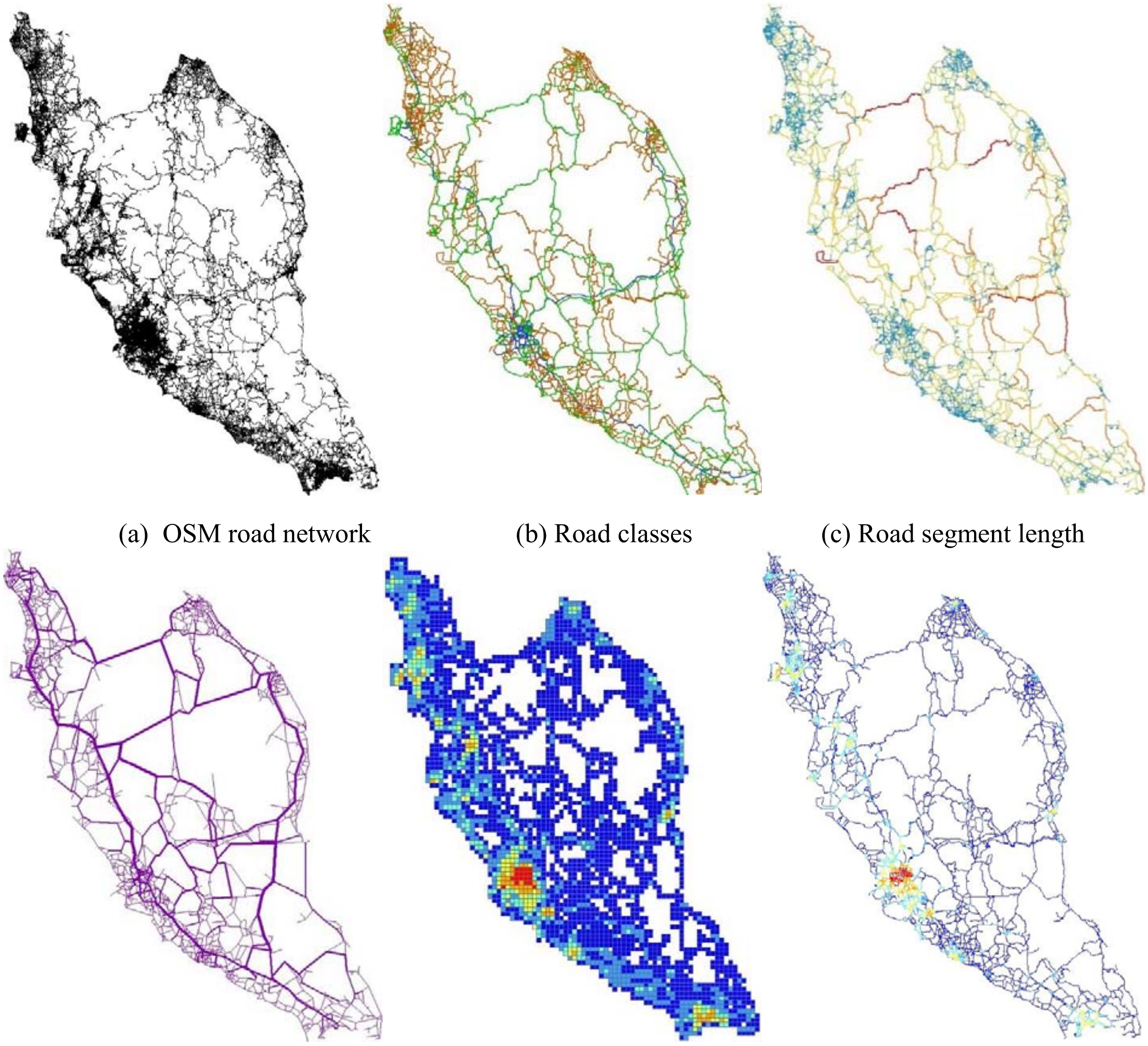
(a) OSM road network (b) Total length grid index (c) Density of road network

Figure 4. Grid index model for density mode

3. Experiment on Main Network of Peninsular Malaysia

The main motivation for analyzing a nation wide scale road network, other than the availability of OSM as a data provider, is to avoid the effect of the boundary condition. A graph theory represents the entire network in response to every existing node and axis. Analyzing the entire network presumably increases the result accuracy. Numerous studies have conducted centrality measures on only a selected region or city. This, however, raises concern to the "edge effect" on the road network to be limited by artificial boundary [24]. As for Peninsular Malaysia, the only road connecting to the bordering countries, Thailand (North) and Singapore (South), are excluded for the area limitation.

IOP Conf. Series: Earth and Environmental Science **479** (2020) 012003 doi:10.1088/1755-1315/479/1/012003



(a) OSM road network (b) Road classes (c) Road segment length

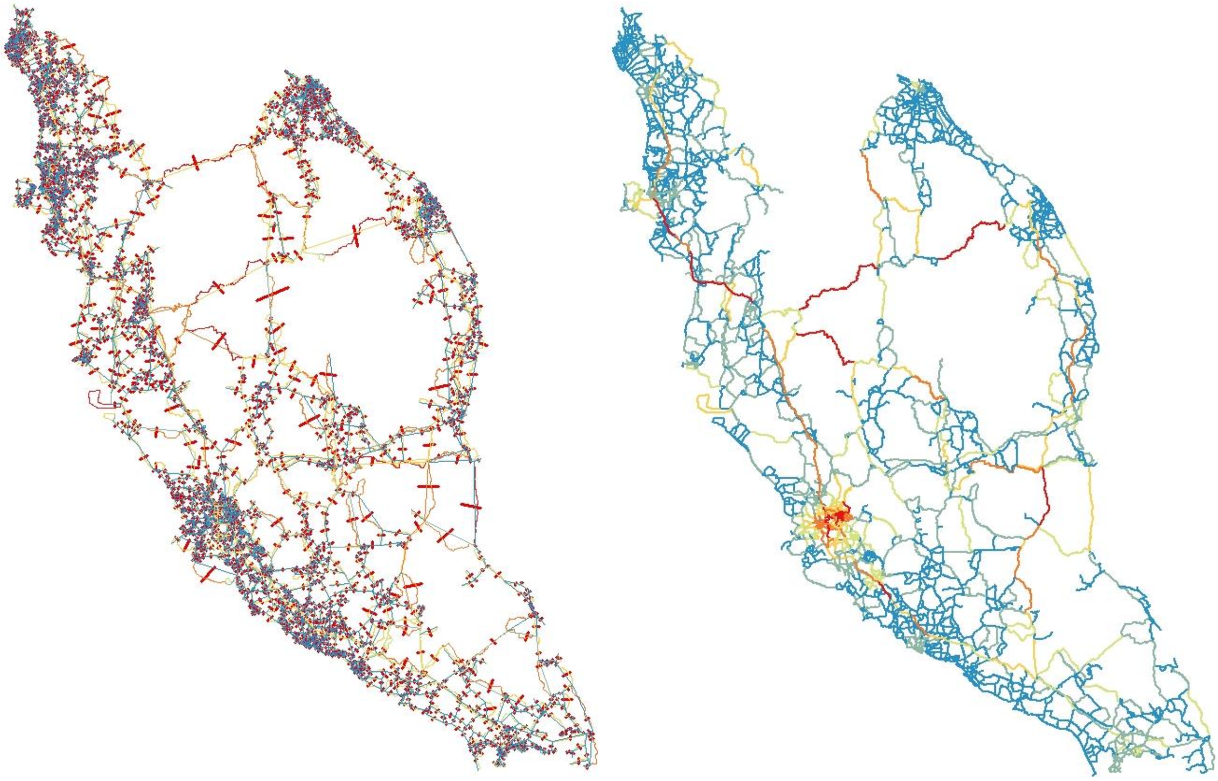
(d) Betweenness centrality (e) Grid index model (f) Density in main network

Figure 5. Grid index model for density mode

OSM road network is filtered by road classes for obtaining the main network as shown in Figure 5(b). A total of 3097 intersections and 4202 road segments are joined of which 245 are expressway (blue), 1395 federal road (green) and 2562 state road (brown). From the road segment model shown in Figure 5(c), the length for each road segment is obtained with the longest stretch of 104.2km and minimum stretch to be 7.3m. The scale is indicated by a color range of red being the highest category and blue to be the lowest. For the next model, nodes from the road segment model are preserved to create an axial line model. This model is tested for centrality measure to obtain betweenness centrality using DepthmapX. The result is shown in Figure 5(d) by line thickness scale measuring from 4900000 to be maximum value and 0 to be minimum. Grid index model is based on the sum of road length from the overall road network as presented in Figure 5(a) in an area of 5x5km. Figure 5(e) showed each grid in contact with the main network consisting of 3174 square grid. Each grid containing the sum of road length value will represent the value of each road segment as shown in Figure 5(f) as road density.

4. Critical Network

In the effort of integrating various types of network analysis, an inclusive outcome can be drawn off the investigated network and concluded as critical network. This final model is developed to integrate both values from the axial line based model and polyline based model by intersecting every existing line of both types stretching from the same connecting nodes, as shown in Figure 6(a). This method enables the intersecting line (red) to recognize the identity of both axial and polyline in contact, therefore allowing the value to integrate. At this point marks the end of line network modeling. A total of 3900 intersecting lines was created to be evaluated.



(a) Intersection model (b) Network reliability

Figure 6. Critical network model

The three data samples used for this experiment are road segment length, betweenness centrality, and road density. The range value of each data were normalized to be 0 as minimum value to 100 as maximum value. It is assumed that all criteria to be of equal importance, hence contributing 1/3 of the total value (33.3%). Figure 7 illustrates the result of the summation of these value on each road segments in ascending order. This graph enables identification of critical segment.

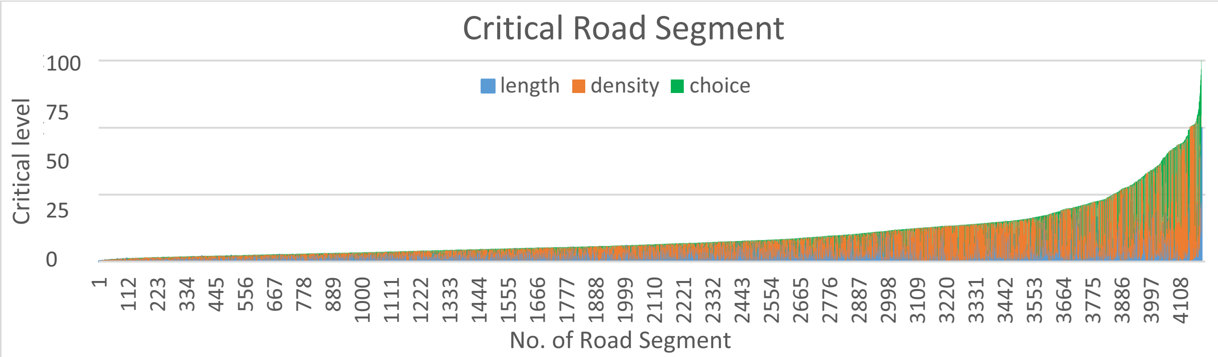


Figure 7. Axial line model for intersection mode

5. Perspectives and Further Research

In general, critical network study concerning centrality measures, when integrated with road attributes, will results in a more reliable outcome. The model developed in this study on Peninsular Malaysia road network opens the possibility of any use of centrality measures from undirected graph analysis, characteristics of the road segment and also from spatial analysis information. However, the prioritization and relationship of any data used are left for future study. This model offers value adjustment on each criterion according to their priority level or specific focus for planners when mitigating potential road disturbance on a critical network.

References

[1] N. Haghighi, S. K. Fayyaz, X. C. Liu, T. H. Grubesic, and R. Wei, "A Multi-Scenario Probabilistic Simulation Approach for Critical Transportation Network Risk Assessment," *Networks and Spatial Economics,* vol. 18, no. 1, pp. 181-203, 2018.

[2] Y. K. Hiroyuki Sakakibara, Norio Okada, "Road Network Robustness for Avoiding Functional Isolation in Disasters," *Journal of Transportation Engineering,* vol. 130, pp. 560-567, 2004.

[3] M. A. P. Taylor, S. V. C. Sekhar, and G. M. D'Este, "Application of Accessibility Based Methods for Vulnerability Analysis of Strategic Road Networks," *Networks and Spatial Economics,* vol. 6, no. 3-4, pp. 267-291, 2006.

[4] S. Zhu, D. Levinson, H. X. Liu, and K. Harder, "The traffic and behavioral effects of the I-35W Mississippi River bridge collapse," *Transportation Research Part A: Policy and Practice,* vol. 44, no. 10, pp. 771-784, 2010.

[5] S. Kim and H. Yeo, "A Flow-based Vulnerability Measure for the Resilience of Urban Road Network," *Procedia - Social and Behavioral Sciences,* vol. 218, pp. 13-23, 2016.

[6] P. Gauthier, A. Furno, and N.-E. El Faouzi, "Road Network Resilience: How to Identify Critical Links Subject to Day-to-Day Disruptions," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2672, no. 1, pp. 54-65, 2018.

[7] S. A. Bagloee, M. Sarvi, B. Wolshon, and V. Dixit, "Identifying critical disruption scenarios and a global robustness index tailored to real life road networks," *Transportation Research Part E: Logistics and Transportation Review,* vol. 98, pp. 60-81, 2017.

[8] L. C. Freeman, "A Set of Measures of Centrality Based on Betweenness," *Sociometry,* vol. 40, no. 1, pp. 35-41, 1977.

[9] T. ICT, *Moving Toward Climate-Resilient Transport: The World Bank's Experience from Building Adaptation into Programs*. 2015.

[10] "Hillier, B., & Hanson, J. (1984). The Social Logic of Space. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511597237."

[11] A. Turner, "From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis," *Environment and Planning B: Planning and Design* vol. 34, pp. 539-555, 2007.

[12] F. Cadini, E. Zio, and C.-A. Petrescu, *Using Centrality Measures to Rank the Importance of the Components of a Complex Network Infrastructure*. 2008, pp. 155-167.

[13] V. Latora and M. Marchiori, "A measure of centrality based on network efficiency," *New Journal of Physics,* vol. 9, no. 6, pp. 188-188, 2007.

[14] S. P. Borgatti, "Centrality and network flow," *Social Networks,* vol. 27, no. 1, pp. 55-71, 2005.

[15] Y. Zhang, X. Wang, P. Zeng, and X. Chen, "Centrality Characteristics of Road Network Patterns of Traffic Analysis Zones," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2256, no. 1, pp. 16-24, 2011.

[16] J. P. Ayse Ozbil, Sonit Bafna, "The Effects of Street Configuration on Transit Ridership," 2009.

[17] L. A.-H. James Sullivan, David Novak, "Application of the Network Robustness Index to Identifying Critical Road-Network Links in Chittenden County, Vermont," University of Vermont Transportation Research Center2010.

[18] F. Zhao, H. Sun, J. Wu, Z. Gao, and R. Liu, "Analysis of Road Network Pattern Considering Population Distribution and Central Business District," *PLoS One,* vol. 11, no. 3, p. e0151676, 2016.

[19] D. Watanabe, "A Study on Analyzing the Grid Road Network Patterns using Relative Neighborhood Graph," *ORSC & APORC,* pp. 112–119, 2010.

[20] S. Zhao, P. Zhao, and Y. Cui, "A network centrality measure framework for analyzing urban traffic flow: A case study of Wuhan, China," *Physica A: Statistical Mechanics and its Applications,* vol. 478, pp. 143-157, 2017.

[21] X. Xia, "A Comparison Study on a Set of Space Syntax based Methods," Master, Faculty of Engineering and Sustainability Development, Hogskolan I Gavle, 2013.

[22] J. R. Meijer, M. A. J. Huijbregts, K. C. G. J. Schotten, and A. M. Schipper, "Global patterns of current and future road infrastructure," *Environmental Research Letters,* vol. 13, no. 6, 2018.

[23] Shamshad and J. Khan, "Road Density and Levels of Development in West Bengal," *Indian Streams Research Journal,* vol. 1, pp. 83-90, 01/01 2012.

[24] J. Gil, "Street network analysis “edge effects”: Examining the sensitivity of centrality measures to boundary conditions," *Environment and Planning B: Urban Analytics and City Science,* vol. 44, no. 5, pp. 819-836, 2016.