K4D | Knowledge, evidence and learning for development

Evidence on impact evaluation of road transport networks using network theory

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Question

What are the recent advancements in technical literature on questions that take into account road transport upgrades in one area causing impacts elsewhere using network theory?

Contents

1. Executive summary

The development of network theory has resulted in a growing understanding of the topological properties of transport networks. This has led to knowledge on how network indicators relate to the performance of a network, their wider socio-economic impacts and insights about how networks can best be extended. It has also provided transport planners with an insight into traffic flow, travel demand, centrality and connectivity of transport networks.

This rapid evidence-review summarises literature (1999-2019) that have used network theory to evaluate the impact evaluation of road networks, it also presents the technological advancements in network theory. The identified studies outline the beneficial impacts of road networks on the economy, how connectivity can be improved to improve network resilience, reliability, performance and reduce maintenance costs. A number of studies describe how networks can be designed to reduce the impact on the environment. However, with the exception of only three studies i.e Kumar and Kumar (1999), Vasas and Magura et al. (2009) and Walker et al. (2013), the impacts are not quantified.

The magnitude of the impact, for a particular network, is a function of the type of model used. As studies could not be found where different models have been used to assess similar impacts, it was not possible to compare numerically the impacts of different model types.

Enhancements to network theory have focused on (i) developing new measures and indicators to assess connectivity, vulnerability and economic impact of transport networks, (ii) applying weightages to nodes and links to evaluate economic and ecological impacts and (iii) developing multiple layers within the network models for better spatial analysis. Recent studies have also expanded network theory and integrated it with risk modelling and probabilistic methodologies to identify vulnerable or critical elements within a given transport network.

2. Network theory applied to road transport

Network, or graph, theory is a branch of mathematics concerned with how networks can be conveniently modelled in order to evaluate the impacts of transport on the economy and how the network can be modified to bring about economic and social benefit (Hamidov, 2019; Zhang and Qin et al., 2015; Ravulaparthy and Goulias, 2014). The majority of the studies reviewed in this report have used network theory to investigate the wider impact of road transport on the economy, improvements to connectivity, network resilience, reliability, and performance of road infrastructure and services (Tanuja et al., 2018; Yonca Aydin et al., 2018; Saberi et al., 2017; Demsar et al., 2008; Appert and Chapelon, 2007). Network theory models have also been developed to show how construction and maintenance costs of rural road networks can be reduced while maintaining appropriate levels of connectivity or accessibility (Kumar and Kumar, 1999).

A literature search was carried out using the University of Birmingham's search engine findit@bham which allows all of the databases of the major academic journals in all subject areas to be searched, GoogleScholar.com, Google.com and Science Direct. The search was augmented by probing DFID Development Tracker, the RECAP, the World Bank and Asian Development Bank's on-line web portals. Twenty-five studies were identified for inclusion in this report. The criteria for selection were that the studies had to be published from 1999 onwards and that they must be associated with the application of network theory to road networks.

A summary of the findings from the gathered literature is presented in Table 1 (see Table A.2 for details), a discussion of the literature is included in the next section. The identified studies are associated with the beneficial impacts of road networks on the wider economy, how connectivity can be improved to improve network resilience, reliability, performance and reduce maintenance costs. A number of studies describe how network theory can be designed to reduce the impact on the ecology.

Table 1: Impact of road transport using network theory

Impact of road transport	*Study (in date order)*	*Network Theory model*	*Findings*
Economy	**Hamidov (2019)**	Conventional network theory with consideration of transportation costs	Road networks are capable of reducing transport costs and contributing to achieving an equilibrium in production and sale of products.
	Zhang et al. (2015)	Global efficiency model based on network theory	Optimal network-level road maintenance policies can reduce the economic costs (measured in terms of time taken to travel between origin and destination) thus impacting the operation efficiency or performance.
	Ravulaparthy and Goulias (2014)	Network theory using link-based multiple centrality indexes (L-MCIs), multiple centrality assessment (MCA) and latent class cluster analysis (LCCA)	The centrality of the road networks have high impact on the distribution of economic activities in a region. High density of economic activities are observed along urban roads in grid format.
Connectivity	**Hackl and Adey (2019)**	Network-in-Network (NiN) approach	Robust planning of urban road networks can aid the flow of traffic even during multiple link failures.
	Tanuja et al. (2018)	Supernode graph structure	Clear planning of urban road networks can reduce delays and congestions.
	Saberi et al. (2017)	Complex network theory	The travel demands evolve depending up on the distribution of activities and interactions between places in cities. Locations with

			greater connectivity and greater attractively tend to have smaller mean shortest path (MSP) lengths.
	Loro et al. (2015)	Conditional minimum transit cost (CMTC) methodology	By having multiple roads that connects a pair of nodes, city planners can ensure significant and sustainable increase in connectivity.
	Rashidy and Ahmed et al. (2014)	Combining network theory and fuzzy logic	Disruptive events negatively impacts mobility. New technologies for communication and better policy implementation can aid in increasing the accessibility of road networks
	Crucitti et al. (2006)	Space Syntax (SS) approach to network theory	The centrality of the road networks have high impact on the efficiency of the network
	Newman (2005)	Centrality measurement using network theory	
	Jiang and Claramiunt, (2004)	Centrality measurement using dual graph (based on network theory)	The structural representation of urban road networks appears to have a direct relationship between space and social activities.
	Kumar and Kumar (1999)	Conventional network theory	The model was used to demonstrate that a core rural road network could be maintained in three districts in India (Adilabad, Karimnagar, and Warangal) which would provide 100% connectivity to villages and habitations, but which would require approximately 53% of the cost of maintaining the entire road network.
Connectivity/ Resilience	**Yonca Aydin et al. (2018)**	Conventional network theory	The connectivity of road networks is highly susceptible to natural hazards such as earthquakes. Identifying critical locations within the network in advance can help in planning evacuations.
	Modarres and Zarei (2002)	Network theory combined with analytic hierarchy process	

Connectivity/ Reliability	**Demsar et al. (2008)**	Conventional network theory-based risk model	Identifying critical locations and vulnerable points or areas within the network can help in improved risk modelling for road networks.
	Appert and Chapelon (2007)	Conventional network theory	The pattern of vulnerability is higher in the city centres in comparison to the outskirts. For example, it was observed that at rush hour, the deterioration of travel speeds on the major links results in less route selection, leading to widespread vulnerability i.e. high volumes of traffic on unsuitable roads.
Connectivity/ Performance	**Mishra et al. (2012)**	Conventional network theory	The performance of a road network is based on the speed, capacity, frequency, distance to destination, activity density of the location, and degree centrality.
Connectivity/ Ecology	**Vasas and Magura et al. (2009)**	Conventional network theory	Highways can be planned by choosing routes that increase connectivity with less environmental impact. This study analysed the impact of road construction crossing the Bereg plain, Hungary to the habitats of carabid species. It was found that the three routes under consideration would significantly fragment the forests and negatively impact the carabid habitat by up to 60%. The study using network theory proposed a new route which would not have any impact on the analysed habitat of carabid species.
Ecology	**Walker et al. (2013)**	Computational graph theory	The logging paths (used by loggers for their benefit) are causing major fragmentation of the Amazon forest. The predicted fragmentation ranges from 1%-8%, depending on the region of the Amazon considered.

3. Advancement in network theory

Transport planners use a large variety of metrics to quantify networks in terms of the coverage, accessibility and connectivity that they yield. These metrics are based on principles adopted from network theory. These approaches analyse the performance of a given transport network rather than its underlying topological characteristics and often require detailed representation. Several studies have also modelled how the transport network may evolve over time based on certain growth principles (Zhang et al., 2015). However, there is a lack of knowledge on how transport networks evolve in a context where investments in surface transport infrastructure reach over long periods of time. This arguably stems from the difficulty of obtaining and compiling longitudinal data, partially attributed to corresponding organisational and technological changes (Hackl & Adey, 2019).

A traditional network theory model was modified by Jiang and Claramunt (2004) who modelled roads by nodes and intersections by edges, creating a ‘dual graph’. The intersection continuity rules used the street name information. Porta et al. (2006) found such a continuity rule unsatisfactory because of the lack of incompleteness of such information in many network databases. Therefore, they introduced an intersection continuity model which uses principles of ‘good continuation’, based on the preference to go straight ahead at intersections and using basic geometrical information of junctions to detect continuing roads. A similar approach using continuity is space syntax (Crucitti and Latora et al., 2006) which measures by how many changes of direction the rest of the network is reachable. The result is the so-called integration value, which represents how integrated or central a given road is in the network.

In transport related network theory models, the hierarchy is given by the functional characteristics of the links. These functional characteristics can be local streets with access to the adjoining land uses, trunk roads linking arterial roads and to highways or freeways. The network in network (NiN) structure proposed by Hackl and Adey (2019) employs a multi-layer network in which vertices are networks themselves, thereby making it possible to implement multiple diffusion processes with different physical meanings. Such an embedded network structure allows multiple pieces of information such as topology, paths, and origin-destination information to be analysed within one network/graph structure. Such an approach has resulted in better results than conventional single layer network (SLN) models employed by Crucitti and Latora et al. (2006). While SLN requires only required network topology, a NiN model also requires path statistics. This is a particular problem for historical networks where such data is no longer available. However, increase in digitalisation is making data from GPS tracking, mobile phones and social media available for use (Hackl and Adey, 2019). In this way, it is possible to estimate how the travellers’ paths will change and to determine the cascading effect in the network. This in turn would help in robust planning of urban road networks even during multiple road failures (for e.g. closures).

In classical network theory, assigning weights to edges is a common practice for generating weighted networks, but assigning weights to nodes is less considered. Tanjua et al. (2018) proposed a supernode structure to model the network as a weighted network by assigning node weight and edge weights. This approach was observed to have a significant advantage in analysing the inherent topological behaviour of road networks. More complex analysis using tools from other areas of graph theory (such as probabilistic graph theory, complex networks research, algebraic/spectral graph theory and structural graph theory) are rarely used (Demsar et al., 2008). However recently, Unsalan et al. (2012) employed probabilistic modelling alongside network theory to detect road networks from aerial images. Some studies reviewed in this report have combined network theory with fuzzy logic (Rashidy et al., 2014) and analytic hierarchy process (Modarres and Zarei, 2002) for evaluating the accessibility and vulnerability of road networks respectively.

Network theory is also applied to social network analysis (SNA), a well-established methodology for investigating networks through the use of mathematical formulations. Recently SNA was proposed by El-adaway et al. (2017) for applications in transport planning. Some commercially available software tools including, Tikz, PGF, NetworkX, Gephi, GraphViz, Saturn and NodeXL have also adapted the principles of network or graph theory (Analytics, 2018).

4. Conclusions

This rapid evidence review presented the evidence from the literature (1999-2019) on the use of network theory to evaluate the beneficial impacts of road networks on the economy, how connectivity can be improved to improve network resilience, reliability, performance and reduce maintenance costs. A number of studies describe how networks can be designed to reduce the impact on the ecology. Only three of the identified studies quantified the results of the model outputs.

Kumar and Kumar (1999) showed through the application of network theory to three regions in India that core rural road networks within the three regions could be established, that whilst maintaining 100% connectivity requirements would reduce maintenance costs by 47%.

Vasas and Magura et al. (2009) showed that network theory could be used to identify routes within the Bereg plain (Hungary) which would preserve the habitat of carabid species, compared to planned routes that would negatively impact the carabid habitat by up to 60%.

Walker et al. (2013) estimated, using network theory, that proposed logging routes in the Amazon rain forest would lead to defragmentation by between 1%-8% in regions of the rain forest.

Recent developments in network theory have focused on (i) developing new measures and indicators to assess connectivity, vulnerability and economic impact of transport networks, (ii) applying weightages to nodes and links to evaluate economic and ecological impacts and (iii) developing multiple-layers within the network models for better spatial analysis. Hybrid models have been developed to expand network theory and integrate it with risk modelling and probabilistic methodologies to identify vulnerable or critical elements within a given transport network.

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6. Appendix A: Network theory and its technological advancements

Network, or graph, theory is a branch of mathematics concerned about how networks can be encoded, and their properties measured. The origins of network theory can be traced to Leonhard Euler who devised in 1735 a problem that came to be known as the 'Seven Bridges of Konigsberg'. In recent decades, network theory has further developed from studies of social and complex networks (El-adaway et al, 2017). In Network theory a graph *G (V, E)* is a data structure consisting of a set of vertices *V* connected by edges *E*. In a spatial systems context, vertices/nodes may represent, e.g., locations or objects in space, groups or aggregates of the latter, or their properties (see Figure A1) (Rodrigue, Comtois and Slack, 2017). Edges/links may represent any causal, statistical, inferential, or spatial relationships or processes. Rules define which edges join which pairs of nodes. An edge that makes vertices/node correspond to itself is termed as a buckle. These connections can be intuitively similar to those in a road network, where the intersections are connected by roads.

See: Figure A1: Basic representation of a transport network using network theory or graph theory, Source: Rodrigue, Comtois and Slack (2017), https://transportgeography.org/?page_id=5998

Network theory has often been used to develop a topological and mathematical representations of the nature and structure of transportation networks namely air (Liu et al., 2011), rail (Derrible and Kennedy, 2009; Erath et al., 2009), maritime (Frazila et al., 2015) and roads (see Section 1). It has been expanded for the analysis of real-world and complex transport networks by encoding them in an information system. In the process, a digital representation of the network is created, which can then be used for a variety of purposes such as predicting traffic flow or planning the construction of transport infrastructure. Network theory measures can also be used to estimate the qualities of a location's accessibility/connectivity that are attributable to the geometric pattern of the transport infrastructure (Ravulaparthy and Goulias, 2014).

'Centrality' is often used within network or graph theory to understand such structural properties of the networks. Centrality measures serve to quantify that in a network some nodes are more important (central) than others. The commonly used centrality measures are degree, closeness, betweeness, straightness and information (Mishra et al., 2012). As defined by Freeman (1978), a node's closeness centrality is the sum of graph-theoretic distances from all other nodes, where the distance from a node to another is defined as the length (in links) of the shortest path from one to the other. Nodes with low closeness scores have short distances from others, and will tend to be more accessible, based on network theory or graph theory. It is also relevant for various spatial factors affecting human life and behaviours (Crucitti et al., 2006). Recent studies have developed different measures ranging from simple to link-based travel speed and congestion indexes to more complex network-based measures to analyse the relative performance of a node or an area in the transport network (Zhang et al., 2015; Mishra et al., 2012). The technical advancements in network theory's application to road transport networks are presented in Table A1.

Table A1: Application of network theory to road transport

Study	*Application*	*Methodology*	*Results*
Ding (2019)	Identifying research gaps	The study carried out a review of network-theory based research (from 2001-2018) on urban-land use and transport interaction and identified the research gaps.	The following research gaps were identified for the application of network theory to urban transport: - Urban traffic network growth and its impact on surrounding land-use - Landscape connectivity properties - Identification of key changed land-use types - Coevolution process - Multimodal-based studies need more concern. Within the existing network theory models, effort should be made to clearly identify the importance of nodes or edges in single-layer and multilayer networks. Although many node indices have been proposed, most of them do not comprehensively consider complex urban properties. For example, consideration of economic contribution of each urban nodes.

Hamidov (2019)	Modelling economic dynamics considering transport costs	This study applies graph theory to model economic dynamics with consideration of transportation costs.	The study used a dual graph with multiple vertices and assumed that an economic system operates on each vertex for a number of products. Transportation costs for a product to be transferred along each of the vertex is modelled alongside production mapping at each node by using Neumann models. The study describes how equilibrium can be achieved in production and exchange of products along each vertices.

Hackl and Adey (2019)	Study change in traffic flow	The study proposed a networks in networks (NiN) approach based on NT to study traffic flow changes caused by topological changes in the transport networks (i.e. due to multiple link failures). The NiN used was a multi-layer approach where each vertex itself represents a network.	NiN has an embedded network structure that allows encoding multiple pieces of information such as the topology, paths used and origin-destination information, within one consistent graph structure (i.e. using only links and edges). Case studies were performed that compared the results of the multi-layer NiN structure with the conventional single-layer network (SLN) and the former performed better than the latter. The following advantages were reported for the proposed application of NiN model to transport networks: - Using a modified multi-layer hypergraph it is formally feasible to describe vertices that are networks themselves. Thereby the relationships in the incidence graph represent the edges connecting different layers. The edges within the different layers are given by a connection model, which allows different topologies in the different layers. - Because each vertex is an independent network in itself, it is possible to implement multiple diffusion processes. Therefore, it is possible to assign different physical meanings to the processes. For example, one process

			can describe how individual travellers switch between different paths, while another process describes the propagation of disturbances through the network - NiN models capture both topological and spatial-temporal patterns in a simple representation, resulting in a better traffic flow approximation than the conventional SLN models.

Tanuja et al. (2018)	Spatial analysis of transport service network	This study utilised approach called **supernode graph structuring** to carry our spatial analysis of bus transport networking using network theory. Unlike the conventional network theory, the proposed approach used a novel supernode graph structuring procedure to combine geographically closely associated nodes based on a specific criterion, resulting in a more compact representation. The proposed supernode graph structure consists of regular nodes, supernodes, regular edges and superedges. While defining the supernode structure some of the original nodes will be eliminated due to the geographical combining of nodes and there might exist self-loops due to the merging of nearby nodes. The significance of the supernode structure can be summarised as follows: - Combining the geographically significant nodes in the network improves understanding of the structural behavior of the network. For example, combining nodes with significant degrees in the network helps identify important hubs in the network	The supernode graph structure was used to analyse important network parameters for the bus transport networks in Hong Kong, London and Bengaluru. The following results were reported: - Hong Kong network is topologically more efficient as compared to the London and Bengaluru networks. - An improved level of clustering was noticed in all the three networks due to the merging of nodes. This property reduces the average shortest path required to travel between two nodes. - The Hong Kong and Bengaluru networks with their average path length close to six degrees of separation under supernode structuring need minor route modifications to behave as small world networks. However, the London network is extremely sparse. - The geographically significant nodes identified with the aid of the demand estimation model indicate the importance of the nodes to the network in local zones. Interestingly, many of these nodes are found to be central nodes in the network from a nertwork theory perspective. Thus, unlike conventional approaches, that used different centrality measures to evaluate the significance of nodes that

		- Supernode structure helps to determine the convenient switching points or transfer points which contribute to efficient routing in the network and improve the overall topological efficiency - Supernode structure aids in assigning node weights which reflect the geographical significance of a node - Supernode structure helps eliminate redundancies in the network for fast computation, i.e., with supernode structure, we can reproduce a network that is close to the original network with a reduced dataset. A static demand estimation procedure was also proposed to assign the node weights in the network by considering the points of interests (POIs) and the population distribution in the city over various localised zones. In addition, the end-to-end delay was proposed as a parameter to measure the topological efficiency of the bus networks instead of the shortest distance measure used in conventional works.	provides information on the static node behavior, node weights were assigned based on the POIs and population density to capture the dynamic behavior of nodes in the network. By understanding the variations in population density and POI statistics around a node, a better estimate on its dynamic behavior can be obtained. Also understanding such dynamic behavior of nodes, bus operators can better plan their routes to avoid a congested travel. - It was observed that the supernode concept has significant advantage in analysing the inherent topological behaviour. The correlation between topologically central nodes and the geographically central nodes reveals the interesting fact that the proposed static demand estimation method for assigning node weights aids identifying the geographically significant nodes in the network in a better way. - The end-to-end delay model offers a better definition to measure the actual structural efficiency in terms of time as compared to the distance term employed earlier. - The effect of dependency of POI density and the distance between two bus stops on the travel speed shows

			that the location of the POI around a bus stop has a major influence not only on its demand estimation but also on the end-to-end travel delay or topological efficiency.

Yonca Aydin et al. (2018)	Evaluating the resilience of urban road networks	The study developed a graph-theory based method to assess the resilience of transportation network when exposed to environmental hazards. The proposed approach integrates graph theory with stress testing methodology and involves five basic steps: - Establishment of a scenario set that covers a range of seismic damage potential in the network, - Assessment of resilience using various graph-based metrics, - Topology-based simulations, - Evaluation of changes in graph-based metrics, - Examination of resilience in terms of spatial distribution of critical nodes and the entire network topology. A case study was carried out for the city of Kathmandu in Nepal following a major earthquake.	The graph-theory based metrics such as network robustness, node betweenness centralities, and network efficiency measures were analysed because they better represent network connectivity, node importance, and network distance measures, respectively. The case study observed that the connectivity of the Kathmandu road network is highly susceptible to natural hazards and that its efficiency decreases significantly under disaster conditions.

Saberi et al. (2017)	Studying patterns of urban travel demand	This study applies a complex network-theory motivated approach to understand and characterise urban travel demand patterns through analysis of statistical properties of origin–destination demand networks. The network measures employed within this study provides a clear picture of connectivity or interaction between places, origins and destinations A network-theoretic analysis of Chicago and Melbourne was presented	The study shows that show that travel demand networks exhibit similar properties despite their differences in topography and urban structure. Results from this study provide a quantitative characterisation of the network structure of origin–destination demand in cities, suggesting that the underlying dynamical processes in travel demand networks are similar and evolved by the distribution of activities and interaction between places in cities. The comparative study of Chicago and Melbourne yielded the following results: - Network of travel demand in Melbourne has larger heterogeneity in connectivity between nodes with a more heterogeneous distribution of interaction strengths compared to Chicago. - Melbourne is more locally connected despite being globally sparser while Chicago enjoys denser connectivity between nodes representing higher interaction between places. This could generally be interpreted as a more homogenous distribution of activities in Chicago compared to Melbourne. - Highly visited nodes are also well connected to other nodes in both cities.

			- Locations with greater connectivity (larger node degree) and greater attractiveness (larger node flux) also have smaller mean shortest path (MSP) lengths.

Loro et al. (2015)	Route-planning while considering the ecological impacts of new roads	This study proposed Conditional Minimum Transit Cost (CMTC) methodology, an innovative graph-theory approach to define wildlife corridors with multiple paths and without bottlenecks, and thus reduce the barrier effect of roads. CMTC defines a corridor that connects a pair of nodes by multiple paths with a similar cumulative cost distance value. The method adopts a network approach, while implementing an iterative GIS methodology to obtain alternative corridors with comparable costs and without bottlenecks below a user-defined minimum width. The proposed method enables the definition of the clearly delimited physical area of corridors according to a geometrical threshold width value, as well as multiple corridor connections for a pair of habitat patches.	This study through a case study of central Iberian Peninsula in southwest Europe presented a new graph theory approach for landscape that defines links by multiple paths that connect a pair of nodes and ensures that: - A corridor’s multiple paths/links defined by different threshold values give significant differences between them in the cumulative cost distance raster distribution - The iterative search pro-cess ends only when at least one path has no bottlenecks - All the multiple paths or branches located in a corridor that connect a pair of nodes will be assessed. By improving the definition of links, this research could have significant practical implications for the calculation of landscape connectivity metrics based on graph theory, and contribute to more sustainable planning of linear infrastructure such as roads.

Zhang and Qin et al. (2015)	Network-level optimisation method for road network maintenance	A quantitative transportation network efficiency measure was presented and optimal network-level road maintenance policy was determined. Global efficiency model (based on network-theory) was employed to evaluate the network performance in a weighted network and the network-level maintenance policy could be determined based on the network efficiency. The study also proposed a sensitivity measure for a transportation network.	The proposed 'global efficiency measure' has a good economic interpretation, since it evaluates the average operation efficiency/performance of the transportation network from the perspective of economic costs (travel time).

Rashidy and Ahmed et al. (2014)	Accessing the accessibility level of a road network	The study introduced a methodology combining network theory and fuzzy logic to assess the physical connectivity and level of service of the road transport network. To this end, two mobility indicators were developed and applied to a case study of a hypothetical Delft city network.	Different centrality measures of network theory were used to assess the impact of network infrastructure and network configuration alongside traffic condition indicators. The merit of using both attributes is to allow the inclusion of different types of disruptive events and their impacts on network mobility. The study also proposed another mobility indicator: network mobility indicator (NMI) to evaluate the overall effectiveness of certain policies or the implementation of new technologies using fuzzy logic.

Ravulaparthy and Goulias (2014)	Impact assessment of network centrality on the economic activities in a region	This study proposed an advancement to the network theory-based approach to urban network analysis to identify the core periphery or centre or subcentre regions and to highlight the prominent role of network centrality measures in the spatial organisation of economic activities in a region. The study developed link-based multiple centrality indexes (L-MCIs) to complement the existing multiple centrality assessment (MCA) model in two ways: - the context of location and its importance are accommodated through weighted link attributes including roadway capacity, population, and opportunities at a place - the relative importance of a link in the network across multiple spatial scales and centrality values is accounted for. The following L-MCIs was used for this study: - Degree: count of the number of edges incident upon a given node - Closeness: measures to what extent a link is close to all the other links along the shortest paths from one link to another on the network	The L-MCIs capture a location's advantage of various places in a city and the importance of a place in the spatial interaction of the entire network. The proposed L-MCI model was used to study the spatial distribution of economic activities in Santa Barbara County in California using the georeferenced National Establishment Time- Series Database of 20,628 business establishments in the region. To compute the L-MCIs, each link in the network was represented as a node (or midpoint of the link) and thereby the number of edges was increased two fold. The L-MCIs study reported the following results: - Centrality is concentrated in downtown areas with a high concentration of transport network links. - On the basis of the spatial distribution of the network centrality measures it was reported that areas with high remoteness values within the 2.5-km network buffer were locations with a high intensity of economic activity and opportunities. - Locations with a high intensity of economic activities are along the corridors in the network with high

		- Distance remoteness: inverse of the closeness centrality measure to have a more meaningful and numeric interpretation - Betweeness: based on the idea that a link is more central when it is traversed by a large number of shortest paths connecting any other two links in the network. It captures the prominence of a link acting as intermediary among many links. - Straightness: represents efficiency of communication between two links, which increases when there is a least deviation of their shortest path from the virtual straight line connecting them, that is, a greater straightness of the shortest-path distance - Reach: measures the number of other links that can be reached along the shorted path on a network. Latent class cluster analysis (LCCA) was also employed to understand the linkages between network centrality and the distribution of economic activities in a region. LCCA uses patterns of variation among many dependent variables (in this case the normalised network centrality measures) and identifies groups of links with relatively homogenous scores.	straightness and reach centrality indexes for all network buffers. Similarly, corridors with high betweenness1 centrality indexes, mainly in the downtown areas, also contain a relatively high density of retail activity; this finding suggests that betweenness may be an important factor in the spatial distribution of retail activities. - In urban regions where the street networks are in a grid format, there is a higher straightness centrality along with high density of economic activities along these street networks. The LCCA linked the L-MCIs of the network with economic activities and studies the composition and characteristics of these economic activities located across the four clusters studied. The LCCA study reported the following results[4]: - There is a high density of economic activities along the street networks that are in a grid format (due to high straightness centrality values). - Major economic activities like professional services, retail trade, and arts and entertainment (including food and accommodation services) are located primarily in highly central

			regions (Cluster 1).This finding could be attributed to the property of the network structure. For example, the roadway links in highly central regions have the highest straightness centrality value; this finding indicates smaller deviations of the network shortest-path distance from the straight-line distance. - In Cluster 2 the major proportion of economic activities is also professional services and retail trade, although there is a relatively high concentration of secondary economic activities like construction and manufacturing when Cluster 2 is compared with Cluster 1. - The composition of economic activities in Cluster 3 (moderately central) is attributed to high betweenness centrality values, in which a place itself may not serve as a final trip destination, but it may take advantage of its unique location in the system as merely a pass-through nexus to generate great economic opportunities. - The composition of economic activities in Cluster 4 (least central locations) is heterogeneous and includes a major proportion of agricultural activities because they are areas dominated by farmland, vineyards and ranches

Walker et al. (2013)	Spatial decision making	The study employed computational graph-theory to evaluate the fragmentation associated with logging road networks in the Amazon forest. To this end, graph-theory was used to construct graphs and simulate spatial decision-making as a function of discount rates, land tenure, and topographic constraints.	This study performed an analysis of the logging road networks and compared the location of these routes with the existing roads. It was found that the logging road networks (existing due to economic objectives of the loggers) are causing major fragmentation of the Amazon forest.

Mishra et al. (2012)	Performance of multimodal urban transport network	The study extending the network theory approach to determine the performance of a multimodal urban transport network. To this end, the study developed connectivity indicators for node, link, transfer centre and region to represent the potential ability of a transport system. The proposed framework was applied to a comprehensive transit network in the Washington–Baltimore region.	- The node connectivity index includes the transit lines passing through it, their characteristics such as speed, capacity, frequency, distance to destination, activity density of the location, and degree centrality. - The link connectivity index is the sum of connectivity indexes of all stops it passes through and normalised to the number of stops. - The concept of a connectivity index of a transfer center is different from the connectivity measure of a conventional node. Transfer centers are groups of nodes that are defined by the ease of transfer between transit lines and modes based on a coordinated schedule of connections at a single node or the availability of connections at a group of nodes within a given distance or walk time. - The sum of the connecting power of each node in the transfer center is scaled by the number of nodes in the transfer center. Thus, a node in a heavily dense area is made comparable to a transfer center located in a less dense area. - The connecting power of a region is defined by the urban form, and the

			characteristics of nodes, lines, and transfer centers. The results of the case study identifies measures in terms of nodes located in rural areas, lines with lower speed, lack of frequency, lower capacity, and missed transfers. The lack of transfer between nodes that occurs in multi-legged trips is a major contributor to the calculation of the connectivity index.
Unsalan et al. (2012)	Road network detection from aerial imagery	The study developed an automated system using probabilistic and graph-theory models to detect the road network from a given satellite or aerial image in a robust manner. In the proposed approach, graph-theory was employed to effectively model the road-network in a parametric and structural form. Case studies were carried out to demonstrate the strengths of the proposed approach	The proposed road network detection system had the following strengths: - The proposed system does not benefit from any prior information such as GIS data and are able to accurately model the complex road networks e.g. close to city centres - It does not depend on the user interaction, such as manually labelling the starting point of the road network

Song and Wang (2011)	Route computation for road networks	This study developed a hierarchical graph model (using graph theory) that supports efficient route computation on large road networks. The model is efficient in computing optimal routes for within-community node pairs and near-optimal routes for between-community node pairs on large-scale road networks. The proposed hierarchical graph model was demonstrated through a case study on a New York road network.	Experimental results demonstrated that the hierarchical graph model is computationally efficient and is readily applicable for networks of unprecedented size.
Vasas and Magura et al. (2009)	Road planning using connectivity measures	The study applied graph-theory to evaluate the environmental impacts to the landscapes while constructing new roads.	The study quantitatively evaluated and compared the three proposed tracks for a future highway crossing the Bereg plain. The study found that all the three planned highway tracks disrupts forest landscape and proposed a fourth option that has less environmental impact.

Demsar et al. (2008)	Risk modelling of urban road networks	The study proposed a graph theory based risk modelling method that combines dual graph modelling with connectivity analysis and topological measures (‘betweenness’ and ‘clustering coefficient’) to identify critical locations in a spatial network. The procedure is based on the assumption that the vertices of the line graph that correspond to critical locations have one or more of the following three properties: - They are cut vertices of the line graph; - They have a high betweenness; or - They have a low clustering coefficient.	A case study was carried out on the street network of the Helsinki Metropolitan Area to identify critical locations. The study identified the following vulnerable points or areas within the network: - All places where many people are located simultaneously: shopping centres, traffic nodes (railway and bus stations), but also mass events (sports competitions and rock concerts); - All places where elderly people, handicapped or ill people or children are located simultaneously: homes for the elderly, hospitals, schools and kindergartens; - Protected objects: cultural heritage objects, churches, hospitals or bomb shelters. The study also recommended that other graph characteristics, such as transitivity, information and eigenvector centralities, colourings, cliquishness, flows, matchings, etc. could be considered for an improved risk modelling for spatial networks.

Appert and Chapelon (2007)	Vulnerability assessment of urban road network	This study measured the vulnerability of urban road network using graph theory and developed two vulnerability indices – link vulnerability and junction vulnerability. The developed approach was applied to a case study of an urban road network in Montpellier	The study determined that a network is vulnerable to varying degrees according to the level of hierarchisation of its links and junctions, which leads to a concentration of routes. The pattern of vulnerability is higher in the city centres in comparison to the outskirts. For example, it was observed that at rush hour, the deterioration of travel speeds on the major links results in less route polarisation, leading to widespread vulnerability i.e. high volumes on traffic on unsuitable roads.
Crucitti and Latora et al. (2006)	Measuring centrality of urban networks	The study proposed a Space Syntax (SS) approach to network theory, where axial lines that represent generalised streets are turned into nodes, and intersections between each pair of axial lines into edges. The output from the SS serves as an input to multiple centrality assessment (of different measures of centrality). The study also proposed a method to calculate the efficiency/performance of the developed graph/network.	Further to numerically quantifying different centrality measurements, this study made the following observations: - Despite striking differences in terms of historical, cultural, economic, climatic and geographic characters of a network, the centrality measures of betweeness, closeness and straightness always shows the same kind of distribution. - Information centrality is differently distributed in planned and self-organised cities, exponential for planned cities and power law for self-organised ones

Newman (2005)	Measuring betweeness centrality	This study proposed a new betweenness measure that counts essentially all paths between vertices and makes no assumptions of optimality. The proposed measure is based on random walks between vertex pairs and asks, in essence, how often a given vertex will fall on a random walk between another pair of vertices.	The proposed measure of betweeness is particularly useful for finding vertices of high centrality that do not happen to lie on geodesic paths or on the paths formed by maximum-flow cut-sets. It was demonstrated that the new measure can be calculated using matrix inversion methods in time that scales as the cube of the number of vertices on a sparse graph, making it computationally tractable for networks typical of current sociological studies.
Jiang and Claramiunt, (2004)	Assessing the urban network structure through centrality measures	This paper proposes a model generalisation approach for the selection of characteristic streets in an urban street network. It is based on the application of centrality measures that consider both local and global structuring properties of named streets that correspond to basic functional elements in the city. The proposed model is applied to a case study to show how the structure of a street network is retained without being broken into separate pieces in the course of selection.	The analysis based on the structural representation of street networks appears to illustrate the relationship between space and social activities. It was observed that streets constitute the structuring part of the city, and are most accessible in terms of transportation and commercial activities allocation. For example, case study on the streets in the city of Gavle shows that four important commercial streets also have important landmarks such as railway stations, theatre, city hall, and central shopping mall etc.

Modarres and Zarei (2002)	Evaluating road traffic pattern during earthquake	Network theory was combined with analytic hierarchy process (AHP) to identify the weak points within the urban transport network when impacted by an earthquake. The proposed methodology was demonstrated using a case study of the Iranian city of Rasht, after the devastating earthquake of 1990.	Network theory was employed to identify the optimum paths (both fastest and safes) from a node of origin to every node of possible destination-type, in the aftermath of an earthquake. Each link was provided weight within the evaluation using AHP and then used to rank the priority of each type of trip. By means of a case study, an evaluation of closeness, quality, options and regulations of different trips were carried out.
Kumar and Kumar (1999)	Rural roads planning	This study proposed a user-friendly model based on graph-theory for the systematic planning of rural road networks. The model considers the accessibility provided to the villages as the benefit as a whole and aids the decision maker to achieve maximum benefit at the least cost.	A user-friendly planning model was developed that provides road connection from each village to nearby market centres and education facilities at least cost. The model can be used effectively as a planning and management tool by rural road organisations. The model uses a simple parameter, that is, the “population served with unit investment,” for prioritisation of rural roads.

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