(5519 words, 2 tables, 5 figures)

A NETWORK MOBILITY INDICATOR USING A FUZZY LOGIC APPROACH

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ABSTRACT

This paper introduces a methodology to assess the mobility of a road transport network from the network perspective. In this research, the mobility of the road transport network is defined as the ability of the road transport network to connect all the origin-destination pairs within the network with an acceptable level of service. Two mobility attributes are therefore introduced to assess the physical connectivity and the road transport network level of service. Furthermore, a simple technique based on a fuzzy logic approach is used to combine mobility attributes into a single mobility indicator in order to measure the impact of disruptive events on road transport network functionality.

The application of the proposed methodology on a hypothetical Delft city network shows the ability of the technique to estimate variation in the level of mobility under different scenarios. The method allows the study of demand and supply side variations on overall network mobility, providing a new tool for decision makers in understanding the dynamic nature of mobility under various events. The method can also be used as an evaluation tool to gauge the highway network mobility level, and to highlight weaknesses in the network.

1. INTRODUCTION

Mobility is essential to economic growth and social activities, including commuting, manufacturing or supplying energy (*1*). Higher mobility (or in other words, a better ability of the network to deliver improved service) is a very important issue for decision makers and operators as it relates to the main function of the road transport network. Consequently, an assessment of road transport network mobility is essential in order to evaluate the impact of disruptive events on network functionality and to investigate the influence of different policies and technologies on the mobility level. Disruptive events may be classified as manmade or climate change related events, the scale of which will also have an impact on road transport network mobility. For example, a small accident may lead to closure of one lane of a local road or a massive accident may cause the closure of a motorway for several hours with cascading effects on the entire network. Climate change related events (e.g. floods, inclement weather and heavy snowfall) may increase be set to increase with resulting impacts on the road transport network. As an example, at the European level, the financial cost of network interruption from extreme weather is estimated to be in excess of €15 billion (*2*) whereas, in USA the estimated repair costs on its network caused by snow and ice is 62 m US$ per frosty day (*3*).

Mobility could have two dimensions (*4*). Firstly, mobility as "the ability of people and goods to move from one place (origin) to another (destination) by use of an acceptable level of transport service" - commonly measured by vehicle kilometres and evaluated through surveys (*5*). Secondly, from the road transport network prospective, mobility is defined as the ability of a road transport network to provide access to jobs, education, health service, shopping, etc, therefore travellers are able to reach their destinations at an acceptable level of service (*6*, *7*). Therefore, mobility is a measure of the performance of the transport system in connecting spatially separated sites which is normally identified by system indicators such as travel time and speed. However here, the mobility concept is used as a key performance indicator to measure the functionality of the road network under a disruptive event, as in the second case above. It is therefore used to reflect the ability of network to offer users a certain level of service in terms of movement.

2. MOBILITY ASSESSMENT

As with many transport concepts, there are no universally agreed indicators to assess road transport network mobility from a network prospective. According to National Research Council (*8*), mobility assessment should take into account system performance indicators such as time and costs for travel. They propose the mobility level is inversely proportional to variations in travel time and cost, whereas, Zhang et al. (*9*) suggested that travel time and average trip length are two key indicators to evaluate system mobility. The study (*9*) developed a performance index to evaluate the mobility of an intermodal system, measured by the ratio of travel speed to the free flow speed weighted by truck miles travelled. However the performance index could be adapted to measure road transport mobility by considering total traffic flow rather than average daily truck volume. In line with this approach, Wang and Jim (*10*) used the average travel time per mile as a mobility indicator, where the distance is geographic distance rather than distance travelled. The use of the geographic mileage rather than travel distance could lead to an overestimation of mobility as it is expected that the geographic mileage is shorter than the actual travel distance between two locations.

Cianfano et al. (*11*) suggested a number of indicators based on link travel time and speed to evaluate road network mobility. Specifically, they (*11*) introduced a vehicle speed indicator, VSI, measuring the variation in speed compared to free flow conditions. A value of VSI of 1 would indicate that vehicles are experiencing a travel speed across the network equal to the free flow speed (i.e. the average free flow speed of the network). Under extreme conditions VSI = 0 indicates a fully congested road network. Cianfano et al., (*11*) also proposed a mobility indicator based on travel time. According to Lomax and Schrank (*12*), transport performance measures based on travel time fulfil a range of mobility purposes. However, researchers (*9,11*) used simple and applicable indictors that could be easily implemented at a real-life network scale. They only considered the impact of traffic flow conditions (presented as the variation in travel speed compared with free flow speed) and took into account the impact of unconnected zones. If some links are not available (e.g. closed due to an incident) they are omitted from the indicator calculations, producing misleading values.

Murray-Tuite (*13*) proposed a number of indicators to estimate mobility under disruptive events, some of which were scenario based measures such as time needed to vacate a towns' population and the capability of emergency vehicles (ambulance, police) to pass from one zone through to another. (*13*) also suggested that the average queue time per vehicle, the queue length on the link and finally, the amount of time that a link can offer average speeds lower than its posted speed limit could also be considered as mobility indicators.

Chen and Tang (*14*) introduced link mobility reliability, calculated using a statistical method based on historical data - speed data for 3 months derived from floating cars. They also investigated the possible influencing factors on mobility reliability. Their result shows that the mobility reliability of an urban road network is correlated with network saturation (volume capacity ratio) and road network density.

At the operational level, (*15*) carried out a survey including Canadian provincial and territorial jurisdictions regarding current practices in performance measurement for road networks related to six outcomes; mobility being one of them. The study found that average speed and traffic volume are widely used as measures of mobility. The study also found that the concepts of accessibility and mobility are used interchangeably in practice which could conflict with academic practice, where accessibility and mobility are very different concepts. For example, Gutiérrez, (*16*) emphasised that the mobility concept relates to the actual movements of passengers or goods over space, whereas accessibility refers to a feature of either locations or individuals (the facility to reach a destination). In other words, accessibility could be defined as the potential opportunities for interaction (*17*) that are not only influenced by the quality of the road transport network, but also with the quality of the land-use system (*18*). Widespread communication technologies could play a crucial role as an important factor in virtual accessibility (*19*).

A number of further mobility indicators have been reported, namely, origin-destination travel times, total travel time, average travel time from a facility to a destination, delay per vehicle mile travelled, lost time due to congestion and volume/capacity ratio (*15*). Meanwhile, Hyder (*7*) suggested three indictors to measure the mobility of the road transport network, namely, maximum volume/capacity ratio, maximum intersection delay and minimum speed. The study (*7*) used linguistic expressions to evaluate the indicators (as shown in TABLE 1) and suggested that mobility is gauged by the lowest value of these indicators.

TABLE 1 Linguistic Expressions and Corresponding Values Of Mobility Indicators (*7*)

Mobility Indicator	low	Medium	High
maximum volume/capacity	>75%	50-75%	<50%
maximum intersection delay	>300 seconds	60-300 seconds	<60 seconds
minimum speed	<25 kph	25-50 kph	>50 kph

However none of the previous research considered the impact of the road transport network infrastructure on network mobility. Therefore, the research presented here considers the impact of network infrastructure and network configuration using graph theory measures alongside traffic conditions indicators as discussed above. The use of the network configuration and traffic flow conditions will reflect the impact of different kinds of disruptive events. For example, in case of a flood, some parts of the network could become totally disconnected whilst other parts of the network could benefit from lower network loading. Therefore the impact of such an event could be masked if the mobility indicator only considers traffic conditions. In the case of adverse weather conditions the overall network capacity could decrease (*3*) leading to congested conditions, but not necessarily affecting travel distance. Consequently, the consideration of both attributes i.e. physical connectivity and traffic conditions, is necessary to cover both cases. In section 3 below, mobility attributes are introduced.

3. MOBILITY MODELLING OF THE ROAD TRANSPORT NETWORK

In the research here, the mobility concept is treated as a performance measure expressing the level of road transport network functionality under a disruptive event. Therefore, mobility is used as a concept to reflect the ability of a network to offer its users a certain level of service in terms of movement. To obtain a single mobility indicator a number of mobility attributes are used to capture a range of mobility issues, as outlined above.

3.1 Mobility Attributes

Based on the definition of mobility (i.e. the ability of the road transport network to move road users from one place to another with an acceptable level of service), two attributes are proposed. Firstly, an attribute is used to evaluate physical connectivity, i.e. the ability of road transport to offer a route to connect two zones. The second attribute is implemented as a measure of the road transport network level of service, based on traffic conditions. Figure 1 shows a schematic diagram of the mobility attributes and the various factors affecting them. In the following sub sections both indicators are presented.

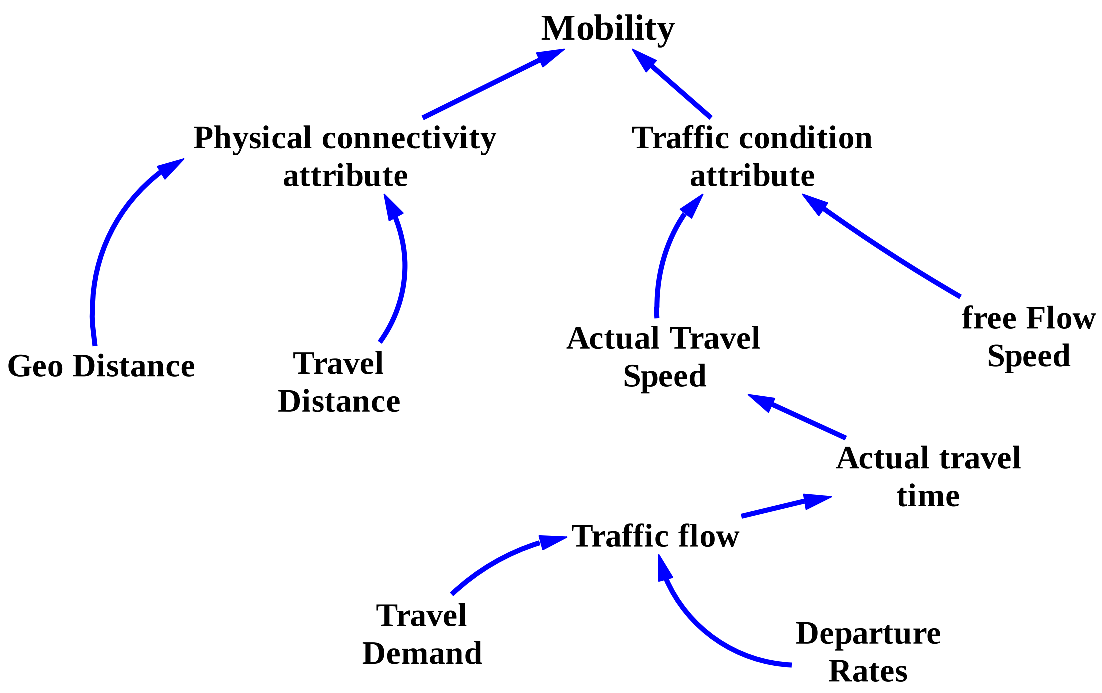


FIGURE 1 Mobility Attributes

3.1.1 Physical Connectivity

The physical connectivity (i.e existence of a path between OD pairs), is a key factor on the network mobility level. For example, the unavailability of a certain route may lead to unsatisfied demand, economic loss or safety concerns arising from disconnecting a group of travellers who are then effectively trapped.

Physical connectivity can be measured by a number of indicators based on graph theory as shown in Levinson (*20*). The influence of network configuration on connectivity could be studied by calculating the gamma index (γ). The γ index is measured as the percentage of the actual number of links to the maximum number of possible links (*1*). The γ index is a useful measure of the relative connectivity of the entire network, as a transport network with a higher gamma index has a lower travel cost under the same demand (*21*). However, γ is not able to reflect the zone to zone level of connectivity and its impact on overall connectivity. Road density has also drawbacks similar to the γ index. The detour index (also referred to as circuity measure) is defined as the ratio of the network distance to the Euclidean distance, or Geo distance, is another graph theory measure that is widely used to investigate the impacts of network structure. According to Rodrigue et al. (*1*), the detour index is a measure of the ability of road transport to overcome distance or the friction of space. Meanwhile, Parthasarathi and Levinson (*22*) concluded that the network detour index measures the inefficiency of the transport network from a travellers' point of view.

In the research here a physical connectivity attribute, PCA, is developed based on the detour index but modified to consider zone to zone connectivity and taking into account the impact of demand (see Eq.1 below).

$$PCA = \frac{\sum_{i \neq j} \frac{GD_{ij}}{ATD_{ij}} d_{ij}}{\sum_{i \neq j} d_{ij}} \quad (1)$$

where GD_{ij} is the geo distance between zone i and zone j, ATD_{ij} is the actual travel distance between zone i and zone j and d_{ij} is the demand between zone i and zone j. The value of PCA varies from 1, representing 100% physical connectivity, to zero where there is no connectivity. In case of high impact disaster the degree of connectivity would be intuitively expected to be zero. In such case, the actual travel distance, ATD_{ij}, may be mathematically assumed to be infinity to express the unsatisfied demand and, accordingly, the value of PCA becomes zero. However, physical connectivity is not enough to reflect the impact of variation in the performance of the transport network on mobility. As a result, the impact of traffic conditions should also be taken into account as explained below.

3.1.2 Traffic Conditions Attribute

There are a wide range of mobility attributes based on traffic conditions as discussed in section 1.3. Some of these are defined using link data such as VSI, while others are based at zone level such as the performance index (PI) and road transport network mobility (M). As physical connectivity is calculated at the zone level, the variation in travel speed between each OD pair is adopted to show the level of service, given it is widely accepted as a mobility attribute (*15*). The travel speed between each OD pair (TS_{ij}) is calculated using Eq. (2) then the traffic condition attribute (TCA) is obtained using Eq. (3) below.

$$TS_{ij} = \frac{ATD_{ij}}{ATT_{ij}} \quad (2)$$

$$TCA = \frac{\sum_{i \neq j} \frac{TS_{ij}}{FFTS_{ij}} d_{ij}}{\sum_{i \neq j} d_{ij}} \quad (3)$$

where TS_{ij} is the travel speed between zone i and zone j, ATT_{ij} is the actual travel time between zone i and zone j and $FFTS_{ij}$ is the free flow travel speed between zone i and zone j. The value of TCA varies between 1 and zero. For example, a value of TCA of 1 indicates that vehicles are experiencing a travel speed across the network equal to the free flow speed (i.e. the average free flow speed of the network). Under extreme conditions TCA = 0, indicating a fully congested road network.

3.2 Network Mobility Index Using Fuzzy Logic Approach

Each attribute (i.e physical connectivity or traffic conditions), can be individually considered to reflect the level of mobility from a certain perspective. Suitable measures can then be introduced to improve the mobility level related to each attribute. However, there is still a need to estimate the overall mobility level by combining the impact of both PCA and TCA. TCA is able to clearly reflect the effects of a congested/free flow network, but it could underestimate the impact of certain events. For example a link closure could lead to detours with some trips rescheduled or cancelled. As a consequence network loading will decrease, leading to improved flow in some parts of the network. To reflect these effects in the mobility index the PCA index can be calculated. Consequently, the network mobility index NMI should be a function of both PCA and TCA as given below:

$$NMI = f(PCA, TCA) \quad (4)$$

To deal with the complexity and uncertainty of traffic behaviour, the randomised nature of traffic data and to simulate the influences of both PCA and TCA, fuzzy membership functions are implemented to scale both attributes.

3.2.1 Fuzzy Membership of Mobility Attributes

Four assessment levels i.e. low, medium, high and very high, are proposed to evaluate PCA and, TCA where each level is defined by a fuzzy function having membership grades varying from 0 to 1. Various membership functions have been proposed in the literature (*23*). However, triangular and trapezoid membership functions are adopted to fuzzify the four assessment levels of the mobility attributes. This is because they are by far the most common forms encountered in practice and also due to their simplicity in the grade membership calculations (*23*,*24*,*25*). Other membership functions such as the Gaussian distribution may be used, however, previous research, for example Shepard (*26*), has indicated that real world systems are relatively insensitive to the shape of the membership function. The membership grade value μ of each attribute, PCA/TCA, is obtained from the following fuzzy triangular and trapezoidal functions:

$$\mu_{low} = \begin{cases} 1 & 0 \leq A \leq 0.25 \\ \dfrac{0.5 - A}{0.5 - 0.25} & 0.25 < A < 0.5 \\ 0 & A \geq 0.5 \end{cases}$$

$$\mu_{Medium} = \begin{cases} 0 & A \leq 0.25 \\ \dfrac{A - 0.25}{0.5 - 0.25} & 0.25 < A \leq 0.5 \\ \dfrac{0.75 - A}{0.75 - 0.50} & 0.5 < A < 0.75 \\ 0 & A \geq 0.75 \end{cases}$$

$$\mu_{high} = \begin{cases} 0 & A \leq 0.5 \\ \dfrac{A - 0.5}{0.75 - 0.5} & 0.5 < A \leq 0.75 \\ 1 & 0.75 < A \leq 1.0 \end{cases}$$

$$\mu_{very\ high} = \begin{cases} 0 & A \leq 0.75 \\ \dfrac{A - 0.75}{1 - 0.75} & 0.75 < A \leq 1.0 \\ 1 & A > 1.0 \end{cases}$$

where A indicates either the PCA or TCA attribute.

The membership grade function outlined above can be adjusted or re-scaled to reflect real life conditions and expertise opinion. However a single membership grade function is assumed for each of the attributes in this paper. The fuzzy matrix for both attributes could be expressed in the following form:

$$R = \begin{bmatrix} \mu(PCA)_{low} & \mu(PCA)_{medium} & \mu(PCA)_{high} & \mu(PCA)_{very\ high} \\ \mu(TCA)_{low} & \mu(TCA)_{medium} & \mu(TCA)_{high} & \mu(TCA)_{very\ high} \end{bmatrix}$$

3.2.2 Fuzzy Evaluation

To obtain a fuzzy network mobility vector the weight vector, $\widetilde{w}$, is introduced to set the score for each attribute. Consequently, the fuzzy network mobility indicator, $\widetilde{NMI}$, can be defined by:

$$\widetilde{NMI} = \widetilde{w} \, o \, R \qquad (5)$$

where $\widetilde{NMI}$ is a fuzzy vector containing the membership values for network mobility at each assessment level and R is the fuzzy matrix defined above. In the current research a number of weight vectors are implemented to investigate its influence on $\widetilde{NMI}$. To calculate a single value for NMI from the fuzzy vector obtained there are a number of defuzzification techniques such as the max membership principle, centroid method (centre of gravity method) and weighted average method. For more details these techniques and their uses, see Ross (*23*).

Here two methods are used i.e the centroid method and weighted average method, as both methods allow an accumulating effect for each assessment level on the calculated NMI (*23*).

In the centroid method, a single value for NMI is obtained from the following Eq. (6):

$$NMI = \frac{\int \mu_c(NMI).\ NMI\ dNMI}{\int \mu_c(NMI)\ .\ dNMI} \quad (6)$$

In the weighted average method, a fuzzy network mobility vector is obtained by introducing a standardising vector to take into account the effect of each assessment level (*23*). The standardising vector, s, shown in Eq. (7) is proposed to obtain a single value for the mobility indicator adjusted on a scale from 0 to 1.

$$s = [0.25\ \ 0.5\ \ 0.75\ \ 1] \quad (7)$$

To test the validity of the proposed model a number of scenarios are studied using a hypothetical road transport network and this is presented in the next section in detail.

4. CASE STUDY

A hypothetical road transport network for Delft city is employed to illustrate the mobility of the road network under different scenarios using the proposed methodology. Delft is a city and municipality in the province of South Holland in the Netherlands. The total population is 98675 with a density of 4,324.1 per km^2 (*27*). In general, cars are widely used in the Netherlands and people use this mode for almost half their trips (*27*). The hypothetical Delft road network model is made available with OmniTrans software (Ver. 6.022). The network is only a representation and may deviate from the real network for the city of Delft. The Delft study case was chosen due to the availability of the data needed to illustrate the methodology. However, the main focus of the research is the methodology itself rather than the empirical findings and the method should be applicable to any road transport network.

The Delft road transport network consists of 25 zones; two of which are under development (24 & 25), and 1142 links; 483 links are two-way whilst 176 are one-way including connectors and different road types (as shown in Figure 2).

In the current case study, user equilibrium assignment (UE) was chosen to obtain the spatial distribution of traffic volume. It is based on Wardrop's first principle, where no individual trip maker can reduce his/her path cost by switching routes. This principle is also known as the user optimum (*28*). The suitability of the UE method for identifying the most critical link is based on two factors (*21*). Firstly, the ability of the method to take into account the level of link functionality by allocating the user onto the best route in terms of travel time, so that users can not improve their travel time by changing their routes. Secondly, using user equilibrium assignment allows investigation of the impact of link removal on both link's user and non-users due to the re-routing of link users. The mathematical formulation of UE is explained in detail in (*29*).

However, traffic data obtained from simulation based on static UE assignment as opposed to 'real-world' observations cannot capture the full effects of unexpected link closures, as this process is not able to capture queuing, imperfect information, etc. To obtain more realistic impact results two issues should be considered; traveller behaviour (e.g. the proportion of travellers who will change their route with a link closure) and the availability of an en-route choice model implemented within the traffic assignment software. However, the main aim of the analysis reported here was to investigate the ability of the attributes to reflect traffic condition importance. The results obtained and reported, therefore, assume that all drivers have good knowledge about the link closure and the availability of alternative routes. As the modelled period is the morning peak it would be quite reasonable to assume that a high proportion of the road users are regular commuters/travellers and nearly all the users have a high level of knowledge about route availability and traffic conditions. Alternatively, in practice a variable massage sign or in-vehicle intelligent transport system may update travellers' knowledge of the link closure and alternative routes.

Two main scenario groups are considered. The first group of scenarios investigate the impact of link closure, e.g. due an accident or roadwork, on both attributes and hence on mobility. The second group of scenarios explores the impact of demand variations under the same road transport network conditions, e.g. capacity and free flow speed on mobility.

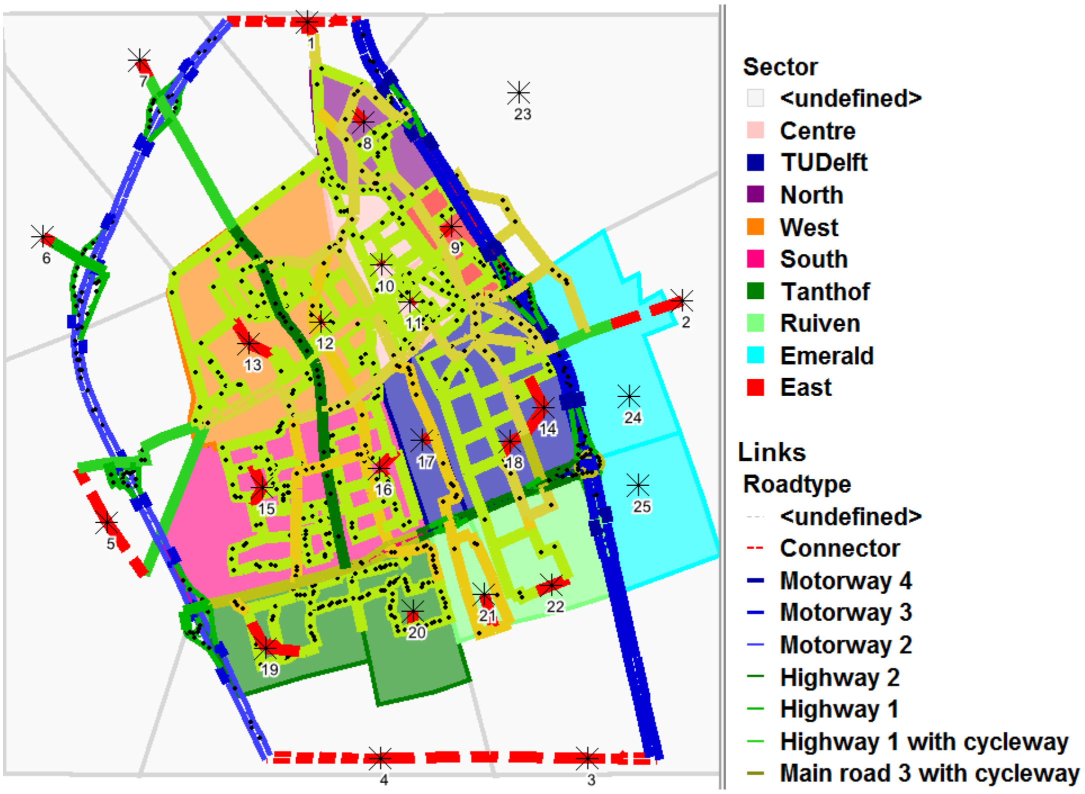


FIGURE 2 Delft Road Transport Network

4.1 Group One Scenarios

A number of links are selected to investigate the ability of the proposed attributes to reflect the impact of link closure on mobility. 10 link closure scenarios were carried out using a static assignment model for the morning peak, for illustration purposes, though many more links could be considered if needed. Furthermore, a previous investigation (*25*) showed that these 10 links had a diverse impact on the network vulnerability. In each scenario only one link is blocked, e.g. closed due to a road accident or roadwork. Both attributes, physical connectivity attribute (PCA) and traffic condition attribute (TCA), are calculated based on the zone level data output in each case. Figure 3 and Table 2 show the results for PCA, TCA and NMI due to 10 link closures. The impact of link closure on both attributes, PCA and TCA, is seen to vary from one link to another. For example, link 11432_1 (link number 11432 in direction 1) has the greatest impact on PCA as the closure of this link leads to a 5% decrease in PCA when compared with full network operation. The closure of links 11415_2 and 11411_1 has the highest impact on TCA as each of these link closures leads to a 10 % reduction in TCA in comparison to full network operation. The highest aggregated impact of the link closure, measured by the decrease in NMI, occurs with the closure of link 11407_2.

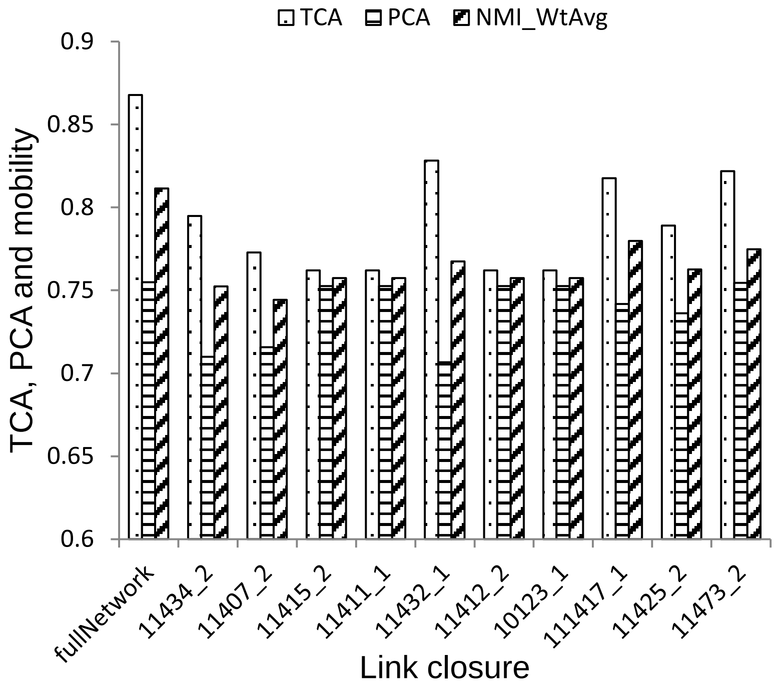


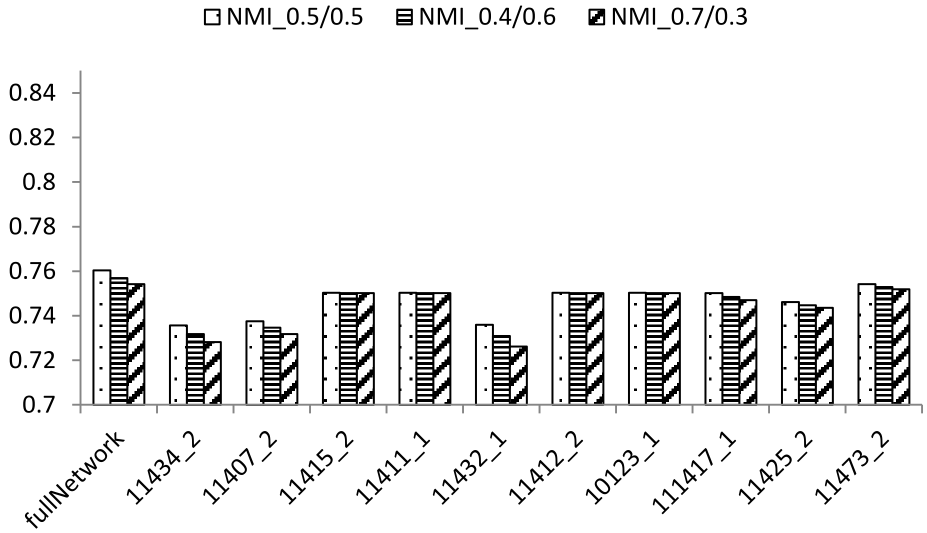
Figure 3 PCA, TCA and NMI Variations due to Link Closure

TABLE 2 PCA, TCA, NMI-Cent and NMI_WtAvg

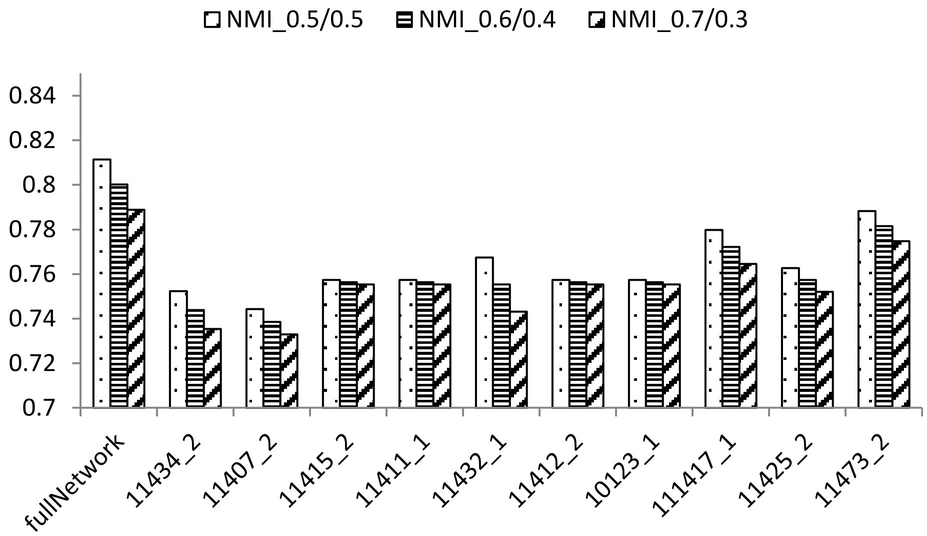
Link Closure	PCA	TCA	NMI_Cent (0.5/0.5)	NMI_WtAvg (0.5/0.5)
Full Network	0.755	0.868	0.760	0.811
11434_2	0.710	0.795	0.736	0.752
11407_2	0.716	0.773	0.738	0.744
11415_2	0.753	0.762	0.750	0.757
11411_1	0.753	0.762	0.750	0.757
11432_1	0.707	0.828	0.736	0.767
11412_2	0.753	0.762	0.750	0.757
10123_1	0.753	0.762	0.750	0.757
111417_1	0.742	0.818	0.750	0.780
11425_2	0.736	0.789	0.746	0.763
11473_2	0.755	0.822	0.754	0.788

Table 2 shows that the weighted average method tends to give higher network mobility index (NMI) values, NMI_WtAvg, than the centroid method, NMI_Cent with some differences. For example, in full network conditions the difference between the two NMI values is about 0.4 whereas for the closure of link 11411_1 the difference between the two values is just 0.007. However, NMI_WtAvg shows greater sensitivity to the variation in the physical connectivity attribute (PCA) or traffic condition attribute (TCA).

To study the influence of the weight vector w (Eq. 7) on NMI, three different weight vectors, [0.5,0.5], [0.6,0.4] and [0.7,0.3], for PCA and TCA respectively were used to calculate NMI using the centroid method (NMI_cent) and the weighted average method (NMI_WtAvg), see Figure 4. The proposed weight vectors in Figure 4 are mainly to illustrate the technique rather than to reflect the importance of each attribute. In practice, this weight vector w could be assigned based on an expert opinion. NMI calculated using the centroid method is always less than that calculated using the weight average method for the same weight vector. The impacts from closure of some links, for example 11415_2 and 11411_1, are less sensitive to variations in the weight vector (Figure 4(a)), whereas, closure of link 11434_2 results in slight changes in NMI calculated by the centroid method, due to changes in the weight vector (Figure 4(a)).



a) Centroid method with different weight vectors



(b) Weighted average method with different weight vectors

FIGURE 4 NMI Estimated by Centroid and Weighted Average Methods using Different Weights

4.2 Demand variation scenario

A dynamic assignment model (Madam) available in the OmniTrans software was implemented to investigate the ability of the mobility indicator to respond to demand increases, i.e. apply different departure rates every 5 minutes. Figure 5 presents the variations in TCA and hence the mobility level under different departure rates. PCA does not show any variation with demand variations as route choice does not change within the madam model. The madam model uses turning movements (proportions) calculated for each node in the network and created by static assignment carried out prior to the madam model run to model route choice. This approach to modelling route choice leads to fixed routes during the dynamic simulation time. Consequently, NMI shows the same trend as TCA. Figure 5 shows that the proposed $NMIs$ decreases as departure rate increases, reflecting the ability of the network to accommodate the increase in demand. However as the departure rate decreases, for example between 7:30 and 8:15, NMI, consequently increases with a slight delay change from 7:45 to 8:30. Furthermore, both NMI_wtAvg and MNI_centroid demonstrate a similar trend. However, NMI_wtAvg is consistently slightly higher than NMI_wtAvg in line with the first scenario observation.

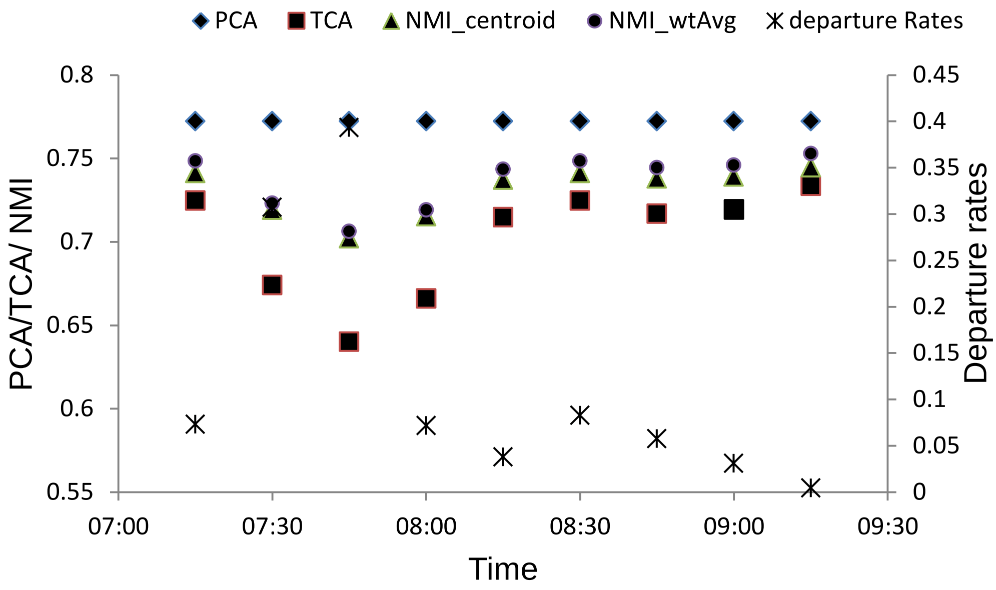


FIGURE 5 Dynamic Variation in NMI

5. CONCLUSIONS

This paper introduces a new mobility indicator based on two attributes: a physical connectivity attribute (PCA) and a traffic condition attribute (TCA), accounting for both network configuration and traffic flow conditions. The merit of using both attributes is to allow the inclusion of different types of disruptive events and their impacts on network mobility. For example, in group two scenarios, a demand increase under the same network conditions, e.g. the same travel distance, leads to a decrease in TCA and consequently the mobility level decreases. However, in a real life situation, a demand increase could also influence the travel distance due to a diversion to less congested but longer routes, hence, PCA will decrease. Furthermore, it has been observed that, under similar disruptive events, the impact on PCA and TCA could vary. For example in group one scenarios, each link closure has different impacts on both attributes; some links closures have more impact on PCA (such as link 11432_1) whereas other link closures affect TCA more than PCA, (e.g. links 11412_2 and10123_1). This emphasises the importance of considering both attributes within a mobility measure. Identifying the level of connectivity and level of service could play a crucial role in highlighting network weaknesses under different circumstances. Despite the importance of measuring the impacts of disruptive events on physical connectivity and the road transport level of service, the aggregated impact of both attributes is still needed. A flexible technique based on the fuzzy logic approach is therefore implemented to estimate the network mobility indicator (NMI) based on PCA and TCA. The proposed NMI could be used by policy makers and Highway Agencies to evaluate the overall effectiveness of certain policies or the implementation of new technologies. However, it is important that the effectiveness of the proposed network mobility indicator be assessed by direct measures of traffic conditions following a decision based on the use of such indicator.

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