

Understanding Large Transport Network Performance Subject to Unexpected Traffic Demand

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ABSTRACT

Existing network modeling methods deal with the network performance in a discrete manner. It means current methods assess the network performance in a set period of time, i.e. every 5 or 10 years. Furthermore, their functionality is usually based on the assumed predictable data. In this research, a new methodology, which combines mathematical modeling and transportation network modeling, has been proposed to obtain the network performance continuously over time. This method incorporates both uniform demand growth and demand shift toward more attractive zones (demand uncertainty). It provides a measure of growth and shift in the traffic load that a network can sustain. Thus, this method can assess the topology of a transport network and investigate the maximum amount of time that it can sustain traffic demand growth without the need to amend the network. It is believed that this measure is useful both in the planning phase of new transport networks and in the performance analysis of the existing networks. The proposed method application has been demonstrated by applying the method to a part of Melbourne transportation network.

Existing transportation network modeling practices consider current and future transport traffic load in a defined period of time e.g., 2010, 2020, 2030 (C.S.Papacostas 2001). They take into account expectable and evaluative events, which are usually captured by traditional four-step modeling or land use/transportation interaction modeling. Defining a concept called traffic demand shift, it is demonstrated that previous models do not provide a systematic way to accommodate for traffic shift in the transport network. Furthermore, lack of consideration for uncertainty in major inputs to the model (such as population and employments) is another issue that these models do not cope with properly.

This paper outlines a methodology to assess transportation network performance over its lifetime. The main difference between the proposed method and existing approaches is to measure network performance continuously and assessing behavior of zones individually, in terms of applying both uniform growth and traffic shift.

Many studies have been carried out to assess transportation network performance. Most of these approaches related to network or travel time reliability and some of them considered this issue from demand uncertainty point of view. Existing reliability approaches were focused on connectivity and reliability of travel time. They do not consider a comprehensive measurement of network performance (Chen, Hai et al. 2002). Chen et al (1990) introduced a new reliability measure, which was based on the probability that the network can sustain a certain travel demand at a particular service level. This method accounted for drivers' route choice behavior. Chen et al (1999) proposed a mathematical model, which was based on reserve capacity for transportation network (Chen, Yang et al. 1999). In this approach, the probability that a network can accommodate with a certain traffic demand were considered. The concept of reserve capacity is based on the largest multiplier, which can be applied to the demand without violating any links capacity in the network. Chen et al (2002) extended their previous study (Chen, Yang et al. 1999) by providing a new methodology, which was a

combination of reliability and uncertainty analysis, network equilibrium model, sensitivity analysis and expected performance measure (Chen, Hai et al. 2002).

The major issue in this method is to evaluate only the maximum allowable increase in the network. These approaches assess the network performance as a largest multiplier that a network can accommodate without violating the link capacities, but they do not take into account the behavior of individual zone. In addition, continuous performance of a network over time has not been considered.

In another attempt, Sumalee and Luathep (2009) introduced a new elastic assessment and design model for transportation network capacity under demand variability (Sumalee, Luathep et al. 2009). The concept of reserved capacity used to evaluate the performance of the network. This model shows the flexibility of the network in terms of O-D demand variation. This model can also determine the optimal network design to improve reserve capacity of the network.

All performed works in the reviewed studies have focused on network performance in viewpoint of reliability, reserved capacity and network uncertainty. It is necessary to propose a methodology to evaluate the performance of a network when it is subject to unexpected traffic growth (traffic shift) over time and continuously.

In this paper, a new methodology will be introduced. Using this method, the performance of a network under various traffic patterns is investigated. Linear or uniform traffic growth and traffic shift are both applied to the network. Linear traffic growth is due to increase in population and other predictable activities, which can be estimated statistically. On the other hand, traffic shift can be a result of population movement and business relocation on transportation network, or lack of consideration for uncertainty in estimation of population and employments.

Linear growth is calculated by increasing the traffic demand gradually until the network cannot tolerate any more traffic load without a major intervention. Traffic matrix between each pair of zones increases by same multiplier, once the first link cannot carry any traffic load; the last multiplier is recorded as a maximum linear traffic growth. In this work only linear growth has been considered, however the developed model can handle non-linear traffic growth as well.

Traffic shift in a network is considered towards more attractive zones in terms of job opportunities or because of the uncertainty in predicting future demographic and zonal data. For example, a recreation centre may substantially increase the demand in some parts of the network. In the rapid developing countries and cities, transport traffic shift is increasingly unpredictable.

This method is combination of a sophisticated mathematical algorithm with the transportation network modeling approach.

Assume a network G has z zones, n nodes and l links. All $z, n, l \in \mathbb{N}$ and the travel matrix of network G is $T(i,j)$. In the first step, the network G is subject to linear growth only. So the maximum linear growth of the network is then calculated. In the next step, the given network is subject to traffic shift and linear growth and maximum unexpected traffic growth (UTG) is derived. Finally, the lifetime curve of a network is depicted according to the achieved values of maximum linear growth and maximum of UTG.

2.1. Calculating of Maximum Linear Traffic Growth

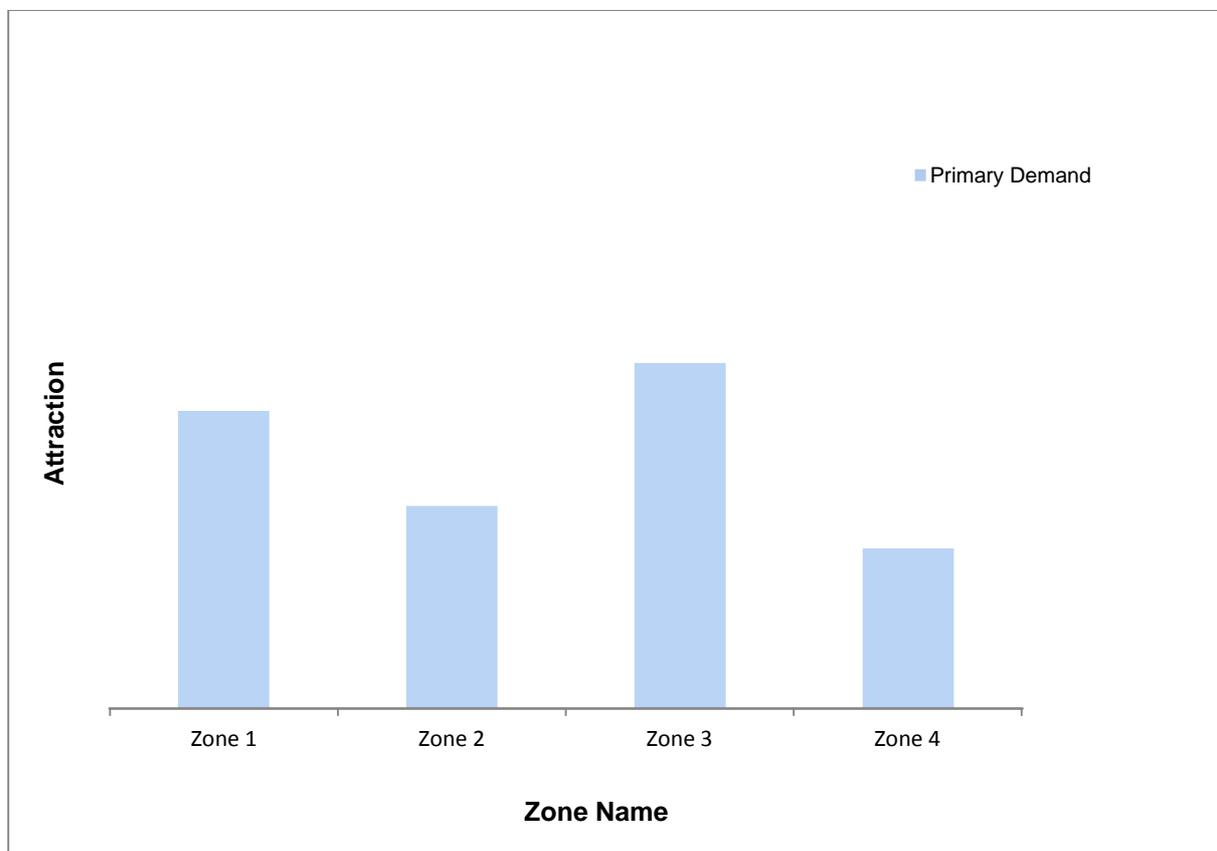
Maximum linear growth is a multiplier greater than 1, denoted by ψ , which $\psi T(i,j)$ is still sustainable. Having enough capacity to support traffic load without violating any links capacity in the network is the criteria of sustainability for the given network G. It means the demand matrix of a transportation network is increased until the network cannot tolerate any more traffic load. In other words, traffic congestion index of link l_{ij} in the network G reaches to the predefined limit value.

$$\frac{V}{C} > \zeta \tag{1}$$

In the above constraint, V and C are volume and capacity of link l_{ij} respectively. ζ is a measure of congestion which is defined for each link in the network. In this study, it is assumed that this measure is 1.15 and identical for all links. Therefore, each link can tolerate 15 percent more traffic load than predefined capacity without any violation.

Figure 1 demonstrates schematically the process of calculating the maximum linear growth (ψ) in a network.

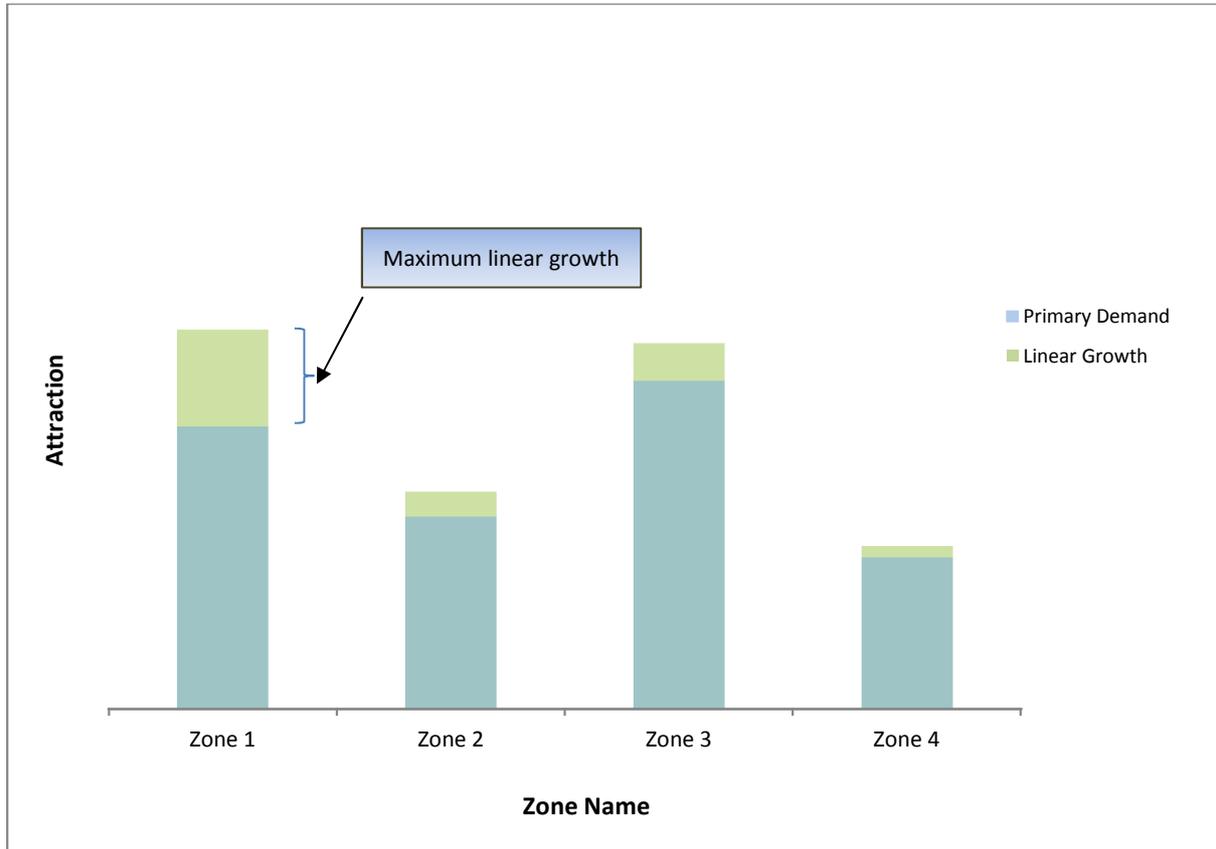
Figure 1: Primary value of zones' attraction



This graph shows the primary attraction of each zone in a network with four zones. In the next step, the attraction of all zones increases while the traffic congestion index of a link reaches to predefined limit (ζ).

Figure 2 shows highest increased attraction value of zones that the network can sustain with the increased demand matrix.

Figure 2: Increased attraction value of zones



As described above, the ratio of increased attraction to primary attraction is maximum linear growth (ψ) for the given network.

$$\psi = \frac{A_i'}{A_i} \quad (2)$$

A_i is primary attraction of zone i

A_i' is the maximum increased attraction of zone i

Ψ is maximum linear growth, which is identical for any zone in the network G

Now the maximum linear growth is calculated, this value indicates that if there is no traffic shift, travel matrix ($T(i,j)$) of network can be increased and reaches to $\psi T(i,j)$. In the next section, the process of calculating the Maximum Unexpected Growth is described.

2.2. Maximum Unexpected Traffic Growth (UTG)

So far the network is only under linear (uniform) traffic growth, which can be result of annually increase of population or other predictable activities. Now a new parameter is defined, it is called Unexpected Traffic Growth (UTG).

Assume in a part of a network, an unexpected event happens and this occurrence has not been predicted before. This event could be result of establishing a new business or creating an educational institute. The result of such unexpected development creates attraction more towards a specific zone. It is called traffic shift. By this measure transportation planners would be able to measure maximum amount of traffic shift for each zone, and consequently for the network.

The attraction and production value of zone i is A_i and P_i , respectively. In any given time in a network, due to meeting the conservation flow criteria total attraction of zones must be equal to total production. In other words, in a network with n zones:

$$\sum_{i=1}^n A_i = \sum_{i=1}^n P_i \quad (3)$$

When the attraction value for a zone increases, other attraction values should be decreased. So in order to calculate of maximum unexpected traffic growth (U), the attraction of zone, which is subject to proposed method, increases until the attraction of a zone in the network reaches zero.

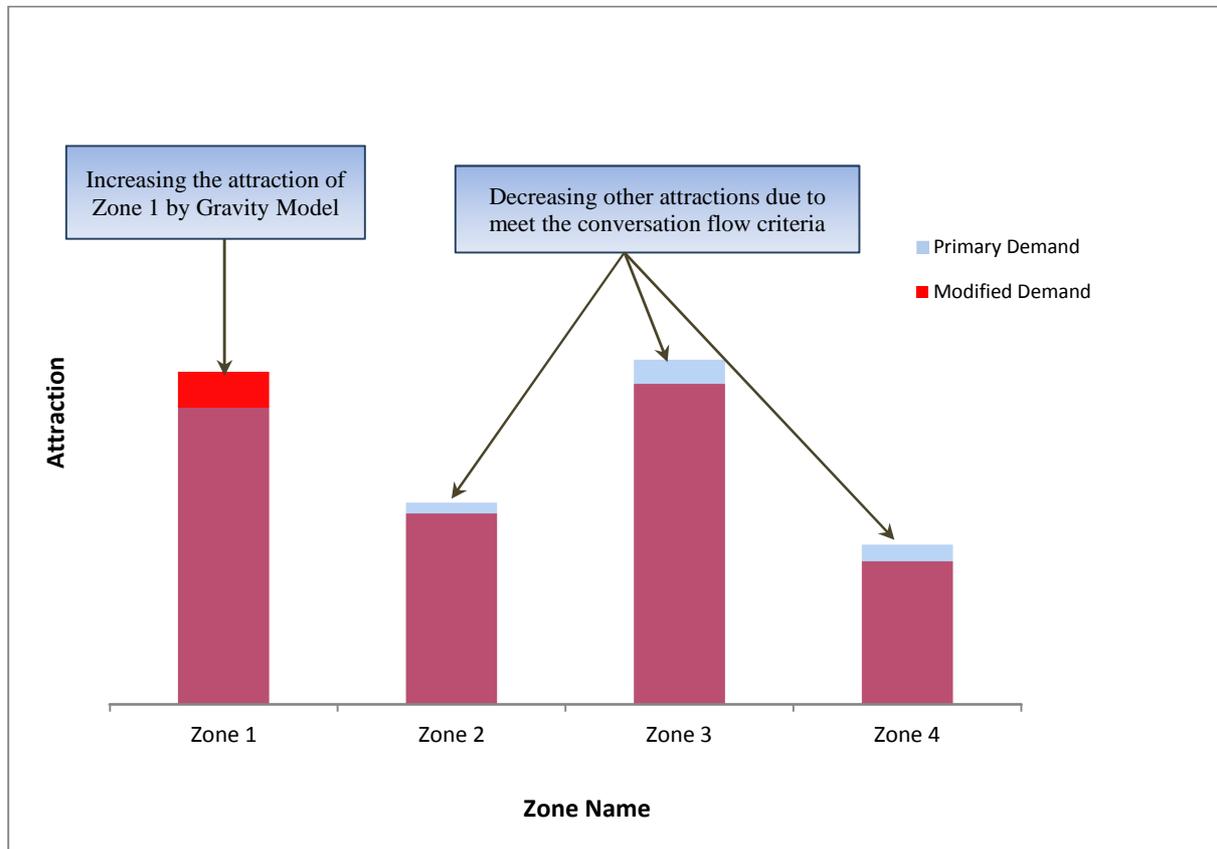
In this paper, it is assumed that zones in the network are subject to UTG individually, but the developed model measures the traffic shift for a group of zones that are subject to UTG simultaneously.

When attraction of zone i increases, the remaining zones' attraction is decreased. For the purpose of finding reduction factor for other zones, the Gravity model, has been used.

In Gravity model travel time, or distance between zones, and value of attractions and productions are two main factors for trip distribution procedure. It means closer zone to a specified zone has greater reduction factor than far zones.

Figure 3 illustrates the procedure for calculating U_{max} schematically.

Figure 3: Modified value of attractions, by Gravity model



In Gravity model:

$$T_{ij} = T_i * \frac{A_j * f_{ij}}{\sum_{j=1}^n A_j * f_{ij}} \quad (4)$$

T_{ij} : trips from i to j

T_i : trips from i , as per our generation analysis

A_j : trips attracted to j , as per our generation analysis

f_{ij} : travel friction factor (function of travel cost, travel time, ...)

Figure 4: Primary value of attraction

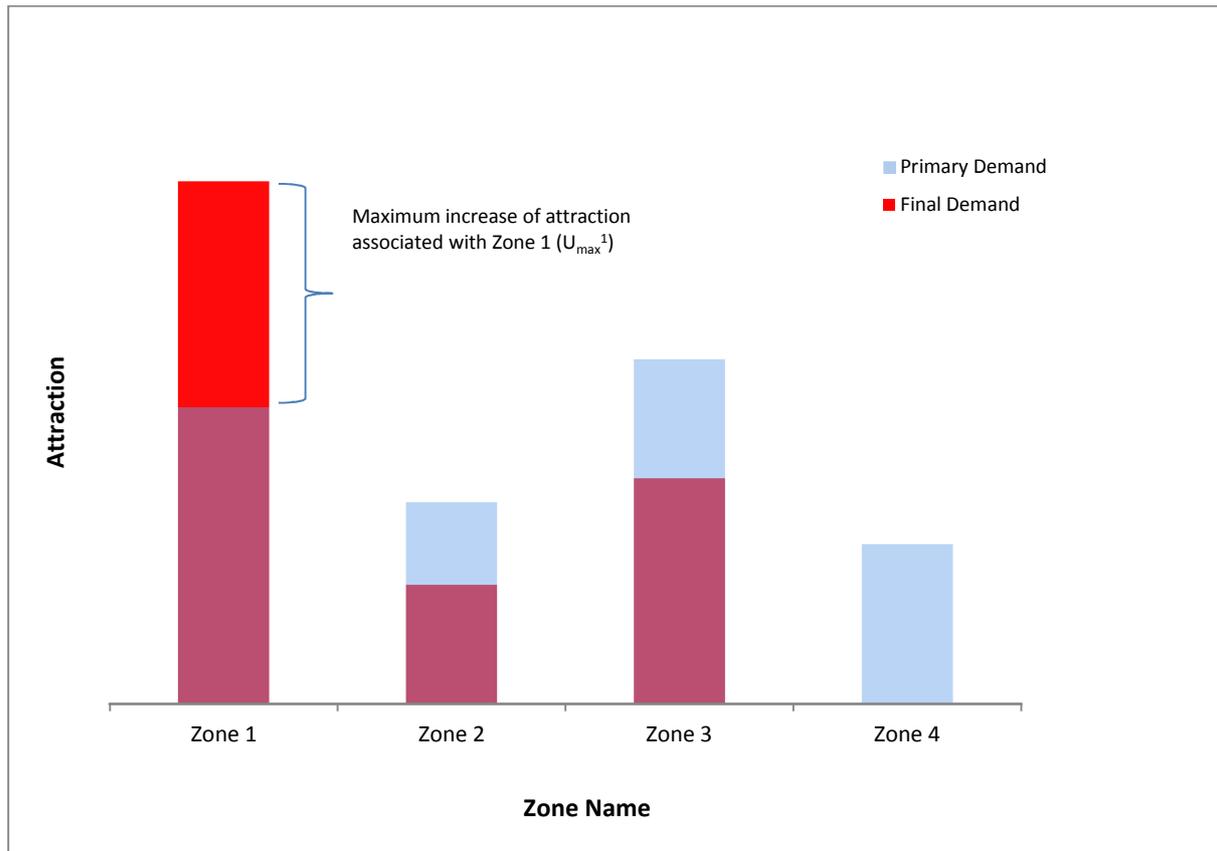


Figure 4 shows that the process of increasing attraction for zone i , and reduction of other zones' attraction repeats until the attraction value of a zone reaches to zero. At this time, the new attraction of zone i , A'_i , can be shown in the form of $A_i \cdot (1+U)$. The magnitude of U is the maximum traffic shift associated to zone i that the network can sustain. For a network with n zones, n scenarios could be defined, each scenario related to a specific zone. In order to obtain maximum traffic shift of a network, minimum U_{max} value of all scenarios should be selected.

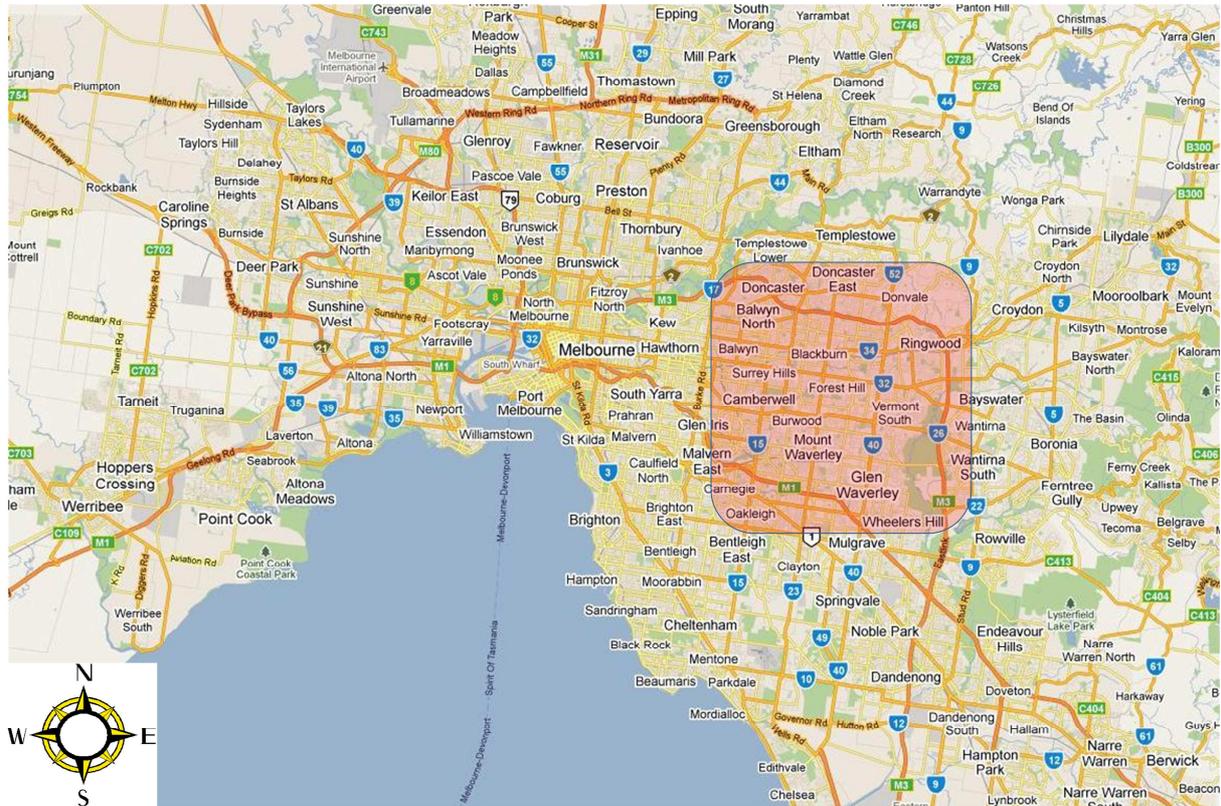
$$U_{max} = \text{Min} \{U_{max}^1, U_{max}^2, \dots, U_{max}^n\} \quad (5)$$

Now both maximum linear growth and traffic shift (U_{max}) of a network are determined. Having these two measures helps transport planners to evaluate the performance of a network by applying various traffic patterns to different zones. In the next section with a real network, this method is more explained.

A part of Melbourne transportation network is selected for the lifetime analysis. This network is located in eastern of Melbourne, including one freeway and some arterials. It consists of 40 zones, 1080 links and 481 nodes. The topology, capacity of links and speed limits are extracted from the main Melbourne transportation network. This network is surrounded by

Doncaster and Doncaster East in North, Heathmont, Wantirna South in East, Glen Waverley and Mt Waverley in South, and Box Hill South and Box Hill North in West. Figure 6 shows the layout of the area.

Figure 6: Layout of the selected area for implementation and analysis



One scenario is defined which allows the travel demand to be changed only on a set of five individual zones out of all forty zones.

3.1. Five-Zone scenario

This scenario includes of 5 zones which are subject to UTG (Unexpected Traffic Growth). Following, five selected zones in the VISUM and input data required for analysis are shown in Table 1.

3.2. Input data

The data, which are required for analysis are:

- expected increment: 0.03 (3% traffic increase per year)

- number of zone(s) subject to UTG: 5
- total zones: 40
- Traffic Congestion index (V/C): 1.15
- data file (following information) and VISUM file

Table 1: Input data for 5-Zone scenario

Zone Number	Zone Name	Attraction (trip/day)	Production (trip/day)
Zone 601	Box Hill North	1560	1222
Zone 609	Burwood	1408	680
Zone 619	Vermont	1426	1162
Zone 1177	Heathmont	259	188
Zone 1603	Donvale	682	559

In this table Attraction is the average number of weekday person trips attracted to each transportation zone and Production is the average number of weekday person trips produced by household within each transportation zone.

Concerning the expected increment, it is assumed that each year the traffic in transportation network increases by 3%. In other words, the production increases three percent per annum. The Traffic Congestion index indicates that the network can be stable while the flow of each link reaches about 15 percent more than the specified capacity. Moreover, the analysis stops once the first link reaches the predefined measure (Traffic Congestion index).

3.3. Results

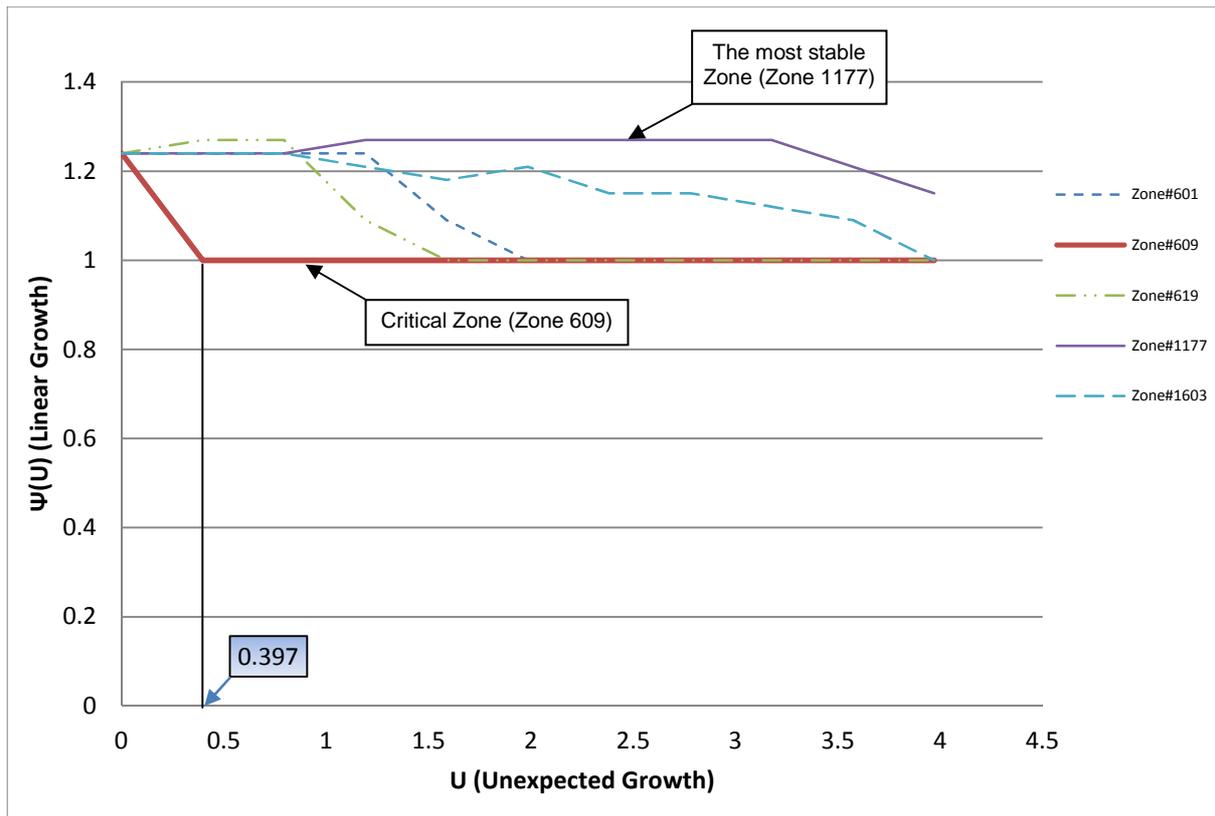
The output data obtained from the computer application developed are given in the following table.

Table 2: Output result for five-zone scenario

	0	1U/10	2U/10	3U/10	4U/10	5U/10	6U/10	7U/10	8U/10	9U/10	10U/10
	0	0.397	0.794	1.191	1.588	1.985	2.382	2.779	3.176	3.573	3.97
Zone 601	1.24	1.24	1.24	1.24	1.09	1	1	1	1	1	1
Zone 609	1.24	1	1	1	1	1	1	1	1	1	1
Zone 619	1.24	1.27	1.27	1.09	1	1	1	1	1	1	1
Zone 1177	1.24	1.24	1.24	1.27	1.27	1.27	1.27	1.27	1.27	1.21	1.15
Zone 1603	1.24	1.24	1.24	1.21	1.18	1.21	1.15	1.15	1.12	1.09	1
Min	1.24	1	1	1	1	1	1	1	1	1	1

The output data are shown graphically in Figure 8. The depicted graph which is obtained from the output table shows the behaviour of individual zones subject to traffic shift over time.

Figure 7: Individual zone behavior subject to UTG



Vertical axis of this graph ($\Psi(U)$) represents of linear traffic growth and horizontal axis (U) corresponds to the value of Unexpected Traffic Growth (traffic shift) in the given transportation network.

Results show that zone 609 (around Box Hill) is the critical zone in the network, because it reaches the capacity limit very soon, as a result it would fail faster than other zones. In this network the maximum feasible linear growth is 1.24 ($\Psi(U)$) in the case of $U=0$ (where there is no traffic shift). It indicates that this network can no longer tolerate any traffic growth after 7 years, assuming 3 percent traffic growth per annum; even there is no traffic shift ($\frac{\ln 1.24}{\ln(1+0.03)} \approx 7$). It also points out that the maximum traffic shift relevant to critical zone is

about $U=0.397$, so without any linear traffic growth this zone and consequently the whole network would experience failure.

The zone 1177 (around Heathmont) has the most stable performance compared to other zones. This zone can carry a huge traffic load over time without any violation in terms of traffic congestion. The maximum feasible linear traffic growth is 1.27 in the case of $U=1.191$. An important observation for this zone is, where $U=3.97$, it has linear growth of 1.15, which means it can last more than 4 years assuming a 3 percent of annual traffic growth. The reason why the maximum $\Psi(U)$ does not start from $U(0)$, refers to characteristics of the network, such as topology, scale of zone in terms of number of links, type of links, and as well the relationship between Attractions and Productions value.

Other zones, for instance, zone 1603 reaches to capacity limits where $U=3.97$ and cannot tolerate any linear traffic growth beyond this point. Zones 601, and 619 reaches to capacity limits on $U=1.985$ and $U=1.588$ respectively.

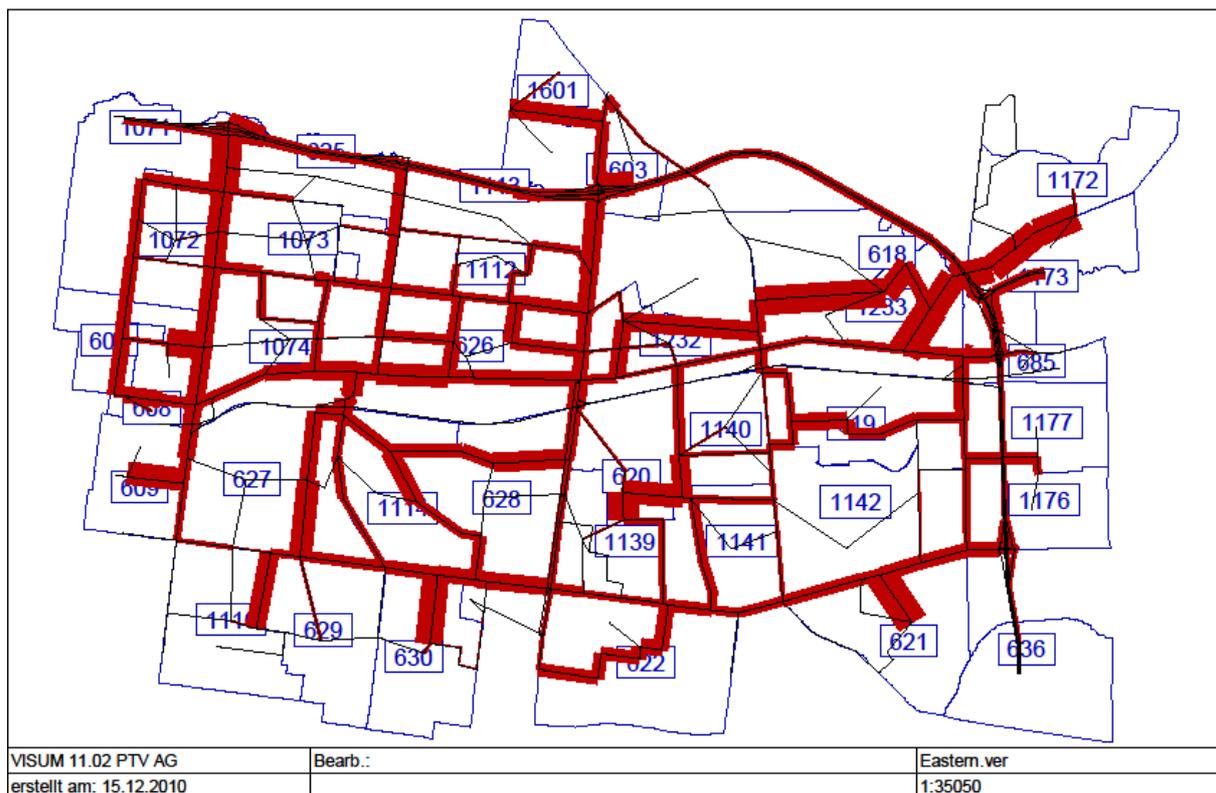
Table 3 demonstrates the congested links in this analysis (TCI is Traffic Congestion Index).

Table 3: Congested links with associated TCI (Traffic Congestion Index)

Link No.	TCI	Link No.	TCI
21663	4.596	39927	1.374
22876	2.77	22877	1.374
22884	1.835	9725	1.178
22882	1.835	22870	1.177
22880	1.835	8515	1.177
21620	1.813	22917	1.157
21648	1.809	9175	1.157
9681	1.425	9113	1.157
23298	1.41	9112	1.157
22874	1.397	8738	1.157
22863	1.397	7979	1.156

Figure 8 shows the resulted traffic volume in the network.

Figure 8: Status of links in the network



In this paper, a new methodology to measure transportation network performance was introduced. This method is capable of assessing the individual zones and links behavior by

applying linear (uniform) growth and traffic shift in the network. On the other hands, sensitivity of zones in terms of changing traffic pattern is evaluated. This measure determines which networks last longer, if the traffic growth is uniform, and which networks last longer under traffic shift. The final lifetime curve indicates maximum linear growth that a network can sustain under a range of traffic shift. Another output of this method is to find out the weakest link(s) in the network, which is important for transport planners to make a proper decision for future.

For the sake of simplicity, selected zones are subject to proposed method individually, but the developed method can consider different scenarios where each scenario includes several zones, therefore a group of zones are subject to the method simultaneously.

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