

New Methods Exploring Urban Traffic Congestion Using Lorenz and Concentration Curves

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Abstract

Congestion is a major concern affecting growing cities worldwide. Congestion mitigation depends largely on our factual understanding of congestion, its nature, distribution and variability. However, traditional measures of congestion such as the Volume Capacity Ratio (VCR) have been criticised for overly being focusing on localised (not network-wide) performance, for omitting measures of actual user travel time and for failing to consider the volume of traffic carried. This research paper presents new methods for exploring congestion, travel time performance and traffic volume impacts on traffic links distributed within an urban traffic network. The approach uses Lorenz curves, and the associated Gini Coefficient parameter, which has been developed in welfare economics as a powerful tool to study income inequality. This study uses the mathematical principle of Lorenz and Concentration curves using traffic related variables: speed and traffic volume. The proposed approach directly addresses limitations noted about VCR based approaches in that it more readily illustrates relative volume of travel across networks as well as relative travel time/speed performance as it impacts individual users. In addition the relative performance of these factors can be more readily compared on a network wide basis and even mapped to identify and prioritise problem link locations.

The paper undertakes two analyses; a cumulative link VCR by cumulative link volume analysis and an analysis of cumulative link speed by cumulative volume to explore distributions of link performance across an urban network using a citywide transport network model. Both analysis (by Lorenz or Concentration curve based measure and VCR measure) of urban network are compared and evaluated. Areas for further development of the method are suggested.

Key words: Urban transport, congestion, Lorenz curve, Concentration curve, Volume Capacity Ratio

1. Introduction

Traffic congestion is one of the most important issues affecting growing cities in the 21st century. However, there is much consensus in transport research that metrics to understand congestion are limited and require further development (BTS, 2003). One of the most common measures of congestion in cities is the Volume Capacity Ratio (VCR). This is a very simple metric to understand but has a number of limitations. As a ratio, VCR does not relate to actual traffic volumes; hence the actual number of people affected is not directly described. It also tells us little about actual travel times which travellers commonly see as an important measure of performance (Scott et al., 2006).

Addressing congestion in cities will require a better understanding of the actual performance of roads in terms of travel time and the volumes of commuters experiencing this performance.

This research paper presents a new methodology to explore the performance outcomes of traffic in cities by exploring outcomes in relation to the volumes and shares of the travelling public that experience these levels of performance. The methodology adopts the concept of the Lorenz and Concentration curve, both approaches commonly used in wealth economics, to explore how the distribution of performance outcomes of travel in cities affects the distribution of commuters across urban traffic links.

The paper is structured as follows; the next section presents a review of relevant research literature concerning definitions of congestion, measures of congestion and their limitations and also presents the concept of the Lorenz and Concentration curves. This is followed by Methodology Development where the new concepts and approaches proposed are described. Results of an application of these methods are then outlined including a discussion of their implications. The paper concludes with a summary of major findings including ideas for future development of the methods proposed.

2. Research Context

Current understanding of urban traffic congestion as well as the development of management strategies largely depends on how traffic congestion is defined. Congestion can be described at a physical level, but because it can be relative and subjectively experienced in various situations and places, the definition of it is still to this date complicated and can lack in precision (ECMT, 2007). Definitions of congestion vary depending on its cause or effect. There are three interconnected categories relating to: 1. demand-capacity, 2. delay-travel time and 3. cost; Table 1 (Aftabuzzaman, 2011)

Table 1: Definitions of congestion

Category	Definition/Description	Author
1 Demand-Capacity	Congestion is a condition in which the number of vehicles using the roadway exceeds the roadway generally accepted service levels.	(Rothenberg, 1988)
2 Delay-Travel Time	Congestion is a travel time delay in excess of that normally incurred under light of free-flow travel conditions.	(Turner, 1992)
3 Cost	Congestion can be a result from under-pricing of the road network and marginal cost pricing can be used to internalize the congestion externality.	(Arnott, 1994)

2.1. Congestion measures and their limitations

Traffic management plays a huge role in optimising traffic performance and prevent congestion. Recent approaches also use the macroscopic fundamental diagram describing the relationship between the number of vehicles and link performance (Knoop et al., 2012)

Measuring congestion is a necessary step in delivering better congestion management. Conventional congestion indicators traditionally measure the congestion *intensity*, a quantification of the amount of traffic. This information is valuable for short-term decision making, but unsuitable for strategic planning. To properly assess the quality of transport a more comprehensive method including measuring congestion costs and congestion *exposure* is suggested (ECMT, 2007). Congestion measures can be divided into two main groups: *engineering* and *economic* with five categories including the following:

1. Volume based, e.g. Volume Capacity Ratio
2. Service based , e.g. Level of Service
3. Travel time and delay based, e.g. Travel Time Index
4. Speed based
5. Cost based measures

Measuring physical and technical system performance (the engineering approach) tends to dominate current international practice (ECMT, 2007). Two of the most commonly used congestion measures are interconnected; the Volume Capacity Ratio and the Level of Service (LOS) (Roess, 2010). They help to address the complicated decision making process of relief strategies (Scott et al., 2006). VCR is an index value of volume divided by capacity of a particular road link. VCR is directly indicating congestion and traffic flow, where value of 0.85 represents the capacity threshold of the particular road link. Values of VCR under 0.85 suggest that the link is operating under capacity. Values near 1.00 signal unstable flow and need for improvement. Values higher than 1.00 denote a link where the demand highly exceeds the capacity, causing significant delays and queues. VCR was originally created for highway-based critical road segments (Ryus et al., 2010).

The Highway Capacity Manual (HCM) describes LOS as a quantitative stratification of a performance (Ryus et al., 2010). LOS is typically calculated from VCR values. Depending on the use, additionally they can be combined with other measures, e.g. delay (Ryus et al., 2010). The HCM divides LOS into 6 categories A – F, where LOS A is representing the highest level of performance and LOS F the lowest.

Many researchers have criticized conventional measures of traffic congestion for their focus on localized solutions that may fail to identify the critical links on a network wide basis (Scott et al., 2006). Scott and Novak (Scott et al., 2006) demonstrated this in an example of a simple network with two nodes and two links between them, where Link 1 has 3 times higher capacity than Link 2. Link 2 has a higher VCR value than Link 1, therefore should be a subject of improvement. However, it is the Link 1 which is in more risk. Because Link 1 carries higher volume of travellers, it is more significant and requires more focus. Clearly as a ratio, VCR can be misleading and should be considered within the context of actual link volume.

Papadimitriou et al. (2010) studied the difference between the perceived Level of Service (LOS) and VCR and found a large dispersion of perceived LOS and VCR. Mallinckrodt (2010) looked into the often neglected problem of VCR effectiveness of regional networks, where a different approach should be used. He developed a new model to determine threshold between economic impacts of congestion and building new roads to increase capacity.

The Bureau of Transportation Statistics of the U.S. Department of Transport has been particularly vocal about calling for new congestion measures. They published a report; *Better Congestion Measures are Needed* (BTS, 2003), where they state: “Better ways to measure congestion are needed to effectively address the problem” (p. 1). Bremmer (2004) warns that measures traditionally based on volume and capacity can be insufficient. That the complex task of measuring congestion should evolve together with the management

strategies. Bertini (2006) calls for caution as commonly adopted congestion measures are used in cases they were not originally designed for (Bertini, 2006). As a result congestion is often measured poorly; hence the understanding of congestion and its distribution is limited. Lyman and Bertini (2008) highlight another fact that VCR based strategies does not included travel time, a significant factor of road user experience directly relating to road operational performance.

2.2. The Lorenz and Concentration curves and the Gini coefficient

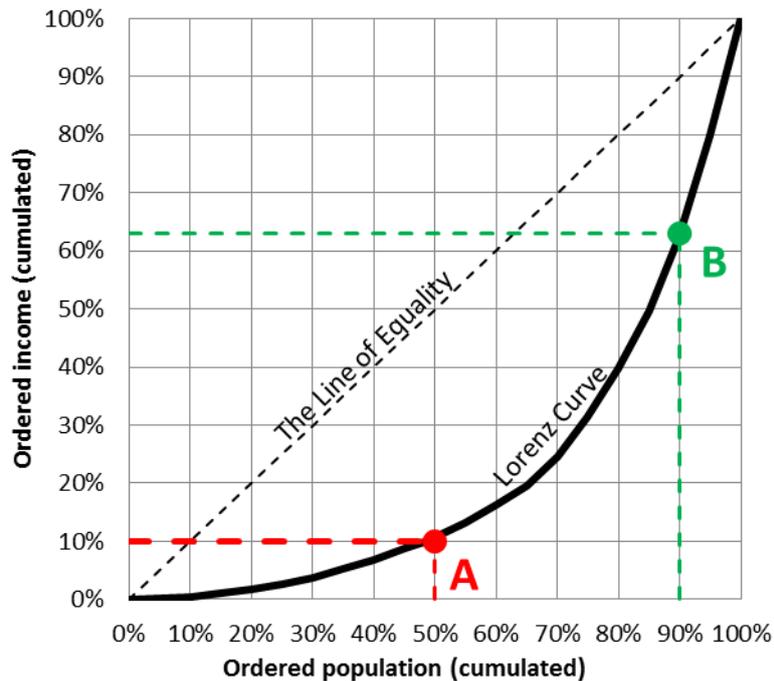
The Lorenz curve is a well-established economic tool typically used to describe inequality in the distribution of wealth and income in society. It was devised by an American economist Max Lorenz in 1905 (Lorenz, 1905). The current shape and formula was brought to public by Corrado Gini, who also named them for the first time Lorenz curves (Gini, 1939, Derobert, 2003). A Lorenz curve is a chart displaying the cumulative proportion of a population on the horizontal axis and a cumulative distribution function of the interest values on the vertical axis, both quantities are presented in percentages (Figure 1). If the cumulative distribution values are perfectly aligned with the cumulative distribution of population ($x = y$), the Lorenz curve results in a 45 degree straight line that is known as the 'line of equality'. The area between the Lorenz curve and the line of equality is a measure of the discrepancy between the income and population distributions (Frees et al., 2014).

Less known is the fact that Lorenz curve is a special case of Concentration curve. Concentration curves are also used in economics for magnitudes other than income (World Bank: O'Donnell et al., 2007). The line of perfect concentration is called 'line of independence'. The main difference between the Lorenz and Concentration curve is that function of Lorenz curve directly takes into account the difference to the ordered mean. Concentration curve does not, therefore the values may fluctuate around the line of independence, or cross it. Concentration curves can also be ordered by an additional sequence or rule (Yitzhaki and Schechtman, 2013).

The area between the straight line of equality (or independence) and the Lorenz or Concentration curve can be characterized by what is known as the Gini Index or Gini Coefficient, (Sen, 1998, Frees et al., 2014). This is a potentially powerful value since it indicates the variability of inequality (or distribution) as a single number for a large dataset. Values of the Gini Coefficient are between 0 and 1, the higher the Gini Coefficient; the more unequal is the distribution of the studied trend or concentration.

The graph (Figure 1) shows an example of Lorenz or Concentration curve in comparison to the line of independence/equality. The red and green lines cutting in at the bottom and top of the Concentration curve demonstrate selected aspects of the distribution. Line A crosses the Concentration curve where 50% of Population earns only 10% of the shared Income. Line B crosses the Concentration curve at the point where the last 10% of the Population earns some 38% of Income. By exploring these aspects of the distribution it is possible to better understand how variable the distribution of income is within the population.

Figure 1: Concentration curve



The idea of using Lorenz or Concentration curves and Gini Coefficients outside of income economics is not new. A number of applications can be found in the spatial sciences. For example Minnich and Chou (1997) used the methodology and Gini coefficient to evaluate the distribution of large wild fires. Ahmad-Kiadaliri et al. (2011) utilized the measure to identify the distribution of health care across the country of Iran. Elvidge et al. (2012) employed Lorenz curve principle for development of a global index describing human settlements and development, based on satellite data.

The application of Lorenz curve in transport can be found in the work of Delbosc and Currie (2011) measuring the distribution of the provision of public transport amongst the population of Melbourne. Juan et al. (2008) applied the concept to analyse the fairness of congestion pricing among road users. Similar analyses were done by Gordon and Peters (2011) looking into the impact of toll revenue on road users and Nahmias-Biran et al. (2014) measuring the equity of transit fares.

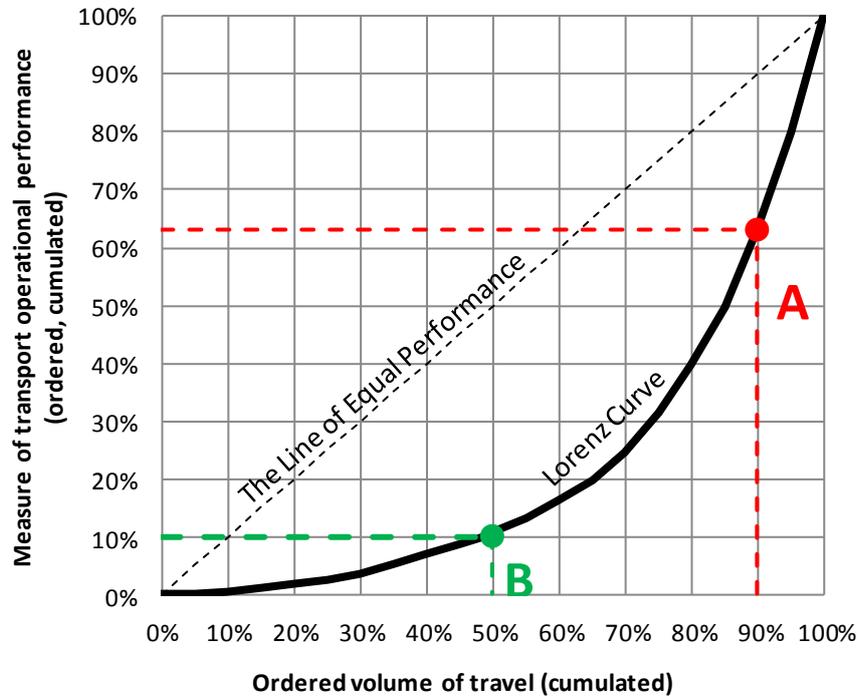
To date no applications of the Lorenz or Concentration curve have explored how congestion or the operational performance of travel varies in urban transport. In this paper the use of the Concentration curve is explored as a means of exploring the spatial distribution of congestion on links in relation to the relative population of travel occurring on links.

Due to the fact that the Lorenz and Concentration curve methodology was rediscovered multiple times in the past, their names are often misplaced, when used for other than income applications. Based on the disposition of our dataset Concentration curve term is used in our methodology.

3. Methodology development

This paper presents the use of Concentration curve as a new concept to measure urban traffic congestion. Figure 2 illustrates a conceptualized version of the Concentration curve and how it might be applied in the context of transport congestion.

Figure 2: Lorenz curve and transport congestion – conceptualisation



In this example it is theorized that travel is examined on road links. The Concentration curve explores the distribution of total travel occurring on each link (X axis) and also the distribution of relative congestion performance (or operational travel performance, e.g. travel time) on each link (Y axis). It is theorized that this might have a number of key conceptual benefits:

- It should highlight (bottom left, point B) the share of total travel which have good operational performance; in this case 50% of all travel on links have travel performance representing only 10% of all travel occurring on all links. These travellers have good operational travel performance (are not experiencing congestion) relative to others.
- It should highlight (top right, point A) the share of travellers with poor performance or larger shares of total travel performance; in this case the last 10% of travel volume incurs the 38% of total operational performance per link.
- It is also hypothesized that this analysis might represent a means of targeting investment in congestion mitigation. The analysis in Figure 2 highlights links with poor performance and high relative volume (top right, A); in theory this should represent locations to target congestion mitigation measures such as the provision of priority for public transport or road capacity improvements for traffic links.
- In addition, the Gini Coefficient can be used to represent the distribution of the operational performance of travel on links using a single numeric measure.

A large number of possible combinations of variables were explored to realise the X and Y axis illustrated in Figure 2. Firstly an alternative operational performance measure; unit

distance per travel time (speed) was explored as a means of investigating congestion on a network perspective. Travel time was chosen only as an example to demonstrate the qualities of the Concentration curve. It has similar characteristics as the Income. The Average Link Speed is used and the quality of operational performance on axis Y is shown in reverse order. In a second round of analyses, the VCR of each link was assessed against link volume on a network wide basis. Results of the both methods were also compared.

3.1. Data description

The key data sources to populate a new congestion measure based on Lorenz curve are transport link based data for traffic including travel volume information, operational performance (such as unit travel time per distance) and link capacity data per link. The main dataset used was generated from the Victoria Integrated Transport Model (VITIM) using morning a.m. peak hour data for 2011. VITIM represents a large dataset of road links (49,000+ records), rich in a range of performance attributes. VITM is a conventional four step transport model, hence much of the traffic data adopted is modelled rather than actual data. Nevertheless this data has been calibrated and validated against actual real world values so is considered generally acceptable as a representation of travel in the city studied. It also a comprehensive dataset; enabling comparison of a large set of link performance data.

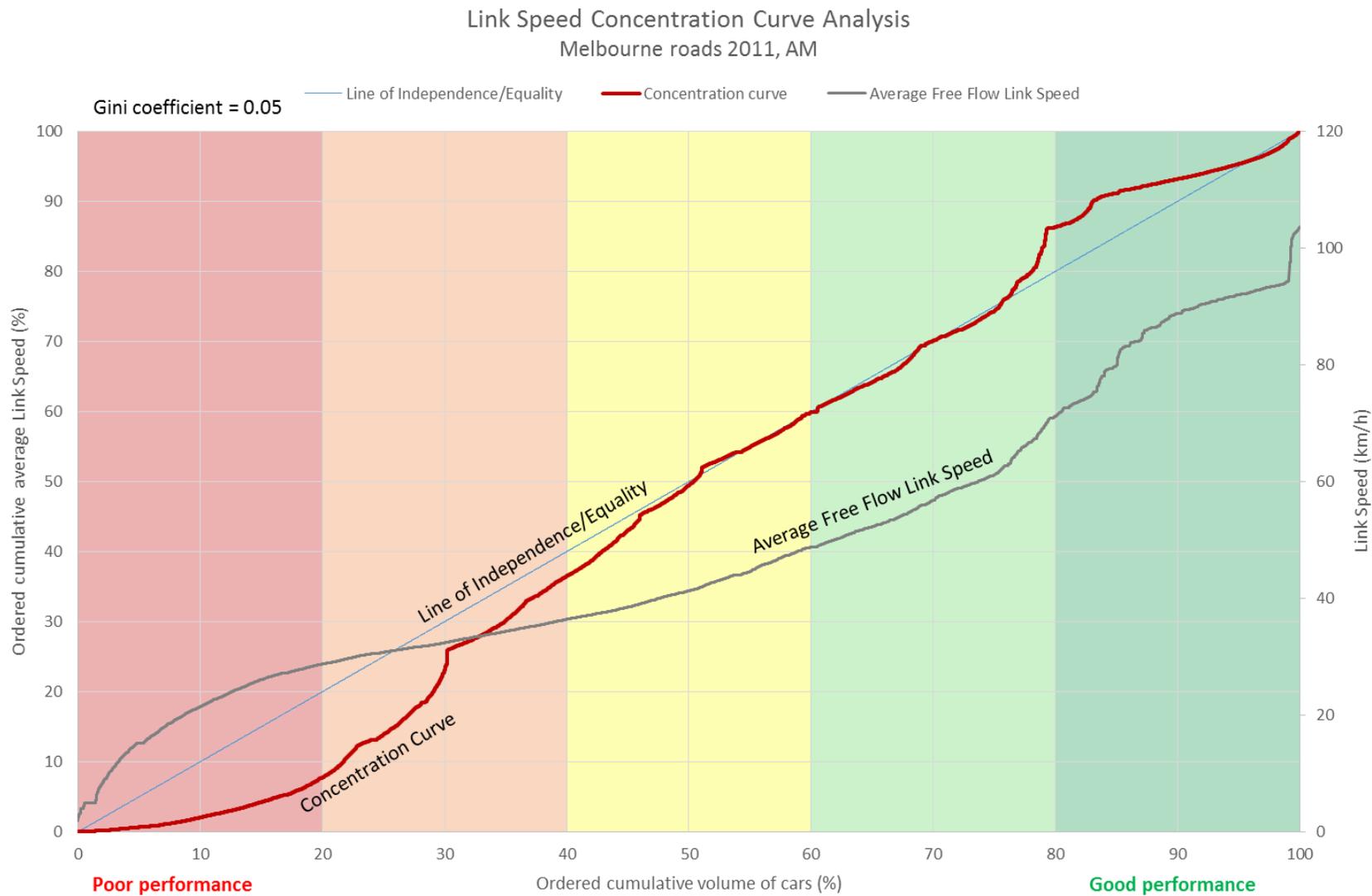
4. Results

4.1. The link speed network analysis

The first round of analyses of Melbourne network wide traffic performance employed the 'link speed' approach to explore the distribution of link distance/travel time by link traffic volume. The results of this analysis can be seen in chart in Figure 3. Axis X shows the ordered volume of travel (number of cars). Axis Y1 stands for the measure of operational performance: Average link speed. Average modelled link speed together with the speed limit of particular links are also illustrated in the Y2 axis. Results show that:

- A range of Link speeds is almost evenly distributed among the traffic volume.
- For point A some 20% of link volume (bottom left) experience about 8% of the lowest link km/travel time performance of less than 8 km/hr. Which is significantly below the suggested speed limits of the road links involved.
- For point B (top right) at 80% of link volume, the 20% of link volume travellers above this have the fastest 15% of link km/travel time (at above around 70 km/hr). These are predominantly freeway based links, as can be seen also from their speed limit.
- The average modelled link speed is almost always below the proposed speed limit of a particular link. But speed limits are homogenously distributed across the network. This in itself suggests that lower speeds of the traffic are not an effect of speed limits.
- The shape of the curve does not resemble typical Lorenz curve, but it is an example of a typical Concentration curve. In the middle section is Lorenz curve aligned with the Line of Independence or equality and also crossing it further along. This means that these is comparable amount of volume of cars experiencing poor performance and also a big percentage of cars having a good performance in relation to others.
- Gini coefficient of the network as a whole is 0.05. It suggests of a high level of equity in the distribution of link speed values across the whole network.

Figure 3: Melbourne roads – Link Speed Concentration curve analysis, 2011 AM peak



4.2. Link speed Concentration curve analysis compared to VCR

A further analysis of the link speed measures in Figure 3 was undertaken to explore how this relates to VCR values on each link. This is illustrated in Figure 4 and 5. Traffic volume is shown on axis X and axis Y1 is reserved for performance measure: average link speed. Absolute values of VCR are shown on the Y2 axis.

VCR values (calculated in the traffic model) cluster as separate lines showing VCR for each separate set of link class. Link classes equate to road classification including number of lanes, speed limit categories and various other types from freeway to local roads.

Results show:

- There are clear differences in performance analyses of Concentration curve and VCR.
- Section A marks the poor performing links recorded only by Concentration curve.
- Section B shows poor performing links that were marked only by VCR.

One of the most interesting features of the analysis in Figure 4 is that while the lowest quintile of link-speed performance is closely associated with high VCR values this is not uniformly the case. There are a scattering of values with cumulative volume share of around 3-4% with VCR's below 0.8. Slow speed performance is not always caused by limited link capacity; lower speed limits and even slow traffic itself can act to reduce performance.

Figure 5 shows a map illustrating the spatial distribution of Zones A and B, poor link recorded only by Concentration curve and poor links recorded only by VCR. It shows lower performance (congested) links in mainly inner parts of Melbourne. These links were NOT highlighted as problematic in any VCR but are clearly a problem calling for attention by the Concentration curve analyses. The purple, poor performance links recorded only by VCR, are almost entirely outbound freeway sections.

Figure 4: Melbourne roads – Link Speed Concentration curve analysis compared with VCR, 2011 AM peak

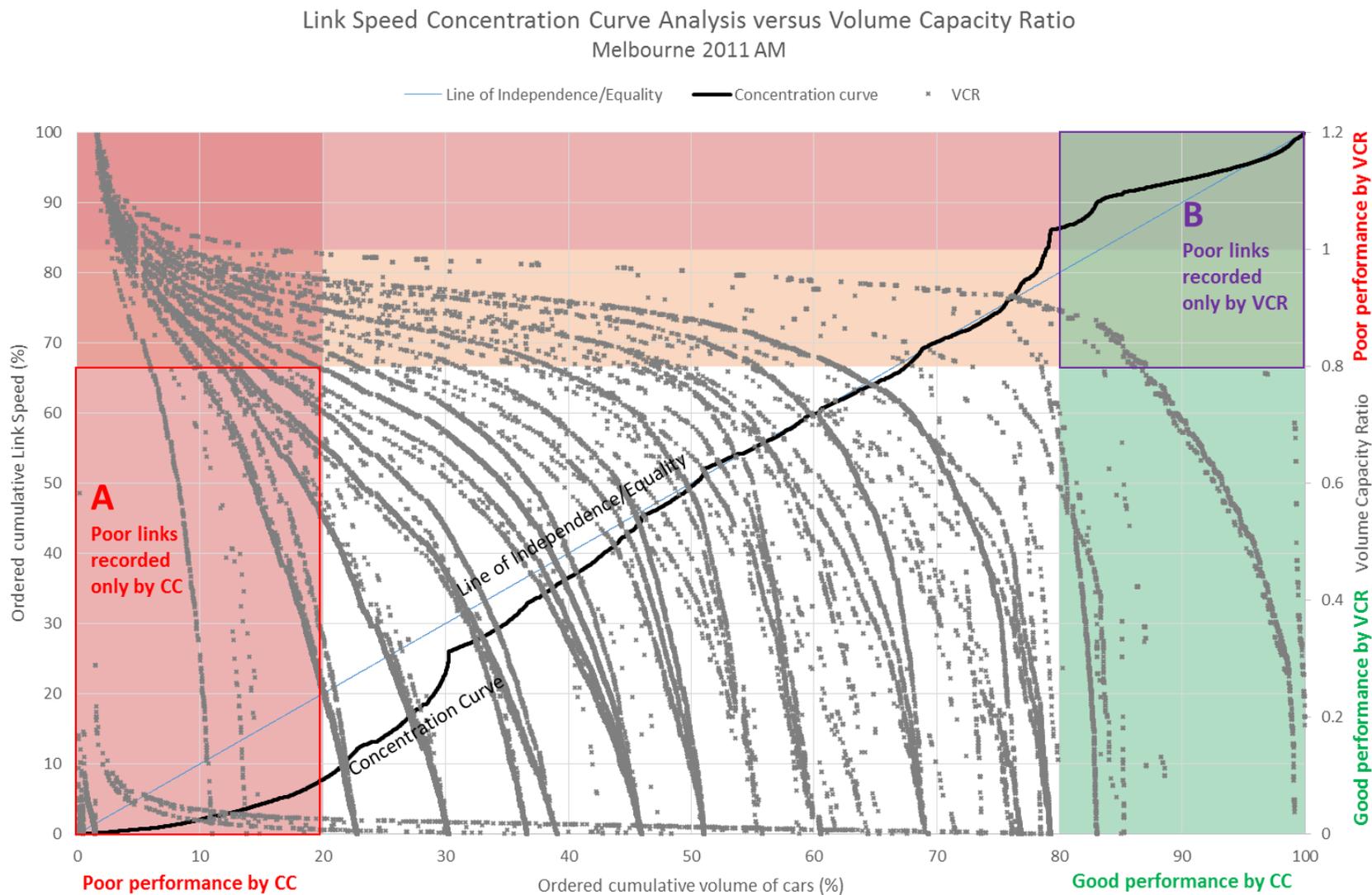
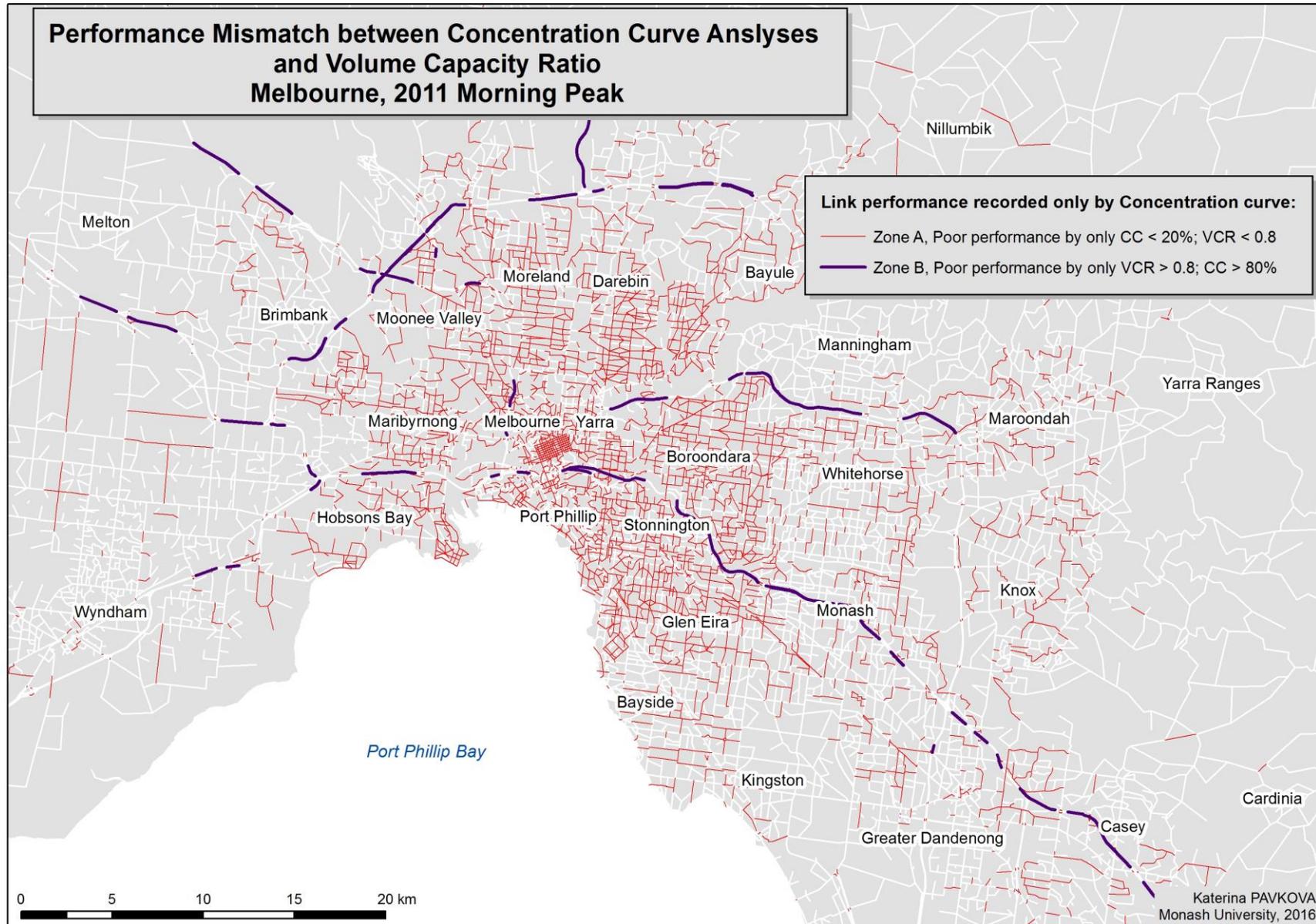


Figure 5: Map of Zone A and C, bottom and top performance



5. Conclusions

This paper has demonstrated a new approach to visualize the distribution of both traffic congestion and link speed performance as a function of link travel volume using Concentration curves. The proposed approach directly addresses limitations noted about VCR based approaches in that it more easily illustrates relative volume of travel across networks as well as relative travel time/speed performance as it impacts individual users. Speed is an important concern of drivers, but VCR omits it. Main benefits of Lorenz and Concentration curves are that they weight the speed by the number of cars affected by the congestion. No additional calculations are needed. In addition the relative performance of these factors can be more readily compared on a network wide basis and mapped together with VRC to identify and prioritise problem link locations.

This research is exploratory and as such represents only a first step in how this interesting tool might be applied and developed. A clear next step it to explore how alternative link performance and congestion metrics might be applied in the y axis of performance. Delay based measures or even measures of reliability might usefully be considered. Another valid development might be to consider alternative traffic volume based metrics for the X axis of the charts. The approach adopted in this paper only aggregated total volume by link but this avoids the problem of link length and event passenger or vehicle volume weighted by link length. An alternative unified measure of link volume might be volume per km, however link length itself might be of interest hence weighted link volume by distance might also be usefully explored.

The wider research program of which this paper is a part is also exploring how these approaches might be explored in understanding congestion between cities and also in exploring how congestion changes in cities over time. These analyses also aim to explore if the Gini Coefficient might be a simple metric to better understand these comparative studies such that complex patterns might be encapsulated in some simple to understand measures.

Overall this research has demonstrated some interesting new ways of exploring and better understanding the issue of traffic congestion and link performance on transport networks. This is a needed area for development to help us better addresses the growing problem of traffic congestion in cities.

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