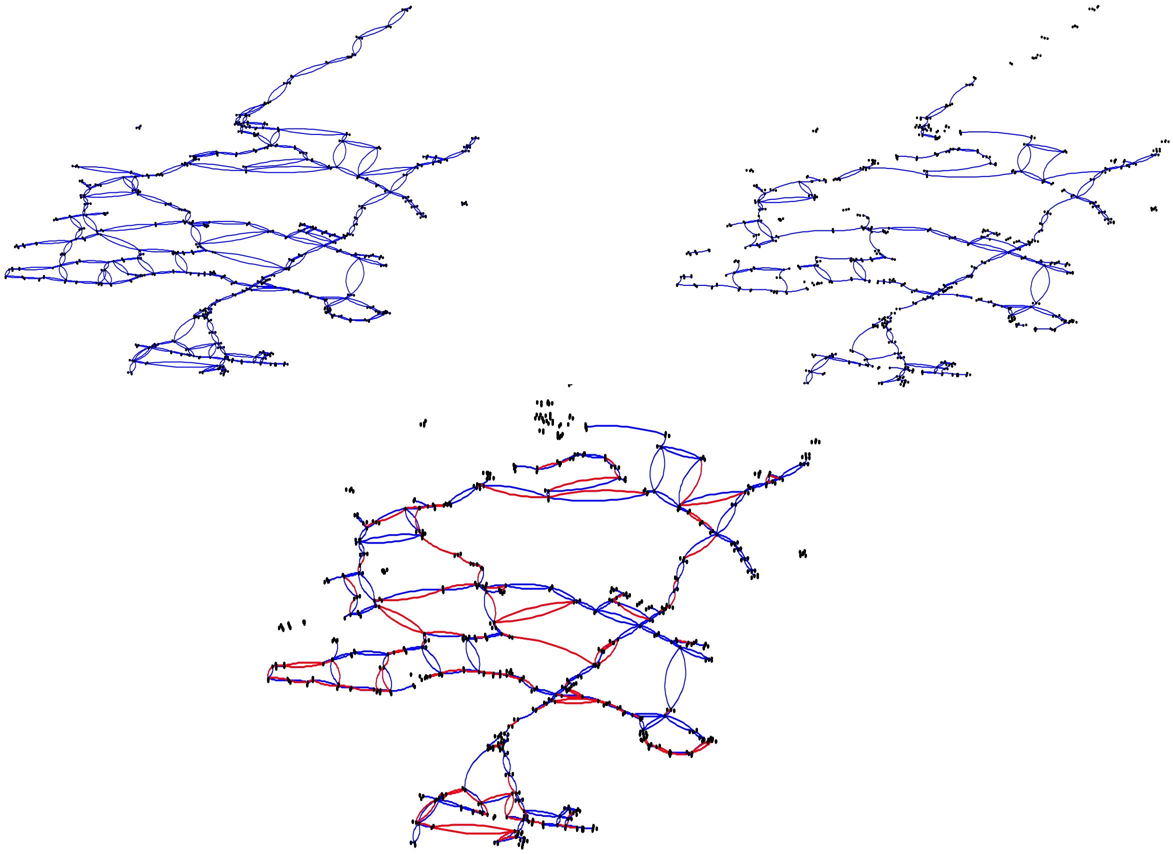

# Observing MFDs for Heterogeneous Traffic Networks with Stop-Line Loop Detector Data


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## Abstract

In urban transportation networks, the concept of Macroscopic Fundamental Diagram (MFD) receives attention since it provides a well-defined relation between space-mean flow, density and speed at a network level under some conditions. Recent researches show the existence of MFDs in homogeneous network and investigate the effects of traffic heterogeneity on shape of MFDs. In this paper we analyse large scale traffic data in heterogeneous network of Sydney and partition the network to observe MFDs in homogeneous parts. Firstly, different traffic states are extracted from fundamental diagrams of stop-line detectors which provide measurements of degree of saturation (DS). Based on information of different states and DS values, a transformation method is proposed to better estimate link densities. Secondly, a modified version of Normalize Cut (NCut) algorithm is proposed to enhance the performance of NCut by adding two additional steps for fine-tuning. The results shows that these two steps are significantly important (i) to make application of NCut feasible and accurate for networks in which information for some links is missing and, (ii) to further decrease the heterogeneity of different clusters. Finally, we could see that MFDs of different regions show different patterns that emphasize the importance of applying appropriate clustering algorithm. Hysteresis loops are also observed for the congested regions of the network. Based on the results, simple control strategies could be used to alleviate the congestion in the network of Sydney. This paper presents preliminary results and more details will be given in an extended version of the work.

## Keywords

macroscopic fundamental diagram – netwrok partitioning – stop-line detectors – degree of saturation

# 1. Introduction

There is a strong understanding and vast literature of congestion dynamics and spreading in one-dimensional traffic systems with a single mode of traffic, e.g. a highway section with cars. Besides traffic scientists, mathematicians and physicists have also contributed to the field of traffic flow. Because of the numerous publications, we refer the reader to [1] for an overview. Briefly speaking, the main modeling approaches can be classified as Car-following models (e.g.) [2], [3], cellular automata, e.g. [4]; gas-kinetic models e.g. [5]; first-order and higher order flow models such as [6], [7], [8]. Literature in network level dynamics and congestion propagation is limited.

With respect to network level, it was recently observed from empirical data in downtown Yokohama [9] that by spatially aggregating the highly scattered plots of flow vs. density from individual detectors (e.g. 1 min data), the scatter almost disappeared and a well-defined MFD exists between space-mean flow and density. The idea of an MFD with an optimum accumulation belongs to Godfrey [10]. The empirical verification of its existence with dynamic features is recent [9]. This work showed that the MFD shape is a property of the network infrastructure and control and not very sensitive to the demand. This is important for modeling purposes, as details in individual links are not needed to describe the congestion level of cities. It can also be utilized to introduce simple control strategies to improve mobility in homogeneous city centers building on the concept of an MFD, like in [11], [12]. The main logic of the strategies is that they try to decrease the inflow in regions with points in the decreased part of an MFD. Networks with an uneven and inconsistent distribution of congestion may exhibit traffic states that are much too scattered to line along an MFD. Recent findings from empirical and simulated data [13], [14] have identified the spatial distribution of vehicle density in the network as one of the key components that influence the shape of an MFD. These findings are of great importance because the concept of an MFD can be applied for heterogeneously loaded cities with multiple centers of congestion, if these cities can be partitioned in a small number of homogeneous clusters. The objectives of partitioning are to obtain (i) small variance of link densities within a cluster, which increases the network flow for the same average density and (ii) spatial compactness of each cluster which makes feasible the application of perimeter control strategies [15].

Despite these findings significant effort is required to further investigate and understand how different network topologies, control applications and distribution of congestion influences the shape and existence of MFD for heterogeneous networks. Definitely, real-life data can shed more light in this direction than computer simulations that try to approximate with a large number of parameters, individuals' complex behaviors. In this study we attempt to observe MFDs in heterogeneous network of Sydney by utilizing real traffic data by the Sydney Coordinative Adaptive Traffic System (SCATS) with high numbers of detectors. This data set provides direct measurements for Degree of Saturation (DS) and the volume during the green time (VOPT) using stop-line detectors. In order to obtain homogeneous regions with well-defined MFDs, static partitioning of network is performed based on the spatial features of congestions. Data from 2700 lane detectors for a network with about 1600 links are utilized (about 30% of the roads are monitored).

The main objectives and critical issues that we try to answer in this work are (1) challenges to deal with the stop-line detector data that do not provide a good proxy for the density of cars in the whole link and experience significant errors, (2) SCATS detectors provide direct measurements for the DS and the volume only during the green time (VOPT) and a transformation is needed, (4) information for some links is missing and the existing clustering algorithms have to be enhanced, and (5) the clustering algorithm might put more weight on connectivity of the network topology than the similarity of densities in networks that are not of grid structure.

The rest of the paper is organized as follows. Section 2 investigates fundamental diagrams of stop-line detectors and corresponding traffic states. Section 3 estimates a transformed value for DS as an approximation of density of the link. Section 4 presents clustering method and extends it to have a better performance in networks which have low connectivity in some parts and missing information in some links. Section 5 shows the MFDs of different regions, and finally, paper concludes in section 6.

## 2. Fundamental diagrams of stop-line detectors

In this section, we investigate fundamental diagram of stop-line detectors and define different traffic states corresponding to each part of the diagram. The location of a detector in a link (stop-line, mid-block or upstream) does not influence the measurement of flows (if the time interval is comparable to a traffic cycle), but significantly influences the density estimation. While the SCATS control logic utilizes stop-line detectors in a very efficient way using a combination of smart algorithms and engineering judgment, the DS value might underestimate the link density in some cases, given that this detector cannot really measure conditions in the whole link. DS is defined as a ratio of effectively utilized green time to the total available green time:

$$DS = \frac{\text{green time} - (\text{unoccupied time} - \text{unavoidable unoccupied time})}{\text{green time}} \quad (1)$$

$$= \frac{g + gap - [t - VOL * (\frac{3600}{MF} - KP)]}{g + gap}$$

where $t$ denotes unoccupied time measured by detector, $KP$ is the time detector is occupied by each vehicle when moving with free flow speed, $MF$is maximum flow, $VOL$ is number of vehicles exit the intersection during green time, and gap is amount of time allocated in the last cycle but was unused. Unavoidable unoccupied denotes the time in which detector is unoccupied when vehicles discharge at capacity with free flow speed.

By observing different VOPT vs. DS graphs for different detectors we identify consistent patterns that not significantly vary from one detector to another (Fig.1). Details about five different traffic stats in Fig. 1 are described in table 1 in terms of different movements (Arrival (A)-Capacity (C)-Decreasing Capacity (DC), Jam (J)). More details will be included in the journal version.

Figure 1 Stop-line fundamental diagrams of all detectors (VOPT units: vehicles/sec/lane, DS units: dimensionless)

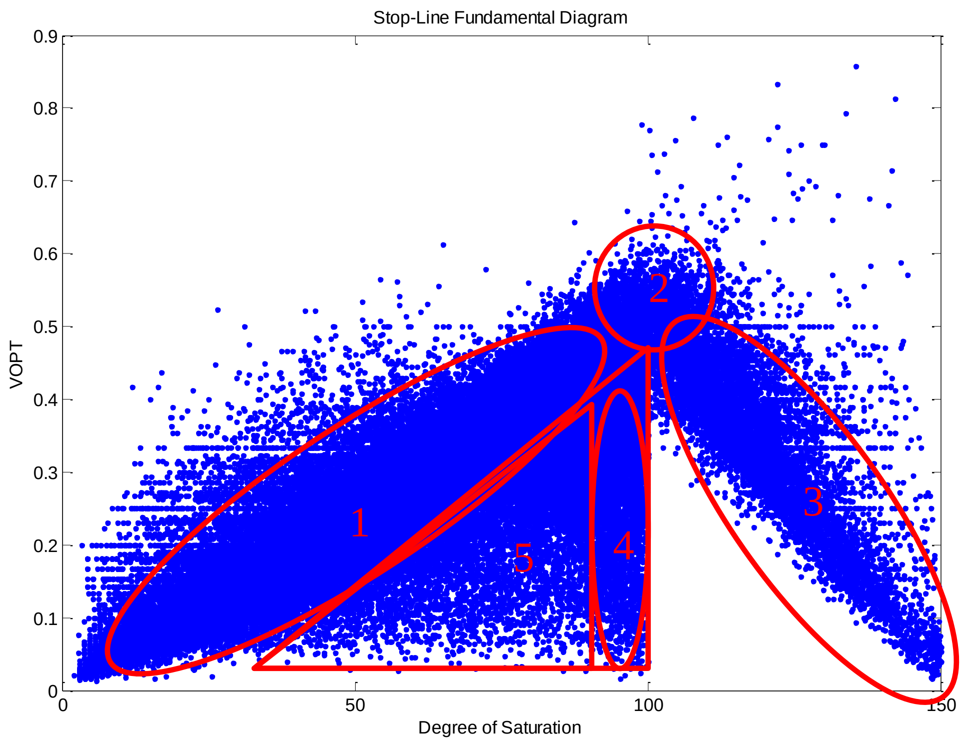


Table 1 Different states in stop-line fundamental diagram

| | | |
|---|---|---|
| 1 | DS << 100<br>flow << saturation flow | There is no spill back and queue discharges and we have both A and C states. In this case, DS is a good proxy for the link density as conditions are under-saturated. (C+A) |
| 2 | DS ≅ 100 , g= $vol/(\frac{3600}{MF})$<br>flow ≅ saturation flow | There is no spill back. No conclusion about vehicles in the queue but at least equal to the volume. Stop-line detector gives a lower bound in the estimation of density for the whole link. So in this case, queue is at least enough so that all vehicles discharge at capacity rate. (C) |
| 3 | DS >> 100<br>flow << saturation flow | There is spill back in the following link and green time is low for discharging queue. Also in this case vehicles moved with speed less than free flow speed. So queue is discharging at flow lower than saturation flow. This decreasing capacity makes DS values more than 100 (J+DC+C) |
| 4 | DS ≅ 100 , g > $vol/(\frac{3600}{MF})$<br>flow << saturation flow | There is a spill back in the following link. Spill-back in this link means that queue length in the downstream link is equal to the length of the link for a fraction of the green phase of the reference link. Thus, the density of the downstream link is probably underestimated by its loop detector. After vehicles start moving, they can discharge with maximum capacity (Saturation Flow). (J+C) |
| 5 | DS ≪ 100 , g > $vol/(\frac{3600}{MF})$<br>flow << saturation flow | There is a spill back in the following link but there are just few vehicles in the queue. Queue discharges before end of green time and in the rest of the green time vehicles exit at lower flow. Case 5 also can occur when conflicting movements are served in the same phase. (J+C+A) |

## 3. New proxy for density

Due to SCATS formulation, in most cases related to congestion DS is not a perfect proxy for density, which is underestimated. A new methodology is proposed to estimate a better proxy $DS_{new}$. In order to estimate $DS_{new}$, it is important to first understand why points in regions 4 and 5 have VOPT less than points in regions 1 and 2, while they have the same DS values. In the second step, a density estimator metric is defined, which can differentiate between these points, which have the same DS values. To achieve this we need some information about different states Jam (J), Capacity (C), Decreased Capacity (DC), arrival (A) and duration of each of them. This information could be estimated using the DS formula and some fundamental knowledge of traffic flow theory. The third step is to define which points need to be changed in the VOPT-DS stop-line fundamental diagram. Mainly we need to identify the size of the triangle for region 5. The fourth and final step is to find points with the same characteristics and try to select the most appropriate value for $DS_{new}$.

## 3.1 First step

Note that in Fig. 1 some points have the same value of DS but with a wide range in the values of VOPT (Regions 2 & 4 – Regions 1 & 5). The similarity between these points is that when vehicles start moving the queue discharges at the same rate, i.e. in regions 2 & 4, vehicles discharge at capacity and for regions 1 & 5, exit flow is lower than capacity (time headway between two successive vehicles is more). But, the significant difference among these points is the fraction of green time in which vehicles stops due to downstream spill-back. For instance, the main difference between points in region 2 and 4 is that vehicles in region 2 discharge at capacity rate during the whole green time, while in region 4 vehicles have to stop (or move slowly) part of green times due to spill-backs. In this case, in the DS formula (equation 1), unoccupied time (t) measured by the detector, is equal to the unavoidable unoccupied time, since all the vehicles in the queue discharge at capacity rate. Thus, it is straightforward that if the time of spill-back is added as occupied time in the estimation, points in region 4 & 5 have more occupied times compared to points in region 2 & 1.

## 3.2 Second step – Estimation of spill-back duration

The idea for $DS_{new}$ estimation is to consider the effect of spill-back time and add this to the occupied time. We first estimate the spill-back time for points in region 4 and 5 and then enter these values in the equation 2 to find percentage of occupied time.

$$\text{Percentage of occupied time} = \frac{t_{occ}}{g} = \frac{g-t}{g} = \frac{t_s + VOL * KP}{g} \quad (2)$$

Where $t_s$ is spill-back time, $g$ is the green time, $t$ is the unoccupied green time. Note that time t is not directly reported in the SCATS data, but when conditions are highly congested the value of gap is expected to be close to zero, which allows an approximate estimation of t.

## 3.3 Third step – Identification of points in regions 4 & 5

In DS formula (equation 1), there is a parameter called gap, which is not known. In points with different DS and green time, the effect of gap values is different. In fact when DS is calculated without gap, the value is smaller compared to the case DS is calculated when gap time is not equal to zero. As it is not correct to assume that value of gap is zero during all cases, we need to take it in to consideration and properly define regions 4 and 5 in which points need to be moved. Thus, we choose a conservative approach and we only intervene in the DS value of points that even if a large value of gap is assumed, the position of these points cannot be explained without considering the effect of spillback. In points with DS greater than 100, spill-backs and stop-and-go effects are guaranteed and values of gap are small.

### 3.4 Fourth step

Points in region 3 show the most congested cases with spill-backs and stop-and-go traffic, where queue discharges at lower rate. Once compared to regions 4 and 5, the main difference of region 3 is that because of strong stop-and-go phenomena and multiple spillbacks, vehicles cannot discharge at the maximum capacity and move with free flow speed. A smaller value of free flow speed (which also results in smaller value of capacity) is utilized in this case. By estimating spill-back time and moving speed in which queue discharges, we can estimate percentage of occupied time in equation (2) by considering changes in KP values. Details about this estimation will be included in journal version. We can find different points with different spill-back times and different VOPTs, which have the same percentage of occupied time. To this end, we cannot assume that DS is always equal to the rightest point in the stop-line fundamental diagram for the same VOPT because we would overestimate link density. So we choose the case in which we model capacity and spill-backs in region 4 with DC (Decreasing Capacity). In fact effect of spill back time and capacity rate are merged into DC.

## 4. Clustering method

There are several criteria that the clustering algorithms to be developed need to satisfy: (1) small variance of density (or DS) values within each cluster, which is meant to guarantee a well-defined MFD; (2) a small number of clusters, which can help to design simple control strategies without a need for detailed origin destination tables and route choice information; and (3) spatially near compact shapes of clusters, which can ease the design and deployment of effective controls.

In this work a partitioning mechanism, which consists of three consecutive algorithms, is used to minimize the variance of the link densities while maintaining the spatial compactness. Firstly, transportation network is over segmented into several homogeneous regions. This step is achieved by using NCut algorithm which can efficiently extract the major components from the network and guarantee spatially compact shapes. In this step, more than desired number of clusters may be produced by over segmenting a homogeneous region into several parts. Secondly, a pair of most similar clusters is merged based on the mean values of their DS until a desired number of clusters is reached. This step fixes the problem of NCut cutting large uniform regions. After these two steps, we obtain a rough sketch of the network partitioned into clusters with different congestion levels. At the 3rd step, a boundary adjustment is applied to further improve the homogeneity of the regions. While steps 1 and 2 are similar to Ji and Geroliminis (2012), an extension of the algorithm is necessary to capture missing data and non-grid network structures. Our results highlight that NCut algorithm tends to give more weight in the topology of the network and it might influence the shape of the clusters and decrease their homogeneity.

The NCut algorithm considers the adjacency of links and requires a connected graph. The whole network of Sydney looks connected (Fig 2a). Since there is plenty of missing data, different disjoint sub-graphs of links could be found in the network (Fig 2b). This is a significant problem for NCut method thus it is necessary to develop an algorithm to infer/estimate the values of variables for some links of the network to create an interconnected graph. We should mention that if one link is added, the value of this link should be estimated by the values of links that are close to that link. In summary the objective is to find some links with the following properties:

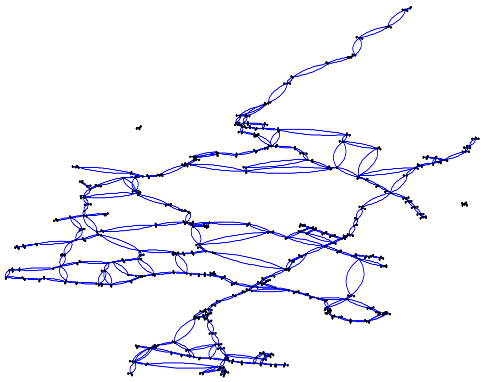
- The addition of data for these links will transfer the directed sub-graphs to a connected graph
- Value of these links could be estimated using links which have similar values (Links which are adjacent to this link)

In order to identify these links, we first add all adjacent links (which have distance equal to one link) to existing links in Fig 2b (links which have data). Not all links, which are added by this method, are useful. For instance, ending links from which cars exit the network or starting node from which they enter the network are not useful in making a graph connected. So we delete links which are at the end or start point which do not help connectivity at all. By applying this algorithm, we obtain Fig 2c in which blue links refer to the links which have data and red links refer to the links which do not have data and their values should be estimated.

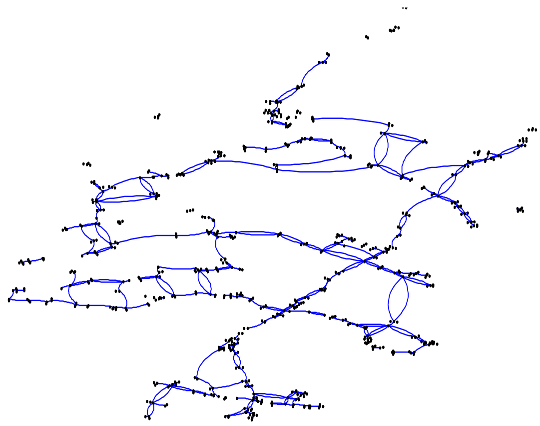
Preliminary result of clustering of the network using N-Cut algorithm with 7 clusters and results after merging with 4 clusters are presented in Fig 3 a & b.

Figure 2 a. Whole network of Sydney, b. Links which have detector data, c. Connected graph with links which have data (blue) and links with estimated data (red)

a)



b)



c)

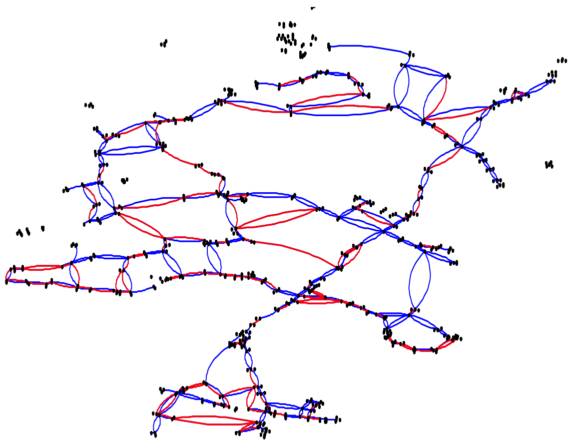
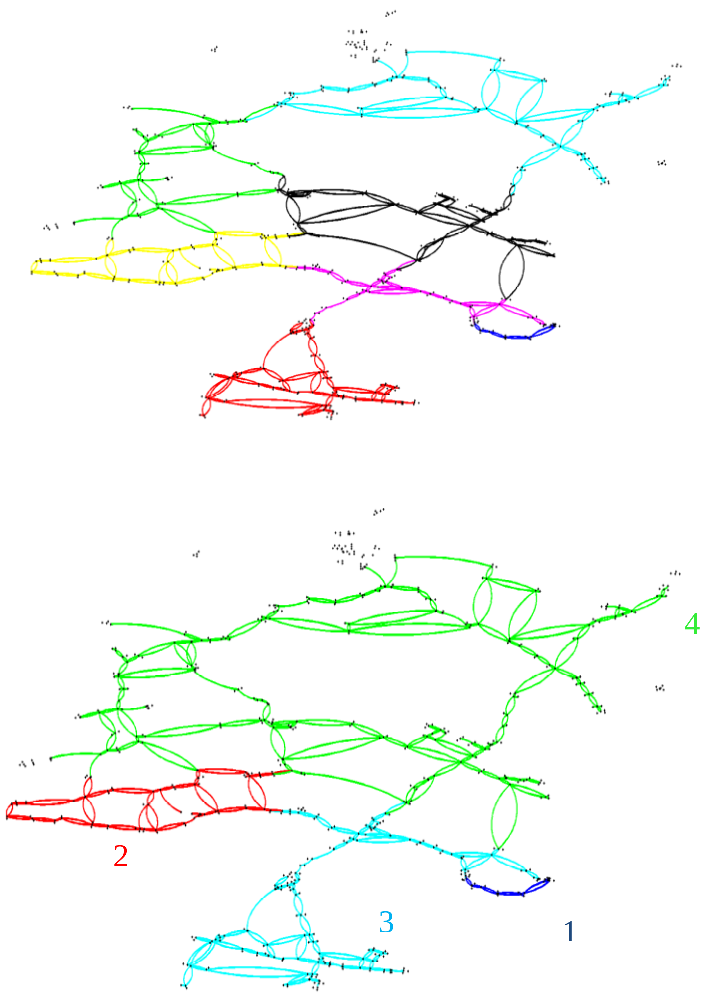


Figure 3 a. Clustering results using NCut algorithm (7 clusters), b. Clustering results after merging (4 clusters)

a)

b)




Sydney traffic network is not a perfect grid network and some parts are more redundant than others. (Redundant is a network that to travel from one origin to a destination there are many possible route choices. As mentioned before, the NCut clustering algorithm might not have an ideal performance when some parts of the network are not well connected. Some additional fine-tuning is performed with an objective to further improve the spatial homogeneity of each cluster (region) without violating the objective of connectivity. This tuning includes:

- Finding sub-graphs that might have adding too many links with no data or having low degree of connectivity to the rest of network. For example, by doing this step, cluster #1 has only 19 links with data and it might be added to an adjacent cluster.

- Finding congested links that include major roads in each cluster and are well connected. By finding these interconnected components of congestion (ICC), the boundary of each cluster, in can be defined and perimeter/boundary control strategies can be implemented in the future. All the other links could be considered as periphery. In this step, we need to include in the ICC some uncongested links which are major roads and facilitate to keep the connectivity.

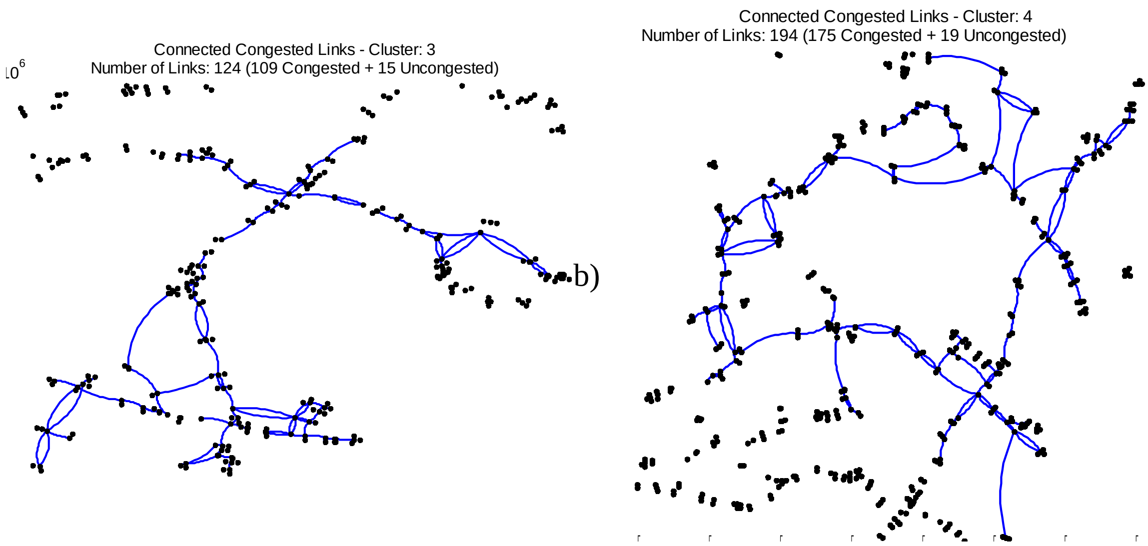
Results of clustering after applying fine tuning with average value of $DS_{new}$ are presented in table 2. Connected congested parts of cluster 3 & 4 are presented in Fig. 4 a & b.

Table 2 Average values of $DS_{new}$ for five different clusters after fine tuning

| Cluster (2) | Uncongested part of Cluster (3) + Cluster (1) | Connected Congested part of Cluster (3) | Uncongested part of cluster (4) | Connected congested part of cluster (4) |
|---|---|---|---|---|
| 87.8995 | 59.59442 | 107.953 | 58.0574 | 107.5122 |

Figure 4 Connected congested links of cluster 3 & 4

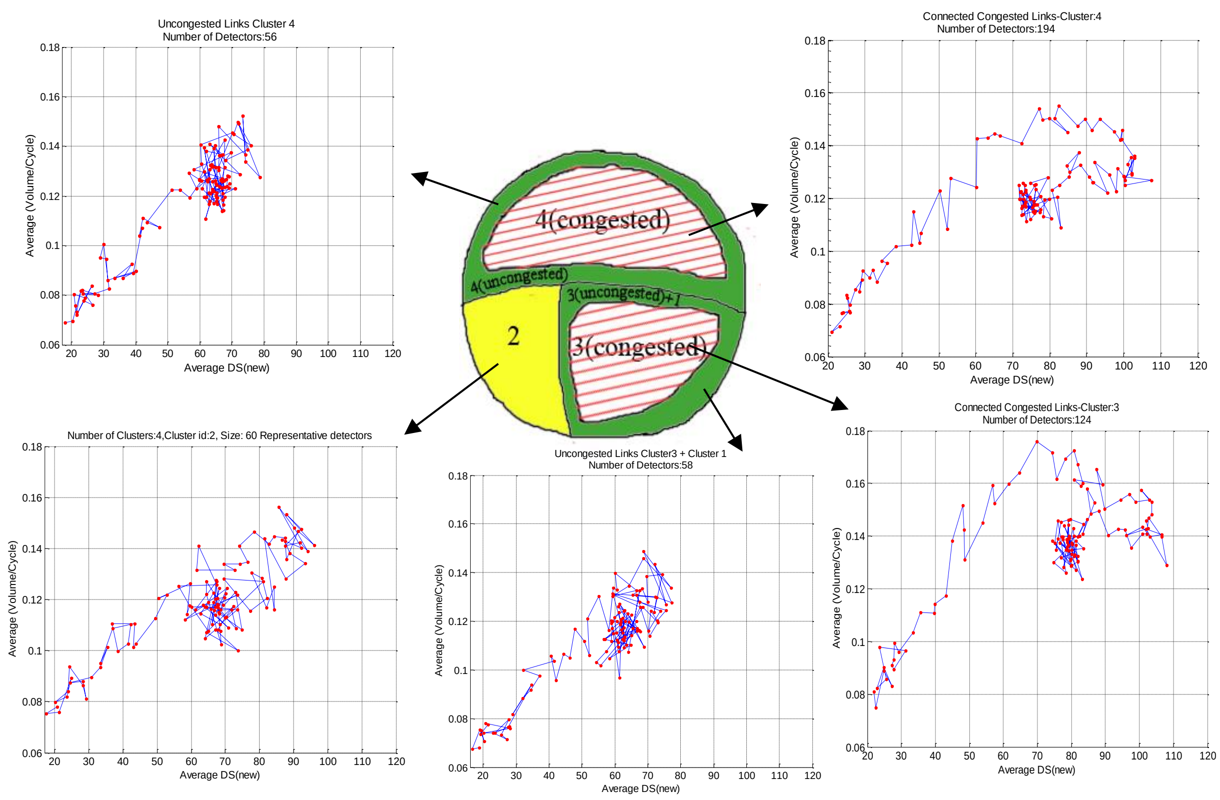
a) b)



# 5. MFD results of different regions

After partitioning heterogeneous network into homogeneous parts, MFDs are plotted for different parts in Fig. 5. It could be obviously seen that two regions are worked in decreasing part of MFD that need more attention in terms of control strategies to avoid/postpone traffic congestion.

Figure 5 Study site and final clustering result with MFDs




# 6. Conclusion and Future Work

In this paper, different traffic states were extracted from stop-line detectors data in Sydney and we proposed a methodology to estimate link densities. In addition, we observed that NCut algorithm might not perform well for the networks which are not perfect grid. Based on this observation, we added intermediate steps to reduce the effect of connectivity in the network on partitioning results. The results show that MFDs of homogeneous regions in this network experience different patterns. This shows the great important effect of clustering heterogeneous networks, that later will be integrated in real time active traffic management schemes. Recent work in utilizing MFDs for control purposes can be found in [16], [17]. There is a hysteresis effect in MFDs that could be the reason of SCATS control logic. We believe that by having phase information, the effect of this hysteresis could be explained more precisely and the explanation will be included in a journal version of this work.

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