Establishment & Assessment of the Macroscopic Fundamental Diagrams for the City of Durban Freeway Network Using Empirical Data

Name of student:
Siphesihle Henry Mthembu

Student number:
SPHMTH001

Supervisor:
Professor Mark Zuidgeest

Programme:
Minor Dissertation – CV5017Z

Department of Civil Engineering
Faculty of Engineering and the Built Environment

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DECLARATION

I **Siphesihle Mthembu** hereby declare that the presented work was done and completed by myself that none of the submitted work that has not been done by myself was proclaimed as my own without acknowledging the author. I fully understand stealing someone's work to act as if it was your work, is misconduct. This behavior is termed plagiarism. When one performs such an act, they shall be ready to face the consequences thereof. I further declared that any source found to be relevant and used on this paper was referenced accordingly, and credit was given to the presiding author.

The research was partially submitted under the faculty of Engineering and the Built Environment- Civil Engineering department for fulfillment of the academic requirement for Master of Engineering specialising in Transport Studies.

Signed by candidate

Name and Surname: Siphesihle Mthembu Signature:……………………………………….
Signed at Pietermaritzburg, South Africa Date: 20 September 2021

ACKNOWLEDGEMENTS

A story of a man who was simply afforded an opportunity.
God is Great!

- This research would have not been possible without the assistance from Professor Mark Zuidgeest, his support and guidance are wholeheartedly acknowledged.
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- I am grateful for the role played by my organization SANRAL for allowing pursuing this degree. In the circumstances where I felt like giving up, I always remembered 'I am the chosen one'. This has kept me going.
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Finally, I would like to thank myself for the character of resilience I have shown in making this study a success, through rain and storm I conquered.
The journey continues….

TERMS OF REFERENCE

Under the supervision of Professor Mark Zuidgeest of the University of Cape Town, this study was initiated, and his instructions indicated clearly that this study shall:

- Establish Macroscopic Fundamental Diagram for the City of Durban Freeway Network Using Empirical Data.
- Review past and recent literature on the Macroscopic Fundamental Diagram.
- Generate and Assess the SANRAL freeway network Data, to establish the MFD.
- Assess the established MFD as the property of the urban scale freeway Network.
- Provide input on the generated MFD and traffic control measures.
- Provide findings, issue recommendations, and draw a conclusion on the study.
- Identify gaps on this topic for future research

The final submission date for the final evaluation of this thesis indicates the 20th of September 2021.

ABSTRACT

The history of traffic flow studies dates to the years between the 1960s and 1970s. This paper reviews the history of traffic flow studies in the context of Macroscopic Fundamental Diagrams (MFD) to date. The recent findings have shown that understanding the Macroscopic Fundamental Diagrams (MFD) in cities can bring success in managing congestions. This study aimed to establish the Macroscopic Fundamental Diagrams (MFD) for the City of Durban Freeway network. Motivated the study was a failure seen in various transportation systems after the 2010 FIFA world cup in South African cities. This failure was associated with the adoption of the transportation system from first-world countries. The South African cities are not densified when compared to the first world countries' cities, of course, due to spatial urban planning and segregation of the past. The key lesson was that SA transportation system~~s~~ problems are unique; solutions should be attributed to the existing travel demand conditions. This birthed the idea that the performance of a traffic system should uniquely serve the specific travel demands. The core aim of this study was to establish the MFD for the freeway network in the City of Durban, South Africa. Two major freeway corridors were evaluated, i,e. the National route 2 and 3. The study used loop detector data extracted from a total of 88 loop detector stations. The loop detector stations were dispersed 100-500 m apart over the network. The data was recorded in September 2019. The collected data was analysed in five minutes intervals. When the MFD was established on the network, aggregated detector loops produced a well-defined MFD on the 2nd,3rd,16th, and the 23rd of September, whereas, on a separate day (30th of September), a scattered MFD forming a hysteresis loop was observed. The formation of the hysteresis was associated with the lack of alternative routes for drivers to avoid congestions in the network. These observations are discussed later in this paper. The study was a success as it did reveal that the MFD was an attribute of the City of Durban freeway network. The established MFD showed that the freeway network operates between the unsaturated and saturated state. This MFD does not reach the saturated flow. The highest recorded density was found at 10.11 veh/km while the highest recorded flow was found at 733.28 veh/hr. The network operates at an average speed of v_{av}= 79.84 km/hr. The estimated average density for the network to reach the gridlocked state was calculated to be 75veh/km.

Table of Contents

ACRONYMS AND TECHNICAL TERMS

Acronyms	**Full word**
CBD	Central Business District
EB	East Bound
ITIS	Integrated Transport Information System
LOS	Level of Service
M	Metropolitan route
MFD	Macroscopic Fundamental Diagram
N	National route
OD	Origin/Destination
R	Regional route
SANRAL	South African National Road Agency Limited

Technical Terms	**Description**
Density(p)	State of traffic condition on a singular lane, presented by the number of vehicular occupying a space (km distance) per lane. . (Measured in veh/km)
Flow(q)	The number of vehicles passing a point in a time interval. (Measured in veh/hr)
Level of Service	Tool of measure used to classify the performance of traffic state and is ranked from A to F- where A represents good performance and F represents poor performance.
Integrated Transport Information System	Modern-day technological systems are often used to monitor, control, and keep records of the traffic data in the region
Macroscopic Fundamental Diagram	An assessment tool to indicate traffic state, relate density in space and traffic flow, denoted in three stages-saturated, unsaturated, and oversaturated state.
Speed(v)	Vehicular measure, calculated by distance over time.
Traffic signal	Often referred to as robots in SA, a control system that controls traffic movement at an intersection.

1. INTRODUCTION

The past two decades have seen a lot of investments into transportation infrastructure and systems of larger South African cities at a scale that is unprecedented in the democratic era post the year 1994. However, the urban structure of South African cities has proven to be a threat to the financial sustainability of these systems. The major cities are experiencing a rise in congestion levels over the past years due to the continual rise in automobile dominance. This calls for a means to evaluate the network systems not only at the microscopic level but also at the macroscopic level. It is possible to characterize traffic flow in an urban street network using relatively simple macroscopic models relating the traffic variables which are: speed, flow, and concentration (Mahmassani, et al., 1987). These traffic variables do not hold only at highways and arterials at a microscopic scale however, they also present themselves at the network level (macroscopic scale), despite the complex interaction and activities occurring on the urban street.

Although the variations in the traffic demand have a prominent impact on the corresponding total travel time. The traffic variables are obtainable despite the fluctuation associated with the origin-destination demand. This solidifies the idea that with or without the data on the origin-destination demands the MFD is a prevailing property of the urban road network (Hu, et al., 2020). The MFD-based approach can bring an impact on solving the network design problems (i.e., Congestions, system bottlenecks, signal timings/synchronizations). This study seeks to develop the MFD in the South African city. MFD can play a role in mitigating and managing congestion on roads more special in peak periods.

It is further argued that the cities can achieve better use of the existing infrastructure to the full efficiency and at the optimal level, also congestion can be successfully managed without having to stress on improving the existing network infrastructure. The MFD analysis becomes a very instrumental tool to understanding these congestion fluctuations.

According to Daganzo (2007), developing countries face similar problems. The drivers in Bangkok spend an equivalent of 44 days a year in a gridlock (Dangazo, 2007). A driver in the City of Durban would on average spend approximately 71 hours equivalent to 2 days a year stuck in gridlock, although this figure has declined due to the lockdown restrictions (Tom Tom, 2021). However, this figure will continue to grow as the automobile preference in the cities continues to take its toll. This will soon require the development of control strategies to relieve congestion and increase mobility. MFD can be used as a guide by transportation policy makers to improve mobility.

Geroliminis and Daganzo(2007) indicated that an MFD demonstrates a robust demand-insensitive relationship between network vehicle density and space mean flow, which can also be expressed as the relationship between vehicle accumulations and network outflow (Dangazo, 2007). Thus, MFD can be a useful attribute of the network infrastructure and can be used as a control tool to system operations (signal controls) and improvement (lane configuration) of the network (Hu, et al., 2020). Shown in figure 1.1 below is the normal /demonstrative shape of the MFD showing the relationship between density and flow.

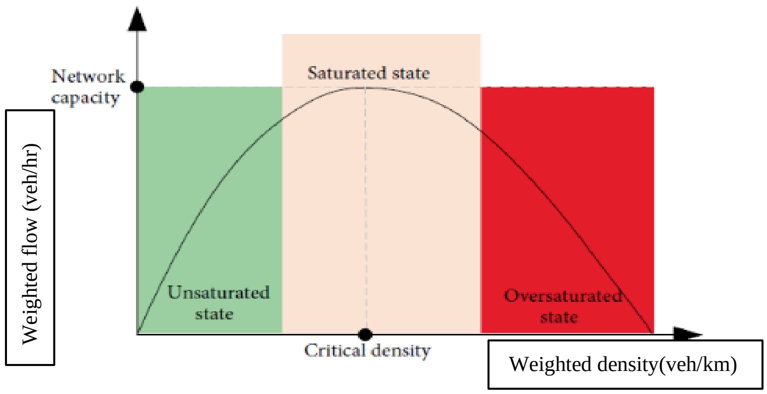

Figure 1.1: A typical shape of the MFD illustrating the relationship between density and flow.

Source: (Hu, et al., 2020)

Figure 1.1 shows a unimodal relationship between weighted average flow and density that represent three states of the MFD, namely: unsaturated, saturated, and oversaturated traffic states, respectively. Geroliminis and Daganzo(2008) argued there is a similar relationship between outflow and accumulation as the ratio of network flow and outflow is constant. In the case of the unsaturated state, there is a gradual increase in the network flow as more vehicles join the network. As more vehicles join the network, the density (vehicles occupying the mean space) increases. This increase continues until the network capacity is reached; at a critical density, this case occurs in the saturated state. Beyond the critical density, as more vehicles join the network, the network flow starts to decrease until the condition termed 'gridlock' occurs on the network. This occurs in the oversaturated state (Hu, et al., 2020). By understanding all the states involved in the MFD assessment will form the basis of the critical element to the reader in the development of this study.

1.1. Research Question

There have been little to no studies conducted to prove that the Macroscopic fundamental diagram holds in cities established in South Africa. The development of this paper seeks to respond to the following question:

- What has been the trend of traffic theory from past studies to date?
- Can these ancient studies in traffic theory be linked to Macroscopic Fundamental Diagrams to this day and age?
- What are the uses of the Macroscopic fundamental diagram?
- Does the Macroscopic fundamental diagram exist in the City of Durban Freeway network?
- What state of the Macroscopic fundamental diagram does the free network operate on, is it unsaturated, saturated, or oversaturated?
- What traffic state (homogeneous or heterogeneous) will the established MFD be associated with and does hysteresis loops forms part of the established MFD?
- What are the operational density, flow, and velocity of the network?
- What can be learned from this MFD that can be applied to assist the decision-makers (government or private sectors) to plan and make informed decisions when amending the transportation policies?
- Lastly, what are the gaps in this study that can be used for future studies?

1.2 Aims and Objectives

1.2.1 Aims

The purpose of this study was to establish & Assess the Macroscopic Fundamental Diagrams for the City of Durban Freeway Network using Empirical Data.

1.2.2 Objectives

1.2.2.1 To collect traffic data generated from the loop detectors and spanning for at least a month on the Freeway network in the City of Durban.

1.2.2.2 Review the past and recent best practices on the traffic theory and Microscopic Fundamental Diagram.

1.2.2.3 Determine the flow, density, and speed of the existing freeway network.

1.2.2.4 Establish the MFD for the city of Durban freeway network.

1.2.2.5 Explore the impact of the topological features on MFD.

1.2.2.6 Perform the analyses of the established MFD as a tool for freeway networks to improve accessibility and mobility (number and types of the existing intersection, signal timing).

1.2.2.7 Explore the relationship between the freeway network and hysteresis.

1.2.2.8 Discover and explain the impact of traffic state (homogeneity or heterogeneity) on MFD shape.

1.2.2.9 Discuss, conclude, and provide recommendations for this study.

1.3 Methodology summary

This research paper follows three stages that are data collection, analysis, and calculations. It later provides a conclusion on the findings and issues recommendation. The data was collected from 88 loop detector stations. These stations are located 100-200 m apart on the N2 and N3 corridors. All the fault stations were discarded for the outcome accuracy. The study was conducted in the eThekwini region freeway network. The extracted data were collected for every five minutes interval. The focus was on the data from September 2019. The decision to utilize data from September month was made because this was the only available and adequate data to perform the analysis.

The success of this paper was guided by the following sources which were found relatable to what the study sought to achieve:

i Desk research

ii SANRAL ITIS system

iii eThekwini Metropolitan Traffic Department.

iv UCT Library sources

v Google Scholar

The information extracted from the sources stated above was then utilized to calculate speed, density, and flow on the existing network to develop the MFD model on Microsoft excel. The MFD was then assessed particularly its saturation state, the shape, and highest flow and density obtained.

1.4 Scope of work and limitations

This study identified the loop detectors station as its main source of data collection. 88 loop detectors were utilized in the process of data collection. For the accuracy of the result, all the fault stations were discarded. The obtained data was provided by Mikros Traffic Monitoring (Pty) Ltd. These stations are administered on behalf of SANRAL. The study was performed in the City of Durban freeway network formerly known as eThekwini region. The area of the study was estimated to be 2.30 km^2. The key corridors being assessed were the national routes 2 and 3. The data extracted from the stations was spanning for one month (September 2019). Traffic counts were detected every 5- minutes interval. No discretion was followed in choosing which month of the year is deemed suitable to perform the study; however, this was based on the availability of the data at the time. Because this study was conducted during the pandemic in the country, data collected during this period(lockdown) was deemed inapplicable to the context of this study because the outcome would be biased and inaccurate. Data collected was used to calculate flow, velocity, and density. This essentially produced the MFD. The established MFD was compared for all Monday in September 2019 month, this allowed to compare apples and apples.

Because these stations operate under open climate conditions, few stations were identified with missing values. This was associated with bad weather. In some instances, values were recorded and later found missing. This was assumed to be due to vandalism. The loop detectors provide a spot density, this may conflict with the results when ideal the focus is on the speed variations along with the evaluated links. It is imperative to note the study was mainly focusing on the freeway corridors. Ideally, one would have been keen to assess the nearby arterial links that join the freeway network to find out what impact do they have on the MFD result.

1.5 Thesis structure

The first chapter in this paper dwells on the aim and objectives of this paper which was to establish & Assess the Macroscopic Fundamental Diagrams for the City of Durban Freeway networks using Empirical Data. This was then followed by the second chapter which looked at the historical findings and the existing literature to date on MFD. Chapter three provides an overview of the methodological approach that was adopted to achieve the objective of this paper. Chapter four discusses the obtained results and provides a summary of the findings. Chapters five conclude the outcomes of this study. Lastly, chapter 6 provides recommendations and provide gaps to be addressed in future research.

2. LITERATURE REVIEW

This literature review seeks to explore and analyse the historic studies on the traffic theory. The review demonstrates how, over the years, relating (speed, flow, and concentration) traffic theories had been useful in managing congestions in the cities. It further compares the different methodological approaches applied using the field data. Guided by the past findings, it outlines the shortcomings of these empirical studies. The development of this literature later reviews some of the best practices of the MFD to this day and age. Therefore, this literature review will consist of two parts, that is, part A and B. Part A speaks to the past practices relating traffic theories to manage congestion in the cities. As the literature progresses, it involves part B that focuses on the recent best practices of the MFD and their applicability and further explains the phenomenon of hysteresis loops and Bifurcation on MFD. The review also discusses the critiques on applications of MFD as a traditional tool for traffic assessment. Ultimately the review concludes that the natural shape of MFD presents itself in all the studies conducted in this paper and a correlation on speed, flow and concentration does exist (Wardrop & Whitehead, 1952).

PART A- THE HISTORY OF TRAFFIC THEORY STUDIES AND CONGESTION MANAGEMENT

2.1 Background

The first impactful studies on the traffic theory date back to the works (Wardrop & Whitehead, 1952). They introduced the mathematical and statistical aspects of understanding the behavior of traffic on a road. One of the key findings showed that vehicle distribution in space on the road can be linked with time. This form of distribution results in a variation of speed. In simpler terms, the increase in the number of vehicles (flow) on the road leads to a decrease in vehicle speed. He then introduced the term 'capacity' which he defined as the "flow which produces the minimum acceptable average journey speed". He argued the distribution of vehicles along the width of the road should be considered when studying the speed. This can be related by applying a theoretical traffic model.

His arguments were supported by the works of Adam(1936) where he expresses traffic as a random distribution in space at a specific point produced by time, t_{i-2}, t_{i-l}, t_o, t_1, t_2. Assuming the vehicles move as time t at a point 0 thereof the distance from point O would be given by:

$$D = V(t) \qquad \text{Equation 2.1}$$

From the above iteration then the distribution of speed in time with flow q_1, q_2, . . . q_c and speeds v_1, v_2, . . . v_c collectively can be expressed by:

$$Q = q_1 + q_2 + \cdots + q_c \qquad \text{Equation 2.2}$$

Expressing equation 2.2 above then:

$$Q = \sum_{i=1}^{c} \quad q_1 \qquad \text{Equation 2.3}$$

Then to $$f = \frac{q_i}{Q}$$ Equation 2.4

He then established the frequency in time of which the speed V_i at the dedicated time.

Then $$f = \sum_{i=1}^{c} \quad fi = 1$$ Equation 2.5

Subsequently, the iteration was followed by the distribution of Speed in Space, flow q_i, and speed v_i, the time interval can be related by $1/q_i$ with the distance given by v_i/q_i, the iteration result to the density in space, which is described as the number of vehicles occupying the road space:

Then $$k_i = \frac{q_i}{v_i}, i = 1,2,c$$ Equation 2.6

The summation of vehicle density in a stream given by k_1, k_2, k_c yielded:

$$K = \sum_{i=1}^{c} \quad k_i = 1$$ Equation 2.7

Subsequently introducing $fi' = k_i/K$ at v_1, v_2, v_c provides the frequency in space.

He then ran an illustration using the existing data to show the relation. These findings are shown in table 2.1 below, in practice, speeds vary continuously, but they have been grouped in 4-mile- per-hour groups.

Table 2.1: Evidence of data showing distributions of speed in space and time collected in the western avenue, Greenford (Middlesex). For dual carriageway on East-bound traffic only.

Speed range m.p.h. *	Flow v.p.h.	Percentage in time	Concentration v.p. mile	Percentage in space
2– 5	1	0·3	0·3	1·7
6– 9	4	0·8	0·5	3·3
10–13	0	0·0	0·0	0·0
14–17	7	1·5	0·4	2·9
18–21	20	4·5	1·0	6·9
22–25	44	9·9	1·9	12·7
26–29	80	17·9	2·9	19·7
30–33	82	18·2	2·6	17·7
34–37	79	17·5	2·2	14·9
38–41	49	10·9	1·2	8·3
42–45	36	7·9	0·8	5·4
46–49	26	5·7	0·6	3·8
50–53	9	1·9	0·2	1·1
54–57	10	2·2	0·2	1·2
58–61	3	0·8	0·1	0·4
Total	450	100·0	14·9	100·0

* Strictly 1½–5½, 5½–9½, etc.

Adapted from: *(Wardrop & Whitehead ,1952).*

From the given data above, it was established that there is a strong correlation between the range of speed, the percentage in time and space. Wardrop & Whitehead (1952) remarks on these findings concluded that there was a difference between them; the bulk of the time distribution was further to the right than that of the space distribution, meaning that speeds are greater on the whole for the time distribution. There will always be such a difference if there is any variation in speed.

2.2 Open Street Capacity by Wardrop and Whitehead

A study conducted in central London (the results are shown in figure 2-1 below) reveals the relationship obtained when they compared the values of running speed (speed while in motion) against the flow on the whole street for several arterials of changing the width in Central London. Relatable is the findings of Glanville (H., 1951). *'It will be seen that, in general, as the flow increases the speed is not appreciably influenced at first, but beyond a certain point the speed decreases steadily with increasing flow. In the case of the narrow streets, the speed begins to decrease at once"* (Wardrop & Whitehead, 1952). The result can be approximated by applying the empirical equation provided below:

$$Vr = 31 - \frac{q+430}{3(w+6)} \ or\ 24\ [mph], whichever\ is\ less \qquad \text{Equation 2.8}$$

where *V*, denotes space-mean running speed in miles per hour,

q -denotes the total flow of vehicles per hour and

W -denotes road width in feet.

Normann and Walker(1948) presented a study conducted in the U.S.A on a single straight-line relating speed and flow on four-lane open divided roads. This iteration provided that the speed given by the formula was not less than 10 miles per hour. A linear relation between speed and flow is nonetheless relatable (Normann & Walker, 1948).

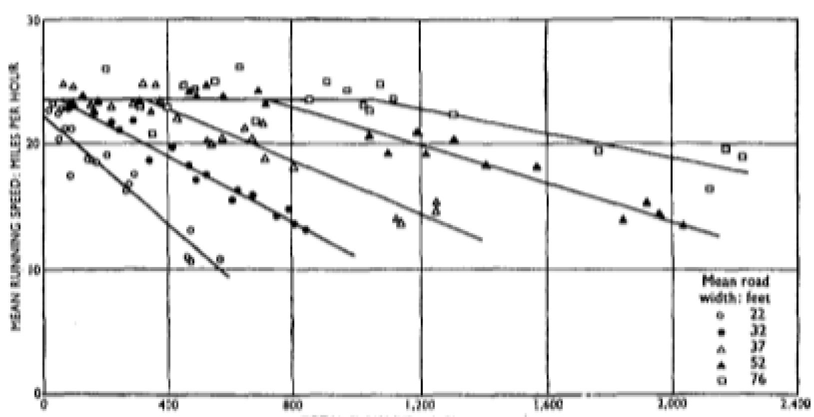

Figure 2.1: Relation between mean running speeds and total flow in central London

Source: (Normann & Walker, 1948)

Given the relation between speed and flow, capacity can be defined as "the flow which produces the minimum acceptable journey speed." The average capacity was calculated for the Central London streets using the equations shown above. The results showed if the minimum acceptable speed was 15 miles per hour, the average capacity of a 30-foot street was about 700 vehicles per hour. In other words, if 700 vehicles require using this street, conditions would allow them to travel at an average speed of 15 miles per hour. The corresponding average capacities for 40- and 50-foot roads were obtained as 1,200 and 1,700 vehicles per hour, respectively.

Thomson, motivated by Wardrop & Whitehead in their initial findings, reinvented the wheel and developed a linear relationship based on the speed-flow model. Working on data from greater London and RRL collected biannually over 14 years. However, the study was based on two data points (each consisting of average speed and flow) for peak and off-peak periods. This established a trend on these two sets of data points which yielded a negative slope for the dataset (see figure 2.2)

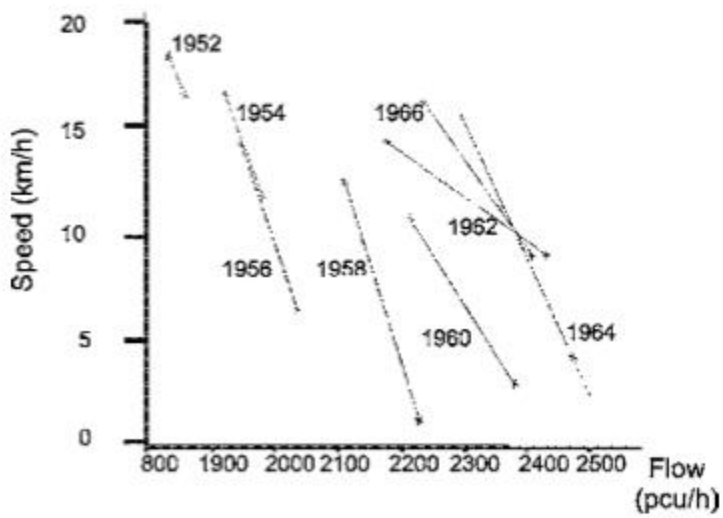

Figure 2.2: Observed Speeds and Flows relationship in Central London for year period 1952-1966,

Source: (Thomson, 1967)

What was significant from these findings was the offset on the trend showing the improvement in the speed and capacity over the period, this was said to be due to improvement in geometric and traffic control in the road features over time. At the later stage, the results were considered biased hence data was captured from only two data points and were deemed inadequate to determine the shape of the curve, as a result, all sixteen data points were used to evaluate the changing capacity of the network were discarded although a linear relationship was noted:

$$v = 30.2 - 0.0086q \qquad \text{Equation 2.9}$$

where *v* is the average speed in kilometers/hour and q is the average flow in pcu/hour.

Thomson further modified the linear relation by working on the data collected on Sunday. The obtained relations from his findings are displayed in figure 2.3 below. This provided a provision to estimate speed and flow (Thomson, 1967).

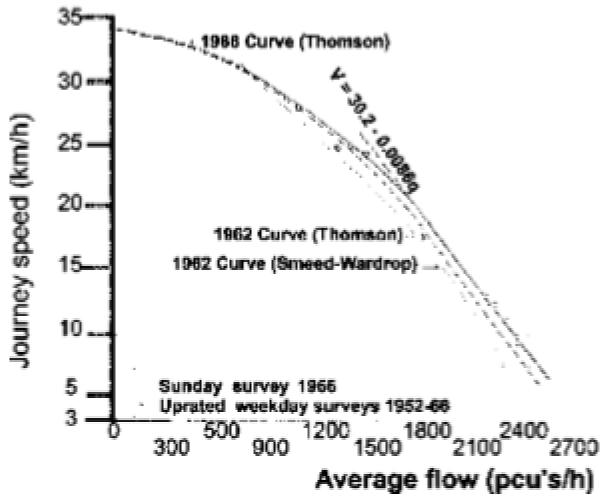

Figure 2.3: The established Speed-Flow Relations for major arterials on the network in Central London

Source: (Thomson, 1967)

The follow-up argument on these findings was that for the selected area of central London it could be further broken into inner and outer zones, and the relationship seen primarily impacted by traffic signal densities.

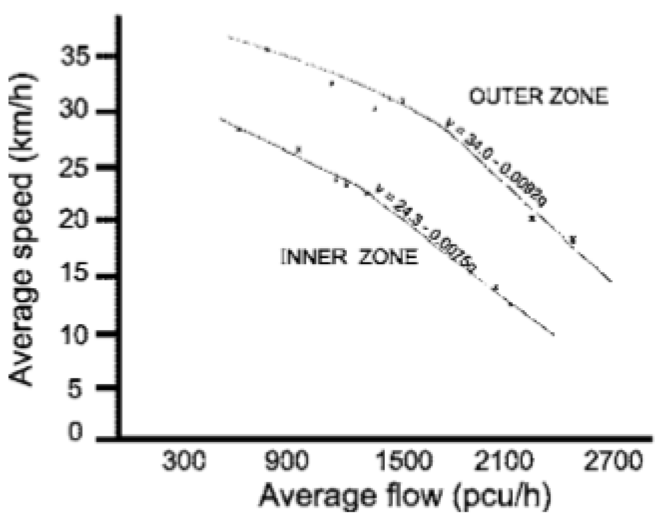

Figure 2.4: The established Speed-Flow Relations for the inner and outer zone in Central London

Source: (Thomson, 1967)

Subsequently, Wardrop & Whitehead (1952) intervene in this study but this time he incorporated features of the streets; average street width, average signal spacing, stopped time, delay at signalized intersections, the number of signalized intersections, flow, and the capacity into a relationship between average speed and flow. Combining all these factors the average speed equation was found to be:

$$v = \frac{1}{31 - \frac{140}{w} + 0.0244\frac{q}{w}} + \frac{f}{100 - 6.8\frac{q}{\lambda w}}$$ Equation 2.10

Equation 2.10 however, can only be applied to geometric and traffic signal features in central London. This equation was disputed as it can only apply to one location and no further studies linked the applicability of this equation to other cities due to the lack of adequate data. Results on all iterations performed are displayed in figure 2.5 below.

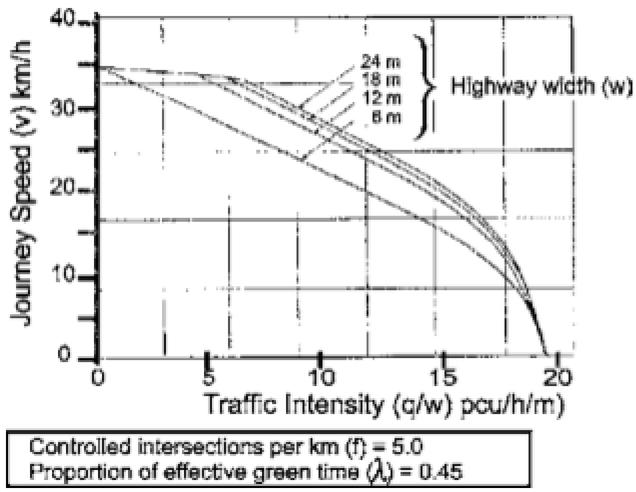

Figure 2.5: Impact on speed-flow relation as the road width changes

Source: (Wardrop & Whitehead, 1952)

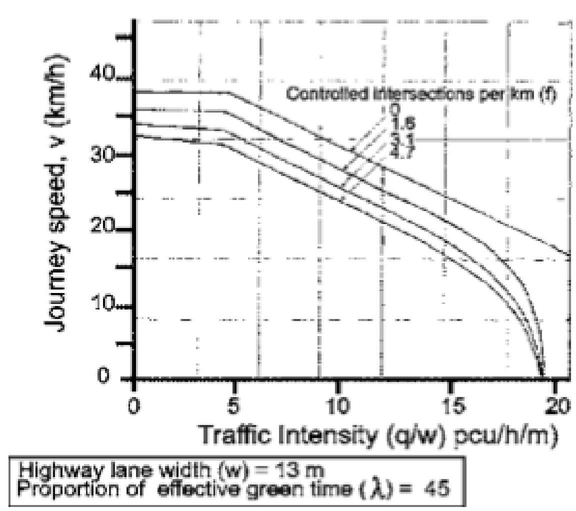

Figure 2.6: Impact on speed-flow relation as the number of intersections changes.

Source: (Wardrop & Whitehead, 1952)

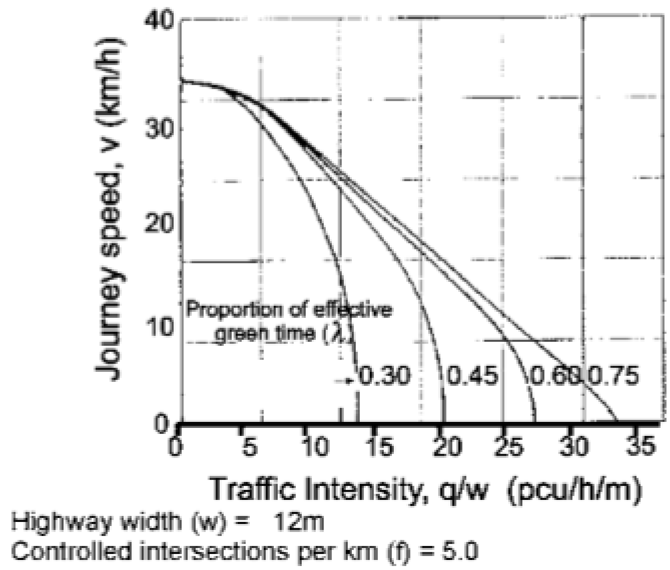

Figure 2.7: Impact on speed-flow relation as the capacity at intersection changes

Source: (Wardrop & Whitehead, 1952)

Godfrey examined the relations between the average speed and the concentration (defined as the number of vehicles in the/a network). His examination on the average speed and concentrations proved otherwise from the notion of expanding the capacity of a single intersection disregarding the nearby intersection. He noted that expanding an intersection to accommodate more traffic (i.e increased capacity) would move the queue to another intersection within the network unless the bottlenecks downstream are cleared.

2.3 Relation on Average Speed and CBD Distance

The application of distance from CBD to derive the average speed on cities was first investigated in the works of Branston, relating five functions of average speed. The study was conducted using data collected in 6 cities in England. The applied data was collected by the Road Research Laboratory (RRL) in 1963. The obtained data were treated separately for each city and fitted to each function using least squares regression and at a later stage combined for the aggregated outcome. City centers were defined as the main point where the radial streets intersected, and the journey speed in the CBD was that found within 0.3 km of the selected city center (Branston, 1974). The first identified function that was derived represented a power curve (Wardrop & Whitehead ,1952).

$$v = ar^b \qquad \text{Equation 2.11}$$

where *a* and *b* are constants estimated from each city-data.

There was an argument that this equation is invalid merely because it predicted zero speeds as one was getting closer to the city center(r=0). Motivated by these findings, Branston (1974) established a more generic equation to estimate the speed at the city center.

$$v = c + ar^b \qquad \text{Equation 2.12}$$

Where c represents the speed at the city center.

Supported works from Branston for introducing a constant c to establish the average speed at the city center. Beimborn(1970), brought a new perspective suggesting that there was a linear relation to speed and distance up to some maximum speed at the city edge (Beimborn,1970). But his findings were disputed because the collected data did not reveal at which point the maximum speed occurred at the periphery of the city.

$$v = a + ar \qquad \text{Equation 2.13}$$

Angel & Hyman (1970) fitted a negative exponential function. Their work suggested a negative exponential asymptotically approaches some maximum average speed.

$$v = a + be^{-cr} \qquad \text{Equation 2.14}$$

The last function was derived by Lynam & Everall (1971). They also provided an infinite average speed occurring at the periphery of the city. The derived equation was previously applied for both ring and radial datasets.

$$v = \frac{1 + b^2r^2}{a + cb^2r^2} \qquad \text{Equation 2.15}$$

The final remarks on the works by Branston (1974) stated that two of the five equations were considered null and void. The first equation, being the modified power curve (equation 2.12), arguably provided ambiguous estimates when predicted a negative speed at the city center for two cities and a zero speed for the overall data. The second equation was the linear model (equation 2.13) which overestimated the average speed by 3 to 4 km/hr. at the city center diminishing the confidence to predict the real-time speed from the increasing distance to the city center. Figure 2.8 below shows iteration for the chosen equations.

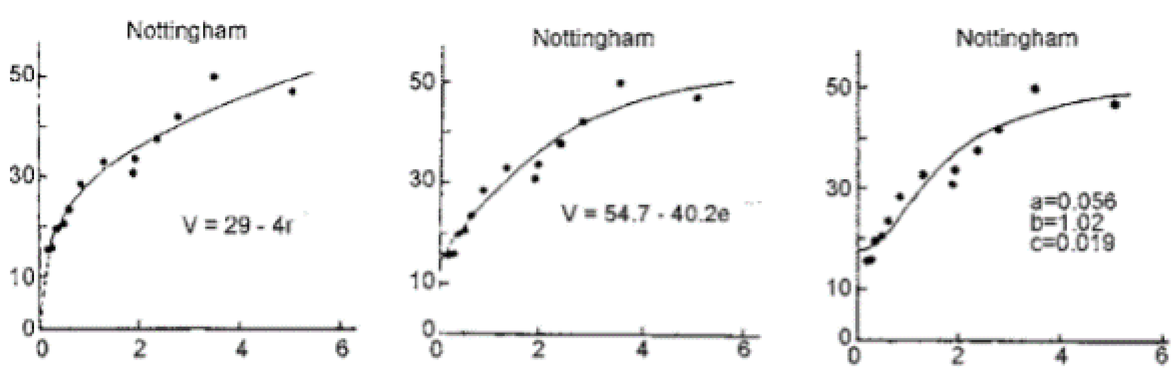

Figure 2.8: Collected data from Nottingham Showing Fitted for three of chosen equations; power curve, negative exponential curve, and Lyman-Everall Curve, respectively.

Source: (Branston, 1974)

In a separate study, Hutchinson (1974) used RRL data collected in 1967 from eight cities in England to reexamine equations 2.11 and 2.13 using his naked eyes as a tool to simplify them. Findings from this study presented various arguments. The traffic flow was fluctuating because of the changing travel demand. There was no clear answer at what distance the average speed occurs from the city center. The obtained radius was not enough to determine the average speed. Each city had unique traffic patterns that were influenced by the prevailing traffic demand. Each route whether a major or minor arterial presented a different level of services because of the prevailing geometric features on that route, just to mention a few ones that stood out.

2.4 Level of Service and Network Performance

Level of service is a qualitative measure describing the operational conditions of a traffic stream and their perception by motorists and/ or passengers in terms of speed, travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety. The operational performance (the Level of services) is ranked from A to F with A representing the best-operating conditions and F representing the worst operational conditions (Ganesh Pawar, Dr. Bhalachandra Khode, et al, 2015).

Table 2.2: Shows the Classification of the Level of services for various facilities and measure of effectiveness.

Type of Facility	Measure of Effectiveness
Freeways	
Basic freeway segments	Density (pc/mi/ln)
Weaving areas	Density (pc/mi/ln)
Ramp junctions	Flow rates (pcph)
Multilane Highways	Density (pc/mi/ln)
	Free-flow speed (mph)
Two-Lane Highways	Time delay (percent)
Signalized Intersections	Average control delay (sec/veh)
Unsignalized Intersections	Average control delay (sec/veh)
Arterials	Average travel speed (mph)
Transit	Load factor (pers/seat, veh/hr, people/hr)
Pedestrians	Space (sq ft/ped)

Adapted from: (Kita, 2000)

2.5 Traffic Models Evaluated at Network Scale

The first theoretical proposal on a macroscopic relationship between average network flow and density with an optimum accumulation belongs to Godfrey (M, 1968). Smeed (1968) established a method to determine the capacity of a city at the network scale. He counted the number of vehicles(N) that can successfully enter the city center and compared this to the time (Smeed, 1968). He then classified the network characteristics (i.e. The number of intersections and type of intersection controls, the width of the road, vehicle classification). After several iterations citing the works of Wardrop and Whitehead (1964) suggested that the number of vehicles that enters the city successful can be given by:

$$N = (33 - 0.003v^3)Jf\sqrt{A} \qquad \text{Equation 2.16}$$

Where *f* is the fraction of area devoted to roads, *J* is the fraction of roadways used for traffic movement range 0.22 and 0.46. *A*, the area of the town and where v is the speed in kilometers/hour.

One of the key findings in his study suggested that the number of vehicles that can circulate in a town strongly depends on their average speed and it is directly proportional to the area of the usable roadway. For any given area (dedicated to roads), the larger the central city, the smaller the number of vehicles that can circulate in the network, suggesting that a widely dispersed town is not necessarily the most economically viable city.

2.6 Network Parameters and Network Models-Two Fluid Theory

Two sets of traffic flow can be established from the kinetic theory of traffic, individual flow, and collective flow (Prigogine & Herman's,1971). These flows are a function of concentration. Understanding this concept, Prigogine and Herman's later introduced two-fluid theories as a description of traffic in the collective flow regime in an urban street network. They argued every traffic stream was represented by two sets of streams: the stopped vehicles and moving vehicles.

The two-fluid model provides a macroscopic measure of the quality of traffic service in a street network which was independent of concentration. The model was based on two assumptions:

- The average running speed in a street network is proportional to the fraction of vehicles that are moving, and
- The fractional stop time of a test vehicle circulating in a network is equal to the average fraction of the vehicles stopped during the same period.

The relation based on the two assumptions provided above yielded the following model termed two-fluid theory:

$$T_S = T - T_m^{\frac{1}{n-1}} . T^{\frac{n}{n-1}} \qquad \text{Equation 2.17}$$

Where *T* is the running time, T_s is the stop time, all per unit distance, *n* is an indicator of the quality of traffic service in the network, T_m is the average minimum trip time per unit distance. These are Parameters influencing the Two fluid Theory.

The parameter *Tm* is the average minimum trip time per unit m distance, and it represents the trip time that might be experienced by an individual vehicle traveling alone in the network with no stops.

2.7 Network Computer Models and Two-Fluid Model

The introduction of the simulation models provided an opportunity to evaluate the relation between speed (V), flow (Q), and density (K) at a network-based level (Mahmassani, et al., 1984). It argued that a similar trend observed on arterials exists at the network-based level. Computer simulations have guided planners to reveal this trend's existence on the networks-based level. Figure 2.9 confirms the relations between speed, flow, and density from a simulation run on the computer model. These findings were observed at concentration levels between 10 and 100 vehicles/lane-mile (Williams et al, 1985). What was noted, the results displayed a close resemblance to their counterparts for individual road sections. Subsequently, figure 2.9d showed a fraction of vehicles stopped from the Two-Fluid models.

The outcome of three models conducted by Mahmassani (1984) and Williams (1987), assumed that Q = KV. That revealed two major outcomes. Firstly, the relatively simple macroscopic relations that link speed, flow, and density do appear to exist at the network-based level and it resembled the concepts witnessed at the individual facility level (arterials). Secondly, the Two-Fluid model serves well as the theoretical link between the postulated and derived functions, providing another demonstration of the model's validity. In the second and third model systems particularly, the derived f-K function performed well against the simulated data.

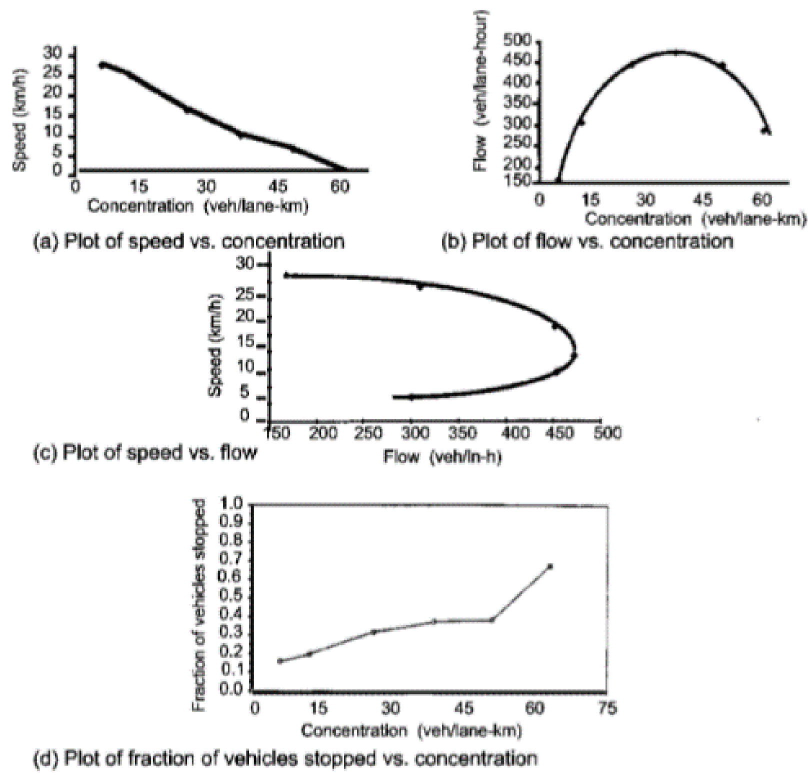

Figure 2.9: Established result displaying a network-based simulation conducted in a CBD

Source: (Mahmassani, et al., 1984)

PART B- BEST PRACTICES OF THE MFD, FEATURES, AND THEIR APPLICABILITY

2.8 Traffic hysteresis and Freeway Network

2.8.1 Background

The pioneer studies of the Traffic hysteresis loop date back to the contributions of Edie (1963) and Treiterer and Myers (1974). These contributions were motivated by seeking means to understand the speed and density curves because of the acceleration and deceleration in traffic theory. (Other impactful studies see works of Yeo and Skabardonis (2009) and Newell (1965) and Zhang (1999)). It once again appeared in the studies using empirical data in Yokoyama in Japan (Dangazo, 2007) and (Geroliminis & Daganzo, 2008). The study was aimed to prove the existence of MFD in an urban network system despite the dynamic traffic states experienced in the city. They found that indeed the city presents a reproducible curve that attributes the various traffic states and is termed 'Macroscopic Fundamental Diagram' (MFD). "The MFD is a property of the network infrastructure and control and not of the demand". These findings were considered as a breakthrough and a stepping stone to the phenomenon of MFD and hysteresis at a network scale. They later prove that if this MFD can be understood well as the property of the road network, it is possible to use it as the basis of traffic control to develop "smart" traffic management systems.

The MFD was derived from an aggregated average network densities and speeds. It is discouraged to apply the MFD as a universal tool because it attributes to conditions of that area derived from (i.e study location). Recent research has begun to look at what network properties or attributes influence MFDs scatter. Real data extracted from the city of Buisson in France revealed the impact of traffic heterogeneity on MFD shape and scatter. The outcome showed that heterogeneity does have a strong impact on the shape/scatter of an MFD (Buisson & Ladier, 2009).

Geroliminis and Sun (2011), Mazloumian et al. (2010) working on arterial networks, investigated the impact of the spatial distribution of vehicle density in the network on the shape and scatter of the MFD. Their findings suggested that there is a lot that can be learned from understanding the variance of the density when looking at the flow and density relation. They did a comparison of the average network flow and density variance where they concluded that the average network flow was inversely proportional to the density variance. Cassidy et al. (2011) complemented this study by looking at something similar although he focused more on the behavior of the link of the congested and uncongested regime.

From these studies indicated in the above paragraph, the outcome had a common factor. It is often to have scattered plots for an individual loop detector presenting itself underneath the shape of the MFD regardless of the type of route considered for the study. Surprisingly, recent observation on a study conducted in the arterial network on empirical data showed that aggregating the scatter plot of individual loop detectors on flow and density could yield a well-defined MFD with less scattered plots. Geroliminis and Sun (2011) took the study further when they investigated Minnesota's freeways using real data to try establishing if a well-defined MFD exists for Minnesota's freeways. As part of their study, they showcased that not only curves with higher scatter plots are expected on freeway networks but also a phenomenon of hysteresis occurs when an aggregated loop detector on a freeway network is analysed (Geroliminis & Sun, 2011)

.

Figure 2.10: Chosen location in Minnesota for the study, with the green dots representing the loop detector locations.

Source: *(Geroliminis and Sun,2011)*

The context of the hysteresis phenomenon at the network level started to get clearer from their publication (Geroliminis & Sun, 2011). They argued that the formation of hysteresis is based on two principles, the first one states that *"there are different spatial and temporal distributions of congestion for the same level of average density".* The second one states that: "*synchronized occurrence of transitions from individual detectors during the offset of the peak period, with points remain beneath the equilibrium curve*." The study also incorporated freeway subnetworks to explore the existence of a well-defined MFD with a lower scatter and they revealed that was not always the case. This statement was indeed proven when the aggregated patterns did not yield a lower scatter. The study found that if the density was known at a particular location and time, it is possible to predict the system's outflow or inflow. This was bound to happen given the derived MFD displays lower scatter plots. However, to expect the same would happen to a derived MFD with high scatter (Hysteresis) was a fallacy. To make a prediction requires a great deal of effort such as knowing the history of the density state over the past years. This was imperative to explore the trend of the density over the entire network and make judgments whether it was something of the past state or genuinely the density of the current state. Like any other problem, to provide a robust intervention, one must know what could have been the cause of the problem. In this case, the problem can be referred to as the density-freeway systems that are hysterical systems with lasting memory properties.

2.8.2 Spatial Analysis on The Entire Network to Verify Existence of Hysteresis Loops

To verify the existence of the hysteresis phenomenon, and MFD derived on average flow and occupancy, for the entire network was looked at. The loop detectors denoted by i were placed in the freeway network and data was recorded in periods of 5 minutes per interval. The density was derived from occupancy using the vehicular average length (for this study $L_{av} = 6m$) through equation $ki = oi/l$. Some publications prefer to use Occupancy over density but in fact, both are applicable to derive MFD. The Loop detectors were closely placed at approximately ½ mile from each other. The key interest in this study was the spatially aggregated patterns of flow and occupancy at the network level. The network average flow was calculated by summing the individual loop detector flow and divided by the total number of loop detectors. And likewise, the same iteration was applied to determine the average occupancy for the network. In this case, N denotes the total number of loop detectors. This introduced a new factor that provided an alert for the possibility of spatial heterogeneity on the network. The global "variance (V)". was derived by looking at the values of occupancy on the individual's links on the network at a specific time. A time-series Data captured on the 22nd of May 2007 that displayed a relation between network flow and occupancy was shown in figure 2.11 below. The x-axis shows the time of the day while the y-axis shows the occupancy and flow.

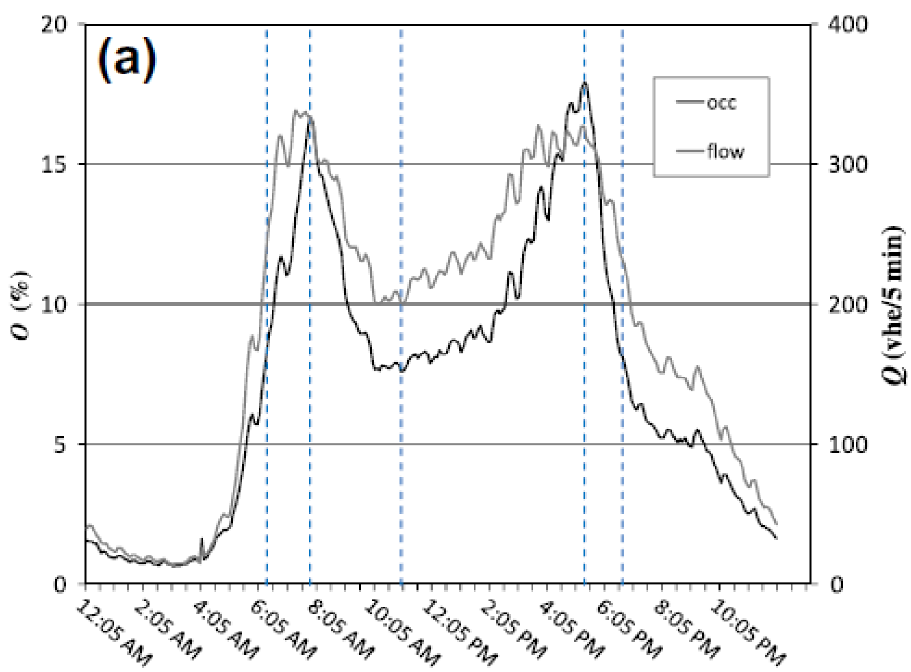

Figure 2.11: Time series data taken on the 22nd of May 2007 shows a relation between time, occupancy, and Flow for the City of Minnesota's freeway network

Source: (Geroliminis & Sun, 2011)

Subsequently, an MFD was established to showcase the existence of the Hysteresis in Minnesota's freeway network. See the derived MFD in figure 2.12 below.

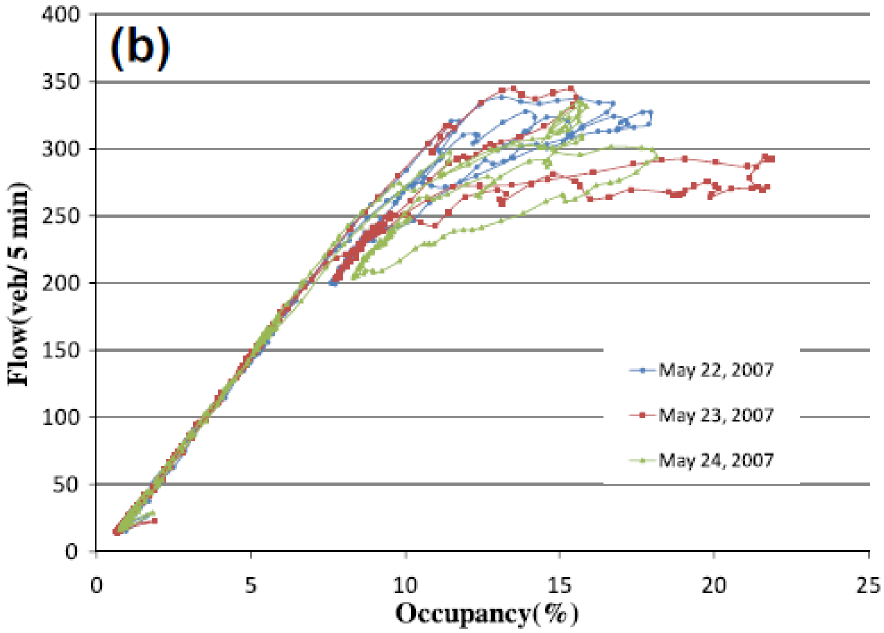

Figure 2.12: Average flow and Occupancy graph showing the existence of MFD with hysteresis loop for the following days-22nd,23rd and 24th of May 2007.

Source: (Geroliminis & Sun, 2011)

Figure 2.12 above, shows the difference in the obtained values of flows when compared to the same value of the occupancy for morning and afternoon peak against the onset and offset times (i.e. O=10%, flow at morning peak (6:05, 10:05), Q was found at approximate (180 veh/5 min; 150 veh/5 min); this suggested that a well-defined MFD for this network may not exist. This was then suggested as the first guide to check whether the network was likely to present a well-defined MFD or not. The second tool of the measure was linked to directly establishing the MFD to identify whether the hysteresis was present on the MFD or not. The hysteresis loop was further associated with the homogeneity or heterogeneity of the network. Figure 2.12 showed that indeed the hysteresis is part of Minnesota's freeway network. A new perspective that suggested not only urban arterials exhibit hysteresis loops, but also urban freeway networks tend to display this phenomenon.

To support their findings, they then looked at the variance of the occupancy from the individual links. Two plots of Q vs. O and V vs. O derived are displayed in figure 2.13 a-b below. Observations verify the existence of hysteresis for this network. A clockwise loop for Q–O and an anti-clockwise loop for V–O was noted. They further noted that the variance was higher in the offset of congestion (7:50–9:00) for the same value of O. High variance was associated with a lower network flow. The cause of this was the flow decrease on either side after reaching a saturated (critical) occupancy. Therefore, as occupancy spreads away from the mean, the flows on either side decrease. On a separate day, a similar behavior was observed, it was then decided to look at this in a more detailed analysis to identify the cause of this variance increase.

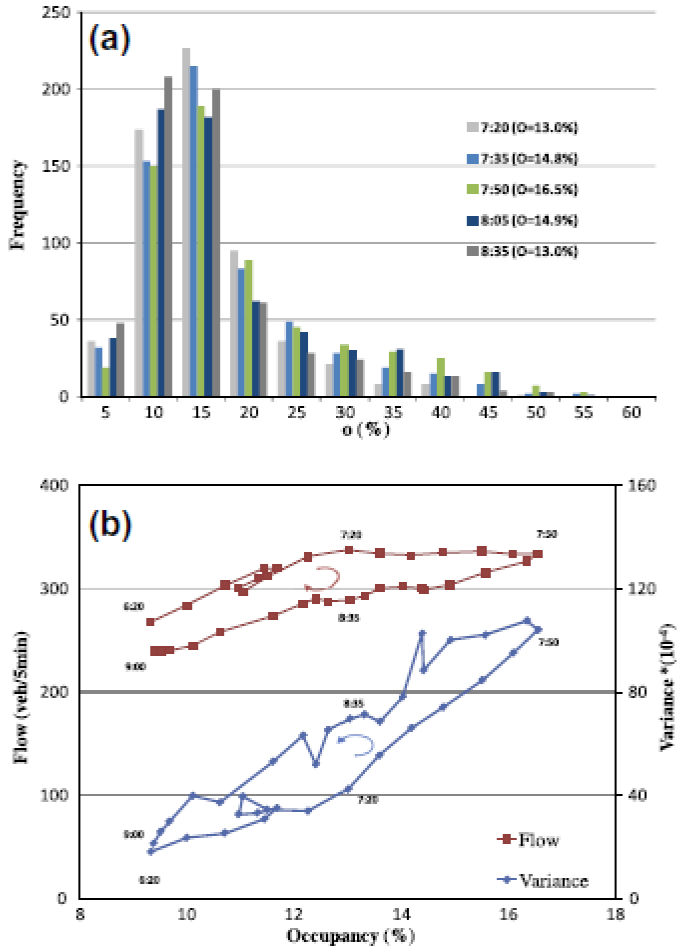

Figure 2.13: Flow vs occupancy and Occupancy vs Frequency plots graph.

Source: (Geroliminis & Sun, 2011)

A network-based analysis was performed by exploring the variations on the occupancy (congestions) of the individual's links to identify the cause of the variance increase. To broadly define this, a map was plotted to display the congestion propagation(pockets) and termed its occupancy contour plots. Highlighted in green circles are the detected locations and there was a proportionality relationship between the circle radius and the density. (Congestion pockets). The analyses were performed between 6:00 am and 9:00 am for six different time instances. These consecutive snapshots show the propagation of congestion in the network (see figure 2.14 below).

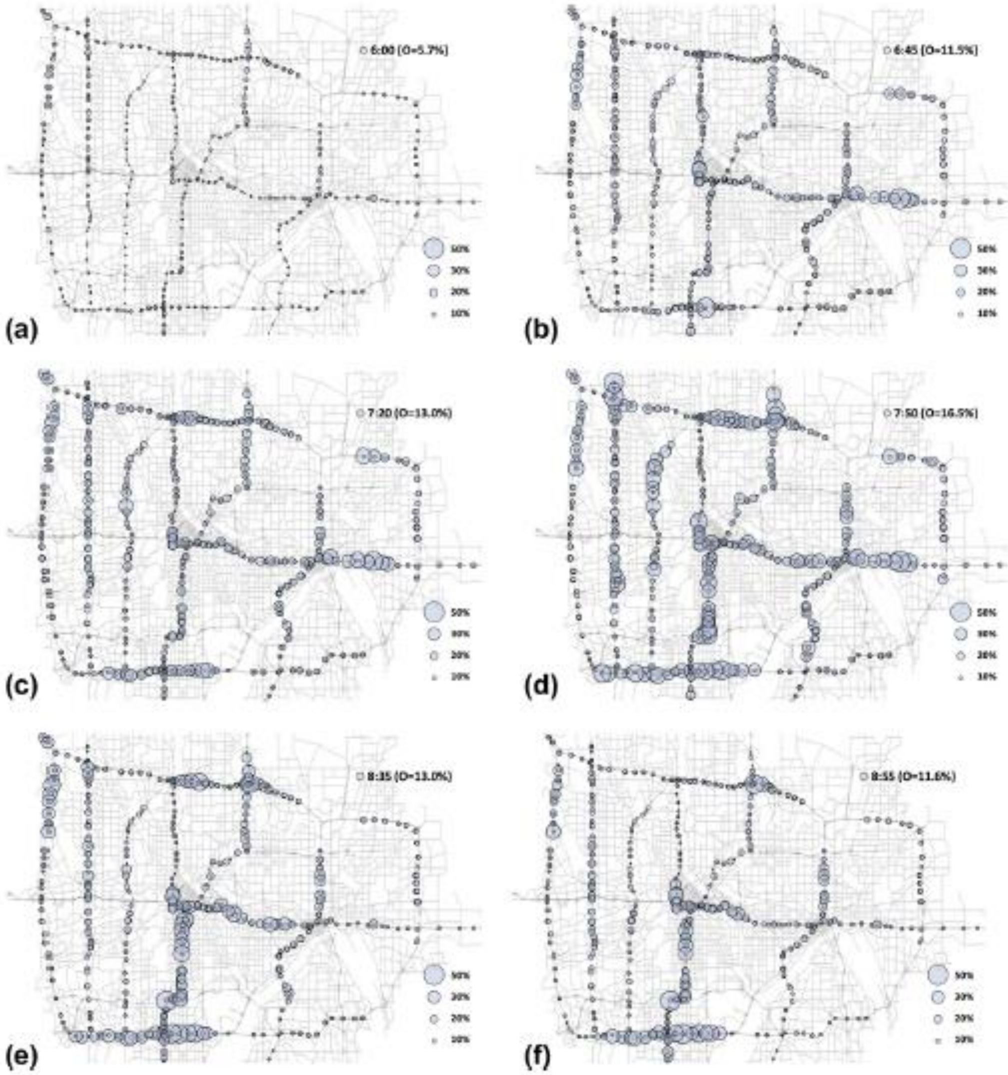

Figure 2.14: Snapshot of the congestion propagation taken from six different times.

Source: (Geroliminis & Sun, 2011)

This type of analysis assisted in identifying pockets of congestions, this further provided an alert to areas that contained active bottlenecks. It is common on arterial networks to find stagnant congestions that require drivers to maneuver using the alternate routes (in events these alternatives routes are missing the drivers are forced to pass through the congestion regardless). This is always the case with many freeways' networks with a limited number of alternatives because of planning for high mobility (lesser access route). The collapse of one or a section of the corridor has a severe impact on the entire network.

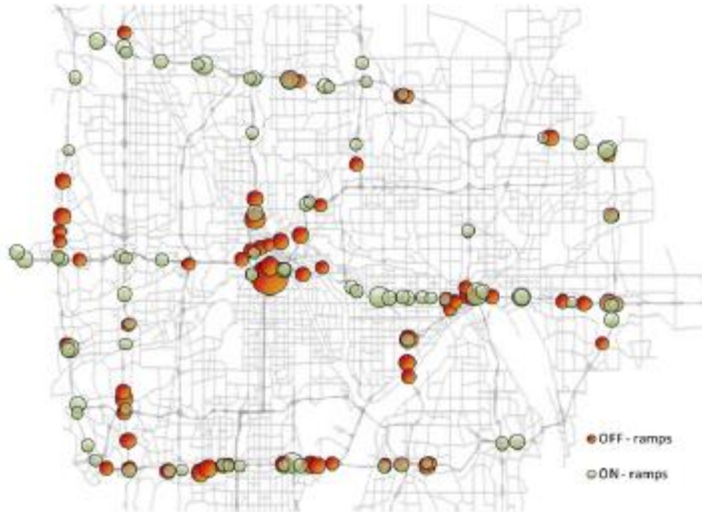

Figure 2.15: offramp and onramp were taken during the morning peak period. Showing the origin-destination path.

Source: (Geroliminis & Sun, 2011)

From figure 2.15, it was observed that more trips are coming into the city center and fewer leaving, revealing the behavior on the spatial distribution of trips origin and destination, it was clear that the spatial distribution of origins was completely different from that of the destinations. There was an even distribution to trips of origin over the entire network while trips of destination were more concentrated in one area and fewer locations. This proved the findings on the histogram that on onset congestion the morning peak it was found that more detectors were operating close to the saturated occupancy and with time, operating detectors dropped as they were getting close to reaching the offset congestion (higher variance-see figure 2.13).

The focus was then shifted to the regime of high hysteresis, between 7:20 and 8:35. as an attempt to link differences in occupancy (Δo_I) and flow(Δq_I) looking at individual detectors. At 7:50, the highest occupancy of -16.5% was recorded. The results are shown in figure 2.16 below.

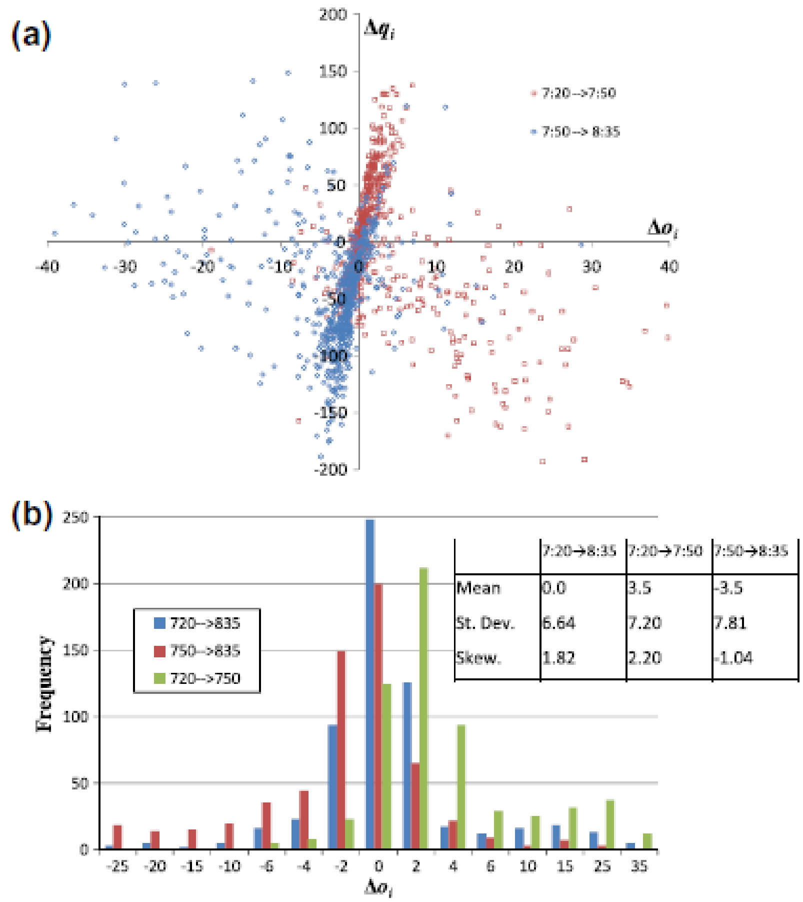

Figure 2.16: change in flow vs change in occupancy, frequency vs change in occupancy.

Source: (Geroliminis & Sun, 2011)

From figure 2.16 above, it was noted that most detectors were found at positive onset and fewer detectors at negative offset congestion. When most of the points were found on the 1st and 3rd quadrant indicating a slope of the free flow regime. Nevertheless, this analysis did not paint a clear picture of movements of congestion to identify the free flow regime as points were scattered all over. This observation however suggested future research should focus on assessing the flow measurement to identify pockets of free flow regime. The second observation provided a hint on possible offset congestion associated with high variance and lower flows.

2.8.3 Relationship between Flow, Variance and MFD hysteresis

Correlation between Flow, occupancy, variance and MFD hysteresis exists (Geroliminis & Sun, 2011). A lot can be understood on the network by paying careful attention to these variables. The study findings were supported by empirical evidence. One typical piece of evidence shown was that in an event when a network is overwhelmed with uncongested areas and consists of reserves for congestions (pockets), it is most likely that the aggregated flow and occupancy from the individual detectors will tend to disappear before the maximum flow and saturated occupancy is reached. Most importantly, the section beyond the maximum flow on the individual detectors will weaken or not be shown on the scatter. See figure 2.17 below. Nevertheless, the core of this study was that the freeway networks do not exhibit a well-defined MFD as always anticipated.

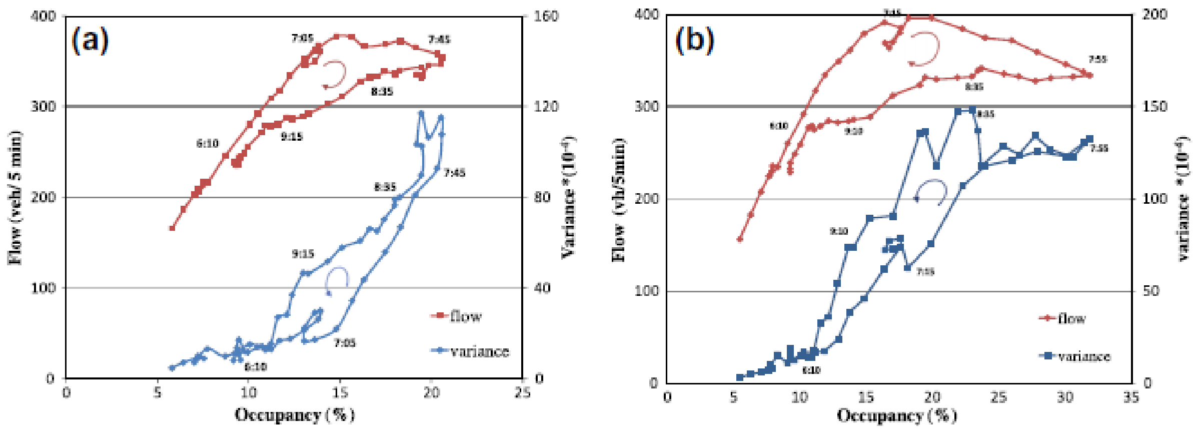

Figure 2.17: A comparison between occupancy, flow and variance, showing the hysteresis formation. For 100 most congested detectors.

Source: (Geroliminis & Sun, 2011)

While MFD can be a useful and simple tool for traffic engineers to use to improve cities' accessibility and mobility, a careful analysis is necessary before control strategies/policies are introduced from the MFD derived from aggregated variables. The previous sections singled out the spatial heterogeneity of the congestion as the main cause of the hysteresis phenomenon.

Attributes of a Well-defined MFD

A study conducted in Yokohama (Japan) showcased that a macroscopic fundamental diagram (MFD) is the soloistic property of an urban neighborhood. This led to the thought that the established MFD was always well defined. A well-defined MFD does not always appear as envisaged (Geroliminis & Sun, 2011). Establishing an MFD from an aggregated loop detector can somehow be deceiving at the other end. It was found that the high scattered plots of flow vs. density associated with individual fixed detectors on the aggregated detectors, the scatter tend to disappear at the end of the curve. It was further argued that these Urban MFDs, as much as they seem to yield a well-defined shape, must not be applied universally. Daganzo (2007) and Geroliminis and Daganzo (2007, 2008), verified that aggregated values in large urban regions can be modeled dynamically if the urban area traffic patterns depict a uniform congested traffic state. Geroliminis and Daganzo(2007, 2008) findings also suggested that the influence of the shape of the MFD found in the scatter plots was highly dependent on the spatial distribution of vehicle density in the network.

Spatial distribution of density was also investigated in a paper cited by Geroliminis and Sun (2011). They were interested in understanding the Density distribution over the network at a particular time of the day if it could tell them more about the expected shape of the MFD. Initially, the assumption made was that

The density was evenly distributed which also led to the assumption that the traffic state was homogeneous (Dangazo, 2007); (Geroliminis & Daganzo, 2008). Geroliminis and Sun (2011) Argued that often freeway networks forever present a dynamic congested state with either active or inactive bottlenecks. This is because of the complex interaction occurring in large urban subcenters (various activities). The freeway network serves continuously changing travel demand with forever changing origin and destination. In essence, they present complex multiple trips that require one to understand the history and movement of congestion. It was certain the MFD developed in such networks may exhibit significant scatter because of a rapidly changing demand.

2.8.4 Hysteresis as A Property of the Freeway Network

According to Gayah and Daganzo(2011), hysteresis is the property of an urban network that shows uneven congestion distribution. This was associated with drivers' behavior for adaptation to a disturbance on the network. It is often a norm that as congestion arouses more drivers tend to seek alternative routes for space. This led to the formation of a clockwise hysteresis loop because of the resilience of drivers to the change. A congested state network tends to be uneven and unstable as more vehicles seek to use uncongested links. This, therefore, results to lower flows on the network. For the network to recovery from congestions, drivers need to adapt to the change. As flow rises the network return to normality. In that case, a quick adaption to the change from the drivers would lead to the absence of clockwise hysteresis loops.

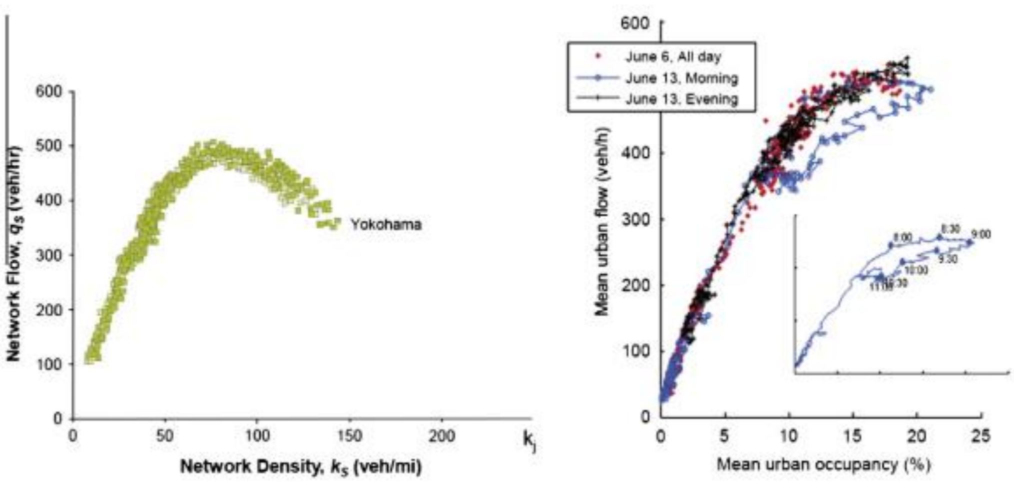

Figure 2.18:A comparison between the MFD founded at Yokohama, Japan; and (b) Toulouse, France. Respectively.

source: Gayah and Daganzo(2011),

This study showcased that hysteresis loops are associated with the state of congestion in the city network. The lower densities are early signs of an unstable and congested network. That uneven distribution within the network determines what type of hysteresis(clockwise/anticlockwise) loop formation is mostly like to occur. During the recovery period in the congested state, the less congested areas recover faster than the severely congested area, this was linked to vehicular turning movements. Drivers' behaviors contribute to the instability o/stability of the network. i.e how they adapt to congestion change. This is because when they are not resilient to the congestion and use the alternative route the more evenly distributed the network is, thus creating a lesser strain to the system. The hysteresis loop is this even is most likely not to happen on the established MFD. Higher adaptive of drivers to respond to the congestion result in the uniform distributed state of congestion on the network which then shown a decline in the magnitude hysteresis loop. The direction of the loop has to do with the load as well as the recovery path of the congestion state.

2.9 An Empirical Analysis of Macroscopic Fundamental Diagrams for Sendai Road Networks

The attention to study MFD started gaining momentum and sparked an interest in traffic modelers after the success in the field findings in downtown Yokohama, Japan(Geroliminis and Daganzo ,2008). Their findings demonstrated a well-defined MFD that existed in an urban scale network despite the chaotic demand existing in a city in various systems controls. They further revealed, guided by this MFD, that city planners can develop robust city management policies that can guarantee success in managing congestions (Wang , et al., 2015). Despite their findings, the followed up studies had proven that a well-defined MFD was not always the case more especial when a network presents a heterogeneous traffic state (see works of (Buisson & Ladier, 2009); (Geroliminis & Sun, 2011); (Saberi & Mahmassani, 2012). The latest developments on MFD have sought means to understand what features of the arterial network that suit or result in a Well-defined MFD. To establish this would entail a complex study that requires an extensive amount of real-time data.

2.9.1 Collected data and Study area description and results- Sendai

What had seemed to single out this study from the previous studies was that long-term data spanning close to a year was collected to perform this study (05/01/2012–04/30/2013). This data was collected using fixed detectors. To perform the analysis, data were split into two segments representing the morning period (0:00-13:00) and evening period (13:00-24:00). Figure 2.19 below shows the area extent covered by the detectors. Notably, the network layout resembled a radial type network.

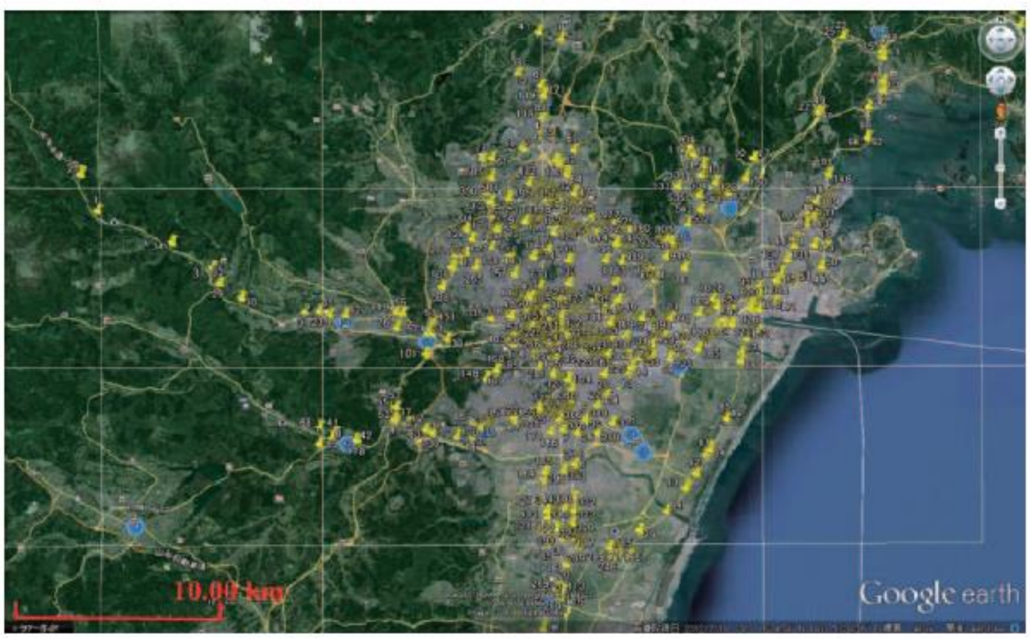

Figure 2.19: Shows the road network in Sendai, Japan covered by the detectors.

Source: (Wang , et al., 2015)

The initial assessment revealed the observed MFD in the morning period consisted of a single loop whereas the evening MFD shown either the two (formation or no formation of the loop). See Figure 2.20 below.

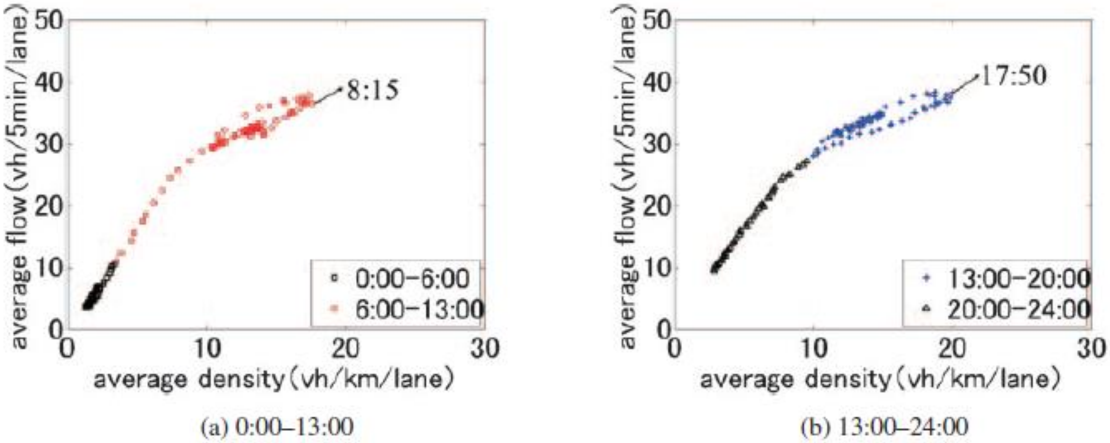

Figure 2.20: Morning and Evening period MFD for Sendai Road Networks on this day of 11/19/2012.

Source: (Wang , et al., 2015)

What had been identified as the critical observation from the presented MFD above (see Figure 2.20) was that hysteresis was forming from both scenarios? Subsequently to these findings they started to look at the MFD by identifying factors that affect its shape.

2.9.2 Traffic Demand fluctuations and MFD

MFD changes with the state of traffic as congestion levels were not stagnant but changing from time to time. To explain this behavior, all the established MFD were looked at from the data gathered on the weekends and holidays. Indeed, the hypothesis was proven to be correct. The presented MFD displayed these common trends; a large loop formed from the Saturday data and a smoothly shaped loop formed from the Sunday data. These two MFDs showed distinctive shapes. See Figure 2.21 below.

These observations had been associated with the traffic demand present on these exclusive days (Sundays or holidays). MFD was analysed in conjunction with the time series to identify this correlation. The outcome revealed that congestion propagation influences the obtained MFD shape. The formation of the hysteresis loop was associated with this effect. The following section explained this effect broadly. This was identified when a time series over the weekend demand was analysed. It was found that low traffic demand on these days had led to no formation of the hysteresis loop. This was linked to the fact that there was no prominent peak observed on either flow or density throughout the day. This then provided a conclusion that weekend or holiday MFD differs from the weekday's MFD regardless of the time of the year. (see Figure 2.21 below)

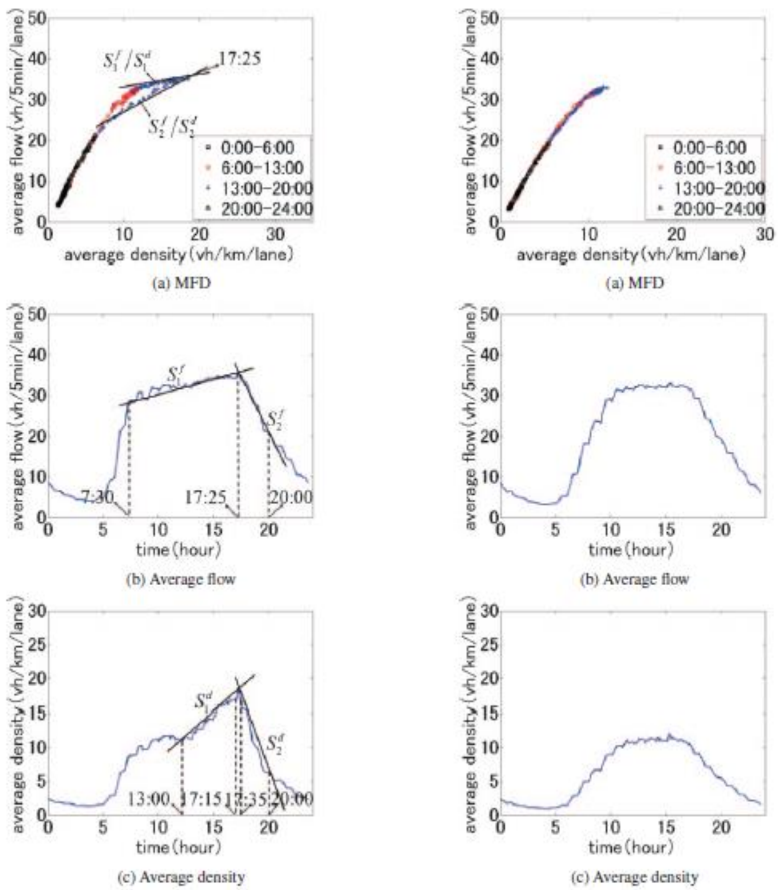

Figure 2.21: shows the obtained MFD for weekend days (Saturday- 11/10/2012 and Sunday- 3/24/2013) Sendai Road Networks.

Source: (Wang , et al., 2015)

2.9.3 Climate conditions and MFD

This section dwells on the impact posed by climate conditions (rainy or snowy days) on the attained MFD. The assessment looked at the bad weather season (days) while analyzing the MFD shape. What was seen to exist is that MFD shape (loop) changes on bad weather days. This was associated with the congestion state period (arguably on the days of bad weather, congestions take a longer time to dissipate when compared to normal good weather days). An MFD to explain this was then established (see Figure 2.22).

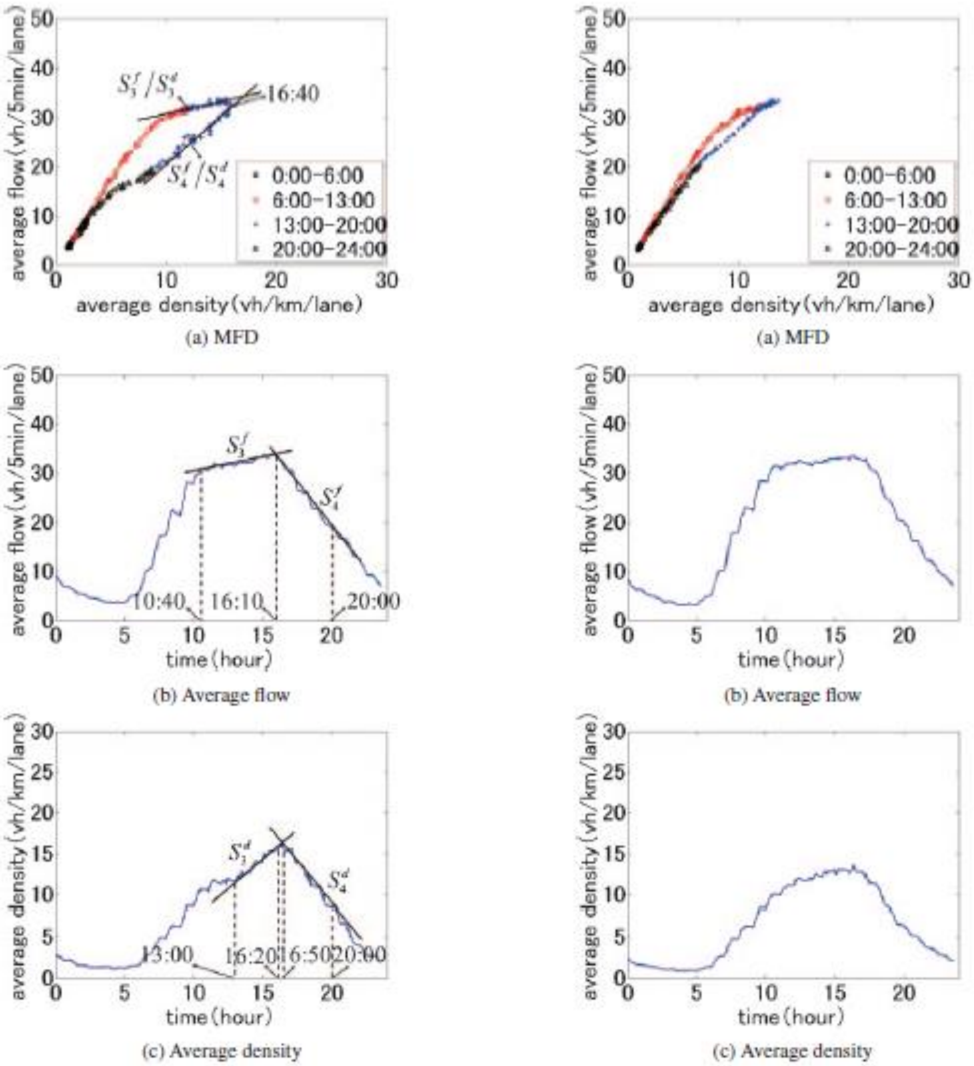

Figure 2.22: Show the established MFD on bad weather days for Sendai Road Networks.

Source: (Wang , et al., 2015)

Notably, the average flow and density drop swiftly, this was associated with poor driving conditions as the network performance drops (while congestions take longer to dissipate). A flattish curve of MFD (with lower average flow and density) was observed (see Figure 2.22).

2.9.4 Area setting effect and MFD

This effect was associated with the change of study region essentially affecting the spatial distribution of the fixed detectors. This effect was investigated through the separation of the regions to analyse the MFD. After this separation, the outcomes confirmed there was a variation observed for each MFD from all the regions. These aspects were identified. The region enlargement had resulted in the decrease in the average density, there was a "variation on the MFD" as the average flow and average density suddenly dropped when the region was expanded.

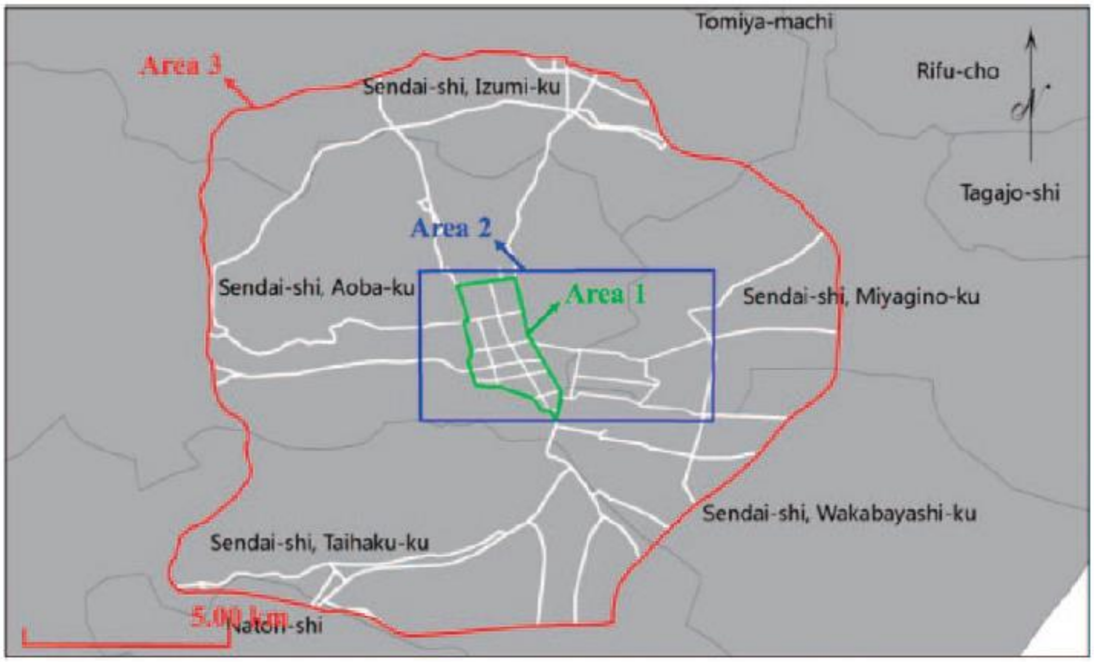

Figure 2.23: Area division in Sendai to observe variation on the MFD.

Source: (Wang , et al., 2015)

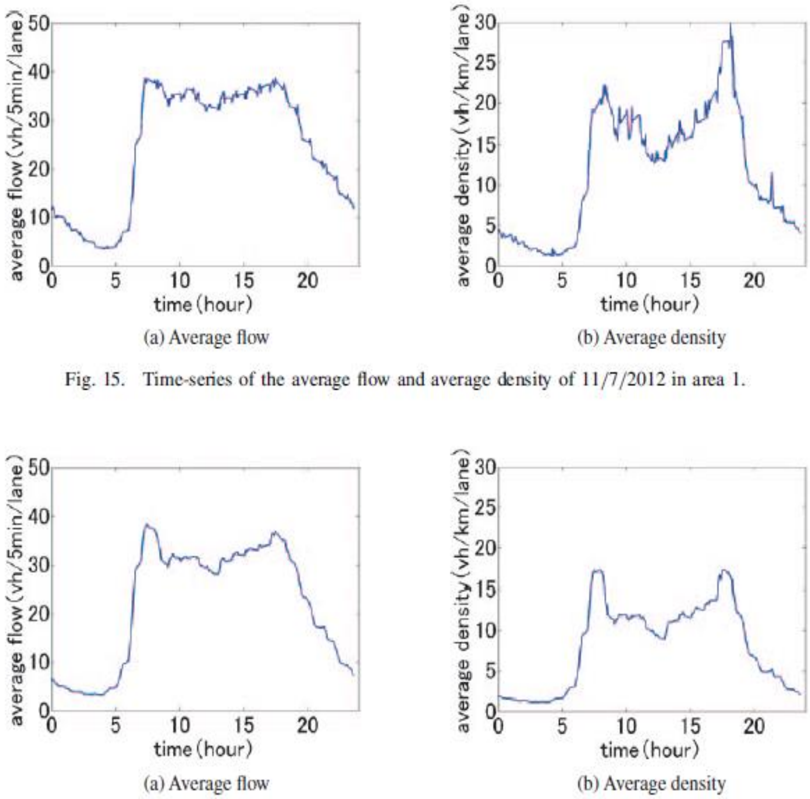

Figure 2.24: Time series for weekday (Wednesday) showing average flow and density for Sendai network regions.

Source: (Wang , et al., 2015)

The areas were grouped from small to bigger with A_1=3.2 km^2, A_2=22.7 km^2, A_3=117.8 km^2. The number of detectors increased with the area. Figure 2.25 below shows the MFD derived from the analysis.

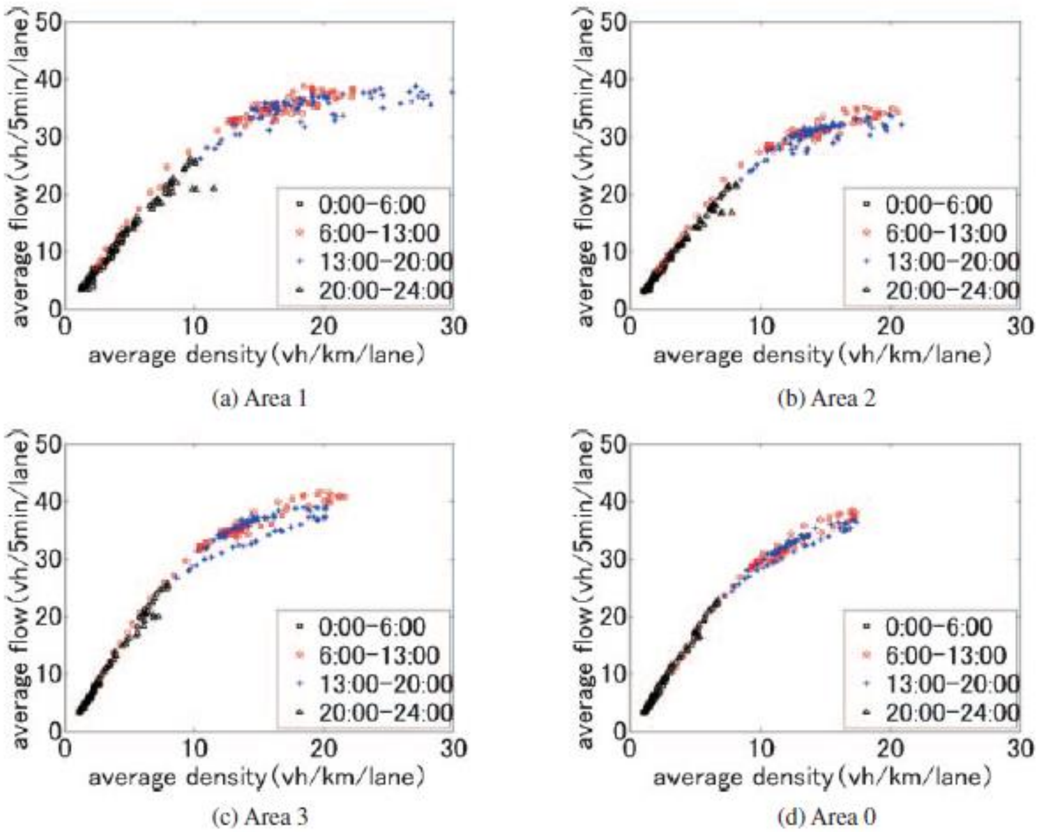

Figure 2.25: Area MFDs detected for the various regions in Sendai for this day of the week 11/7/2012 at sunny weather conditions.

Source: (Wang , et al., 2015)

The crucial findings from the above-mentioned effects with regards to the MFD shape were consolidated and summarised below:

- The study was the first of its kind to use data for the whole year (05/01/2012–04/30/2013) to perform the analysis for the MFD.
- A well-defined MFD seemed to exist for the Sendai Road Networks.
- A well-defined MFD can be associated with good weather conditions. The hysteresis loop was observed in the analysis. This was said to be the result of good weather conditions. Furthermore, the Hysteresis loop was associated with morning peak and afternoon peak periods.
- And high peaking shapes on the MFD could have been the result of poor road topology conditions.
- The varying shapes were observed for MFD analysed from the Saturday and Sunday data. The Saturday data showed a large single loop whereas the Sunday data showed the absence of the loop.
- The extent of the area analyzed has an impact on the outcome of the MFD. The study had shown large areas bring variation to the MFD when compared to small areas. The larger the area, the more traffic states can be detected.
- Loops were not forming in the days of low traffic demand (Sundays or holidays). And had only been witnessed on the normal weekdays (where traffic volumes are high). This confirmed the idea

that when the time series vs average flow and the average density are understood correctly a lot can be understood about the MFD and so was the congestions propagations.
- The study did not reveal the impact the class of the corridor has on the Shape of the MFD despite touching on the area size (number of loop detectors) to MFD variation.

2.10 Macroscopic Fundamental Diagram for Brisbane, Australia Empirical Findings on Network Partitioning, and Incident Detection

This study took its inspiration from the findings in the city of Yokohama, Japan. The study applied a combination of data extracted from Bluetooth, Loops, and Signals to verify the MFD existence in the City of Brisbane, Australia (Tsubota , et al., 2014). However, the study focus was shifted to the outcomes established from the loop detector data.

2.10.1 Study site and Data collection

This study was said to be the first of its kind to investigate MFD on a radial-type road network. The past studies seemed to have been focused on a grid-type network layout (Tsubota , et al., 2014). The data was collected using the Coordinated Adaptive Traffic System (CATS). These devices were placed on the streets of Brisbane, the data was collected at every 5 minutes interval and stored in the City council management system.

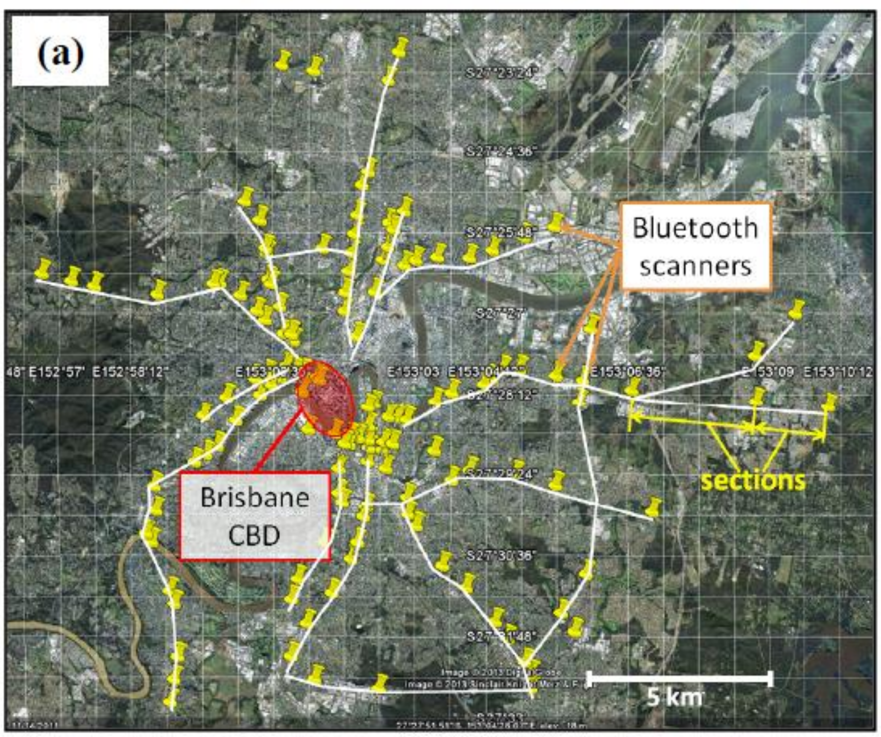

Figure 2.26: The study site showing the covered network of the city of Brisbane.

Source: (Tsubota , et al., 2014)

From Figure 2.26 above, yellow pinned location/points are the Bluetooth detectors dispersed over the entire network. The aforementioned detectors were equipped in 2012. The major road on the network was represented by the white lines expanding radially from the Brisbane CBD. About 155 intersections were analysed. Other results were omitted due to detecting equipment fault or the collected data presented errors. This was merely done to avoid discrepancies on plotted cumulative MFD.

2.10.2 MFD Result for City of Brisbane Network

The MFD is defined as the relationship between network 'production', the weighted sum 32 of flows of all links, and 'accumulation', the weighted sum of link densities (both quantities are 33 weighted with the link lengths – units of lane-kilometers). The variables of interest were the average flow and the average density. The Methodological approach used was adapted from the works of Mahmassani (1984).

$$Q = \frac{\sum_i \quad q_i l_i n_i}{\sum_i \quad l_i n_i}$$ Equation 2.18

$$K = \frac{\sum_i \quad k_i l_i n_i}{\sum_i \quad l_i n_i}$$ Equation 2.19

Where q_i and k_i represent an average flow and average density at that section on the link *I* respectively. The link length was represented by l_i and n_i represented the number of lanes, both at section *i*. After numerous iterations, an MFD output was presented for the city of Brisbane network. The data captured was adapted on the day of 22nd – 26th October 2012. Ultimately the results displayed a well-defined MFD presenting low scattered plots.

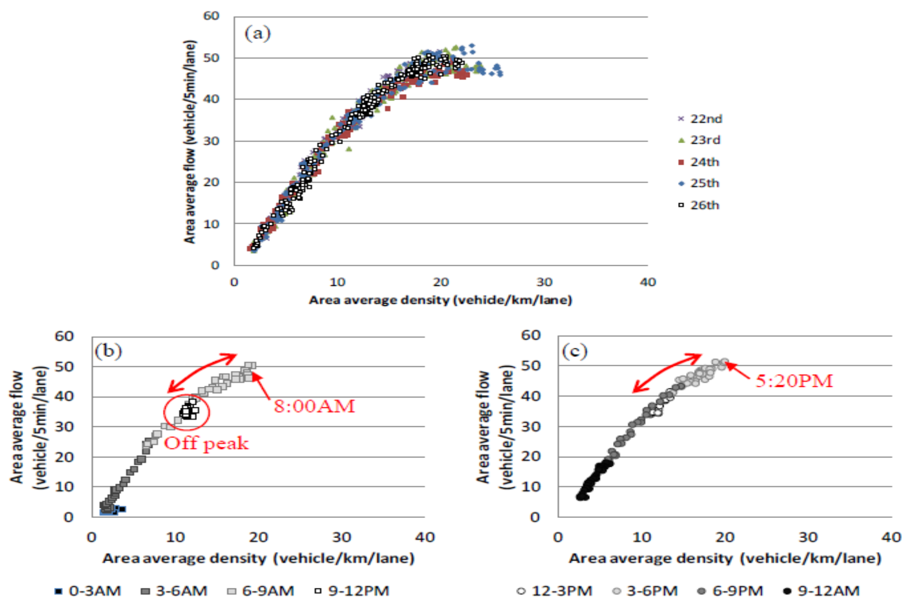

Figure 2.27: The established MFD for the City of Brisbane network.

Source: (Tsubota , et al., 2014)

The critical findings were consolidated and summarized below:

- A well-defined MFD was proven to exist in the City of Brisbane network. This MFD also presents a low scatter plot (see Figure 2.27 above).
- Network partitioning can play a crucial role to understand the network traffic flow behavior. This was also suggested in the works of Tsubota et al (2014).
- Partitioning Based on the Distance from City Centre can be instrumental and beneficial in managing congestions when the city presents a radial network planning. By introducing measures such as congestion pricing and signal coordination.
- Density estimation is not straightforward from the loop detectors, an effort is required to estimate the density.
- Detecting systems positioning varies with the kind of management system used to monitor signals. i.e. for SCATS preferably inline detecting system is preferred whereas SCOOTS require an upstream detection system.
- Density estimation in a freeway network can be most valid, because of the uninterrupted flow in the network whereas urban arterials present interrupted flows.
- Construction and accident delays do have an impact on the shape of the MFD.
- There is an existing relationship between traffic homogeneity and MFD. The coefficient of variation (CV) measure can be applied to assess this homogeneity.

2.11 Should the MFD be established based on Mode? -An Empirical multimodal traffic Network study in Zurich based on 3D Macroscopic Fundamental Diagram

The development in the MFD studies had been neglecting the impact of having multimodal traffic in a network. The contribution of this paper looked at MFD in a 3D context to unpack these overlooked discrepancies. This study was conducted in the city of Zürich, Switzerland. The study focused on two different areas in the city. There were two sets of data sources that were utilized, loop detectors and automatic vehicle location devices (AVL). It is said that public transport and private vehicle have different levels of contribution to congestion (Ji & Geroliminis, 2012). To verify this statement, this study looked at two regions in Zurich city (east as City center and Wiedikon). Each zone differs with the road topology however the focus was on the lanes covered by both private and public transports. For instance, it was reported in Wiedikon that 60% of lanes were covered by public transport whereas in the city center 75% were covered by public transport.

2.11.1 Collected data on Vehicles and Public Transport

The collected data from vehicles was recorded between 6:00-24:00 on the weekdays (26th and the 30th of October 2015). This period was chosen to accommodate the public transport operating hours. Each count was recorded at a 15-minute interval. The loop detectors were used as the source of data collection.
A total of 213 vehicles, with 145 vehicles from the city center and 68 vehicles from the Wiedikon region. An effort was made to determine the density k, as only the occupancy was the product from these detectors, through using the space-effective mean length l_e of a car ($k=o/l_e$). In this paper, the effective mean length used was l_e =6.3m (AKP Verkehrsingenieure, 2016; DAV, 2015).

2.11.2 The outcome from the loop detectors

The result for the 5-day analysis at 15-minute intervals is displayed in Figure 2.27 below. This comparison looked at vehicle accumulation versus vehicle production. For this study, the focus was on the results generated from the loop detectors. In Figure 2.27, there was a similar trend in each region witnessed from the accumulation and production. Although there was a slightly lower production that was shown in the Wiedikon region. The regions showed a decline in production, shortly after the critical accumulation was reached. "*While Wiedikon shows a decrease in production once the critical accumulation is reached, this congested branch of the MFD is absent for the City center"* (Ambül, et al., 2017). Notably, this behavior was linked to peak hour congestion control. Ultimately, the obtained shapes were attributed to a well-defined shape of MFD. It was imperative to note the fault loops were omitted before the calculation process. The shape effect had been linked with the region being assessed said to be smaller, leading to less margin of error which means high accuracy. Also, the chosen interval was considered an added factor to this MFD shape. Lastly, the regions had a lesser number of routes dedicated to cars which left the drivers with limited options to adjust to traffic conditions. See the obtained MFDs for both regions in Figure 2.28 below.

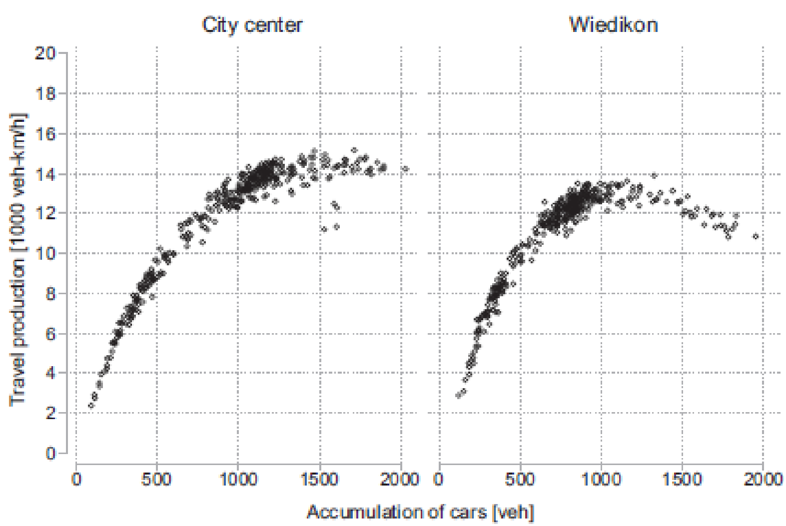

Figure 2.28: Accumulation vs travel production for cars in the city of Zürich.

Source: (Ambül, et al., 2017)

The analysis was repeated but this time the public transport system was the key element. The data of interest included: travel times from one stop to the next (added the dwelling time), distance from stop to stop and passenger occupancy. Factors that were calculated include the average speed, Accumulation and Public transport vehicle production. All these factors mentioned above were critical to the establishment of the MFD, shown in figure 2.29 below.

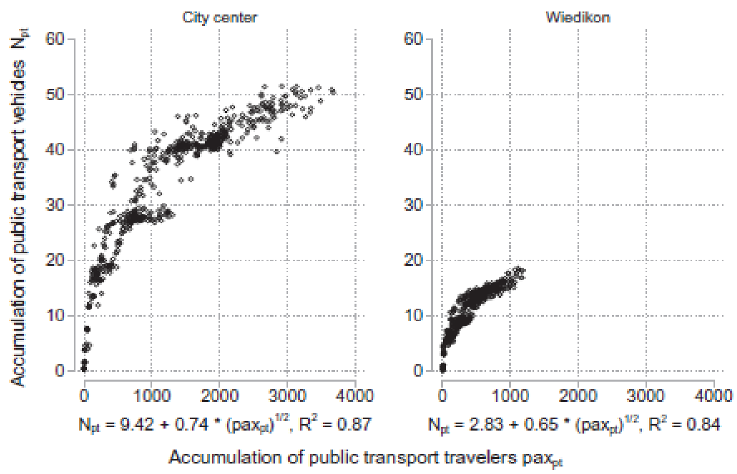

Figure 2.29: The established relationship between the accumulation of PT operational times and public transport travelers.

Source: (Ambül, et al., 2017)

An effort was made to correlate all the findings into one graph that presented both cars and public transport in both regions. A 3D MFD was modeled. This MFD represented a multi-modal interaction looking precisely at the implications of speeds for both cars and public transport. The resulting 3D MFD was shown in Figure 2.30 below with a horizontal axis showing the accumulation of both modes and the y-axis showing the total production.

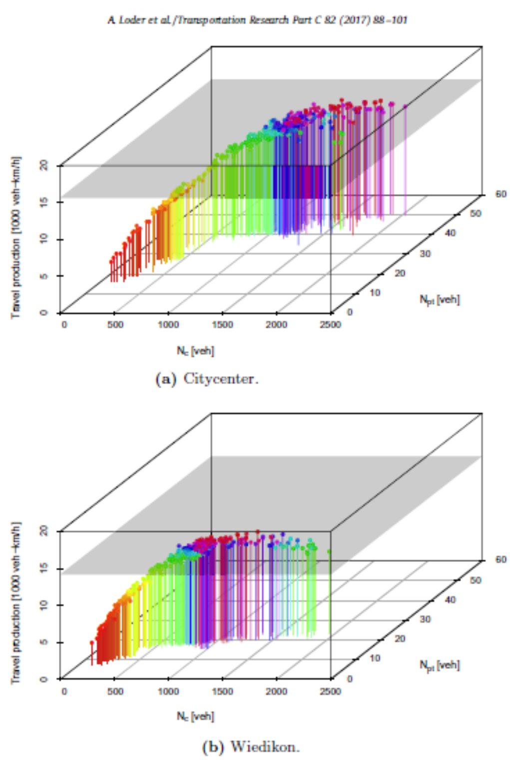

Figure 2.30: The established 3D MFD for the City center and Wiedikon district of Zurich.

Source: (Ambül, et al., 2017)

The following contributions were noted from this paper (Ambül, et al., 2017):

- MFD exists on the urban scale network City center and Wiedikon district of Zurich.
- Cars and public transport have different contributions to the congestion levels.
- Introduction of Public transport dedicated lanes decreases interaction that impacts congestions levels.
- Speed contributions from each mode can be understood when the MFD is assessed based on modal share using the 3D MFD.
- MFD is guided by homogeneity assumptions and similar road hierarchy (arterials MFD differs from freeway MFD).
- 3D MFD can be instrumental to determine each mode's optimal allocation of time.
- Dedicated lanes for public transport possess an impact on the resulting MFD, thus it is imperative modes in MFD are differentiated. Giving priority to Mass transit has an impact on this behavior.
- There is a correlation that exists and has an impact on the resulting MFD that is associated with the network having longer links and a higher number of intersections more especially in situations where public transport is given priority at the intersection (signal controls).
- Prioritizing the public transport movement is essential to improve the urban travel speed.
- Using the 3D MFD city planners can create policies dedicated to cars or public transport modes.
- The accuracy of these findings could have been compromised by the data limitations. For example, public transport constant timetables, the built model was based on conceptual inputs (producing indicative result), the complete car data was missing for some links on the network and lastly, there was an assumption made for effective car length.
- The chosen time interval of 15 minutes was influenced by the public transport time intervals; this was done to avoid scatter of points on the resulting MFD due to small time intervals.

2.12 Empirical Macroscopic Fundamental Diagrams using Data from Loop Detector and Floating Car Data.

A different study conducted in Zürich, Switzerland attempted to showcase the existence of the MFD in an urban scale network (Ambül, et al., 2017). Their study used a combination of loop detector data (LDD) and floating car data (FCD) to showcase the MFD (Ambül, et al., 2017). The existence of the MFD had been originally given an assumption that congestions distribute evenly on a network and are often associated with the term 'homogeneity' and secondly the congestion was independent of the demand patterns as long as the distance traveled was constant or remained unchanged. This study sought to prove that these assumptions were not always the case. A separate study by Ji & Geroliminis (2012) made an effort to verify the homogeneity assumption. Furthermore, the efforts to verify congestion homogeneity and that MFD was independent of the origin-destination (Leclercq, et al., 2015). They investigated a Well Define and Reproducible MFD based on two data sources using empirical data from loop detector data (LDD) and floating car data (FCD). For this study, the anticipated outcome was shifted to loop detector data (LDD).

2.12.1 Data set from of the loop detector

The city of Zürich, Switzerland consists of approximately 400’000 inhabitants, with an approximate area of 91.9km^2. The road networks stretch to about 740 km covered distance, and 4852 loop detectors are operated by the Zürich traffic management institution with 384 detectors found at the intersections. The majority of lanes are dedicated to public transport with less priority being given to private cars. The loop detectors were also said to play a paramount role in identifying and monitoring congestions. The data was collected on the day of 26/10/2015 to 01/11/2015 (Monday to Sunday). Each data set was collected at a 3 minutes interval (the shortest interval so far in this literature). The variables of interest on the collected data were flows(detected number of passing vehicles) and occupancy (percentage spell of the number of private cars that occupied the loop detector) and also the link attributes (loop detectors coordinates, lane configuration, link length and distance).

2.12.2 MFD from loop detector data

The established MFD was estimated from the city region. Out of all the days that were analysed, Mondays were seen to have convincing MFD results. The data collected was then used to calculate flow and occupancy for all loop detectors. It was imperative to note that fault loops were discarded during the calculations to minimize the inaccuracy of the result. The approach used to reach the outcomes was referenced in the paper by Geroliminis and Daganzo (2008). Figure 2.31 shows the obtained result from the loop detector data.

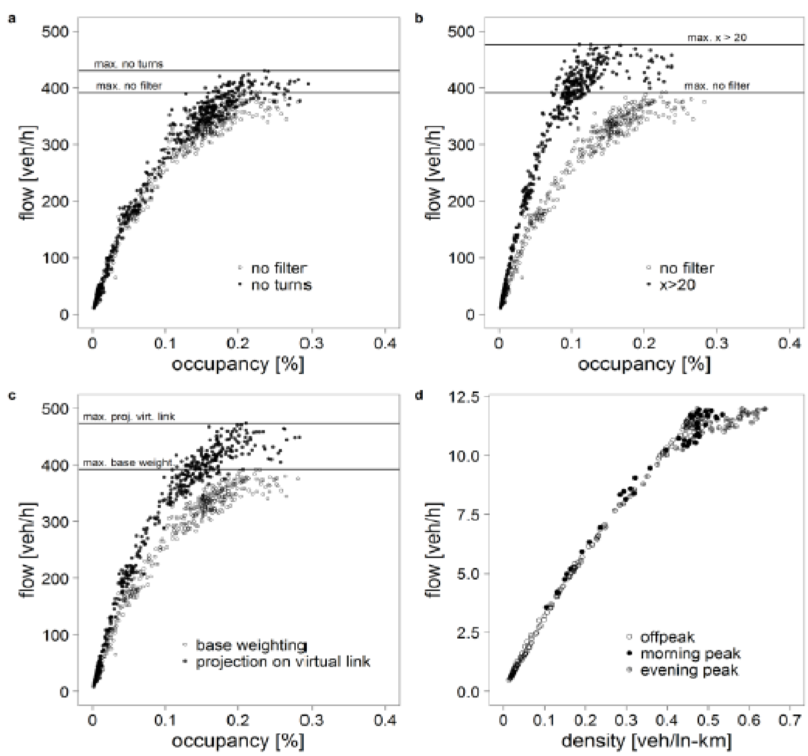

Figure 2.31: Shows the estimated MFD from using the loop detector data in the City of Zürich. Occupancy vs flow and density vs flow.

Source: (Ambül, et al., 2017)

Relatable findings from the works of Geroliminis and Daganzo (2008) in a study in Yokohama, Japan was relatable to this paper's outcomes. A well-defined and reproducible MFD exists in the city of Zürich. What was interesting about these findings was that the changes made during the process of evaluation and the impact they had on the maximum capacity. These findings were discussed below:

- The distribution and the relative distance of the loop detectors from each other have an impact on the established MFD. This was already proved in the works of (Ambül, et al., 2017). To prove this impact, they restricted the loop distance to 20 m from downstream, which enabled them to incorporate loops near the intersection as they contribute to the calculated occupancy. The study recommended the *projection on a virtual link* method to rectify and minimize such biases.
- Uniformly distributed loop detectors from all the intersections produce an accurate MFD (Courbon 22 et al, 2011)
- There is no existing evidence to support the existence of discrepancies when converting occupancy to density (Ambül, et al., 2017).
- Exclusion of the turning lanes flow has an impact on increasing the maximum flow. This is said to be the result of shorter green time for turning lanes when compared to straight vehicles at the intersection. figure 2.31 above demonstrates this effect.
- Loop detectors represent the pertaining conditions on that loop detector location. This hinders the possibility and accuracy of estimating the occupancy for the entire link as traffic state changes over the link (Ambühl and Menendez, 2016).
- The combination of the loop detector and floating car data can achieve a more accurate MFD if used in combination.
- There is still a need for research to assess the implications of the assumed effective vehicle length to the estimated MFD (Yokohama s=5.3 m and Zurich s=6.3 m).
- A counterclockwise hysteresis loop for region "City" and a clockwise hysteresis loop for region "Hard" was observed in the MFD. These variations were attributed to the signal peak and off-peak as traffic controls respond to the demand (congestion level) fluctuations.
- The period of assessment should consider the disruption which may elapse from the construction work.
- It is imperative to note and bring appropriate measures when filling or emptying the city in the morning and afternoon peak periods because peak and level of congestion changes with time. The morning peak controls may differ from afternoon peak controls.

2.13 Hysteresis and Bifurcation Phenomena vs MFD

This study resonated around existing works of literature, which had proven the existence of the MFD relating the average flow and density in the arterial network. It disputes the notion that a well-defined MFD is expected on the urban network regardless of the conditions. Motivated by the works of Buisson and Ladier (2009), the paper argues the trend on these established MFD had been linked to the formation of hysteresis loops and bifurcation phenomena, both these phenomena dispute the idea of a well-defined MFD and alluding the congestions were not always homogenous on the network. The network presents a dispersed congested state that responds to the arterial conditions. The study introduced the phenomena of bifurcation at a broad scale, for an urban scale network in South Korea. The study used data from both weekdays and weekends extracted over a long period.

2.13.1 Study area, Data collection, and Outcome

The study took place in the City of Daegu which is the third-largest metropolitan in South Korea. The city consists of 2.5 million inhabitants and is covered by a network spanning 2400 km long. The road network leads to the CBD. The city experiences higher congestions during the morning and afternoon peak periods. See figure 2.32 below.

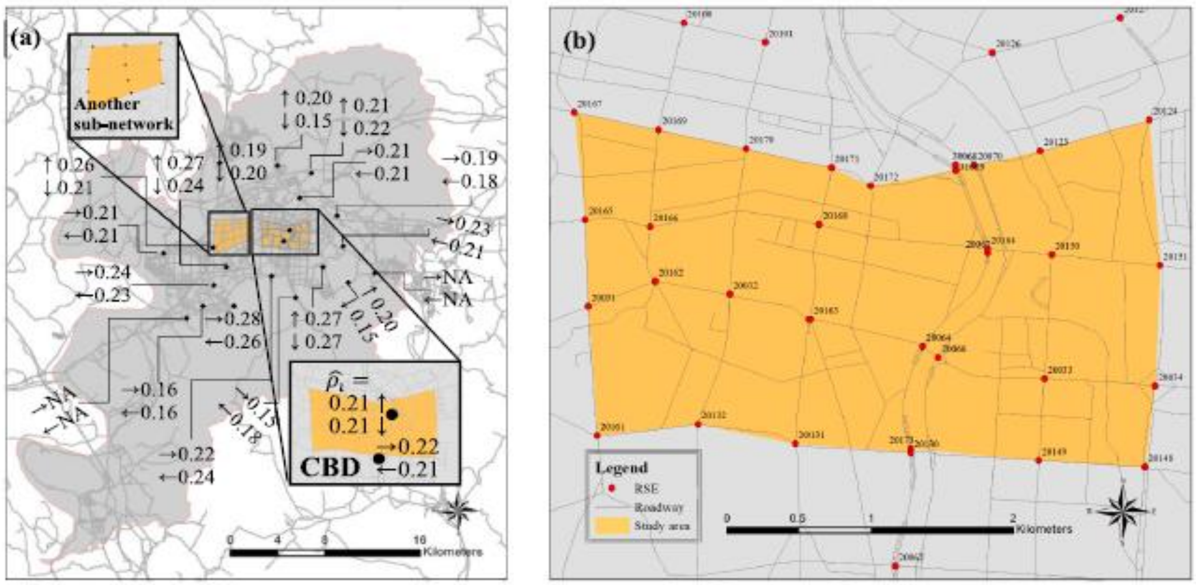

Figure 2.32: City of Daegu with the approximated area of 8.6 km^2

Source: (Shim, et al., 2019)

The focus of this study was on the road network close to the city Centre. It reported 174 detectors were used to collect data. These detectors consisted of transponders that communicated trips from vehicles tagged with transponders that detected vehicles' identities. And for several days, the results are issued below for the MFD. Figure 2.33 shows the estimated MFD that relates to average flow and density exist. The displayed MFD was estimated over 9 consecutive days from the (10th to 18th of October 2015). The data was captured in 15 minutes intervals. A well-defined MFD was noted on both the weekday and weekend data. Notably, the established MFD was seen to take a constant shape particularly from a Monday to Friday data with slight variation observed on Saturday and Sunday MFD. The weekday MFD produced a high average flow and density whereas weekend MFD showed a slight drop in the average flow and Density. A clear bifurcation was also witnessed on the weekday MFD see Figure 2.33.

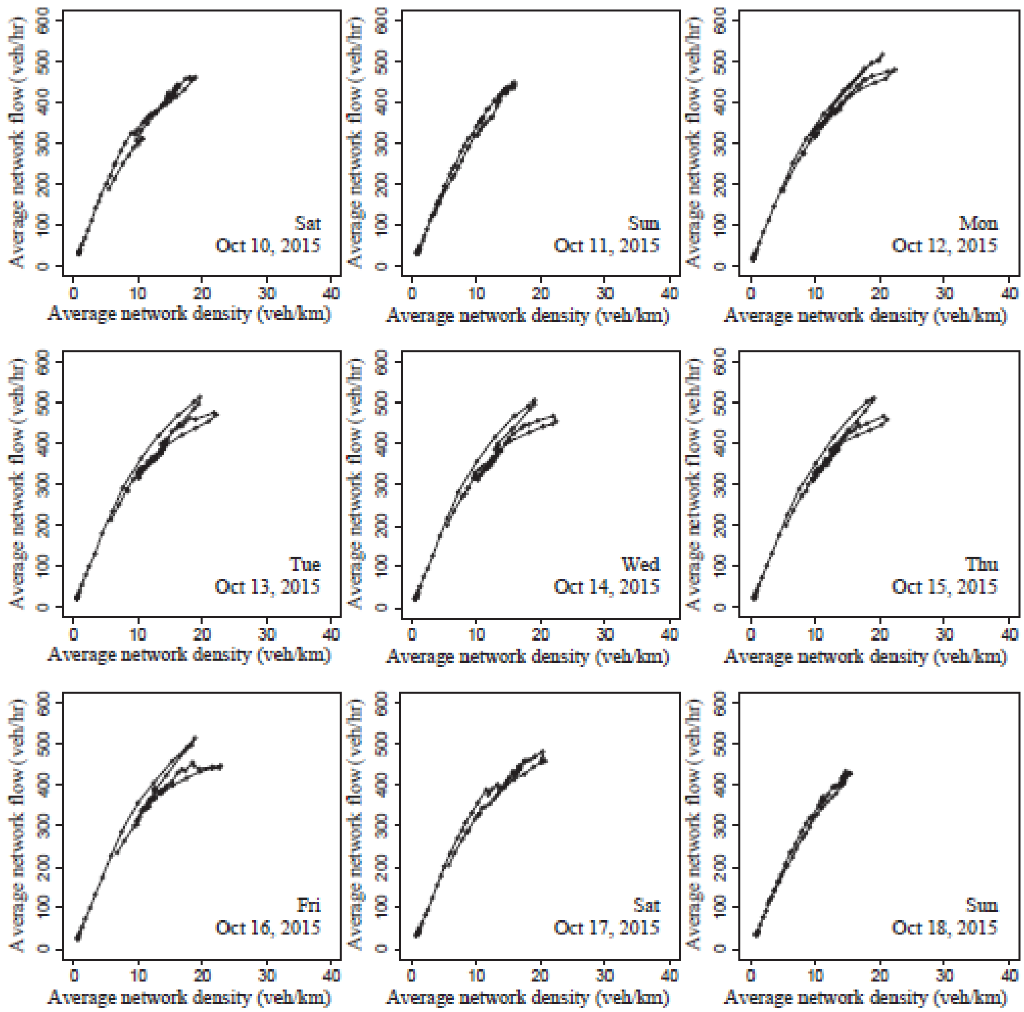

Figure 2.33: A series of MFDs established from weekday and weekend data of the city of Daegu.

Source: (Shim, et al., 2019)

To get a clear picture of the bifurcation an MFD was established for separate regions (for subnetwork) using the weekends and weekdays data. This time 12 detectors located west of the CBD were used to establish the MFD. A quite similar trend was observed, with weekday data showing a clear bifurcation. The results are/were shown in Figure 2.34 below.

What was seen to exist, there was a gradual increase in the morning peak on the average flow and density. The increase was associated with the morning peak period loading on the network. The evening peak period however showed a slight increase and then took a sudden drop in the average flow and density. This resulted in the formation of the bifurcation. A pattern where different values of flow at a point were associated with the same value of the density. This was believed to be associated with the traveler's trip generation. However, it was astonishing behavior. If this behavior could be understood correctly, this would mean that two sets of control shall be implemented on the network. One that is dealing with the morning peak and the other one that would deal with the afternoon peak

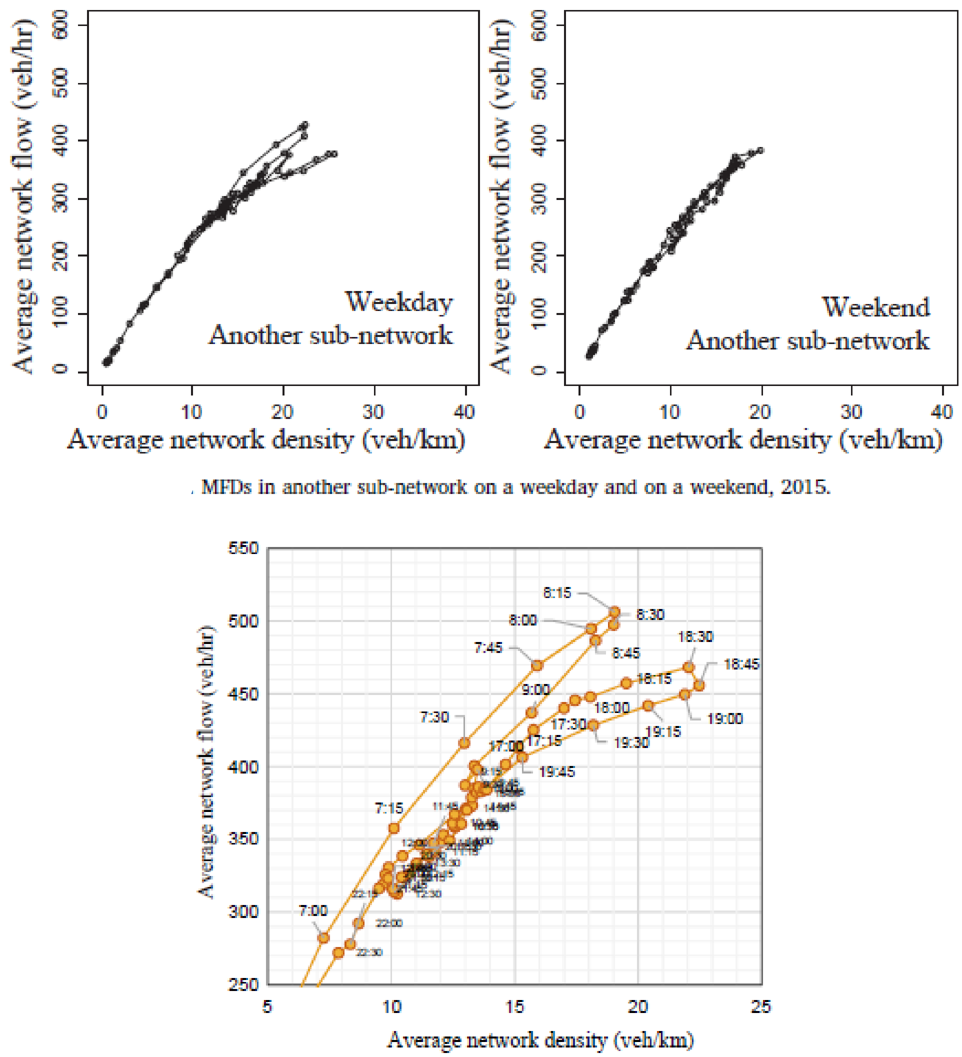

Figure 2.34: The phenomena of bifurcation and hysteresis showcased on the weekday data in the city of Daegu.

Source: (Shim, et al., 2019)

In conclusion, a summary of the findings are discussed below in this paper:

- MFD produced from the weekend data was found to be well defined; evidence linking the space density and the average flow was observed while the observations changed on the weekday data. As much as the MFD seems to be well defined a high bifurcation was observed.
- The bifurcated loops consisted of a higher average network flow in the mornings whereas low network flows were observed in the evenings although the density remained unchanged. This trend was associated with the driver's behavior patterns (i.e. the same drivers make two or more trips in the same region).
- The passenger detour can be highly linked with bifurcation.
- The size of the loop varies with the distribution of the congestion on the network.
- An MFD shape is not constant, however, it varies from time to time depending on the congestion propagation.

- The exaggeration of the penetration rate can result in biased MFD.
- The idea of having two sets of controls (morning and evening peak) being introduced to the network as the result of bifurcation still requires extensive research using real data.
- The paper suggested the impression that the MFD is not affected by the O-D matrix, is premature and not enough research to prove such has been conducted as data for such kinds of studies is not easily available.

2.14 Argument on MFD Application-On Fundamental Diagram and Macroscopic Fundamental Diagram

This part of the paper discusses common arguments and critics associated with the application of the MFD as a tool for traffic management. It breaks down what is often overlooked and potentially leads to misleading information that may risk the accuracy of the outcome. These shortfalls must be highlighted, assessed, and corrected before one even attempts to build models to avoid mathematical and logical flaws.

(Reztsov, 2016) compiled a study using actual data from the arterial networks and motorways. The study focused on developing an advanced practical method for the measurement of actual traffic throughput and reducing cascading congestion. A summary of instrumental sources that brought an impact to the development of MFD was identified. Discussed in this section.

Firstly, studies of the relationship between flow, speed, and traffic density date back to the works of Greenshields (1933) where he studied the relation using photographic measurement on the link of highways. He observed various relations on speed, flow, and density. This led to the development of what was perceived as the first impactful diagram in traffic studies termed the ‘Fundamental diagram (FD). It was noted that this diagram only contained traffic variables (speed, flow, and density) and was independent of time. As technology advanced, it allowed accommodating time on traffic evaluating systems.

Secondly, the introduction of the integral and differential equation that links space allowed planners to solve transportation problems. Both contributions outlined above provide the same fundamental diagram (FD) with the same curve. An effort was made to try and combine the two approaches to verify FD's existence. In that process, these disadvantages were identified.

- On a mathematical model, during the calculation processes errors may occur and they could lead to a deceiving outcome. Figure 2.35 demonstrates a practical example of this effect.
- Mathematical models are often useful and very easy to use, however they are not applicable in all situations. Traffic on the network is dynamic and responsive to the demand as traffic flow changes swiftly. These models can be useful to stable traffic conditions that present situations where flow and density do not change swiftly and often remain stable for longer periods. And these kinds of situations are rare to find in a real traffic scenario.
- The derived MFD and FD in most cases do not consider all aspects of traffic states, for example, incidents, driver behavior, weaving, etc.
- The smooth shape can be deceiving as not all aspects of traffic are somehow accommodated such as the impact of a multimodal behavior, see figure 2.36.

- Over the past years' MFD and FD had been classifying data based on a singular location and arguably do not represent the entire state of traffic over the network and means to access traffic from all links shall be motivated.

Figure 2.35 below shows data that was generated from a single loop detector. The scattered plots differed from what was anticipated. The derived scatter was nothing the same as a smooth MFD curve like the one presented in chapter one of this paper (see figure 1.1). This made it extremely difficult to analyse data for decision making, however, if the analysed data resulted in a smooth curve, an immediate conclusion would have been made on the state of traffic. This raised awareness to question the computational algorithm used by the detectors. In this case, data verification was imperative. In summary, in cases where the MFD is not well defined and requires critical decisions, planners should not be quick to give precise decisions as the result may be premature. It was imperative to assess the suitability of the established MFD before it applied the project investigated.

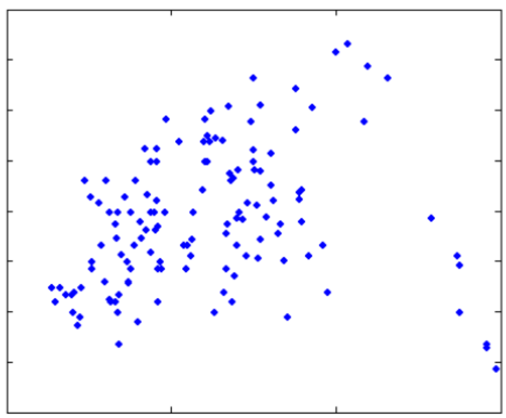

Figure 2.35: Typically collected data on loop detectors, shows scatter.

Source: (Reztsov, 2016)

In recent years, researchers are attempting to analyze the MFDs for a possibility of improvements. The ultimate intention to advocate for the improvement of the MFD properties was to create awareness and emphasis on a more rigorous approach to perform traffic analysis. These arguments did not seek to dismiss the use of the MFD but instead, advised the users to take caution when it comes to its application to each project requiring traffic impact analysis.

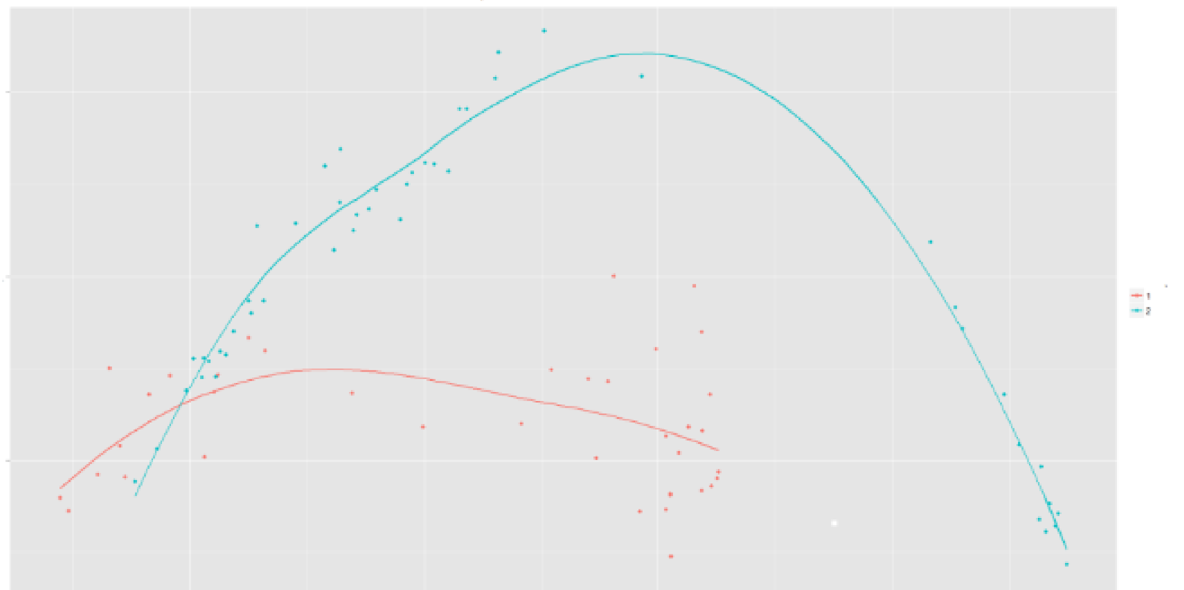

Figure 2.36: Generated traffic model and actual traffic state.

Source: (Reztsov, 2016)

Closing remarks and lesson:

- More effort must accompany the application of FD and MFD. Relying only on its properties may not be enough to provide a robust solution. Every situation differs with the condition of traffic and every situation must be approached with care (analytically and statistically) when using real traffic data.
- Past years had seen the use of MFD gain more momentum than FD despite the latter being invented first. This switch had allowed the analysis of traffic state at network scale compared to single individual locations on a link. Does MFD have those properties that are beneficial for traffic monitoring? Recent studies have shown the potential of these constructed MFDs and their success in managing congestions.
- The obtained real traffic data consisted of low and high values for density and flow on the recorded time interval. When the flow and density points were averaged, they gave a well-defined curve. This occurred while a high variation in the values for flow and density was observed. Some values were extremely high, and others extremely low. The margin of how close or far apart were the values of flow and density was overlooked amid the averaging process. This drew misleading information. Figure 2.37 below demonstrates this scenario: for the same value of the density at five minutes intervals different values of flows were observed, some points were closer to each other and others were far apart. Different flow values were recorded in a short period (1st subset - pink circles, 2nd subset – green triangles, 3rd subset – blue squares). In this short period, a point of high density was observed. A higher flow close to the critical density with a somewhat congested state was most likely within this regime. Taking all

the stated points above and averaging them, free flow regime (low Density and low Flow) points were observed. The final data point was exactly the black data point, and black data points were not associated with a saturated state regime and were deceiving. Although the derived shape of the MFD looked well defined, the reality is that the whole curve was made up of misleading data points. These kinds of results were premature to be used for critical traffic projects.

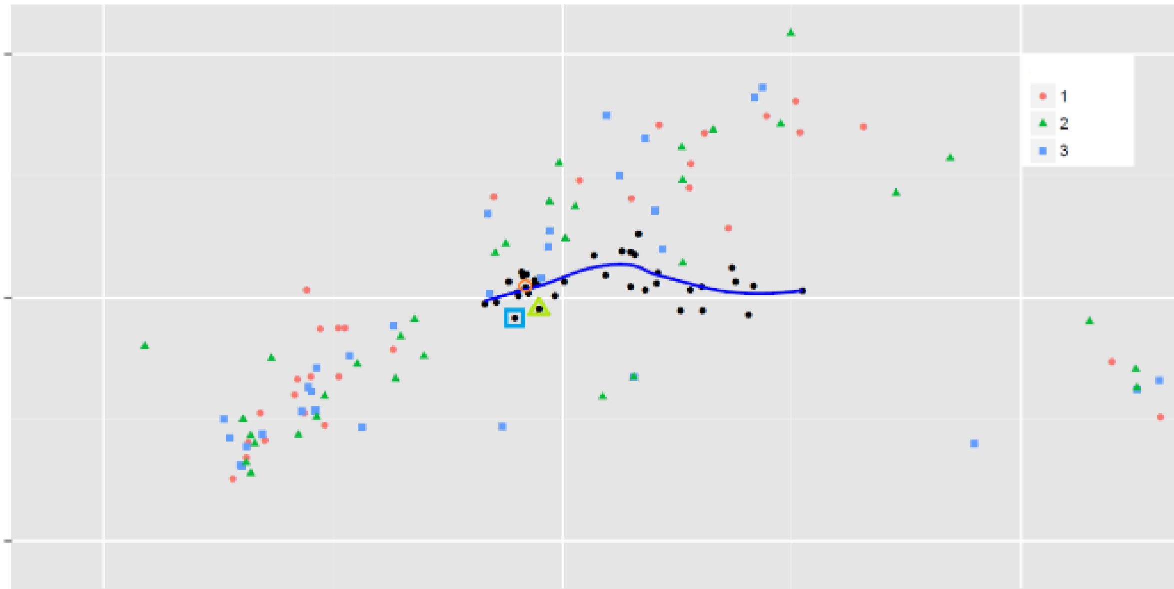

Figure 2.37: Recorded data for three different 5 minutes intervals and all points were averaged to yield a well-defined shape of the MFD (not the case here) represented by the black line.

Source: (Reztsov, 2016)

- Using real traffic data, the derived MFD tends to have a distinctive shape because of the shape of the original data used. Often in cases, you get that FD shapes are embedded on the derived MFD (see figure 2.38). In nutshell, the FD shape tends to reveal itself each time when one inputs data for MFD purposes. It is imperative to distinguish the two scenarios.

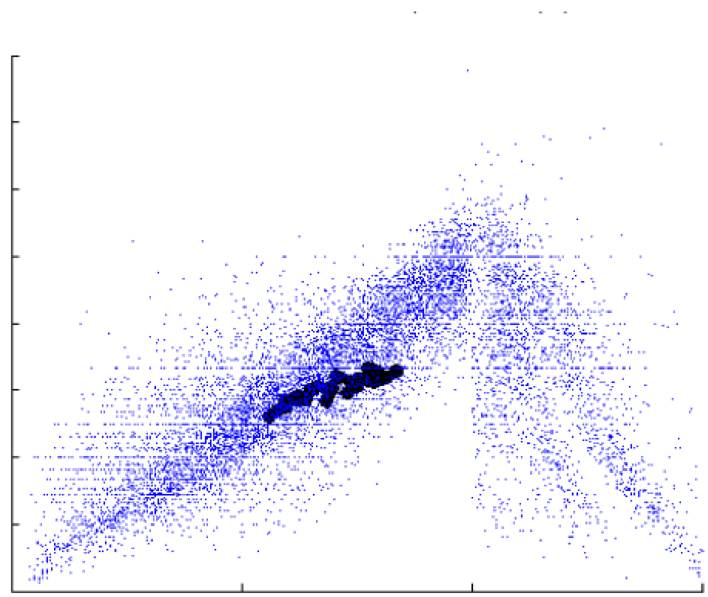

Figure 2.38: Average curve on Real traffic data that represent a normal MFD and FD has FD-shaped geometric structure.

Source: (Reztsov, 2016)

- In the past years, traffic planners had been advocating for computer models because they are easier to use and quick. MFD simulation models were no exception to this topic. The generated data often showcased desirable MFD properties. Almost every traffic simulation program that exists today mostly can simulate the MFD properties. Despite the overwhelming popularity, precautionary measures must be always in place to make sure the derived outcome is a true reflection of what transpires on the ground. The majority of the simulated MFDs depict a well-shaped MFD because of the input traffic data generated in the rigorously matching way to achieve the desired outcome. Researchers tend to assume an evenly spread congestion and simulate traffic data to match the morning and afternoon peak counter-flows. This led to a well-defined MFD diagram meeting the envisaged outcome for peak period travels. To account for this, sometimes researchers applied statistical (i.e. "white noise") to rectify these undesirable outcomes. However, some discrepancies are associated with this attempt, and this was demonstrated in the previous section. Hence, it is imperative to note that if the FD-shaped data are connected to the nice geometric property, the resulting curve automatically would be FD-shaped. A form of backup to support the outcome generated from a computer model must be developed. Transport problems change with every situation. Computer traffic simulation should form the basis of preliminary outcome and not an ultimate output to guard critical decisions in large infrastructure projects.

In closing, the motive of the arguments stated above was not to discourage the use of MFD to rectify the transportation crisis, however, the call was to encourage the transport planners to critically analyze the output data before they are certain that the problem was solved. Analytical verification and statistical analysis prevent such complications. The past has proven otherwise by heavily relying on computer simulation models, massive projects turning out badly because of the wrong or misinterpretations of the MFD results.

Regardless of wrong outcomes, the MFD still leads to impressive outcomes. That was because when the congestion levels arose (flow and density increases) and reached the saturated state (density and flow are high at the time) the formed MFD did not precisely pick up the actual peak flow and density because of the aggregation.

Lets, for instance, assume during the interpretation process the density was picked up far left from the actual saturated density, and the traffic modeler (optimistic the curve of the MFD was correct) went on to proceed to rectify the congestion problem using the identified density(i.e. by say changing the traffic signals to give priority to particular directions of traffic) and fortunately the high congestion levels were solved and everything worked out perfectly despite the selected density being premature. And seeing everything has worked out so perfectly the modeler would be confident that the problem was solved whereas this was done too early because MFD was not precise at the optimal peak yet, nevertheless this prevented the traffic collapse. While on the other hand if the situation was left to become severe could have led to massive delays for travelers and increasing the traveling time (slow traffic movement has an impact on cost- slow production). Try to think of so much effort because of the conclusion drawn from the wrong MFD and the bad implications it could have on the economic viability of the city.

The same would apply to situations where the point was picked up beyond the actual saturated density and the modeler would react to the congestion levels as per the wrongly derived MFD curve, the failure could have been avoided a little bit earlier to avoid the collapse of traffic. Consequently, the congestion rose to an uncontrollable level that led to harsh delays to travelers. In the overall impact, no one would assume the cause being the wrongly interpreted MFD that led to the wrong decision-making. Instead, the blame would be shifted to the unfortunate combination of events.

Improvement of the obtained Outcome:

- Modelers of traffic should develop tools to verify (statistically and analytically) the constructed MFD curves before even attempting to use them on a bigger project and it is recommended real data form bases of the verification process (Reztsov, 2015).
- The computer-simulated output shall be treated as the preliminary outcome despite them looking nice and very impressive (Reztsov, 2015).
- Learn to admit that MFD results are not always going to be well defined as might be anticipated, in the event, this happens the MFD can be vetoed while exploring other means to rectify the problem. In a nutshell, MFD is not always the answer!
- Intensified research on this topic still needs to be undertaken, to find an alternative tool to complement the MFD. Experts from the industry and academia form partnerships to execute these kinds of research. And road authorities should support by providing real data if needed for the study.

2.15 Case Study- A field experiment in Yokohama (Japan)

2.15.1 Introduction and Site description

A field study conducted in Yokohama (Japan) using the empirical data was the first of its kind to prove the existence of MFD at a network-based scale. It has been proven that an urban neighborhood indeed exhibits "Macroscopic Fundamental Diagram (MFD)'' that relates speed, flow, and density. This section reviews the approaches used to execute the study, findings, and gaps for future research. The study used two sources of data; the loop detector data and taxi recorded data and for this study, the focus was on the outcomes achieved from the loop detector data.

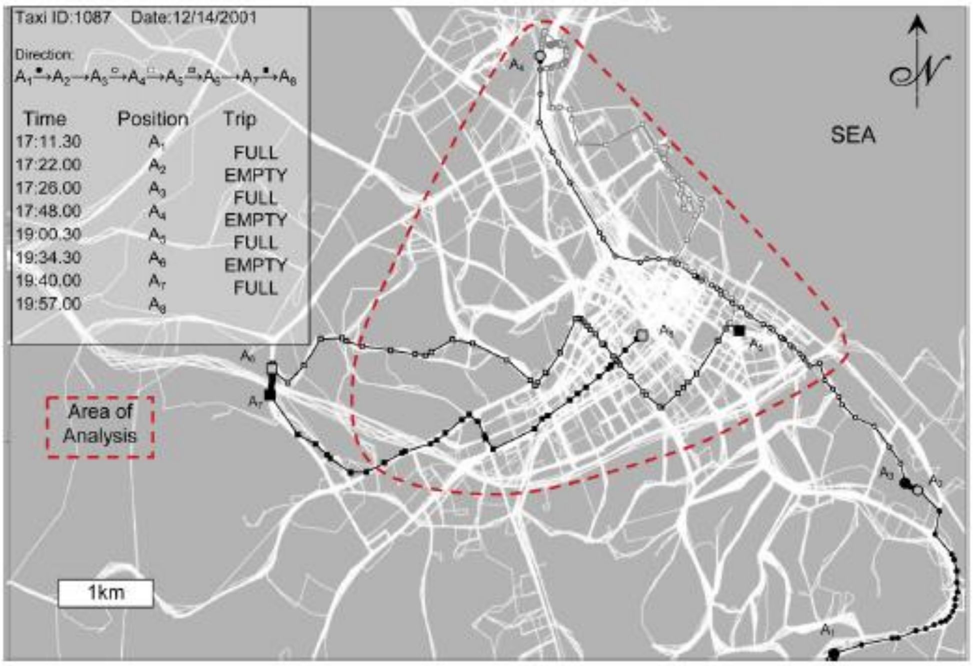

Figure 2.39: Area of the study indicated by the red dotted line.

Source: (Geroliminis & Daganzo, 2008)

The city of Yokohama is the second largest city in Japan with over 3.6 million inhabitants. It is a major commercial hub of the Greater Tokyo Area and the most populous municipality of Japan. The streets layout consists of few elevated freeways with most urban streets covered with signal controls spaced on 200-300mm offset. Major intersections are also controlled by traffic signals. The high volumes of traffic are experienced during the weekdays with an average speed detected to be 10 km/hr during the peak period.

2.15.2 Methodology

The generated data was for the December month and recorded at 5 minutes intervals. A combination of 500 ultrasonic and loop detectors located at approximately 100m upstream of the major intersection was used to record the data. The second source of data was the mobile sensors installed and about 140 taxis were detected by the GPS as they maneuver around the city. The values of interest obtained from the taxis included hazard light, left blinker, trip start and end time, and parking brake activation and deactivation.

They defined a road segment (l_i) between two road intersections where i represent the individual loop detector number. From each station, they were interested in inflow (q_i) and occupancy(o_i). The density was derived from occupancy using the relation $k_i = o_i/s$ where s denotes average vehicle length, and in this study, they assumed vehicle average length as s ≈ 5.5. They further define letters A and A' to lane segments on the network. The interest of this study was the relationship between occupancy and flow at the individual loop detector and the aggregated loop detectors. They considered both the weighted and unweighted values for density and flow defined by Edie (1963) . This was discussed in detail in the next section of this paper.

2.15.3 Results obtained from Loop detectors

After the loop detectors were assessed individually, the result showed a scatter plot forming when the flow was plotted against occupancy (see figure 2.40 below). The obtained data were assessed at 5 minutes intervals for weekdays because the time interval in which the data was assessed is greater than the cycle time for a traffic signal. The impact of endured delays elapsing from the traffic signal was negligent to the outcome. What appeared when they plotted the relationship between occupancy and flow from the individual loop detector the MFD yields a maximum flow at occupancy (oi) ≈ 0.3. The points on the scatter were all over for both detectors (see figure 2.40 a). Take note of the scatter observed on the saturated occupancy, in this case, ≈ 0.3. The scatters observed were said to be caused by changing queue length and the phases of the signals during the assessed period. This scatter was also investigated to see if it would persist when the individuals' links were aggregated. They then aggregated all the individuals' loops to plot the occupancy vs flow graph. This was done for the weekdays (12/14/2001 and 12/16/2001). They again developed a time series between average flow and occupancy versus the time of the day (shown in Figures 2.40b and 2.40c) and the plots on the relation between occupancy and average flow (shown in figure 2.40d). The time series plots indicated the city was congested for the afternoon times of the days on weekdays with the peak flow at time 17:00. The congestion level dropped on weekend days. Also, take note of the variation in occupancy and flow over the time of the day. This was associated with varying origins and destinations during the time of the day.

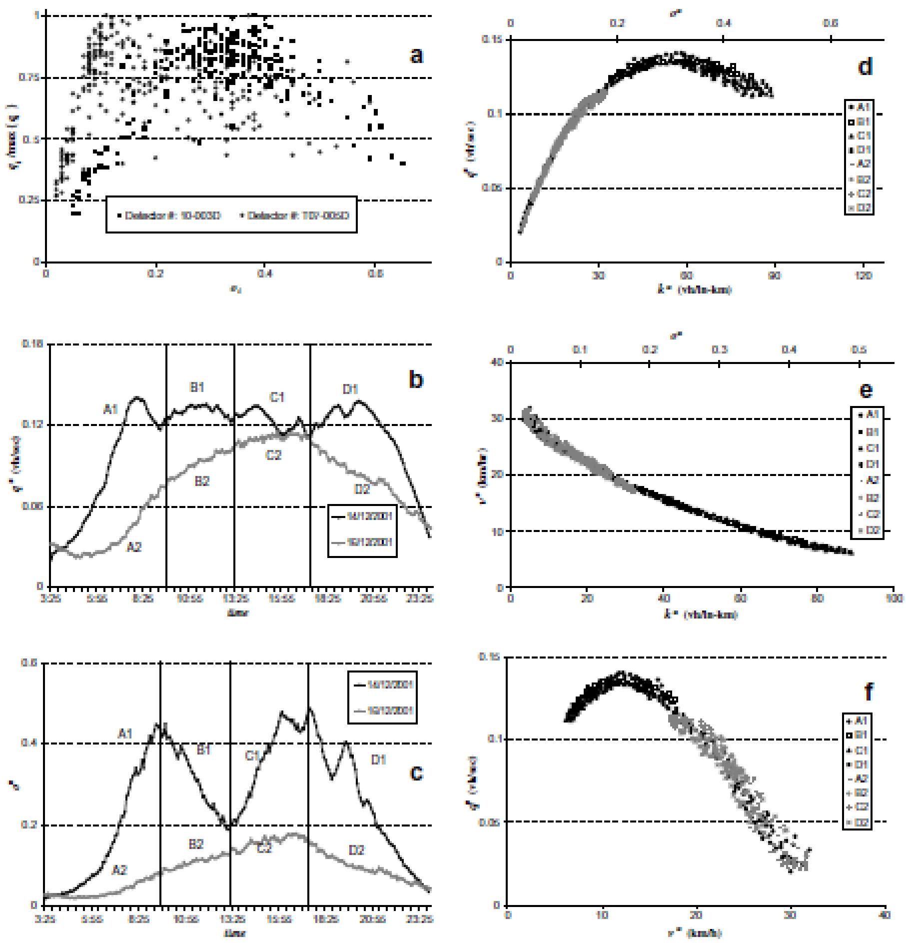

Figure 2.40: Obtained outcome from loop detectors showing (a) individual loop detector flow vs occupancy (b) time of the day vs flow (c) time of the day vs occupancy, (d) aggregated loop detector occupancy vs average flow, (e) aggregated loop detector occupancy vs average speed and (f) aggregated loop detector average speed vs flow.

Source: (Geroliminis & Daganzo, 2008)

Figure 2.40d, e, and f show the result from the aggregated loops for average speed, flow, and density. A well-defined MFD that correlates density and flow seems to exist for a network in an urban neighborhood covered by loop detectors (see figure 2.40d). The aggregated loops MFD shown lower scatter plots when compared to MFD established from individual loop detectors. It was noted that an MFD from aggregated loop detectors in a network exists despite variations in origin and destinations during the time of the day.

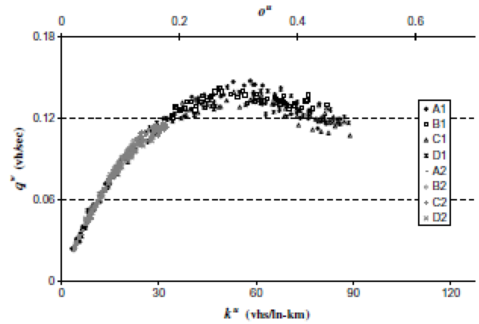

Figure 2.41: The established weighted density and flow from the loop detectors data showing a well-defined MFD Source: (Geroliminis & Daganzo, 2008)

Figure 2.40 showed that average speed vs occupancy was monotonically decreasing. A careful assessment of this established MFD indicated that the network average flow occurs at occupancy of about 0.3 and the average speed was reached at about 13 km/hr (see figure 2.40e). The study further revealed the hysteresis phenomenon explained in the works of Treiterer and Myers (1974) when it was first witnessed on individual lanes. It was attested that if this MFD can be well understood, it can assist in improving perimeter controls. Like introducing controls on traffic that enters or leaves the CBD. For this study, the only outcomes that were achieved from the loop detectors were reviewed, nevertheless, the effort from the authors is acknowledged. The study continues to examine the relationship between the trip completion rate and weighted flow.

2.16 Conclusion

Many researchers have sparked an interest to develop knowledge on this topic. Loop detectors can be instrumental in developing an MFD. Ultimately these findings had shown that indeed MFD is the prevailing property of urban networks (infrastructural components and traffic control measures) and is independent of the origin and destination. With or without knowing the origin and destination the MFD still presents itself on the network. There is a relation between speed, flow, and density in a mean space. The benefit of establishing these MFDs was that they can be used to improve accessibility in the cities for example introducing price measures, improved control traffic measures. In the context of freeway networks, MFD can be used to improve mobility by introducing improved network infrastructure (Daganzo ,2007 and Geroliminis & Daganzo ,2007). Aggregated loops do not always derive a well-defined MFD. Hysteresis and bifurcation tend to somehow occur when loops are aggregated. This was associated with the spatial distribution of the loop detectors.

In closing, what has been of a significant trend in this literature was that the natural shape demonstrated in the early 1950s presents itself in all the studies conducted above, and a correlation between speed, flow, and density does exist (Wardrop & Whitehead, 1952). The vast availability of data nowadays presents an opportunity to revisit and refine some of the identified gaps discussed earlier on this literature; the impact of loops spacing on the MFD shape, freeway network MFD and hysteresis, the impact of mode class to MFD shape, validation of MFD derived from empirical data (one source of data). The traditional approach to traffic studies in modeling has always been influenced by the 'Before and After' studies of speed changes because of changes that occurred on the road layout, such factors include parking, road width, right turns, and lane markings on the behavior of traffic.

3 RESEARCH METHODOLOGY

3.1 Introduction

This section discusses the methodology that was followed to achieve the objective of this study. The section firstly defines what is MFD, followed by the discussion of the concepts behind the data collection on loop detectors. It provides a brief description of the study area and clearly outlines the assumptions and limitations made along the calculations process. The success of this research was guarded by having adequate data available to perform the calculations. The displayed figure 3.1 below outlines the strategic approach that was followed.

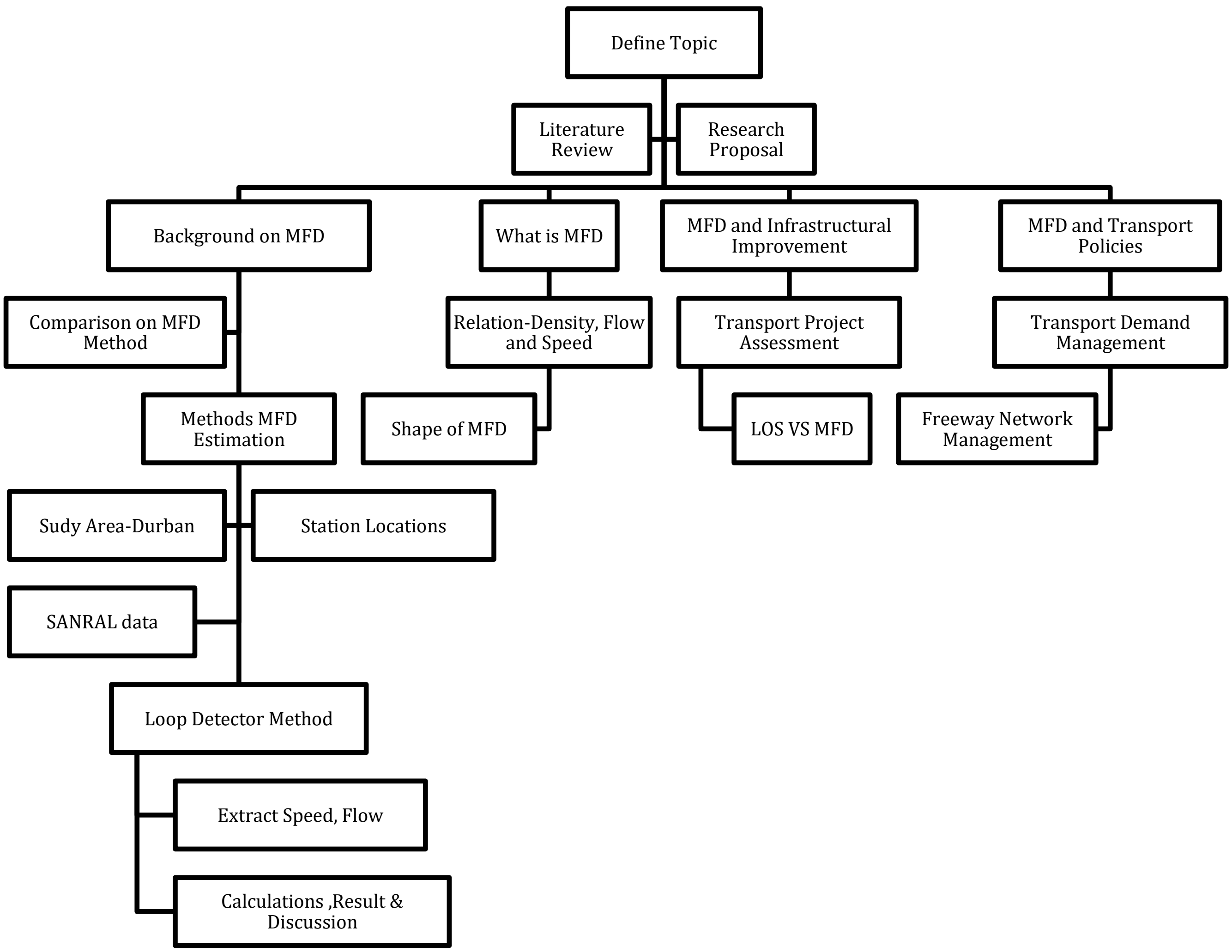

Figure 3.1: Methodological approach

3.2 Definition of an MFD

Macroscopic Fundamental Diagram (MFD) had been widely used and became a very popular tool for traffic and transport engineers to rectify transportation problems. It is rare to find a modern transport professional who does not know what an MFD is and explains its properties. Figure 3.2 demonstrates the typical shape of the MFD and shows the relationship between traffic flow and density.

For a general traffic system, the traffic state begins in point A, where lesser traffic flows are observed on a road with low density, this state is termed free flow or unsaturated state. As time continued, there was an increase in density as more vehicles joined the network at some point in time, the flow rises to a moderate level (point B). Likewise, the speed decreases as more vehicles are joining the networks. As more and more vehicles join, the network density increases while the flow increases until the ultimate state is reached-often termed saturated density or maximum flow (point C). If the density increases beyond this point, we will see flow starting to decrease slower (point D). As the density continues to increase as more vehicles join the network beyond point D, jam density is reached, at this stage no vehicular movement will happen and this state is called oversaturated density, gridlock will result. Note it is assumed that these Density-Flow relationships do not depend on time. An exact pair of coordinates could be found at any time of the day on the MFD curve.

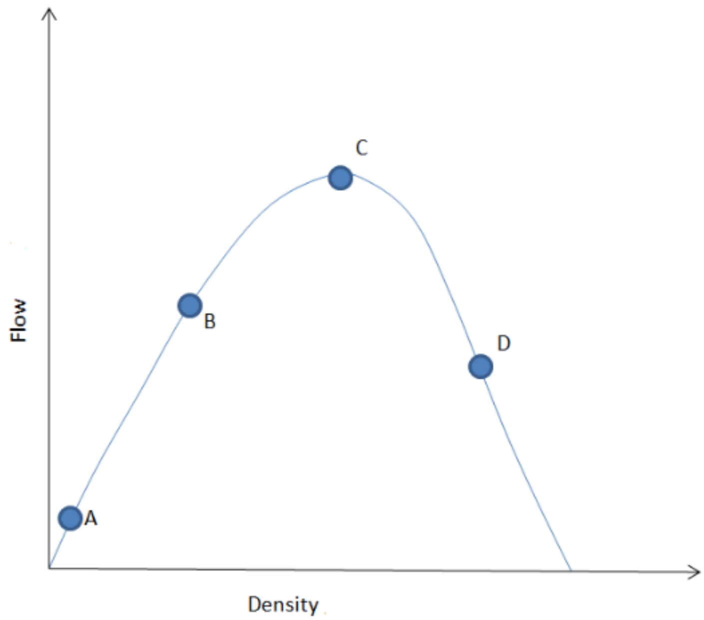

Figure 3.2: Basic graph of MFD to demonstrates flow vs Density and presiding stages.

Source: (Reztsov, 2016)

3.3 Loop Detector Method

3.3.1 The Principle/Theoretical Aspect of the Loop Detector

Numerous methods have been proposed to study and calculate the MFD, ultimately each method was complemented by the type of instrument or source of data. These methods have presented advantages and disadvantages about their uses to establish the MFD (Leclercq, et al., 2015). This study has resorted to applying the Loops detector method merely because that was the only source of data that was available and loops detectors are the most common and famous source of data in traffic engineering. The Loop detectors simply aggregate the volume (N_i) of vehicles on the links (i) for a 5 minutes time interval to establish the ideal state of traffic in the network. To understand the principle behind the loop detector, consider vehicle k, on a loop detector covering a distance from x to $x +$ on a link i. The passing time for the vehicle k at x link distance on the simulator can be derived from the equation:

$$t_k(x) = max\ (t_k\ (0) + \frac{x}{u}, t_{k-n_i k(l_i - x)}(l_i) + \frac{l_i - x}{w} \qquad \text{Equation 3.1}$$

From the equation above, the t_k is the passing time of vehicle k at distance x. From this data, the average speed for traffic was obtained at a time interval t, subsequently, the aggregated volume (Ni) was then applied to further obtain the traffic flow and density for the traffic state. Figure 3.3 below demonstrates the process involved.

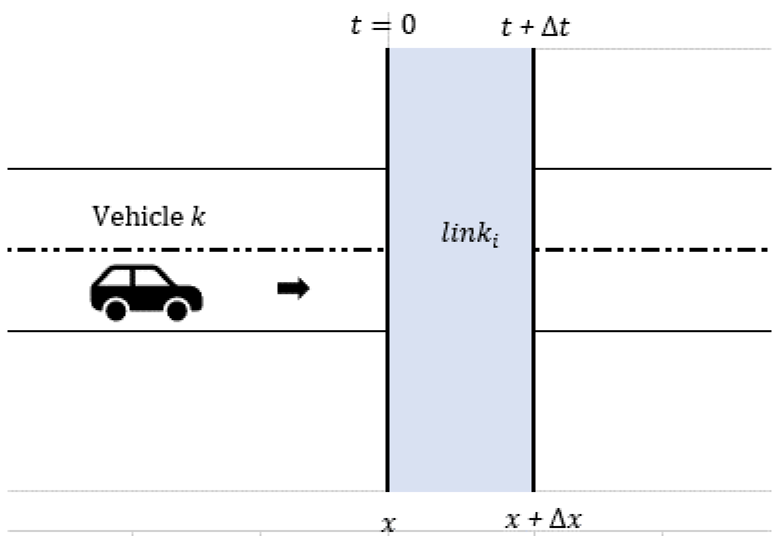

Figure 3.3: A demonstration of vehicle k passing loop detector l_i.

From the above illustration on the loop detector technique then one can use the outputted volume and speed to determine the flow q_i and density k_i by applying (Edie, 1963) definition:

Flow:

$$q_i = \sum_k \frac{d_k}{\Delta x \Delta t}$$ Equation 3.2

Density:

$$k_i = \sum_k \frac{\tau_k}{\Delta x \Delta t}$$ Equation 3.3

Where d_k denotes the distance by vehicle k and τ_k denotes the time spent by vehicle k on the loop detector.

3.3.2 Loop Detector principle and MFD

Figure 3.4 displayed below shows the steps followed to establish the MFD.

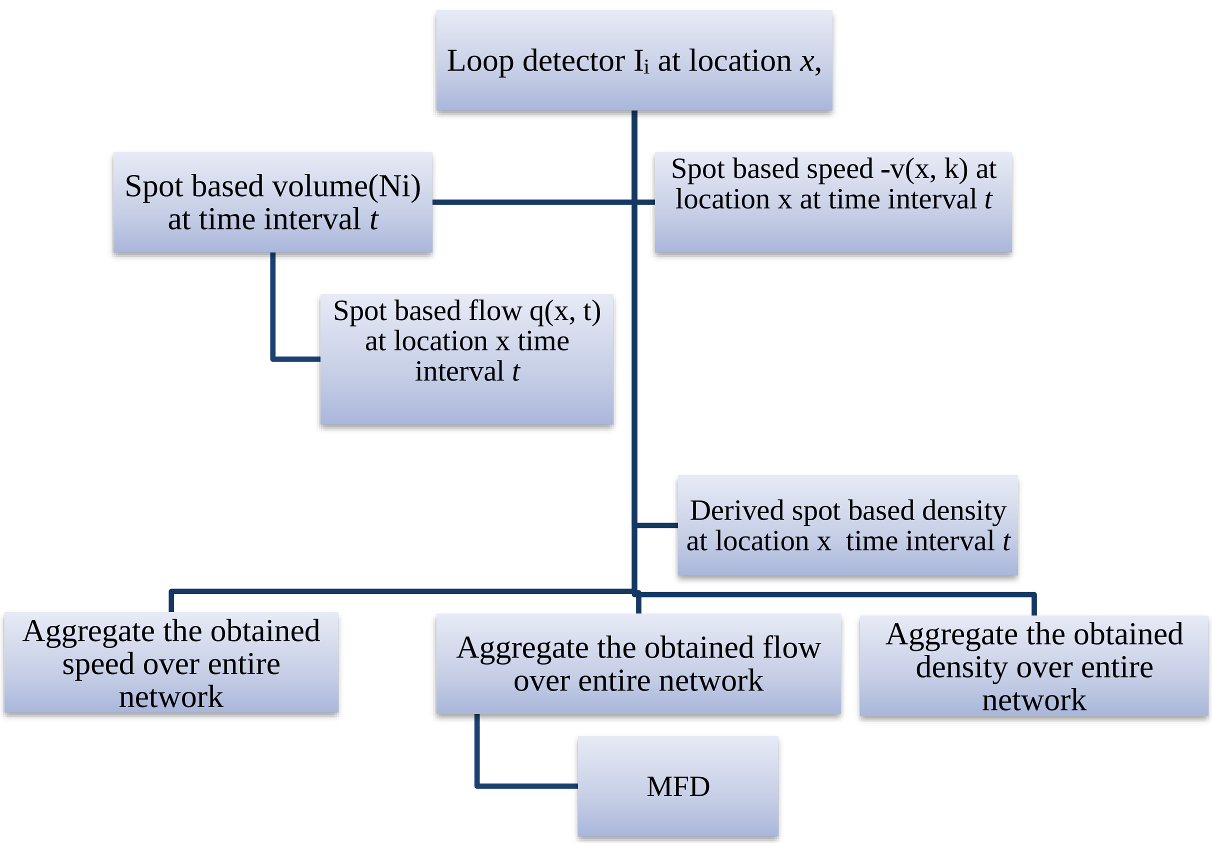

Figure 3.4: Steps to determine the MFD

Influenced by the principle that holds on the loop detector, the MFD resorted to the same concept by simply replacing the *qi* and *ki* on equations 3.2 and 3.3 displayed above. This method is formally known as the Loop Detector method. The derived MFD is restricted to the links which are covered by the loop detectors. Ideally, to establish an MFD that characterizes a route network, the distribution of the loop detectors on the links must resemble a network. Therefore, the derived MFD can be used as an estimate of the entire network MFD (Geroliminis & Daganzo, 2008). The positioning, spacing, and the number of loop detectors have a greater impact on the shape of MFD to be derived on that network (Buisson & Ladier, 2009).

3.3.3 Average Flow and Density and Speed

Generally, the number of loop detectors existing on the network is summed up to determine the average flow and average density. The average speed was detected on the loop detector during the analysis period. Arguably, loop detectors spaced one kilometer apart can provide an estimate of the mean flow and speed with lesser discrepancy. The Space mean speed and flow for locations x_i and x_{i+1} at time interval t can be estimated as follows:

$$v(x_i,x_{i+1},t)=\frac{1}{N_i}(v(x_i,t)+v(x_{i+1},t)) \qquad \text{Equation 3.4}$$

The average flow along section (x_i, x_{i+1}), can be approximated by:

$$q(x_i,x_{i+1},t)= (q(x_i,t)+q(x_{i+1},t)) \qquad \text{Equation 3.5}$$

The speed v is detected from the loop as vehicle k passes the detector at a time t interval thus from (Edie, 1963) definition of the relationship between flow, speed, and density, the average density in section (x_i, x_{i+1}):

$$\rho_{av}\ ((x_i, xi_{+1},t)= \frac{q(xi,xi+1,t)}{v(xi,xi+1,t)} \qquad \text{Equation 3.6}$$

where:

- i = loop detector index(station),
- v (x, t) = speed recorded at location x, for a duration period or time interval t. Measured in kilometer per hour (km/hr),
- q (x, t) = flow calculated at location x, for a duration period or time interval t. Measured in vehicles per hour per lane (veh/hr/lane),
- v (x_i, x_{i+1}, k) = average speed taken between the station's links at location x_i and x_{i+1} for a duration period or time interval t (km/hr),
- q (x_i, x_{i+1}, k) = average flow calculated between location x_i and x_{i+1}, for a duration period or time interval t. Measured in vehicles per hour per lane (veh/hr/lane),
- ρ (x_i, x_{i+1}, k) = average density calculated between location x_i and x_{i+1}, for a duration period or time interval t. Measured in vehicles per kilometer per lane (veh/km/lane).

3.3.4 The Disadvantages of using the Loop Detector on Density and Flow Estimation

For this study, it was imperative to look at the shortcomings of the loop detector because the entire data was collected using loop detectors placed at various positions. The above procedure is called the loop detector method. Like any other method, there are advantages and disadvantages associated with its application. The most common criticism is inadequate to estimate the density distribution between two loop detectors. Essentially the estimated density only provides the information at only the station position (that is why it is often termed "spot density"). Arguably, a lot can be missed on the provided data because the collected data disregard the information between the stations. This is most likely to happen when the stations are located far apart from each other (in the circumstance of the long stretch of highways) and or in cases where the section definition may not be compatible or appropriate for traffic control.

Another common critic includes its high maintenance costs to keep them running. They deteriorate pavement structure during its installation process and bad climate conditions may lead to discrepancies and loss of important data.

3.4 Description of the Study site

The project was conducted in the City of Durban, an urban development that consists of mixed land use development and varying from high-income to low-income residential areas. The Central of Business District (CBD) is located at the one end of the city as the main centre of employment for the residential areas. The City population is estimated to be 3 752 850 (Census,2011). The city is formerly known as eThekwini and is the third-largest city in South Africa, known for its relaxation to tourist attractions. It continues to play a pivotal role in facilitating trades between international alliances and Southern African countries because of its prominent port located at one end of the city center. This major commercial hub has been instrumental to the economic development of South Africa and as a result, it has led to an immense impact on the traffic volume exiting and entering the city. Connecting the city to the economic metropolis of Gauteng is the N3 route Freeway, which starts in the central business district and heads toward the inner lands of the city via the Mayville and Westville suburbs. The first tollgate to encounter before exiting the city is the Marianhill Tollgate. Adjacent to the N3 route is the N2 Outer Ring Road running from the coastline of Western Cape, Eastern Cape, and KwaZulu Natal province to later tie to Mpumalanga province. Joining these two major routes is the EB cloete interchange. The mentioned corridors are very important and are at the core of the economic development of South Africa because of freight shipping from the upper regions of the country for a transfer to the Durban port.

Forming part of the highway network are the metropolitan arterials and provincial routes. The inner part of the city consists of a grid street layout with a national route at the periphery of the city (forming a radial layout). The EB Cloete Interchange located east of Westville connects the N2 Outer Ring Road and the N3 Freeway, found at approximately 5 km to the city centre. Adjacent is the provincial route R102 which serves to connect the sprawling townships to the city centre before connecting the metropolitan street (M4, M12, M10, M17) which connects via to the CBD. Figure 3.5 shows a pictorial description of what was mentioned in this subsection.

Figure 3.5: Study area; showing the existing network (Forms a radial direction)

Source: (Durban Map, 2020)

The freeway network includes various types of traffic control systems at the intersections. They vary from at grade intersections which consist of signalized control to high order interchanges that facilitate the free flow movements. The spanning of the interchanges ranges between (1km–5 km) center to center. The number of lanes from the freeway ranges between 1-4 lanes with some forming single divided/undivided carriageways and others as dual divided/undivided carriageways. The speed limit is 120 km/hr on the freeway and drops as one moves to arterial routes, range 40-80 km/hr.

3.5 Data collection

The region being investigated in this study consists of an area of approximately 2.30 km^2 with 88 loop detector stations placed at various positions along the N2 and N3 corridor (see figure 3.6 below). The traffic stations are administered by Mikros Traffic Monitoring (Pty) on behalf of SANRAL. The data extracted from the traffic stations was spanning for one month (September 2019). The data was collected at every 5-minutes interval. No discretion was followed in choosing which month of the year was appropriate to perform the study; however, this was based on the availability of the data at the time. Of course, data collected during the lockdown period (due to the Covid-19 pandemic) was deemed biased and ruled out for the context of this study.

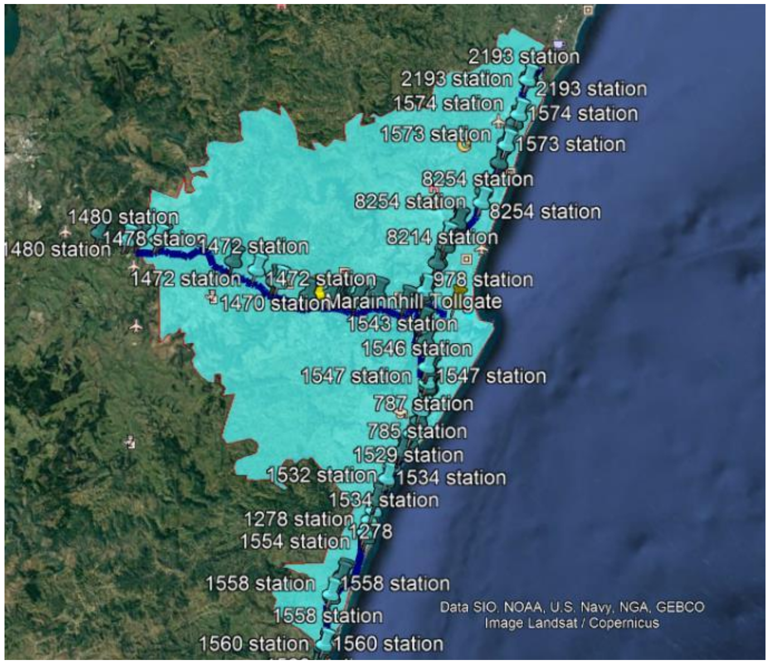

Figure 3.6: Study area showing loop detector stations.

Source: Google earth

Critical to the context of this study, each loop detector was analysed for its location, the number of lanes it consists of, the amount of traffic volume recorded at five-minute intervals, and the speed detected during the time interval. Figure 3.7 below shows the station details from one of the loop detectors.

Station Information

Site Identifier	1280	**Site Number**	1280
Site Name	Westmead W/B		
Site Description	Westbound between Queensburgh & Richmond Rd		
Site Type	Permanent Piezo	**Owner**	SANRAL
Physical Lanes	3	**Responsibility**	NON-TOLL
Logical Lanes	3	**Installation Date**	1999-09-23
GPS Longitude	30.833218	**Termination Date**	
GPS Lattitude	-29.827351	**Status**	In Use
Region	East	**Companion Site**	
Road	N003	**Speed Limit**	120
Route	N003	**Count Type**	Normal Traffic Counting Station
Section	01	**Distance**	21.80

Lane No	Lane Description	Stream No	Stream Description	Direction	Reverse Lane No	Pos
1	Slow to Pietermaritzburg	1	To Pietermaritzburg	North-West	0	1
2	Middle to Pietermaritzburg	1	To Pietermaritzburg	North-West	0	2
3	Fast to Pietermaritzburg	1	To Pietermaritzburg	North-West	0	3

Figure 3.7: Station details from loop detector 1280.

Source: Mikros data,2019

Fixed loop detectors positioned at approximately 100-500 m on both the N2 and N3 corridor, displayed various trends on the traffic counts. The ultimate objective was to determine the flow and density in the investigated area from the provided 5-minutes time interval data. The station location and description are provided in tables 3.1 and 3.2 below (Adapted from Mikros data).

Table 3.1: Station name, number, and position for N3 route.

National route 3(N3)			
Site Name	**Site Number**	**Site Description**	**Route**
EB Cloete East	792	Between Mayville I/C and St James I/C	N003-1
EB Cloete West	979	Between St James I/C and Mayville I/C	N003-1
Westmead W/B	1280	Westbound between Queensburgh & Richmond Rd	N003-1
Westmead E/B	1281	Eastbound between Mahogany & Richmond Rd	N003-1
Westmead WIM WB	3028	Westbound between Queensburgh & Richmond Rd	N003-1
Rainbow Camperdown	1357	Between Cato Ridge & Camperdown I/C	N003-2
Ashburton	529	Between Ashburton I/C and Lion Park I/C	N003-2

Table 3.2: Station name, number, and position for N2 route.

National route 2(N2)			
Site Name	**Site Number**	**Site Description**	**Route**
Py89 707Hibberdene	771	Northern side of Hibberdene I/C	N002-23
Winkelspruit Piezo	1278	Between Umgababa I/C and Winkelspruit R603 I/C	N002-24
Oppenheimer Bridge	1166	50m North of Oppenheimer Bridge N2	N002-24
Prospecton	785	Between Joyner & Prospecton I/C	N002-24
Airport - Gateway 1	787	N2 S/B Between Higginson I/C and Dbn Int Airport	N002-25
Airport - Gateway 2	788	N2/M4 Between Dbn Airport & Higginson I/C	N002-25
Airport - Gateway 3	789	N/Bound N2/M4 Split South of Higginson Highway	N002-25
Airport - Gateway 5	1056	N2 S/B to Airport & M4 S/B to Airport	N002-25
Airport - Gateway 4	1055	M4 S to Airport (N2) Isipingo & Umlazi	N002-25
NPC	1165	Outside NPC on N2	N002-25
EB Cloete South	980	Between Edwin Swales I/C and Umgeni Rd I/C	N002-25
EB Cloete North	978	Between Umgeni RD & Edwin Swales I/C	N002-25
Nandi NB Flash	1381	South of the Imvubu Place Bridge (NB Only)	N002-25
Nandi SB Flash	1382	Before the Nandi Drive Bridge (SB Only)	N002-25
Kwa Mashu I/C	794	Inside KwaMashu I/C	N002-25
King Shaka SB Ramp 1	2742	Southbound on-ramps at King Shaka Airport I/C	N002-26
King Shaka SB Ramp 2	2743	Southbound on-ramps at King Shaka Airport I/C	N002-26
Tongaat NB Off 1	2192	Northbound Off-Ramp to Watson Highway I/C	N002-26
Tongaat NB Off 2	2193	Northbound Off-Ramp to Watson Highway I/C	N002-26

Tongaat SB on 1	2194	Southbound on Ramp from Watson Highway I/C	N002-26
Tongaat SB on 2	2195	Southbound on Ramp from Watson Highway I/C	N002-26
Tongaat North 1	2202	Northern Ramps of Watson Highway I/C	N002-26
Tongaat North 2	2203	Northern Ramps of Watson Highway I/C	N002-26
Tongaat North NB 1	2204	Northern Ramps of Watson Highway I/C (NB Only)	N002-26
Tongaat North NB 2	2205	Northern Ramps of Watson Highway I/C (NB Only)	N002-26
Tongaat North SB 1	2206	Northern Ramps of Watson Highway I/C (NB Only)	N002-26
Tongaat North SB 2	2207	Northern Ramps of Watson Highway I/C (SB Only)	N002-26

During the calculation process, some loop detectors presented errors and discrepancies in the collected data i.e. in the form of speed and volume with some recorded time intervals presented blank spaces for either speed or volume detections, obviously, for the sake of this study, those loop detectors were left out prior data analysis.

3.6 Calculation of Flow and Density

This section of this paper describes the method followed to calculate the variables of the established MFD.

Step 1: The station information details are the first point of interest i.e station number, location, number of lanes it covers as well as the date and time of operation. In table 3.3 below station number 788 was used as an example for the purpose of this paper.

Table 3.3: Station recorded data

Site ID	Date	Time (Min)	Duration (Hours)	No. of lane
788	9/2/2019	5:00:00	00:05	4
788	9/2/2019	5:05:00	00:05	4

Step 2: From the loop detector, the speed and volume were generated every 5 minutes. The general equation to determine the density is the flow/speed. In the process note that density is obtained per lane. The loop detectors provide volume output, so the volume was then used to calculate flow per lane. The outputted data is shown on the excel spreadsheet below:

$$q_v\ ((x_i,\ xi_{+1},t)= \frac{5\ Volume}{60}\ x\ \frac{1}{number\ of\ lane}$$

$$q_v\ ((x_i,\ xi_{+1},t)= \frac{5\ x57}{60}\ x\ \frac{1}{4}.$$

$q_v\ ((x_i,\ xi_{+1},t)$=171 veh/hr *(see table 3.3 below raw 1 column 8)*

Table 3.4: Estimated flow after conversion.

Site ID	Date	Time (Min)	Duration Hours	No. of lane	Speed (km/hr)	Volume (veh/min)	Flow (veh/hr)
788	9/2/2019	5:00:00	00:05	4	65.45	57	171
788	9/2/2019	5:05:00	00:05	4	66.8	48	144

Step 3: The obtained velocity and flow are then used to calculate the density applying equation 3.6.

$$\rho_{av}\ ((x_{i,}\ xi_{+1},t)= \frac{q(xi,xi+1,t)}{v(xi,xi+1,t)}$$

$$\rho_{av}\ ((x_{i,}\ xi_{+1},t)= \frac{171}{65.45}$$

$$\rho_{av}\ ((x_{i,}\ xi_{+1},t)=2.61\ veh/km\ (see\ table\ 3.4\ raw\ 1,\ column\ 4)$$

Table 3.5: Estimated density.

Speed (km/hr)	Volume (veh/min)	Flow (veh/hr)	density (Veh/km/lane)
65.45	57	171	2.61
66.8	48	144	2.16

Step 4: Then a plot between density vs flow is produced. This was plotted for all Mondays in the month of September 2019.

Table 3.6: Calculated values of the Density vs Flow.

Time(Min)	30- Monday Afternoon PEAK		
	Density(veh/km/lane)	Flow(veh/hr/lane)	Variance
16:00:00	8.28	630.35	23.50297
16:05:00	8.40	635.12	25.78424

Step 5: Using the excel tool a plot of density vs flow was generated.

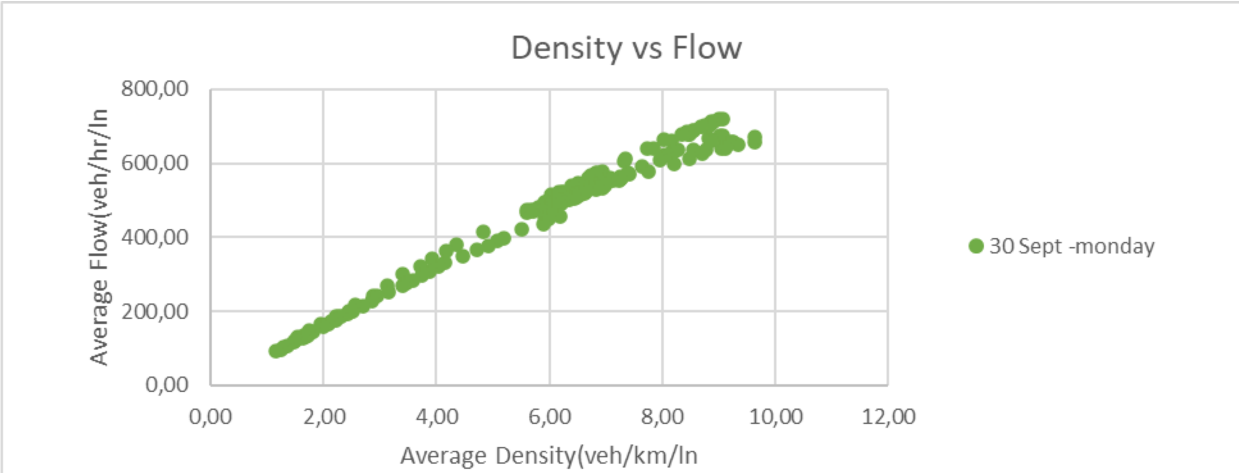

Figure 3.8: Density vs flow graph (MFD)

3.7 MFD and Hysteresis phenomenon

One of the main objectives of this study was to establish whether the presented MFD was well defined or not. And to conduct the analysis, a methodology presented by Geroliminis and Sun (2011) on Hysteresis phenomena for freeway networks was followed. The observed relationship between flow, density, and variance confirms the existence of a well-defined MFD. The formation of the hysteresis loop was associated with observed variance for density and flow. Lower network flows are associated with a higher variance. From the normal shape of the MFD, as the density moves further away from the saturated density (at maximum flow), the flow decreases on either side of the graph. This prevailed itself at a network scale. When density spreads away from the mean, network flow decreases, and a high variance is expected.

4 RESULT AND DISCUSSION

This chapter seeks to explore the results achieved from the data analysis. The loop detector method was adapted and followed to perform the calculations. The results presented are based on the weekday data from all Mondays in September 2019 (i.e., 02/9/2019, 09/9/2019, 16/9/2019, 23/9/2019, and 30/9/2019). The outcomes were presented in the form of tables, line graphs, histograms, and bar charts. The limitations and assumptions made during the data analysis were highlighted in this section. Calculation steps were/are explained in detail in the attached appendix(A). Most importantly, the section sought to discuss the findings obtained and link the outcome to what has been discussed in the literature thus far. In closing, identify gaps and an opportunity to address uncertainties in future research.

4.1 Time series and Daily Traffic Patterns

To have an idea of the traffic trend to the freeway network, it was imperative to first establish the time series for the network. It was found that the region exhibits a congested state during the weekdays. The time-series graph indicated that at time 7:20 the network was at the most congested state (Q = 733.28). See figure 4.1.

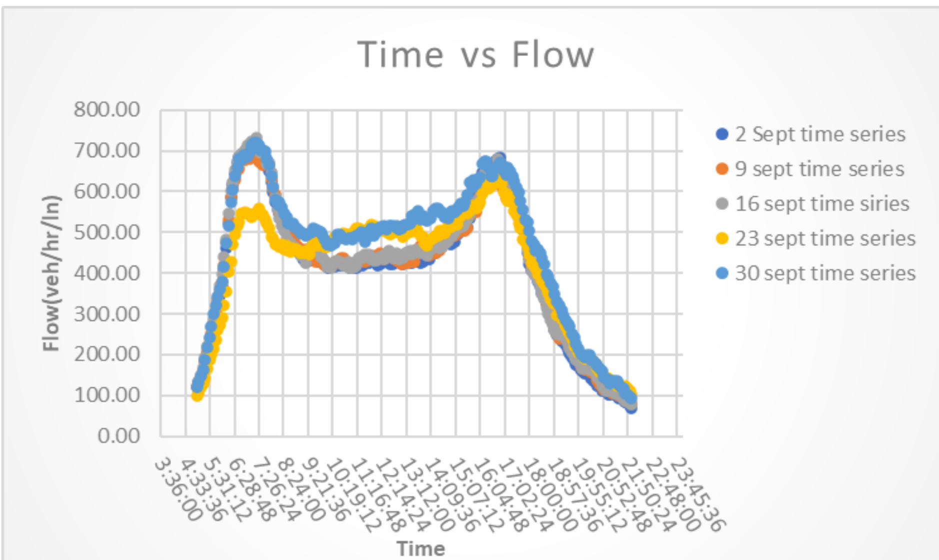

Figure 4.1: Time series of average flow for City of Durban freeway network, shown for the conservatives Mondays -2nd,9th,16th,23rd, and the 30th of September 2019.

From figure 4.1 above, what was noted was the peak period for the morning travels occurs between 6:30-9:00 and likewise, the afternoon peak period ranged between 16:00-18:00. This indicated that the morning peak lasted for a longer period when compared to the afternoon peak period. The highest value in the morning peak was found at Q=733.28 Veh/hr whereas in the afternoon peak Q= 682.88 Veh/hr. This was an early sign that a well-defined MFD was not a subject of this study given the obtained morning and afternoon peak flows shown distinctive values. To verify if this argument would hold, an MFD from individual loop detectors was established using data collected for every Monday (2nd, 9th, 16th, 23rd, and 30th) of September 2019. Later the loops were aggregated to explore the MFD at the network level. Geroliminis and Sun (2011) revealed that ''If the spatial distribution of link occupancy is the same for two different time intervals with the same average network occupancy, then these two-time intervals should have the same average network flows, i.e. in an MFD plane these two points are close to each other. This was broadly analysed to see if the network presents this behavior. The MFD was also analysed for the shape and pattern of the scatter.

4.2 Single Loop detector and MFD Analysis

The individual loop detectors were then analysed for the period between 5:00- 22:00 and the ultimate goal was to establish the MFD. What has been noted from the derived MFD, a scatter plot that consisted of dispersed points. These plotted points seem to take a parabolic that shown the existence of the Macroscopic Fundamental Diagram at a single loop detector. This was relatable to the study in Yokohama-Japan(Geroliminis & Daganzo,2008). See figure 4.2 below.

Nevertheless, these observations came as no surprise. A plot of density vs flow on a freeway network for an individual loop detector often presents a scatter about an underlying curve (Geroliminis & Sun,2011). Recent observations from empirical data in arterial networks showed that in some cases by aggregating the highly scattered plots of flow vs. density from individual loop detectors, the scatter plot almost disappears, and a well-defined MFD exists linking space-mean network flow and network density. This was investigated in the subsections of this study.

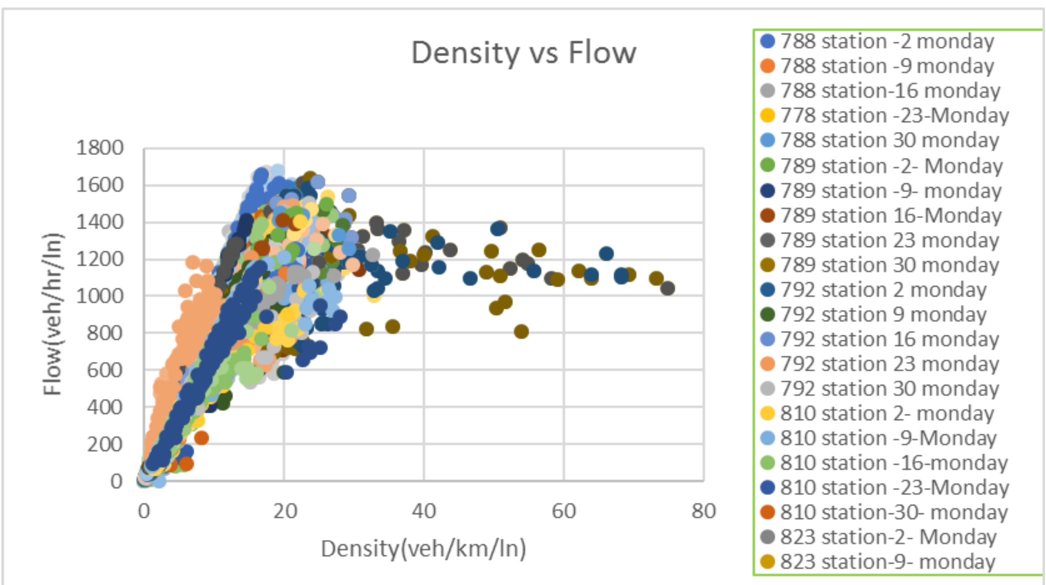

Figure 4.2: Findings when density vs flow was plotted from individual loop detectors.

From figure 4.2 above, the links presented a high flow between with the density 10-20 veh/km/ln. It was further revealed that a station with the highest flow was station no. 1165, with a flow of 1680 veh/hr at the density of 19 veh/km/ln. The station was located between the M10/N2 interchanged and M1/N2 interchange (see figure 4.3 below). This was associated with the fact that M10 and M1 are major municipal routes that link the freeway and CBD.

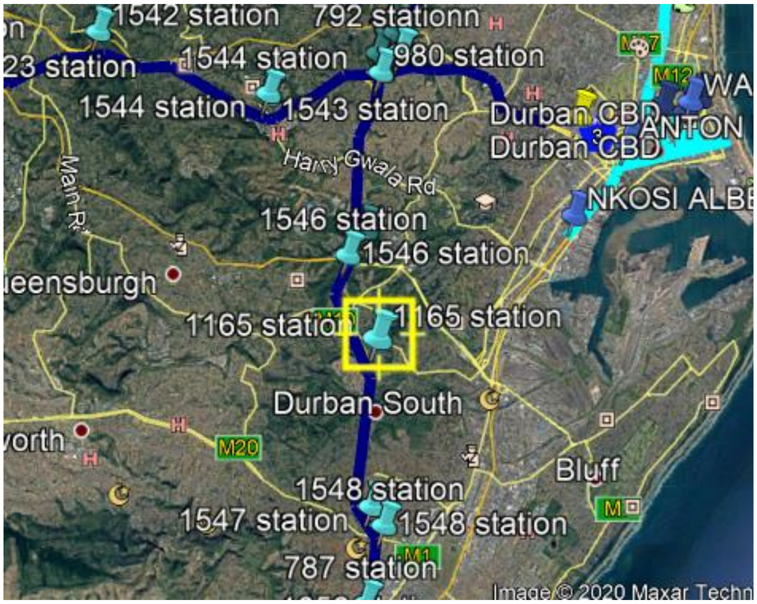

Figure 4.3: Station generated the highest flow- Station no.1165.

It was further noted that the station that presented the highest density was station no. 1531 with the density at 75 veh/km and flow at 1040 veh/hr. This station was identified on the N2 corridor located between the N2/R102 interchange and the N2/M35 interchange (see figure 4.4).

Figure 4.4: Station with the highest density station no.1531

The density is dependent on the number of lanes present on the link. When the density approaches about 25 veh/km, there is a gradual drop to the flow before it begins to form a hysteresis loop. This was associated with the section being located in proximity to the industrial area and Isipingo town. R102 is the provincial route that connects the residential townships to the CBD, and this is a major exit and entry point to the CBD.

4.3 Aggregated loop detectors on the Network and MFD Analyses

4.3.1 Aggregated MFD for 2-September 2019

The establishment of MFD for Monday of the 2nd of September 2019, a well-defined MFD, was seen to exist on the network. The graph presented a free flow regime between 1 veh/km/ln to 7 veh/km/ln with the highest density obtained at 9.18 veh/km/ln at a flow of 719.67 veh/hr. The MFD did not reach the maximum flow and density. One can conclude that the freeway network MFD on this day was well within the unsaturated and saturated state with a well define MFD.

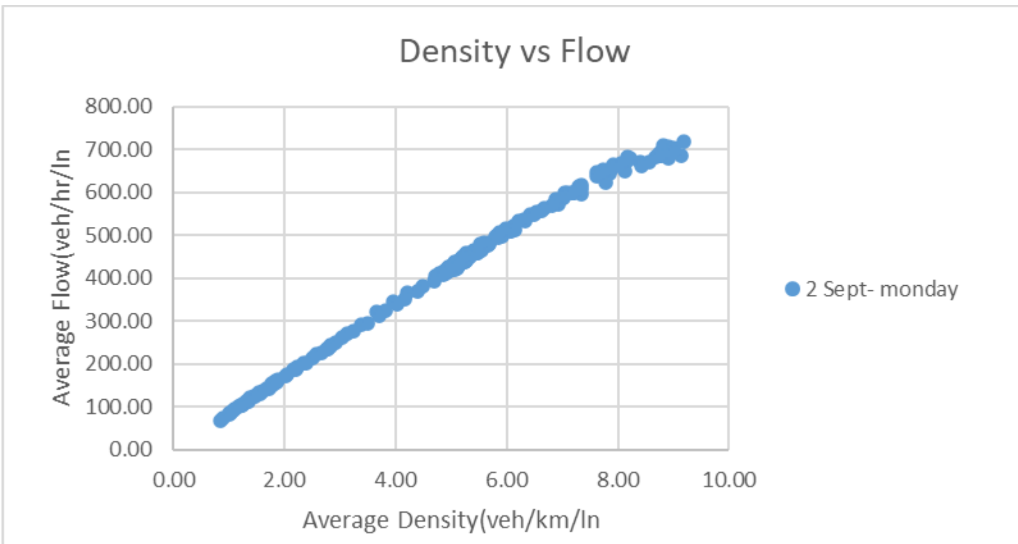

Figure 4.5: The established MFD from aggregated data on the 2nd of September 2019.

The findings supported the findings by Geroliminis and Sun (2011) which stated that on a dynamic network system that produces a well-defined MFD with no hysteresis, one can able to perform an analysis to predict inflow and outflow at an intersection at specific locations at a specific time given that the density is known.

4.3.2 Aggregated MFD for 9-September 2019

The second analysis was done on Monday of the 9th of September, a low scatter was observed on the MFD for density between 7 -10 veh/km/ln. These findings disputed the idea that freeway network MFD is always well defined, essentially with a hysteresis loop observed forming shortly after the density has reached 7 veh/km/ln.

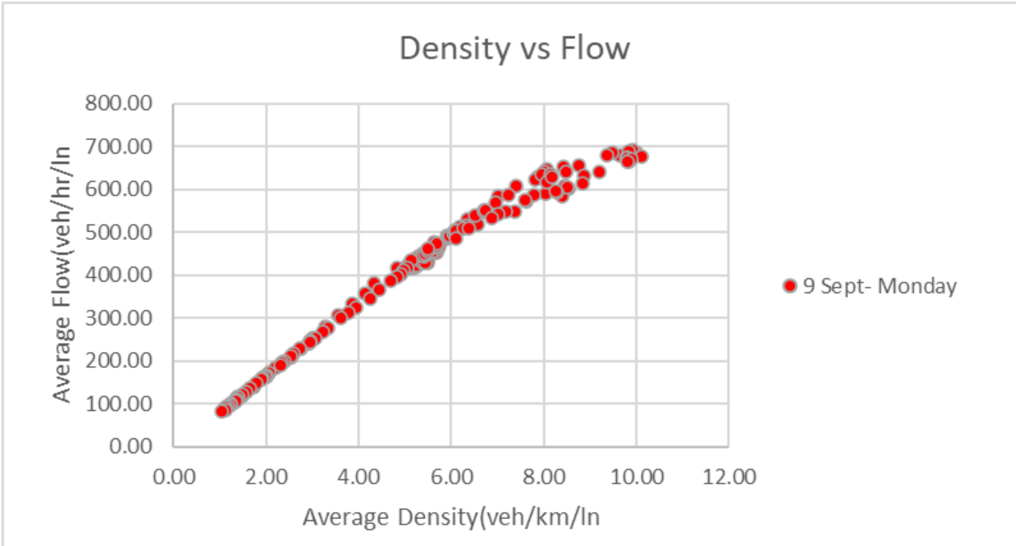

Figure 4.6: The established MFD from aggregated data on the 9th of September 2019.

In the following section of this paper, the phenomenon of hysteresis was discussed in detail when looked at what could be the cause and what are the early warning signs that the network MFD may present this phenomenon.

4.3.3 Aggregated MFD for 16-September 2019

The MFD that was further established for the Monday of the 16th of September displayed a similar trend to what was observed on the Monday of the 2nd of September. The state of traffic was matched with the one observed on the preceding Mondays with the highest flow at 733.28 veh/hr at a density of 9.60 veh/km. The graph was premature to state the saturated density, however, a shape of a slightly well-defined MFD was observed.

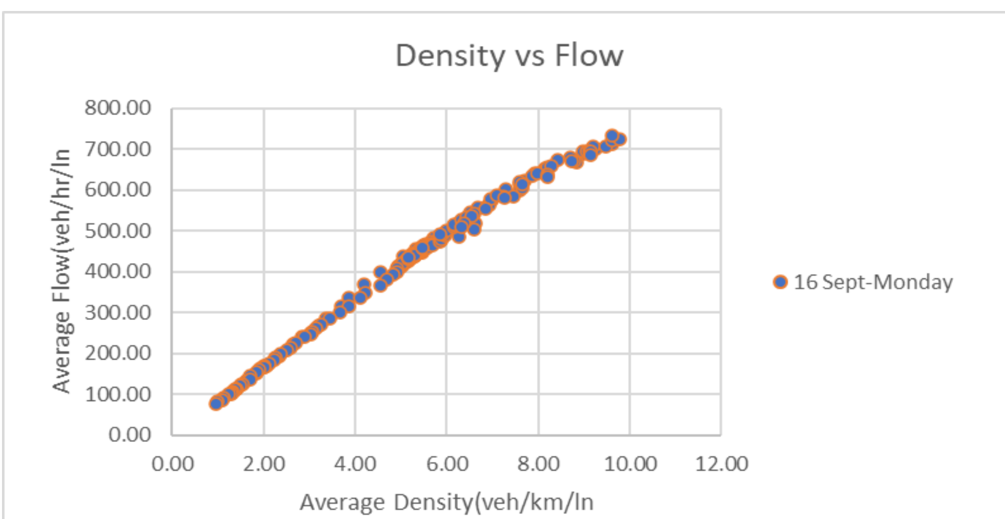

Figure 4.7: The established MFD from aggregated data on the 16th of September 2019.

4.3.4 Aggregated MFD for 23-September 2019

On this day, a graph that seems to follow a trend of a straight line was observed and one could attest that traffic volumes were very low on this day with the highest flow obtained at approximately 650 veh/hr and density found at 8 veh/km/ln.

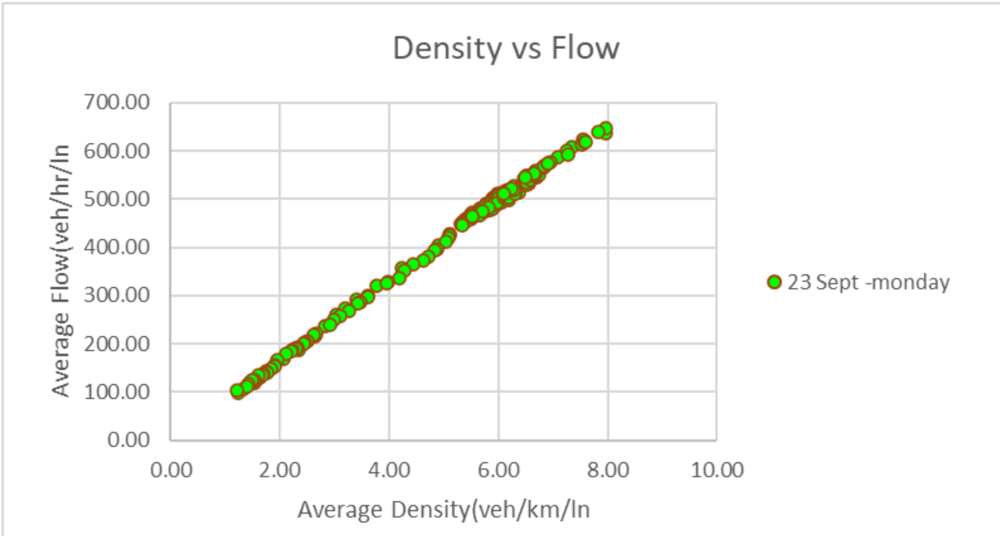

Figure 4.8: The established MFD from aggregated data on the 23rd of September 2019.

4.3.5 Aggregated MFD for 30-September 2019

An interesting observation occurred on the aggregated loops for the Monday of the 30th. What was observed was that the density vs flow plot created a scatter plot that follows a clockwise hysteresis loop. The highest flow was approximated at 720.23 veh/hr and the density at 9.08 veh/km. This was explained in detail in the subsequent sections.

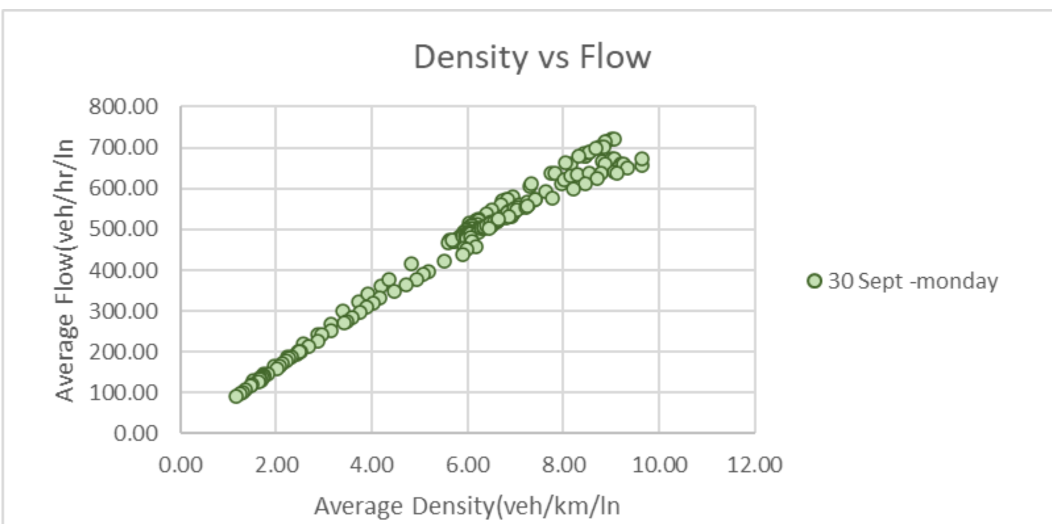

Figure 4.9: The established MFD from aggregated data on the 30th of September 2019.

4.4 The Combined and Aggregated MFD for all Mondays -2nd, 9th, 16th, 23rd, and 30th of September 2019

The combined MFD painted a clear picture of the Freeway network and that it operates between the unsaturated and saturated state. The derived MFD does not reach the maximum flow (at saturated density). The highest recorded density was found at 10.11 veh/km. Likewise, the highest recorded flow was found at 733.28 veh/hr. The network operates at an average speed of v_{av}= 79.84 km/hr.

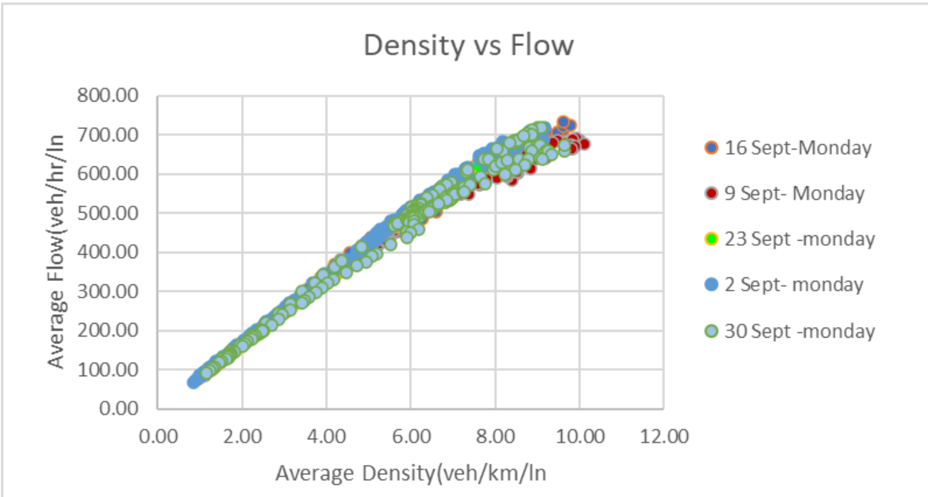

Figure 4.10: The obtained MFD when all Monday data was combined for September.

From figure 4.10, it was concluded that the scatter plots that present themselves when an MFD was established from a single or individual loop detector (as seen in Figure 4.1), tend to disappear when all the individual loops were aggregated. A well defines MFD was found to take shape.

The result further revealed that the distribution and positioning of the loop detectors should be in a way that they able to detect as many traffic situations as possible, i.e., upstream and downstream of traffic signals, interchange loops, and in the middle of the link. In that way, the derived MFD would represent the real traffic condition of the network.

4.5 Relationship between Density and Speed

To understand speed variation on the network, a morning peak period was analysed to understand the relationship between speed and density. Data from the first Monday of the month (2 -September 2019) was used to perform these analyses. The onus to choose this date was because often these dates are the busiest times of the month where most people have got paid. A declining trendline was noted when the density vs speed scatter was plotted. As one would expect, the more the vehicles occupy the space of the road, the most likely the speed will decline. See figure 4.11 below.

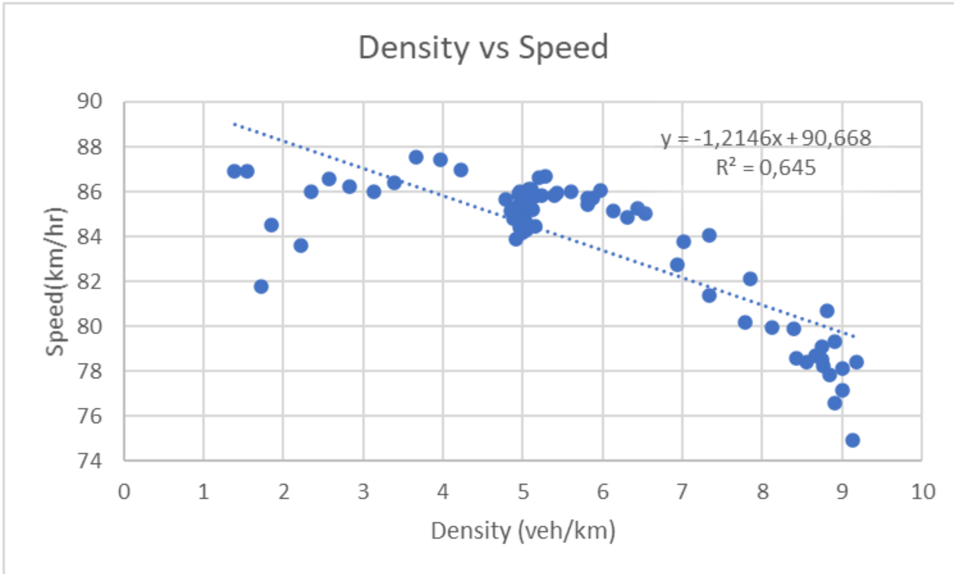

Figure 4.11: The observed relation between Density and Speed on the 2 September 2019.

From the trendline, it was estimated at what density would the network reach a gridlock state. This was based on the assumption that speed within that state is equivalent to zero. The estimated density was 75 veh/km.

4.6 Well Defined MFD vs Hysteresis

The result showed that when loop detectors are aggregated, a lower scatter plot does exist in an urban network attributed to works of (Geroliminis & Daganzo, 2008). However, it is common to find a freeway network that depicts a scattered MFD with points underlying the shape of the curve. This has also been alluded to by Geroliminis and Sun (2008). Durban freeway networks have an uneven and inconsistent distribution of congestion (see figure 4.1). This was associated with traffic heterogeneity. The same can be said about the distribution of the density over the network links which has a similar impact on the scatter of an MFD and its shape. The second reference can be made based on the relationship between the flow and density when the observed density shows a high variation on the density (density variance). In other words, the average network flow is consistently higher when link density variance is low, for the same network density. Recently proven by Cassidy et al. (2011), For macro-relations in freeway networks, if data comes from periods where all lanes on all links of the studied network are either in the congested or the uncongested regime. As the point of start, onset/offset times for the morning and afternoon peak periods were identified and assessed. The results are displayed in table 4.1 and 4.2 below.

Table 4.1: Morning peak period and hysteresis formation

Time (Min)	30- Monday Morning PEAK period		
	Density(veh/km/lane)	Flow(veh/hr/lane)	Variance
6:30:00	7.72	639.03	27.84045
6:35:00	8.15	659.10	32.51085
6:40:00	8.48	679.13	35.33784
6:45:00	8.47	678.93	31.96789
6:50:00	8.55	689.60	32.49971
6:55:00	8.49	684.94	28.4048
7:00:00	8.55	687.59	29.54022
7:05:00	8.81	697.57	33.21322
7:10:00	8.97	714.44	32.95736
7:15:00	9.02	720.46	33.39613
7:20:00	9.10	720.23	33.26175
7:25:00	8.87	713.43	32.35674
7:30:00	8.81	702.64	31.93772
7:35:00	8.89	701.44	33.18883
7:40:00	8.72	697.48	32.12747
7:45:00	8.37	679.62	29.77391
7:50:00	8.06	664.57	25.25125
7:55:00	7.80	638.54	22.82526
8:00:00	7.37	611.79	19.44456
8:05:00	6.99	579.04	17.38556
8:10:00	6.73	568.61	14.57624
8:15:00	6.88	573.81	14.47135
8:20:00	6.71	561.47	12.73923
8:25:00	6.52	546.21	13.58041
8:30:00	6.42	538.21	12.07098
8:35:00	6.14	520.94	11.86461
8:40:00	6.22	523.79	11.23372
8:45:00	6.23	522.49	11.38224
8:50:00	6.18	512.45	11.86767
8:55:00	6.08	510.09	11.95252
9:00:00	6.04	504.38	10.54982

Subsequently, the MFD for these mornings and afternoon peak periods was drawn from the onset/offset times. The results are shown in figure 4.11 below.

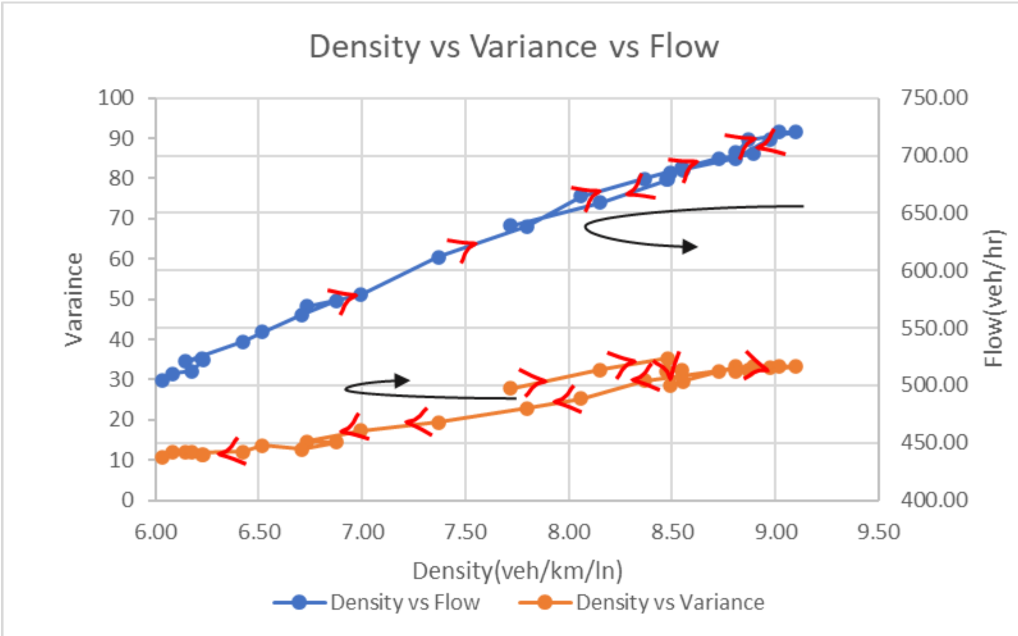

Figure 4.12: An MFD plot for the morning peak period, plotted between 6:30-9:00.

These findings revealed that a clockwise hysteresis was present on the network, and this confirmed the existence of heterogeneity on the network (speed changes over time because of various modes). These are studies that looked at the relationships between the hysteresis loop sizes and network-wide traffic conditions (Wahaballa, et al., 2018). But for this study, the focus was on early warning signs of the existence of hysteresis in the network. If it does exist, what does it say about the network? In this case, the study has shown that the network exhibits spatial heterogeneity hence a formation of the hysteresis loop was observed.

The same analysis was repeated for the afternoon onset/offset peak and sought to investigate the presence of the hysteresis loop. In this case, the peak period was found between 16:00-18:00. Therefore 16:00 was taken as the onset time and 18:00 as the offset time. Table 4.2 shows the result obtained from the analysis.

Table 4.2: Afternoon peak period and hysteresis formation

Time (Min)	30- Monday Afternoon PEAK		
	Density(veh/km/lane)	Flow(veh/hr/lane)	Variance
16:00:00	8.28	630.35	23.50297
16:05:00	8.40	635.12	25.78424
16:10:00	8.95	667.86	31.66582
16:15:00	9.17	673.01	32.73875
16:20:00	9.19	673.72	30.12937
16:25:00	8.99	659.70	31.01871
16:30:00	8.66	637.44	30.53082
16:35:00	8.87	638.10	32.73945
16:40:00	9.39	658.05	43.01041
16:45:00	9.72	658.26	61.68082
16:50:00	9.71	672.89	45.5817
16:55:00	9.39	658.87	40.4207
17:00:00	9.28	649.73	41.81027
17:05:00	9.13	640.93	44.67575
17:10:00	9.38	658.58	46.89739
17:15:00	9.47	650.53	52.70874
17:20:00	9.22	638.89	54.0219
17:25:00	8.76	624.74	42.81043
17:30:00	8.54	611.66	38.73879
17:35:00	8.26	599.00	33.48513
17:40:00	7.83	576.76	27.02669
17:45:00	7.27	555.75	20.09674
17:50:00	6.86	532.58	16.95179
17:55:00	6.70	524.85	15.43409
18:00:00	6.45	503.28	14.13656

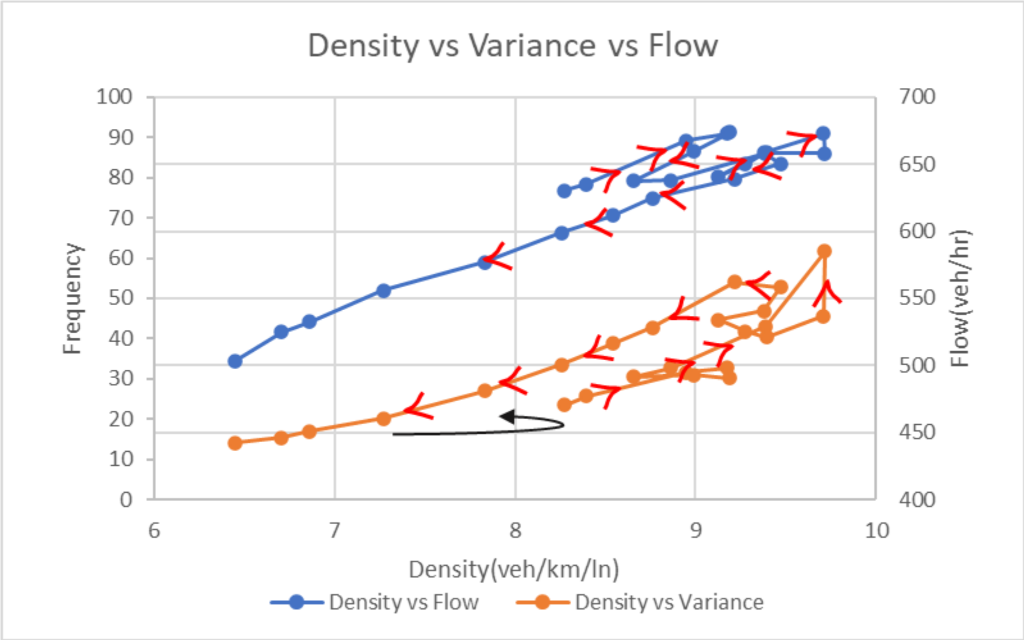

Figure 4.13: An MFD plot for the morning peak period, plotted between 16:00-18:00.

From this observation, a clockwise hysteresis loop and an anticlockwise variance were observed on the scatter plot. Two Mondays showed that the MFD was not as well defined as sought it to be and subsequently, aggregated loops do present a hysteresis scatter plot although the shape of the scatter plot looked well defined in the initial stages. This concludes as much as the MFD looked as well-defined hysteresis loops forms, and the links depict variation on congestions levels. This was associated with changes in inflows and outflows from the interchanges. The analysis conducted above indeed reveals that the Durban freeway network system is hysteretic and influenced by levels of congestion on individual loops meaning the system is path dependent. To understand the state of traffic as it approaches the saturated density it is necessary to look at the congestion propagation.

4.7 Freeway Network MFD and Hysteresis

Generally, freeway networks planners would advocate for higher mobility (free flow) instead of accessibility. To fully understand the traffic state on the investigated network, one is sought to understand the relationship between network flow and density variance. A better understanding of the phenomenon could be beneficial to implement freeway strategies that decrease density variance that could lead to increased network flow and trip endings.

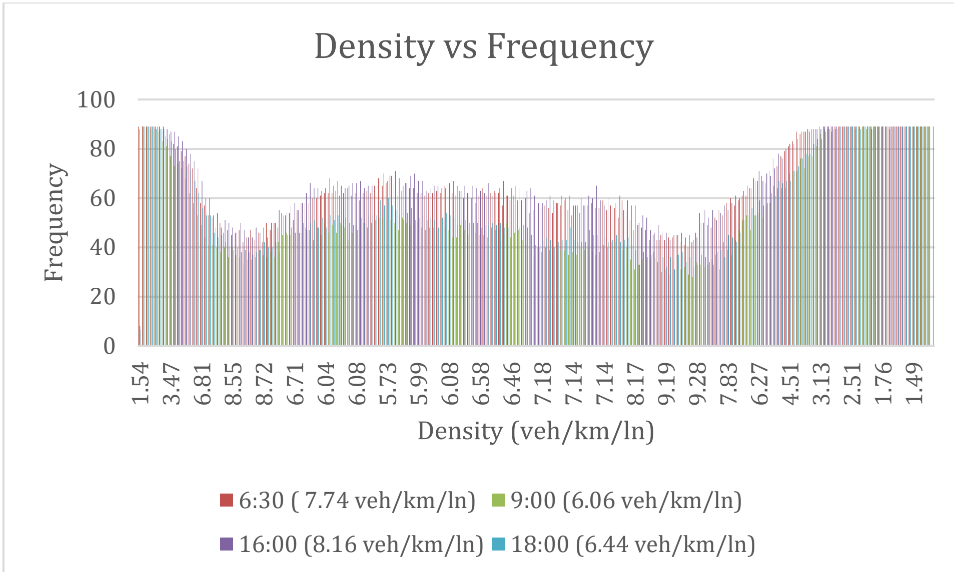

Figure 4.14: Density vs Frequency for morning and afternoon peak period.

The graph presented in figure 4.13 above showcased that the congestion was not evenly distributed (also refer to figure 4.1 on individual loop detectors). It indicates certain parts of the freeway network are more congested than others. This happens because of fluctuating travel demand during the day and bottlenecks present on the network. As more parts of the network become congested, the frequency of density distribution decreases. Note that the distributions of density showed a huge variation with the early and late hours of the day showed a high frequency. This was looked at in more detail when the attention was shifted to the morning and afternoon peak period onset and offset (6:30, 9:00, 16:00, and 18:00).

Figure 4.13 showed the variation on density when compared against onset (6:60-16:00) /offset (9:00-18:00) times. The diagram proves the existence of variation in the density which essentially indicates the spatial distribution of congestion within the corridors. For example, the density of 8.16 veh/km taken from the onset time-16:00 was recorded as the most frequent density. This essentially means the planning for the network should resort to this density. While the highest density 9.72 veh/km (critical) recorded the list frequency for both the onset/offset times densities. This suggested that as much as there was congestion, however less individual loop detectors are operating at the critical density

.

Table 4.3: Time Series, Density, and Frequency

Time	Density	Frequency, Time & Density			
		6:30:00	9:00:00	16:00:00	18:00:00
		ρ_{av} =7.74	ρ_{av} =6.06	ρ_{av} =8.16	ρ_{av} =6.44
16:00:00	8.28	43	35	46	36
16:05:00	8.40	45	38	49	43
16:10:00	8.95	43	34	46	36
16:15:00	9.17	45	30	46	32
16:20:00	9.19	43	31	43	36
16:25:00	8.99	44	29	45	31
16:30:00	8.66	44	35	45	37
16:35:00	8.87	45	37	46	38
16:40:00	9.39	42	31	44	34
16:45:00	9.72	41	32	45	36
16:50:00	9.71	40	29	43	32
16:55:00	9.39	42	28	44	33
17:00:00	9.28	46	34	50	37
17:05:00	9.13	54	33	55	36
17:10:00	9.38	50	32	52	34
17:15:00	9.47	49	33	55	33
17:20:00	9.22	48	35	51	38
17:25:00	8.76	52	37	54	39
17:30:00	8.54	55	31	57	36
17:35:00	8.26	53	42	55	45
17:40:00	7.83	58	39	58	44
17:45:00	7.27	60	37	61	42
17:50:00	6.86	57	43	60	46
17:55:00	6.70	59	47	63	51
18:00:00	6.45	61	51	65	53

Table 4.3 above shows 16:45 is the most congested time of day with a density of 9.72 veh/km/ln.

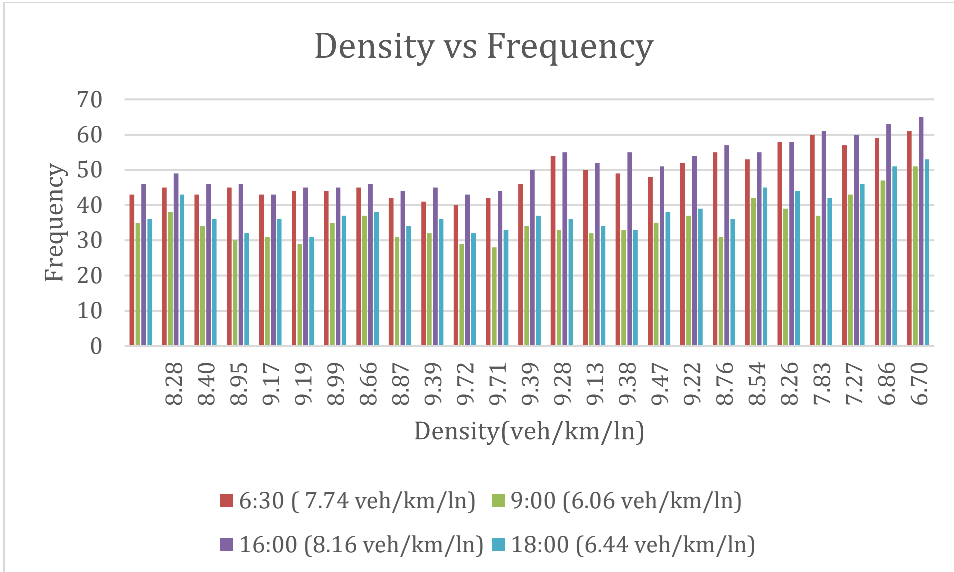

Figure 4.15: Density vs frequency for the onset and offset period.

The displayed data in figure 4.14 above has shown that despite the presence of the density variation on the network, the majority of the loop detectors are operating at the onset congestion. More detectors are operating at the onset density which was lower than the peak density-9.72 veh/km. With time the network becomes stable and operates at both the onset and offset density. This was suggested by the frequency increase for all time as the congestion passes the high density.

5. CONCLUSION

This study was a success as it was able to achieve its objectives. The result showed that a well-defined MFD exists in the Durban freeway network, and it is a property of an urban freeway network (see figure 4.10 above). This MFD exists despite the absence of the origin and destination data (which was earlier proven by Hu, Lu, Wang, and Whalin (Hu, et al., 2020). Properly understanding these MFDs could form a basic tool to assist transport planners to make informed decisions when they attempt to alleviate congestions to improve mobility and accessibility. The study was able to identify congested sections on the network using the individual loop detectors, known as the pockets of congestion. This analysis can be instrumental to alleviate bottlenecks in the network. It was further established that the networks attribute an uneven and inconsistent distribution of congestion (see figure 4.13). This was highlighted by the formation of the hysteresis loop on a separate Monday. This further validated the findings of Geroliminis and Sun (2011) which suggest that MFD in freeway networks is likely to exhibit hysteresis loops, this is because the topology of the freeways contains fewer alternatives which then limit drivers to adapt to the system. The freeway systems are often designed to advocate for mobility. The peak period for the morning travels occurs between 6:30-9:00 and for the afternoon travel, the peak period occurs between 16:00-18:00. The highest average flow on the network for the assessed period was 733 veh/hr at a density of 9.6 veh/km. The network average speed was approximated as v_{av} = 79.84 km/hr. The estimated density for the gridlocked state on the network was 75veh/km.

In closing this paper, showed that MFD was a soloistic property of the Urban highway network despite the chaotic travel demand resulting from the origin and destination. Proper understanding of these MFDs can assist planners to improve mobility and accessibility in the city, for example, the internal movements within the city can be controlled by manipulating the traffic signals located at the periphery of the city to minimize congestions within the city. The culture of transport planning has always been improving accessibility through providing improved infrastructure or by modifying the infrastructure (widening the existing roads by adding lanes, slip lanes on intersections, construction of interchanges and flyovers, manipulating signals timing). However, MFDs have proven success without a great deal of effort in changing the available infrastructure. Knowingly the amount of street space allocated to the traffic is limited if not depleted. The MFD would surely be influential to understand the impact of these imposed changes at the planning stages of the project. A study that will assess the impact of traffic heterogeneity and the spacing of loop detectors on the shape of the MFD should be compiled for future studies. This study shall also incorporate the subnetworks of the City of Durban.

6. RECOMMENDATIONS

- The literature dates back to the very first studies of traffic theory between the 1960s and 1970s. If this correlation can be linked to studies of MFD nowadays, future studies should seek to find the balance between the traffic theory literature at that time to the MFD literature nowadays.
- Because of limited access to data and the inability to access detailed data on the subsequent network routes, the study was somehow compromised. The subnetwork does have an impact on freeway congestion (i.e. Durban Metropolitan route). Future studies shall seek to accommodate these kinds of routes.
- The loop-detector positioning must detect as many traffic states as possible, i.e. upstream and downstream of traffic signals and in the middle of the section. In that case, the resulting MFD can represent the actual traffic condition on the ground. The uniform distribution of detectors reduces the discrepancies because it allows the detection of the different traffic states within links.
- When aggregated values are used to rectify problems, implement policies, and introduce new strategies in traffic management systems (i.e . by implementing measures such as pricing or perimeter control, by observing whether their system is in a state that is producing the desired mobility levels). A careful analysis on the aggregated MFD must be applied before the strategies being implemented because outcomes achieved may be premature or deceiving (it was seen that with the established MFD on the 30th Monday of September which showed a formation of Hysteresis loop).
- MFD outcomes are attributed to the condition of the area investigated and any of these outcomes should not be attempted to be applied universally.
- A study to link the relationship between the MFD and infrastructure should be looked at in future research.
- The benefit of understanding and advocating for the use of the MFDs is that if these MFDs are well understood by transporter planners, this can guarantee success in monitoring and managing traffic patterns continuously. Through implementing strategies that decrease density variance, increase network flow, and trip ends.

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APPENDIX A- Stations Information

Station Information

Site Identifier	980	**Site Number**	980
Site Name	EB Cloete South		
Site Description	Between Edwin Swales I/C and Umgeni Rd I/C		
Site Type	Permanent Piezo	**Owner**	SANRAL
Physical Lanes	6	**Responsibility**	NON-TOLL
Logical Lanes	6	**Installation Date**	2002-07-11
GPS Longitude	30.955694	**Termination Date**	
GPS Lattitude	-29.844223	**Status**	In Use
Region	East	**Companion Site**	
Road	N002	**Speed Limit**	120
Route	N002	**Count Type**	Normal Traffic Counting Station
Section	25	**Distance**	16.80

Lane No	Lane Description	Stream No	Stream Description	Direction	Reverse Lane No	Pos
1	To Pietermaritzburg N3N	1	To Pietermaritzburg	North-East	0	1
2	Slow to Durban N3S	1	To Pietermaritzburg	North-East	0	2
3	Fast to Durban N3S	1	To Pietermaritzburg	North-East	0	3
4	Slow to Stanger	1	To Pietermaritzburg	North-East	0	4
5	Middle to Stanger	1	To Pietermaritzburg	North-East	0	5
6	Fast to Stanger	1	To Pietermaritzburg	North-East	0	6

APPENDIX B – Density/Flow Calculation Example

Consider station no.788

Data recorded on the 2/09/2019 at 5 minutes at Time 5:00 am :-

- Average speed:65.445 km/hr
- Traffic volume: 57 veh/5 min
- Number of Lanes : 4

Flow Calculation:

Traffic Volume (veh/5 minutes) conversion to Flow in veh/hour:

Flow= Traffic volume x 5 min/ 60 min= Flow (veh/hr)

$$\text{Flow} = 57 \text{ veh/5 min x } (\frac{60 \ minute}{5 \ minutes}$$

Flow= 684 veh/hr

Flow per lane: Flow/ Number of lane

$$\text{Flow} = \frac{684 \ veh/hr}{4}$$

<u>Flow= 171 veh/hr/ln</u>

Density Calculation

$$\text{Density} = \frac{Flow}{speed}$$

$$\text{Density} = \frac{171}{65.445}$$

<u>Density =2.613 veh/km/ln</u>

APPENDIX C
FLOW AND DENSITY CALCULATION RESULTS

Time (Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
5:00:00	1.39	120.84	1.50	119.25	1.52	123.14	1.25	99.40	1.54	121.99
5:05:00	1.54	133.84	1.60	130.59	1.64	134.60	1.34	105.76	1.55	131.23
5:10:00	1.72	140.63	1.75	139.18	1.83	149.60	1.53	119.78	1.79	146.72
5:15:00	1.85	156.37	1.93	159.52	2.08	170.00	1.63	130.16	1.98	164.46
5:20:00	2.22	185.59	2.21	184.83	2.34	192.63	1.77	142.48	2.28	187.86
5:25:00	2.35	202.08	2.53	208.71	2.64	221.41	2.07	167.52	2.59	218.56
5:30:00	2.57	222.48	2.76	227.44	2.85	240.61	2.35	188.17	2.90	243.37
5:35:00	2.83	244.00	3.05	251.98	3.20	266.79	2.45	200.92	3.16	269.00
5:40:00	3.13	269.26	3.29	278.88	3.37	286.58	2.63	215.34	3.47	300.44
5:45:00	3.39	292.86	3.56	305.64	3.69	315.78	2.83	236.76	3.76	321.25
5:50:00	3.66	320.36	3.88	332.37	3.87	336.51	3.05	259.20	3.94	341.67
5:55:00	3.96	346.10	4.13	357.25	4.19	368.59	3.20	273.30	4.24	361.88
6:00:00	4.22	367.06	4.34	380.64	4.55	398.00	3.41	291.20	4.37	378.80
6:05:00	4.79	410.16	4.83	417.59	5.06	439.20	3.76	321.74	4.85	414.87
6:10:00	5.39	462.49	5.62	477.06	5.71	484.23	4.24	356.29	5.60	473.70
6:15:00	6.13	521.97	6.34	530.37	6.52	546.14	4.89	403.92	6.06	515.50
6:20:00	7.01	587.25	7.02	585.43	7.28	601.03	5.10	427.99	6.81	573.60
6:25:00	7.34	617.10	7.39	608.34	7.70	623.60	5.64	472.06	7.32	604.23
6:30:00	7.85	644.51	7.86	629.06	8.14	653.15	5.93	493.91	7.72	639.03
6:35:00	8.39	670.38	8.41	652.03	8.41	675.17	6.24	515.38	8.15	659.10
6:40:00	8.67	682.11	8.74	656.91	8.96	688.03	6.29	526.28	8.48	679.13
6:45:00	8.90	681.59	9.65	679.46	8.97	694.09	6.55	547.93	8.47	678.93
6:50:00	9.14	684.88	9.48	685.14	9.05	694.33	6.52	547.45	8.55	689.60
6:55:00	8.74	691.25	9.37	678.98	9.24	701.18	6.50	549.02	8.49	684.94
7:00:00	8.77	686.16	9.97	685.60	9.61	712.70	6.52	547.10	8.55	687.59
7:05:00	8.84	687.89	9.83	679.37	9.47	705.76	6.61	544.34	8.81	697.57
7:10:00	8.90	706.06	10.01	685.34	9.60	722.14	6.49	537.37	8.97	714.44
7:15:00	8.81	710.85	9.90	691.30	9.77	724.33	6.57	545.01	9.02	720.46
7:20:00	9.18	719.67	9.83	690.31	9.60	733.28	6.63	548.59	9.10	720.23
7:25:00	9.00	703.31	9.79	675.19	9.20	708.00	6.67	557.68	8.87	713.43
7:30:00	9.01	694.96	9.79	672.84	9.11	695.57	6.47	542.93	8.81	702.64
7:35:00	8.75	687.17	9.84	666.04	9.15	695.07	6.70	544.94	8.89	701.44
7:40:00	8.56	671.03	10.11	675.89	9.14	685.97	6.57	531.93	8.72	697.48
7:45:00	8.42	661.73	9.87	670.06	8.84	669.19	6.36	522.08	8.37	679.62
7:50:00	8.13	649.77	9.79	666.30	8.77	670.79	6.18	510.72	8.06	664.57
7:55:00	7.78	623.88	8.87	633.23	8.11	645.82	5.85	489.17	7.80	638.54
8:00:00	7.34	597.20	8.45	607.21	7.61	614.88	5.83	485.46	7.37	611.79
8:05:00	6.93	573.51	8.05	591.81	7.23	585.02	5.54	469.98	6.99	579.04

Time (Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
8:10:00	6.54	556.03	7.62	571.78	6.69	556.61	5.49	470.01	6.73	568.61
8:15:00	6.43	548.09	7.37	547.66	6.48	534.92	5.47	463.19	6.88	573.81
8:20:00	6.31	535.27	7.18	548.92	6.63	517.24	5.53	471.53	6.71	561.47
8:25:00	5.98	514.69	6.58	518.38	6.59	502.87	5.39	457.16	6.52	546.21
8:30:00	5.82	498.89	6.34	514.86	6.25	487.09	5.57	468.24	6.42	538.21
8:35:00	5.87	503.10	6.12	506.20	5.82	477.00	5.41	454.96	6.14	520.94
8:40:00	5.81	496.33	6.07	499.96	5.65	475.03	5.36	451.74	6.22	523.79
8:45:00	5.60	481.56	5.95	489.42	5.48	462.64	5.43	460.20	6.23	522.49
8:50:00	5.42	465.82	5.92	485.93	5.53	464.47	5.51	459.39	6.18	512.45
8:55:00	5.28	457.67	5.71	466.09	5.44	459.29	5.40	458.54	6.08	510.09
9:00:00	5.20	450.59	5.73	462.11	5.33	456.11	5.35	452.58	6.04	504.38
9:05:00	5.23	448.73	5.54	448.97	5.26	443.13	5.33	449.39	6.08	496.63
9:10:00	5.07	435.44	5.57	449.97	5.23	441.72	5.35	451.27	5.99	498.93
9:15:00	5.10	439.26	5.67	457.56	5.13	425.93	5.34	447.86	5.96	492.10
9:20:00	5.12	436.22	5.61	455.57	5.26	445.06	5.44	456.66	5.96	493.97
9:25:00	5.07	436.70	5.52	441.73	5.47	459.73	5.32	447.59	5.99	496.84
9:30:00	5.14	440.99	5.50	440.99	5.55	466.99	5.51	465.18	6.04	501.22
9:35:00	5.03	430.80	5.48	436.36	5.38	453.01	5.64	475.65	6.08	509.50
9:40:00	5.15	434.97	5.40	428.58	5.50	464.89	5.65	479.11	6.08	508.16
9:45:00	5.03	429.11	5.38	429.48	5.45	457.22	5.62	468.09	6.09	503.55
9:50:00	4.97	427.29	5.32	429.08	5.26	441.43	5.65	481.00	5.97	499.72
9:55:00	4.95	425.00	5.25	426.31	5.29	441.21	5.71	477.98	5.94	493.44
10:00:00	5.02	425.55	5.25	420.12	5.14	430.85	5.50	463.38	5.83	481.57
10:05:00	4.91	417.04	5.18	418.41	5.00	415.80	5.49	463.41	5.74	471.97
10:10:00	4.91	412.01	5.04	418.56	5.06	422.09	5.53	466.68	5.66	471.07
10:15:00	4.92	417.17	5.10	416.73	4.94	414.18	5.63	473.10	5.61	468.35
10:20:00	4.96	420.46	5.20	425.55	5.08	423.42	5.72	478.46	5.73	472.08
10:25:00	4.88	415.85	5.22	429.20	5.11	426.66	5.77	488.18	5.68	474.69
10:30:00	5.04	424.75	5.16	425.65	5.18	432.09	5.84	488.44	6.13	494.38
10:35:00	4.96	419.60	5.28	435.16	5.13	429.40	5.77	490.30	6.07	493.54
10:40:00	5.01	423.94	5.26	438.41	5.12	424.92	5.76	484.51	6.00	489.23
10:45:00	4.99	420.08	5.29	436.60	5.02	419.92	5.96	496.44	5.93	485.25
10:50:00	4.97	419.46	5.15	426.91	5.04	417.78	5.91	492.66	5.96	482.20
10:55:00	4.94	421.62	5.11	424.25	5.17	426.96	5.94	494.95	6.06	486.54
11:00:00	4.85	413.07	5.06	419.99	4.94	411.61	5.88	495.05	5.99	484.99
11:05:00	4.88	413.72	5.11	421.18	4.99	412.26	5.87	492.90	5.98	483.41

Time (Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
11:10:00	4.99	423.04	5.18	424.23	4.99	415.90	5.92	504.09	1.94	488.66
11:15:00	4.90	413.25	5.08	425.30	5.03	418.92	5.99	510.26	6.07	492.72
11:20:00	5.08	424.42	5.19	434.34	5.24	436.69	5.99	508.63	6.05	491.50
11:25:00	4.98	422.56	5.18	433.33	5.24	439.81	5.95	506.21	6.26	502.36
11:30:00	4.96	417.88	5.21	432.41	5.29	438.11	5.98	504.84	6.03	489.14
11:35:00	5.12	431.14	5.14	428.06	5.40	446.77	5.90	501.56	6.03	476.74
11:40:00	5.08	430.94	5.19	430.79	5.37	444.14	5.98	507.01	6.08	489.80
11:45:00	5.05	426.38	5.22	434.41	5.47	445.89	6.11	510.98	6.26	500.19
11:50:00	5.16	435.49	5.24	436.18	5.21	432.74	6.16	520.05	6.44	510.64
11:55:00	5.05	426.56	5.34	444.14	5.17	431.13	6.12	516.31	6.23	492.46
12:00:00	5.13	432.07	5.27	436.88	5.16	432.46	6.02	511.28	6.33	501.20
12:05:00	4.94	417.46	5.29	442.78	5.24	437.20	6.02	503.84	6.40	503.09
12:10:00	5.03	422.51	5.39	450.00	5.31	438.65	6.09	508.02	6.51	512.49
12:15:00	5.17	435.08	5.26	440.66	5.30	443.47	6.03	509.55	6.55	510.48
12:20:00	5.09	430.28	5.21	434.24	5.21	434.44	6.03	505.04	6.58	516.40
12:25:00	5.11	431.86	5.37	446.34	5.40	448.32	5.88	499.68	6.53	507.98
12:30:00	5.08	426.11	5.50	453.42	5.51	456.68	5.97	503.83	6.51	516.15
12:35:00	4.94	421.16	5.37	448.10	5.35	443.52	5.87	493.57	6.51	516.87
12:40:00	5.01	422.55	5.28	440.45	5.19	436.38	6.01	504.42	6.48	515.18
12:45:00	5.06	428.28	5.27	433.74	5.28	437.86	5.92	500.41	6.48	513.75
12:50:00	5.10	431.97	5.19	429.46	5.39	449.55	5.98	506.55	6.55	517.37
12:55:00	5.15	433.32	5.18	428.97	5.19	434.86	5.93	501.18	6.39	505.73
13:00:00	5.13	435.52	5.06	420.57	5.30	439.90	5.91	500.00	6.46	509.70
13:05:00	5.05	420.77	5.11	424.08	5.28	438.41	5.78	488.67	6.51	515.65
13:10:00	5.11	429.77	5.17	427.85	5.45	450.26	5.88	493.45	6.65	518.88
13:15:00	5.17	439.70	5.25	423.52	5.45	453.08	5.94	502.36	6.59	519.33
13:20:00	5.27	439.73	5.50	427.79	5.42	456.19	5.94	500.35	6.68	523.40
13:25:00	5.10	423.69	5.37	428.05	5.39	447.27	6.04	507.95	6.89	541.74
13:30:00	5.23	436.88	5.45	429.18	5.48	454.07	6.10	514.51	6.92	543.84
13:35:00	5.28	441.61	5.68	453.67	5.50	459.26	5.99	505.84	6.94	534.50
13:40:00	5.24	439.47	5.68	457.88	5.44	455.21	5.99	501.12	7.18	553.41
13:45:00	5.06	425.76	5.74	466.93	5.41	448.65	5.85	491.61	6.93	532.79
13:50:00	5.08	429.01	5.60	464.31	5.46	456.95	5.89	488.98	6.97	540.47
13:55:00	5.16	435.15	5.53	456.03	5.41	453.46	5.75	474.19	6.91	535.64
14:00:00	5.18	435.62	5.43	452.11	5.30	441.78	5.65	466.42	6.88	528.71
14:05:00	5.18	435.43	5.41	444.41	5.50	455.66	5.85	478.39	6.98	535.06

Time(Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
14:10:00	5.26	446.13	5.39	448.31	5.50	457.98	5.89	481.30	6.77	533.16
14:15:00	5.32	449.86	5.62	456.82	5.67	469.06	5.97	487.20	7.05	552.14
14:20:00	5.35	449.43	5.45	449.33	5.70	468.43	6.04	492.26	7.14	558.25
14:25:00	5.47	457.86	5.66	465.33	5.65	468.15	5.99	492.67	7.10	559.03
14:30:00	5.45	460.18	5.49	454.79	5.59	460.40	6.09	503.95	7.06	550.82
14:35:00	5.54	465.50	5.68	467.10	5.70	465.39	6.15	502.71	7.06	550.07
14:40:00	5.56	473.22	5.69	475.11	5.89	476.99	6.20	499.11	6.86	537.83
14:45:00	5.59	474.44	5.91	490.64	5.85	473.99	6.20	504.80	6.85	540.47
14:50:00	5.69	483.15	5.98	492.19	5.89	479.00	6.36	515.23	6.96	535.60
14:55:00	5.54	469.82	5.94	487.35	5.96	487.99	6.30	512.46	7.03	549.62
15:00:00	5.68	480.43	6.00	491.84	5.91	490.74	6.34	522.51	7.14	552.54
15:05:00	5.65	477.95	5.97	491.54	5.99	501.33	6.52	530.54	7.11	548.85
15:10:00	5.84	494.29	6.06	499.20	6.16	510.39	6.29	520.58	7.24	554.57
15:15:00	5.91	498.43	6.23	508.39	6.24	517.59	6.52	535.14	7.31	561.49
15:20:00	6.07	510.66	6.18	511.74	6.22	512.18	6.58	540.06	7.47	572.44
15:25:00	6.06	510.82	6.06	504.55	6.16	515.88	6.75	550.00	7.30	565.45
15:30:00	6.10	514.82	6.09	505.22	6.32	527.80	6.69	555.73	7.49	573.11
15:35:00	6.13	513.53	6.27	510.73	6.45	532.55	6.64	547.57	7.73	592.08
15:40:00	6.32	535.11	6.52	540.72	6.60	543.28	6.65	551.32	8.17	621.30
15:45:00	6.62	557.18	6.72	550.17	6.90	564.82	6.82	565.63	8.08	610.48
15:50:00	6.68	564.75	6.70	549.16	7.00	575.41	6.83	566.30	8.32	629.27
15:55:00	6.88	583.86	6.73	551.04	6.94	563.92	6.71	559.23	8.15	620.77
16:00:00	7.04	599.02	6.96	568.94	6.96	577.44	6.83	568.78	8.28	630.35
16:05:00	7.09	598.34	7.22	587.97	7.11	587.67	6.90	573.40	8.40	635.12
16:10:00	7.61	646.84	7.82	624.83	7.59	620.19	7.26	595.57	8.95	667.86
16:15:00	7.74	654.11	8.06	647.29	8.16	646.31	7.57	621.38	9.17	673.01
16:20:00	7.93	665.48	8.01	640.78	8.19	655.83	7.54	623.72	9.19	673.72
16:25:00	7.86	656.59	7.96	634.22	7.93	640.34	7.33	607.05	8.99	659.70
16:30:00	7.89	654.99	8.14	634.25	7.88	634.72	7.52	612.35	8.66	637.44
16:35:00	7.73	646.77	8.07	618.19	7.99	641.90	7.57	617.96	8.87	638.10
16:40:00	8.18	674.49	8.18	629.22	8.28	659.43	7.97	637.74	9.39	658.05
16:45:00	8.22	681.46	8.49	639.90	8.71	681.54	7.97	648.15	9.72	658.26
16:50:00	8.17	682.88	9.19	641.10	8.71	672.06	7.83	638.36	9.71	672.89
16:55:00	8.06	667.41	8.82	613.31	8.21	637.03	7.58	619.01	9.39	658.87
17:00:00	7.63	637.52	8.52	603.06	8.20	632.60	7.25	599.41	9.28	649.73
17:05:00	7.29	613.62	8.40	583.86	7.60	598.62	7.09	587.07	9.13	640.93

Time (Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
17:10:00	7.35	607.63	8.50	606.71	7.66	606.50	6.94	577.13	9.38	658.58
17:15:00	7.19	600.42	8.27	593.78	7.66	613.61	7.27	593.11	9.47	650.53
17:20:00	7.19	599.96	8.26	597.94	7.47	585.62	6.91	573.36	9.22	638.89
17:25:00	7.19	598.36	7.78	587.53	7.26	580.94	6.64	553.41	8.76	624.74
17:30:00	6.81	570.93	7.60	576.50	6.85	554.68	6.49	545.08	8.54	611.66
17:35:00	6.48	549.38	7.02	542.79	6.54	535.58	6.24	521.23	8.26	599.00
17:40:00	6.21	534.67	6.87	533.99	6.39	518.39	6.10	510.83	7.83	576.76
17:45:00	5.87	505.87	6.37	509.27	6.33	509.15	5.81	483.73	7.27	555.75
17:50:00	5.52	480.13	6.11	486.23	5.85	490.39	5.71	475.61	6.86	532.58
17:55:00	5.20	447.84	5.51	460.90	5.46	459.48	5.52	463.95	6.70	524.85
18:00:00	4.96	422.41	5.15	433.97	5.17	435.36	5.33	445.78	6.45	503.28
18:05:00	4.72	405.92	5.06	416.36	4.91	407.61	5.10	424.00	6.09	480.47
18:10:00	4.86	407.86	4.96	410.16	4.91	400.12	5.09	420.19	6.13	471.21
18:15:00	4.68	393.36	4.92	403.54	4.83	394.06	5.05	413.32	6.04	454.16
18:20:00	4.49	379.85	4.82	395.11	4.69	381.86	4.88	397.24	6.27	457.95
18:25:00	4.39	368.55	4.70	386.49	4.55	366.55	4.84	393.27	6.06	449.79
18:30:00	4.17	352.07	4.44	366.23	4.22	347.86	4.72	380.99	5.98	437.24
18:35:00	4.02	339.30	4.25	346.33	4.13	335.87	4.62	373.10	5.59	420.77
18:40:00	3.82	324.15	3.96	324.10	3.86	314.40	4.45	364.88	5.22	397.33
18:45:00	3.70	313.89	3.79	313.39	3.66	299.89	4.27	352.16	5.12	390.87
18:50:00	3.51	293.37	3.61	300.50	3.45	286.27	4.20	336.89	4.93	376.10
18:55:00	3.23	277.99	3.33	277.07	3.26	271.89	3.98	327.88	4.76	365.86
19:00:00	3.04	260.22	3.22	267.79	3.13	261.36	3.95	324.43	4.51	349.46
19:05:00	2.93	249.66	3.01	251.52	3.05	250.25	3.61	298.54	4.19	330.85
19:10:00	2.84	241.87	2.92	240.63	3.05	249.76	3.61	298.18	4.04	320.27
19:15:00	2.76	233.75	3.07	252.49	3.05	252.64	3.47	287.06	3.91	308.41
19:20:00	2.78	235.93	2.95	245.47	3.03	247.12	3.43	285.05	3.76	296.05
19:25:00	2.66	224.40	2.95	242.54	2.90	239.27	3.26	268.69	3.58	284.44
19:30:00	2.51	212.94	2.73	227.71	2.71	226.73	3.10	256.81	3.48	275.19
19:35:00	2.39	202.39	2.59	218.20	2.60	215.13	3.00	251.02	3.46	270.80
19:40:00	2.24	192.54	2.53	211.83	2.51	206.47	2.93	240.26	3.13	251.69
19:45:00	2.17	185.78	2.40	198.55	2.37	197.60	2.66	222.13	2.99	242.04
19:50:00	2.05	176.34	2.34	194.92	2.26	188.54	2.63	219.56	2.86	227.82
19:55:00	2.03	172.92	2.31	188.95	2.23	183.19	2.50	206.54	2.73	213.84
20:00:00	1.88	162.31	2.06	171.05	2.12	174.98	2.46	203.09	2.49	201.21
20:05:00	1.85	159.04	2.02	167.11	2.02	166.20	2.44	200.02	2.55	200.21

Time (Min)	2 Monday		9-Monday		16- Monday		23- Monday		30- Monday	
	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow (veh/hr/lane)	Density (veh/km/lane)	Flow(veh/hr/lane)
20:10:00	1.78	152.90	2.00	164.47	2.01	167.63	2.29	189.30	2.47	194.01
20:15:00	1.80	154.36	2.00	164.16	2.02	168.64	2.32	193.20	2.47	198.32
20:20:00	1.79	151.93	1.93	160.25	1.92	162.39	2.31	190.42	2.51	199.81
20:25:00	1.68	142.59	1.89	157.51	2.00	166.42	2.23	187.71	2.33	187.37
20:30:00	1.62	136.81	1.91	157.35	1.89	158.59	2.22	185.12	2.28	185.38
20:35:00	1.57	131.21	1.79	149.39	1.84	152.54	2.12	179.36	2.22	176.84
20:40:00	1.46	123.95	1.66	136.15	1.72	143.71	1.96	166.00	2.16	172.65
20:45:00	1.48	123.62	1.56	127.71	1.71	137.26	1.90	155.75	2.08	164.98
20:50:00	1.35	112.86	1.50	122.49	1.54	123.36	1.90	154.28	2.02	160.18
20:55:00	1.34	113.61	1.37	114.11	1.49	121.00	1.85	147.35	1.82	146.14
21:00:00	1.31	112.38	1.40	116.51	1.40	112.55	1.74	143.71	1.76	141.73
21:05:00	1.25	103.73	1.36	110.25	1.40	111.46	1.78	141.23	1.74	138.74
21:10:00	1.21	103.66	1.35	110.01	1.39	112.61	1.70	138.60	1.68	130.11
21:15:00	1.25	106.69	1.32	103.94	1.38	111.06	1.67	134.95	1.75	136.09
21:20:00	1.21	102.06	1.37	109.99	1.32	106.21	1.61	133.50	1.67	135.65
21:25:00	1.18	98.98	1.36	105.95	1.33	104.13	1.51	123.95	1.67	134.57
21:30:00	1.11	94.17	1.24	100.01	1.29	101.29	1.54	123.46	1.64	127.90
21:35:00	1.07	91.99	1.24	98.32	1.25	100.65	1.51	120.60	1.51	119.99
21:40:00	1.03	86.61	1.19	92.94	1.12	91.37	1.46	121.01	1.49	117.49
21:45:00	1.00	84.45	1.14	92.24	1.09	86.73	1.49	123.14	1.35	106.23
21:50:00	1.01	82.23	1.12	91.46	1.10	84.77	1.42	117.33	1.32	102.52
21:55:00	0.90	74.42	1.12	85.33	1.01	81.94	1.39	112.20	1.27	96.56
22:00:00	0.86	68.47	1.05	82.15	0.97	76.84	1.23	103.36	1.16	91.81