Spatial and temporal analyses of traffic flows in the city of Almelo: in search for a Macroscopic Fundamental Diagram (MFD).

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March, 2010

Spatial and temporal analyses of traffic flows in the city of Almelo: in search for a Macroscopic Fundamental Diagram (MFD).

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Thesis submitted to the Faculty of Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, Specialisation: **Urban Planning and Management**

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Abstract

Land use and its related activities generate and distribute trips between places. Traffic flow analysis is an essential component of a city's traffic and transport systems since these flows could (and often do) lead to the occurrence of congestion on our roads. As a result of the increasing congestion menace, transport engineers, planners and relevant authorities put in measures to try to ameliorate congestion and its effects. Most of these measures (based on segment-based indicators) are normally geared towards solving localised congestion problems on the road network, whereas the named problems are typically area-wide or even city-wide.

In an attempt to come up with area-wide traffic management measures, this research performs spatial and temporal analyses of traffic flows within the city of Almelo, The Netherlands, in search for a macroscopic fundamental diagram (MFD), which primarily shows the relation between a network's average speed and its average volume over a demarcated area. The performance of road networks enables transport planners, traffic engineers and network operators to assess how the network has performed in the past, how it is performing now and how its future can be planned to meet increasing demand levels. Although segment-based indicators are very essential in understanding performance levels of road segments, this may not be enough for urban planning and management purposes of an entire area or even a city. This makes area-wide indicators such as the MFD, an appropriate indicator, which considers the performance of the entire city, selected parts of the city or trajectories within the city.

Area-wide spatial-temporal analyses were carried out to assess performances of different road trajectories with respect to their percentages of free flow speeds, in the city of Almelo. Studies were also conducted into the feasibility of the existence of the MFD for the city as a whole and this led to a speed-flow model for Almelo. The performance of the road segments during morning and evening peak periods were also studied using speed profile curves.

The spatial and temporal analyses revealed that some level of variation existed between different trajectories in terms of traffic flows and speeds during morning and evening peaks. Significant differences in the performance of trajectories were found when different trajectories were compared. This implies that some trajectories perform better than others. The analysis also suggests that the MFD exists for the city of Almelo but there are no data in the congestion part of the diagram, and thus there is little congestion in Almelo. Results from the MFD again indicated that a strong relation between average speed and volume exists and that the average traffic volumes can account for 92% (R^2 of 0.92) of the variations in the average speeds. The profile performance analysis (comparing relative speeds on the segments) also revealed that there is little congestion in Almelo (at a city-scale level) but some individual links experience some levels of congestion during peak flows.

Although the current levels of travel demand show that traffic flow within the city is generally good, information from the results is important for the municipality to consider for further traffic planning operations in the city of Almelo. Operationalising these measures will enhance traffic circulation within the city. This new approach of using the percentages of free flow speeds provides insights into the study of performance levels of road trajectories.

Keywords: Congestion, Spatial and temporal analyses, Macroscopic Fundamental Diagram, free flow speed, speed profile, area-wide analyses, trajectory.

Acknowledgements

*His steadfast love for me never ceases, His mercies never come to an end. They are new every morning and great is His faithfulness….*Thank you Dear Lord, for how far you have brought me. I am forever grateful to You.

I would like to express my sincere appreciation to my Supervisors for their countless support. Dr. Ir. M. H. P. Zuidgeest, I am forever grateful for your words of encouragement, moral support, friendship, and not forgetting the pieces of advice you have been giving me. Dr Tom Thomas, your constructive criticism, guidance and pieces of advice have helped me in diverse ways and I say, I am deeply indebted to you. Ir. Mark Brussel and Ing. Frans van den Bosch, your support in this thesis is well appreciated.

I am also grateful to the Erasmus Mundus Scholarship Fund for granting me this opportunity to further my studies. My profound gratitude also goes to Dr Connie Blok, Ir. Bas Retsios and Prof. Kraak, who assisted in diverse ways in providing the speed data for Almelo. To Wendy, I never met you in person but the traffic volume data you prepared and used for your PhD studies have really helped me. I say, I am grateful. To Drs Hulleman (traffic and transport section of the municipality of Almelo), I say I am grateful to you as well, for taking time off your busy schedule to discuss with me the various traffic operations in the city.

For their valuable contributions to my education in ITC, I express my sincere thanks to the staff of UPM and staff of ITC. My introductory lessons in Python (x,y) was facilitated by Messrs Oh, Nyaruhuma, Kipkemei and Butau. Many thanks to you all. To the Ghanaian Students in Enschede, you really made me feel at home. I am grateful to you all. The members and my colleague Leaders (2009) of the ITC Christian Fellowship have also been a great family. God richly bless you all. Many thanks go to the Management and Staff of Delin Consult Limited, for your numerous support and words of encouragement.

Special thanks also go to the following: Emmanuel, Ike, Beatrice, Janet, Racheal, Adriana, Stephanie, Jerl, Sandy, Seth, Joyce, Bright, Kingsley, and to all the members of the family. This is how far your love, prayers and support have brought me.

And to all my UPM colleagues, I say, I really enjoyed you company for 1.5 years. Amos, Emma and Eric, thanks for your words of encouragement and support. I cherish you all.

Finally, my appreciation will not be complete without saying I am forever grateful to my parents; Mr and Mrs Danquah, Mr and Mrs Antwi-Boateng and Mr and Mrs Yeboah. Thank you all for your love and support.

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List of Acronyms

ASCII	American Standard Code for Information Interchange
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
CBD	Central Business District
CSV	Comma Separated Value
DBF	DataBase
GIS	Geographic Information System
GPS	Global Positioning System
HCM	Highway Capacity Manual
LOS	Level of Service
LUP	Land Use Planning
LUT	Land Use-Transport
MFD	Macroscopic Fundamental Diagram
MV	Measured Value
OD	Origin-Destination
PHF	Peak Hour Factor
SABIMOS	Satellite Based Information Management Operating System
SMS	Space Mean Speed
SPSS	Statistical Package for the Social Sciences
TMS	Time Mean Speed
TRL	Transport Research Laboratory
TXT	Text format
V/C	Volume to Capacity
WGLUP	Working Group on Integrated Land Use Planning

1. Introduction

This introductory chapter sets the frame for the research. It begins with an introduction to the study and looks at the background and justification of the research. It goes further to identify the research problem and defines the research objectives and questions. Finally, it looks at how the research aims to achieve its intended objective by providing a research design matrix; which gives an overview of the entire work.

1.1. General Introduction

Global cities face rising traffic congestion problems. This situation is getting worse and is becoming a major concern of the general public. Traffic congestion is a condition of traffic delay, because the number of vehicles using a road exceeds the operational capacity of the network to handle it (Weisbrod, Vary et al. 2003). Congestion has several causes such as: the volume of traffic being close to the maximum capacity of the road link (where congestion is occurring), as a result of too many vehicles crowding available road space. It can also be caused by traffic accidents or road maintenance works resulting in reduced capacity of the network at that particular location, time etc.

Congestion has a number of negative effects: productive hours are lost and this has adverse effects on the economy. It also contributes to air pollution (which has a debilitating effect on quality of life), global warming etc.

In view of the above-mentioned effects congestion has, there is the need to manage traffic congestion and help reduce its effects. This could be done through effective traffic management, which has become an increasingly significant task that involves schemes to guide traffic flows effectively. Road traffic situations require frequent monitoring so as to solve problems that occur. This will ensure the regular flow of vehicles thus improving the efficiency of the road network. Traffic management may involve series of tasks which when operationalised, will improve mobility, increase safety on roads etc.

As we may all have experienced or witnessed congestion in our daily lives one way or the other, it is observed that it occurs on individual links within a network thereby making it a localised problem. The cause of which has to do with spatial-temporal distribution of demand and supply which therefore makes it possible to experience its effect when considering the performance of the entire network (making it a macroscopic issue). This then points out the fact that network operators should be able to relate the effects of these localised congestion situations on road links to the entire network, which calls for appropriate indicators to be used to measure network performance.

Performance of road networks over the years is typically measured at link and intersection levels and this makes it quite difficult when assessing the performance of an entire network. To be able to put effective traffic and transport management practices in place for an entire city, it will be ideal to consider measuring performance of roads at higher levels. This will also help to know the state of the network. The performance of a city's road network which can be studied at a macro level could be attributed to the planning of the city. A well planned city has, as part of its characteristics, good accessibility and mobility, thus, less congestion. In order to help improve accessibility and mobility, planners ought to study and understand how space is used for transport and how this space can be managed effectively. A macroscopic fundamental diagram (MFD) can be used to study the performance of road networks. Such a diagram shows the relation between average flow in the network and the network's average traffic density or speed (Gonzales, Geroliminis et al. 2008). It has been established that, an MFD linking space-mean flow, density and speed exists on a large urban area and that, decision makers can use valuable information from it to evaluate demand-side policies for improving a neighbourhood's mobility (Daganzo and Geroliminis 2008).

1.2. Background and Justification of the research

1.2.1. Background

Almelo is a city in the province of Overijssel, with a population of about seventy two thousand four hundred (72,400), (as of 31st December, 2008) according to Statistics Netherlands (Statistics Netherlands 2009) . The population increase from 66,936 in 2000 to 72,428 in 2008 may also have contributed to an increase in economic activities, businesses etc over the years. Modern shopping centres and department stores that were found in much larger cities have been opened in Almelo as a result of the booming economic activities. The city also serves as a host to festivals, live music and other activities both on weekdays and on weekends. Its proximity to cities like Enschede , Hengelo and tourist towns like Ootmarsum, Delden and Markelo has also been another major factor in the increase in the city's economic activity (Wikipedia contributors 14th November,2009).

The above-stated increase in population, business and economic activities also has effects on traffic flow in the city. In view of that, the Municipality ought to engage in urban planning and management measures to ensure effective flow of traffic. This will enhance traffic circulation in the city, thereby enhancing the city's mobility and accessibility levels.

With transport planners aiming at ensuring the efficient operation of urban highway systems used by travellers (Donaghy and Schintler 1998), there is always the need to assess the performance of road networks at a point in time since this will enable planners to know how effective the network is performing in terms of traffic flow. Analysing the variations that exist in the performance of the network also helps in understanding the overall performance of the network in terms of its ability to handle volumes of moving traffic. Thus, measures to enhance the effective performance of the network could be proposed. Also, with population increasing year after year, there is the requirement for measures to be put in place so that the network can withstand the high demand from vehicular use.

Several indicators used to measure the performance of road links exist and have been used for ages. Among these are travel time reliability, capacity reliability, disaggregate models of link-level performance, speed-delay studies, queue length etc. All these performance measures have been used extensively already but planners and engineers require " consistent, reliable means to evaluate traffic performance in a network under various traffic and geometric configurations" (Williams 1996). More recently Macroscopic Fundamental Diagrams (MFDs) have been introduced as a measure for network performance. The MFD is seen as a good option and the most promising out of the lot, according to recent studies (Geroliminis 2008).

Several theories describing vehicular traffic movement in cities on an aggregate level have been proposed but these do not produce a macroscopic model (city-scale) with varying inputs and outputs that could describe the dynamics of rush hours well (Geroliminis 2008). Based on a field experiment that was carried out in Yokohama (Japan) by Geroliminis et al, an MFD linking space-mean flow, density and speed exists on a large urban area. It was also observed by them that when the "chaotic" scatter-plots of speed versus density from individual fixed detectors were aggregated the scatter nearly disappeared and points grouped neatly along a smoothly declining curve. By this, they pointed out that an MFD exists for the network. "The term MFD more aptly applies to the relationship between average flow in the network and the network's average traffic density" (Gonzales, Geroliminis et al. 2008).

Currently, most cities are growing and motorising at a very fast rate thereby limiting the urban space to travel. In order to help improve accessibility for all, planners need to study and understand how this space is used for transport and how it can be managed effectively. In providing accessibility, consideration should be given not only to the density of opportunities as determined by the city structure but also to the speed with which people can move about the city (which can be described as the mobility provided by the transportation system), since accessibility depends on these factors (Gonzales, Geroliminis et al. 2008). To improve accessibility, infrastructural facilities could be studied and modified because the amount of street space allocated to cars, buses, etc may affect a neighbourhood's MFD.

"MFD is an approximate property of a network's structure which when estimated empirically, gives decision-makers valuable information to evaluate demand-side policies for improving a neighbourhood's mobility" (Daganzo and Geroliminis 2008). Since the aim of transport planners is to ensure the efficient operation of urban highway systems used by travellers (Donaghy and Schintler 1998), the MFD may help in that respect by assisting to manage traffic flow on road networks and improve mobility.

1.2.2. Justification

Macroscopic models common to traffic-related simulations have a long history, starting with the study of fundamental diagrams by Greenshields in 1935,(Greenshields 1935) as cited in (Muñoz 2004). According to Dixit and Radwan (2007), the measurements and relationships that exist between macroscopic variables (speed, density and flow) have been broadly studied for traffic streams theoretically and practically (Edie 1963; Gazis 1974) as cited in (Dixit and Radwan 2007). Much work was also carried out on how fundamental diagrams could be used to describe traffic patterns at signalised intersections or incident areas by Lighthill and Whitham in 1955, (Lighthill and Whitham 1955) and (Lighthill and Whitham 1955) as cited in (Lo, Chang et al. 2001). Again in 1974, the same authors (Lighthill and Whitham) studied how vehicular traffic could be modelled macroscopically (Whitham 1974) as cited in (Klar and Wegener 2000).

"Macroscopic Fundamental Diagrams (MFDs) can be used to control demand and improve mobility and accessibility within a city" (Geroliminis and Daganzo 2008). According to Daganzo and Geroliminis (2008), it is very complex to really understand traffic situations in large cities at a microscopic level. Also, they point out that, some disaggregate models produce unreliable results, as compared to aggregate models which are observable and produce reproducible results. In addition to that, Magne, Rabut et al (2000) emphasise some advantages of macroscopic approaches such as: input needs for macroscopic simulation are reduced and large scale city network modelling is easier, less computation time is required and their calibrations are easier as compared to microscopic ones. Geroliminis (2008) shows in his paper that several theories describing vehicular traffic movement in cities on an aggregate level have been proposed but these do not produce a macroscopic model (city-scale) with varying inputs and outputs that could describe dynamic rush hours. In line with this, the MFD has been proposed.

Although the existence of an MFD has been researched for a large city like Yokohama in Japan, it has not been used to predict the performance of the city in terms of mobility and accessibility. And it is in this line that this research intends to study the feasibility of the existence of the diagram for the city of Almelo in The Netherlands and to study and describe the performance (in spatial and possibly temporal terms) of selected parts of the city or trajectories within the city. By performing spatial and temporal analyses of parts of the city or trajectories within the city, the existence of the MFD can be investigated. Knowledge about the performance of these parts or trajectories will help planners know about the city's performance in terms of traffic flow. Makoriwa (2006) suggests that "there is no ubiquitous and encompassing definition for network performance" and while it is conceded that the definition of network performance has to take cognisance of other network state variables (Makoriwa 2006), the performance of a network in this research looks at how traffic flow is effective on the city's network, thereby reducing congestion. With this assertion, a city experiencing such type of flow could be said to perform well in terms of traffic flow.

Urban transport has spatial networks as parts of its components which collect and distribute goods and people (Bertaud 2002). In our ambition as planners and engineers, to transport people and goods to, from, and within cities effectively, localised congestion problems are transferred onto other segments that constitute the network and urban transport engineers have difficulties in optimising their network as a result of these problems. Screenline data could therefore be collected for capacity analysis on these segments. But for the purposes of urban planning and management of the entire city, there is the need for an area-based indicator and not a segment-based one. The MFD will thus be the indicator for such analysis, and spatial temporal analysis will give planners and engineers the requisite information to be able to optimise the design of networks so as to maximise their efficiency. Once their efficiencies are maximised, their performance levels, which show how the total system responds to increasing travel demand levels (Williams 1996), are consequently enhanced.

In this research the exploration of the existence of the MFD will be looked at in two ways. The first is with regards to how its results from traffic flow analysis are used in planning; by comparing the models for different trajectories within the city. By so doing, planners can use this indicator to study the performance of the network so as to improve upon its mobility and accessibility levels where necessary. The second is with regards to how the models are used in managing traffic flow on the network; by comparing the observed data points for similar time periods (spatial-temporal correlations). This will help traffic and transport managers in describing traffic situations on the network.

The MFD primarily shows the relationship between the number of vehicles in the system (accumulation) and the rate of trips reaching their destinations (outflow). The maximum outflow also depends on the infrastructure and control of the street network and the number of vehicles using the streets (Daganzo, Li et al. 2007) . Establishing an MFD for a city and putting in place mechanisms to monitor the state of traffic flow, it is possible to know if the network is producing the desired accessibility levels at all times or not. By so doing, existing strategies can be refined to enhance the network's performance and this is very vital for planners, in that, the levels of service that are provided to motorists, pedestrians etc could be monitored to assess the city's ability to manage growth (Williams 1996) . This performance could also be attributed to the planning of the city. In this regard, a typical MFD for a city may help explain if the city is well planned or not, or if some selected sections (of spatial interest) are performing better than others so as to know how to allocate resources for transport network improvements in an equitable manner.

1.3. Research Problem

The field experiment carried out in Yokohama (Japan) by Geroliminis et al. on the existence of an MFD for that city has further paved the way for much work to be done on the existence of such diagrams for other cities. The results of the experiment revealed "that an MFD linking space-mean flow, density and speed exists on a large urban area" with Yokohama as an example (Geroliminis and Daganzo 2008). These MFDs show a plot of the average flow of traffic in the network versus the network's average traffic density (Gonzales, Geroliminis et al. 2008), on an aggregate level.

These diagrams, according to the researchers, could be used to help improve a city's mobility and accessibility levels. Although the city of Almelo has tools and traffic management schemes to solve segment-based problems, it also requires an area-based indicator for urban planning and management purposes of the entire city. It is in this regard that this research looked at the spatial and temporal analyses of traffic flows within the city and also explored the feasibility of the existence of the MFD which serves the purpose of providing vital information for planning purposes. Information from such analyses will help determine what planning and management schemes should be put in place to effectively ensure the flow of traffic within the city.

It is therefore upon performing these analyses that "decision-makers can obtain valuable information to evaluate demand-side policies for improving the city's mobility" (Daganzo and Geroliminis 2008). Since the aim of transport planners is to ensure the efficient operation of urban highway systems used by travellers (Donaghy and Schintler 1998), area-based indicators will help in that respect by assisting to manage traffic flow better and thus improve mobility.

1.4. Research Objectives and Questions

1.4.1. Main Research Objectives

The main objective of this research is to perform spatial and temporal analyses of traffic flows in the city of Almelo, and different parts or corridors of the city. Segment-based indicators are very essential in understanding the performance levels of road segments but this may not be ideal for urban planning and management purposes of an entire city. This makes area-wide indicators such as the MFD, an appropriate indicator (for this research) which looks at the performance of the entire city, selected parts of the city or trajectories within the city. Knowledge from this analysis aids the understanding of how different geographic areas or road trajectories are performing (in terms of traffic flow) relative to others and such information is very relevant for engineers and planners to better plan traffic operations in the city at an area-wide level.

1.4.2. Specific Research Objectives

Specifically, the research objectives are:

1. To perform spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo.
2. To study the feasibility of the existence of an MFD for the city of Almelo.
3. To give recommendations on how information from the established models can be used to better plan traffic operations in the city.

1.4.3. Research Questions

In order to operationalise the research objectives, the following research questions have been formulated and have been answered in due course of the research.

Table 1-1: Research Objectives and Research Questions

Number	Specific Research Objectives	Research Questions
1	To perform and study spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo.	• Are there any variations between different parts of the city or different trajectories within the city?
		• What is the performance of the selected parts of the city or trajectories, relative to each other, in terms of traffic flow?
		• What could be the reason(s) for the variations of the selected parts or trajectories?
2	To study the feasibility of the existence of an MFD for the city of Almelo.	• Does a network-based MFD exist for the city of Almelo, given the available data and software?
		• What kind of mathematical relations (models) exist between speed and volume for the city of Almelo?
3	To give recommendations on how information from the established models can be used to better plan traffic operations in the city.	• How can information from the models be used to better plan traffic operations in the city?

1.5. Conceptual Framework

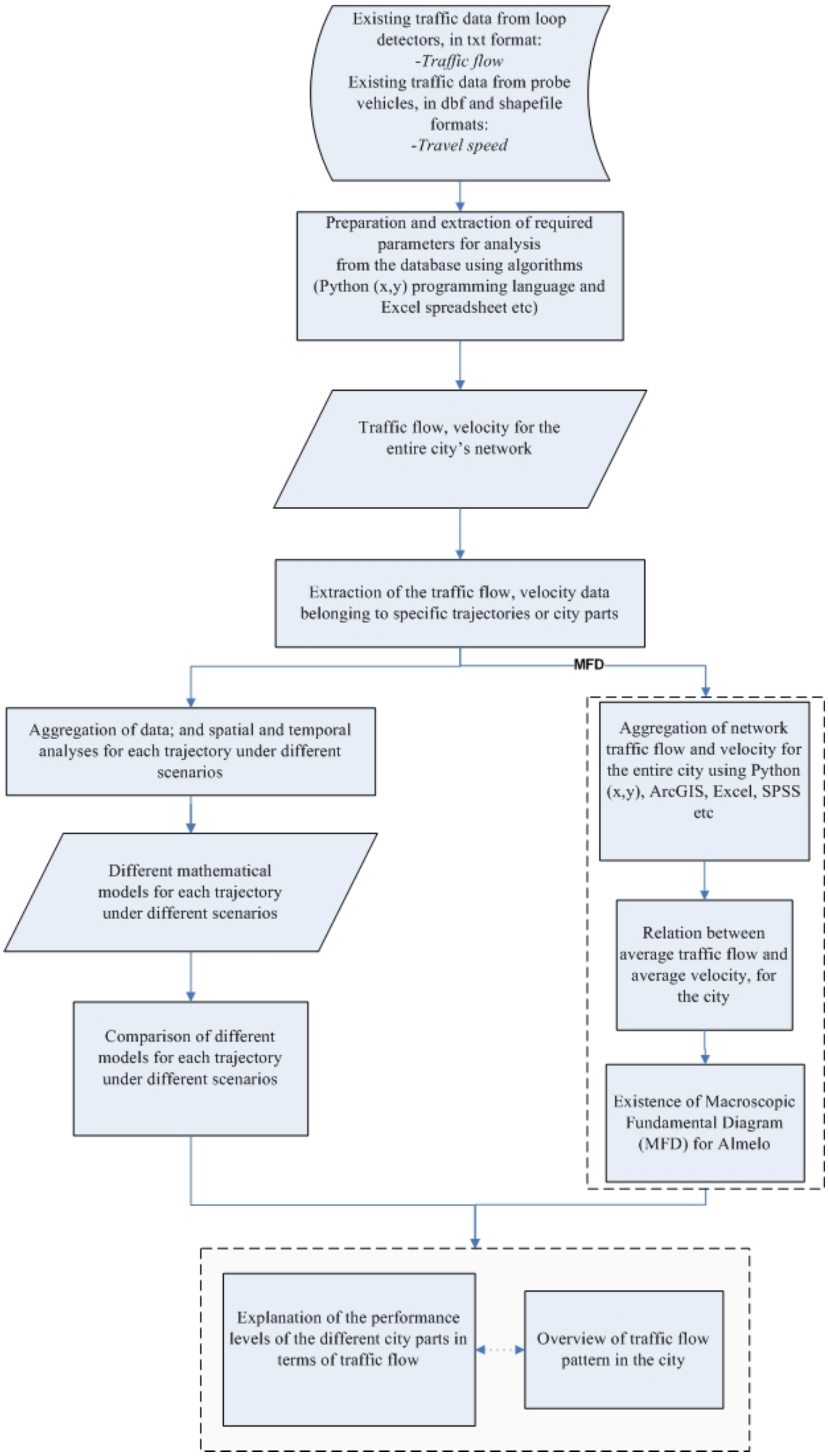


Figure 1-1: Conceptual frame work

The conceptual model shows the concepts and relations existing between them, which were employed in this research. The approach to establishing an area-based indicator for a city like Almelo, The Netherlands is based primarily on the relationship between average traffic flow and speed for the entire network. The data for this relation is collected by loop detectors and probe vehicles over a period of time. Developing very effective strategies to enhance traffic flow conditions on road networks require knowledge on the state of road at any point in time and space. Different methods for collecting information about traffic flow on roads exist, and depending on different factors, a method or combination of methods is chosen for data collection (also depending on the type of study).

This data was prepared and analysed in different ways to obtain the desired variables/ parameters that needed to be compared; for explanations, conclusions and recommendations to be made. In this instance, algorithms were used to aggregate and analyse the data after extracting the required data from the whole. The relationship between average traffic flow and speed for the network was an area of focus since this establishes the MFD, which will be used to comment on the performance of the city's road network.

Based on the above illustrated concept (figure1-1), the performance of the network in general could be determined after the spatial and temporal analyses. The performance should also help in describing the accessibility and mobility levels of the city in that, a network which performs well shows much reduced levels of congestion. Congestion has a lot of negative effects and measures are to be put in place to help monitor traffic flow states on networks. Based on results from the monitoring, recommendations have been given which when operationalised, could help to reduce congestion. One of these performance measures is the MFD which will help improve mobility and accessibility and help explain if the city is well planned or not, or if some selected sections are performing better than others.

1.6. Research Design

The processes that were employed in this research have been summarised in figure 1-2 below. Available literatures have been extensively consulted, making it possible for the research problem to be identified, as the unavailability of an area-based network performance indicator such as the MFD for Almelo. Knowing the research problem made it possible for appropriate research objectives and questions to be formulated and operationalising them have helped in providing answers to the research problem. Already existing data from loop detectors and probe vehicles were used after being refined into the desired format for analyses. These data came in the form of *txt files, dbf* and *shape file* formats. Some were converted to Comma Separated Value *(CSV)* formats for easy analysis. The study area has some intersections with loop detectors which are linked to controllers; and data (for each intersection) from the loop detectors are sent to the controllers for storage. This makes the database very huge because each time vehicles occupy the loop detectors, information picked from them is sent to these controllers. Parameters in the data which did not contribute to the aim of this research were left out and only those required for the purpose of this research have been analysed.

The huge nature of the dataset made the data processing a very laborious task and computationally intensive. The type, quantity, resolution and quality of the data also had effects on the results of the analysis. In the analysis phase, algorithms were partly written using Python (x,y) programming language, and some further analyses were done in Excel, ArcGIS, SPSS, Grapher. Assumptions were made during the analysis process, and statistical and spatial analyses were also carried out based on the selection of different trajectories. This gave rise to different mathematical models and an MFD for the city, which could determine the performance of the city as well as which trajectories were performing better than others. Based on the research findings, conclusions have be drawn and recommendations, proposed.

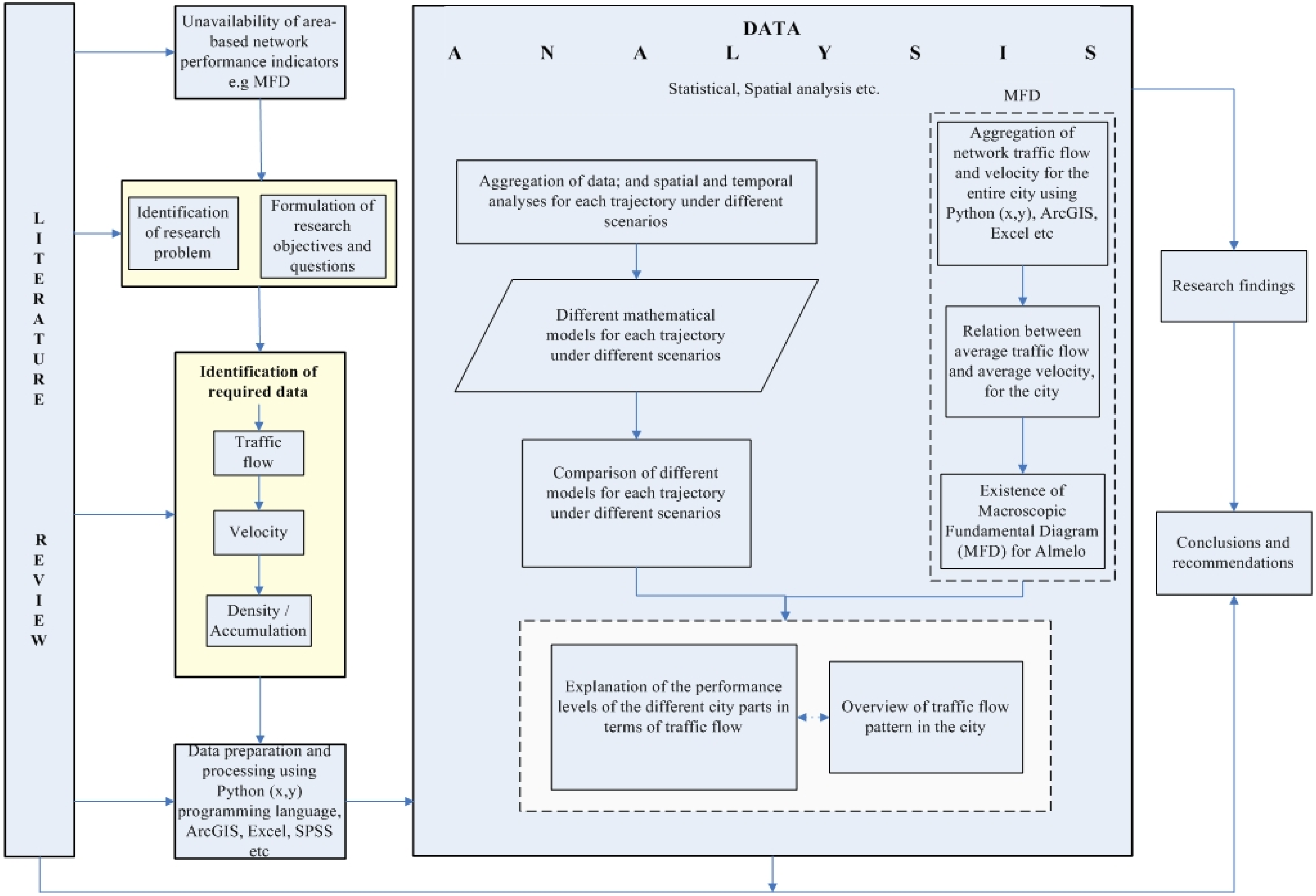


Figure 1-2: Research Design

1.6.1. Research Matrix

Table 1-2: Research matrix

No.	Specific Research Objective	Research Question	Data Required	Data Acquisition Tools	Data Source	Method of Analysis
1	To perform and study spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo.	Are there any variations between different parts of the city or different trajectories within the city?	Traffic flow, velocity data, road network map for the city, relevant literatures on variation analyses.	Loop detectors and probe vehicles.	Secondary	Preparing data by writing algorithms using Python (x,y), Statistical Analysis, Spatial Analysis etc using excel and SPSS. Comparing results among city parts, trajectories etc. Interviews on bottlenecks at activity locations. Analysis in ArcGIS, Grapher, Literature reviews etc
		What is the performance of the selected parts of the city or trajectories, relative to each other, in terms of traffic flow?	Relevant literatures on variation analyses, traffic flow analysis etc. Results of previous analyses.	-	-	Comparing results among city parts, trajectories etc. Interviews on bottlenecks at activity locations. Relevant literatures on correlation and variation analyses, traffic flow analysis etc.
		What could be the reason(s) for the variations of the selected parts or trajectories?	Relevant literatures on variation analyses, traffic flow analysis etc. Results of previous analyses	-	-	Interviews on bottlenecks at activity locations, Relevant literatures, observations from study area.
2	To study the feasibility of the existence of an MFD for the city of Almelo.	Does a network based MFD exist for the city of Almelo, given the available data and software?	Relevant literatures on MFDs, Traffic flow, velocity data , road network map for the entire city	Loop detectors and probe vehicles	Secondary	Literature review, Python (x,y) programming language, ArcGIS, Statistical Analysis, SPSS etc.
		What kind of mathematical relations (models) exist between speed and volume for the city of Almelo?	Relevant literatures on variation analyses, traffic flow analysis etc. Results of previous analyses.	-	-	Statistical Analysis, Spatial Analysis etc using excel and SPSS etc.
3	To give recommendations on how information from the established models can be used to better plan traffic operations in the city.	How can information from the models be used to better plan traffic operations in the city?	Relevant literatures, Results of previous analyses.	-	-	Relevant literatures, Comparing the different models etc.

1.7. Benefits of the Research

Findings in this research will generate some benefits, amongst which are:

- The Municipality will be acquainted with the results from the spatial and temporal analyses which will give them an idea of which city parts or trajectories are performing better than others. Knowledge about this will help the traffic and transport department put in place traffic management measures to ensure effective flow of traffic within the city. Further planning of the city will therefore take into cognisance, the findings from this research.

- The MFD resulting from the research will serve as a road network performance indicator, which tells the performance levels of the city in general, in terms of traffic flow.

- Studying these diagrams and models from the analyses will help in putting in place measures to help improve the network performance, accessibility and mobility levels. That is, they will be used to plan and manage traffic flows on the network.

- It will also serve as a platform for researchers to carry out further research based on the recommendations.

- The researcher gains much knowledge, experience and skills in the use of different methods and tools during the research period. Experience is also gained through the study of the MFD and other forms of spatial-temporal analyses of traffic flows, how they measure performance of networks, how these are used in planning purposes etc

1.8. Thesis Structure

The thesis is organised into six chapters and have been outlined as follows:

Chapter 1: Introduction: This chapter provides an introduction to the study and looks at the background and justification of the research. It goes further to identify the research problem and defines the research objectives and questions. It finally looks at how the research aims to achieve its intended objectives by providing a research design matrix etc.

Chapter 2: Literature Review: This chapter gives the theoretical background for the study by looking at traffic flows and transport within cities. This sets the platform for a look at the theory of traffic flow; and considers the relations between traffic flow parameters. In the same domain, mention has been made of some road performance indicators and what effects unreliable road networks have on a city. Land use and transport also have a lot in common in terms of their interactions and this has been discussed in this chapter.

Chapter 3: Study Area: The spatial context within which the study was carried out is shown in this chapter. It looks at the study area, Almelo in The Netherlands, its population dynamics over the years from 1960 to 2008, some economic activities and ends with traffic and transport statistics of the city.

Chapter 4: Research Methodology: This chapter describes the secondary data collection and further expounds on the approaches used in the data verification process and analyses. It also talks about the devices that were used in collecting the data and how these data were validated. The data analyses processes have also been discussed in this chapter.

Chapter 5: Analyses, Results and Discussions: Chapter five basically looks at the in-depth analyses that were performed in this research. Spatial-temporal analyses that cover the entire city and selected trajectories were discussed. Results from the analyses have been shown and further discussed.

Chapter 6: Conclusion: The final chapter reviews the aims and objectives that set off the thesis. The main findings as per the objectives have been documented in this chapter. The limitations encountered in the course of the research have also been discussed, and lastly, some recommendations to planners, engineers, policy makers and possible directions for future researches have been enumerated.

2. Literature Review

This chapter gives the theoretical background for the study by looking at transport within cities; leading to the study of the theory of traffic flow, and considers the relations between traffic flow parameters. In the same domain, mention has been made of some road performance indicators and what effects unreliable road networks have on a city. Land use and transport also have a lot in common in terms of their interactions and that been discussed in the chapter.

Since MFDs consider relations between traffic flow parameters, the way they relate to each other, the effect their relations have on road segments both at link and at network levels have also been discussed. The location of activities in space over geographical areas has effects on traffic flow and this in turn may affect the MFD for different locations. Apart from looking at how these parameters relate, it is also necessary to see what kinds of information can be derived from them to enable planners and engineers plan in that direction, thus the essence of traffic flow theory in this segment.

2.1. Transport within cities

Transportation serves many useful purposes in our day-to-day lives. The level of mobility and accessibility provided by transport systems have been playing essential roles in not only shaping countries and influencing the location of social and economic activities, but also, influencing the form and size of cities permitting access to people, resources etc. (Zuidgeest 2005). The transport process eventually leads to trips being produced and distributed between and within zones. The traffic flows that result from transportation according to Zuidgeest (2005), may on the longer-term change activity patterns (shifts in modal choice, trip frequency choice etc) and eventually land-use patterns.

In urban planning processes for a city, the need to consider an efficient approach to curb the negative effects of traffic flows on networks is required. According to Daganzo and Geroliminis (2008), it is very complex to really understand traffic situations in large cities at a microscopic level. Although segment-based indicators are very essential in understanding the performance levels of road segments, this may not be enough for urban planning and management purposes of an entire city. This makes area-wide indicators such as the MFD, an appropriate indicator for the purpose of this research, which looks at the performance of the entire city, selected parts of the city or trajectories within the city. Before the feasibility studies of the MFD, various spatial-temporal analyses need to be carried out first to get an insight of how different geographic areas or road trajectories are performing (in terms of traffic flow) relative to others and such information is very relevant for engineers and planners to better plan traffic operations in the city at an area-wide level.

To really understand traffic flows within cities and be able to address the problems that come with it, the various components of urban traffic and transport need to be studied, and that leads us to the study of the fundamentals of traffic flow below.

2.2. Introduction to Traffic Flow Theory

Transportation, which is seen as a system that considers the complex relationships between its core elements: networks, nodes and demand (Rodrigue, Comtois et al. 2005), plays an essential role in our daily lives. This relation gives rise to the flow of traffic on road networks. The mathematical representation of the interactions between vehicles, their operators and the infrastructure can be explained by traffic flow theories (Gartner, Messer et al. 1992) which seek to understand and develop optimal road networks that will allow the movement of traffic efficiently and help reduce congestion. Road space is limited and traffic engineers have to maximise the capacity of the road as much as possible. The measurement of the capacity and what influences it, according to O'Flaherty and Bell (1997), lie at the core of traffic flow theory.

According to Rodrigo et al.(2005), the sole aim of transportation is to meet demand levels for mobility. In this regard, Maoh et al. (2009), see travel demand modelling as an important factor in transport planning processes (Maoh, Kanaroglou et al. 2009) in that demand levels could directly be as a result of the outcome of varied economic activities, without which they would not occur; so there is the need to be able to predict demand levels so as to plan towards their effects.

As mentioned earlier on, traffic flow plays very essential roles in our day-to-day lives and one cannot underestimate the role transport plays in spatial relations between different locations. By virtue of this relation, transport enhances access to different land use types; because of the kind of interaction transport has with land use.

Although traffic flow plays these requisite roles, their negative effects on the environment is one that should be well considered. An indirect effect of congestion caused by transportation is pollution (air and water); and this affects health standards of people. Also to talk about is its safety issues because growing traffic is linked to growing number of fatalities and accidents. With respect to its environmental effects, Rodrigo et al.(2005) are emphatic to say that “decisions relating to transport need to be evaluated taking into account the corresponding environmental costs”. Other cost considerations which have effects on economies can also be seen from the delays spent in congestion and although transportation may have these negative effects, it plays very essential roles by supporting transport demands that are generated by the diversity of activities that are brought forth by the urban society.

2.3. Networks and Traffic Flow

A city’s transport system may be characterised as a network; with a set of nodes (interchanges, intersections etc), links (linear features that provide movement) and loading elements (Ben-Akiva, Bierlaire et al. 2001). The nodes are those locations where movements are originating, ending and are being transferred (Rodrigue, Comtois et al. 2005) and have attributes such as node numbers, locations etc. The segment between two nodes is a link and each link has its own characteristics such as length, number of lanes, capacity, free flow speed, direction etc. Ben-Akiva, et al. (2001), describe the loading elements as those areas where traffic is either generated or attracted. In this respect, they can either be nodes or loading links and therefore, are a generalisation of the zone centroid nodes.

In traffic flow, the movement of discrete units (vehicles or people) on these links is of great importance and these units move without the influence of the other, yet they may interact (Taylor, Bonsall et al. 2000). It therefore becomes appropriate to know how different components interact with one another on road links to form traffic streams. This gives an idea as to how they contribute to congestion on roadways, so that measures are put in place to reduce it to appreciable levels. As described earlier on, the network (supply) planning nature of cities should be such that they can accommodate traffic demand levels even during variations; and this is vital for this research because

MFDs can be used to control demand levels and improve mobility and accessibility (Geroliminis and Daganzo 2008).

2.4. Traffic Flow Parameters and their relationships

Parameters used to describe traffic streams could be categorised as microscopic (considering the behaviour of individual vehicles in a traffic stream with respect to each other) or macroscopic (considering traffic stream as a whole). Some microscopic traffic flow parameters include spacing, headway etc. whereas density, speed and volume/ rate of flow could be seen as macroscopic parameters.

2.4.1. Microscopic Flow Parameters

Although this research looks at spatial-temporal analyses of traffic; and an MFD, which are at a network level, it is also appropriate to look at other microscopic parameters at their individual link and intersection levels because these individual links together form the network. Headway and spacing are two characteristics of microscopic traffic flow because they relate to individual pairs of vehicles within traffic streams. Spacing is the distance between successive vehicles in a traffic stream; and this is measured from common reference points on the vehicles (e.g.; back wheel, front bumper, rear axle etc). A typical example is illustrated in the figure below:

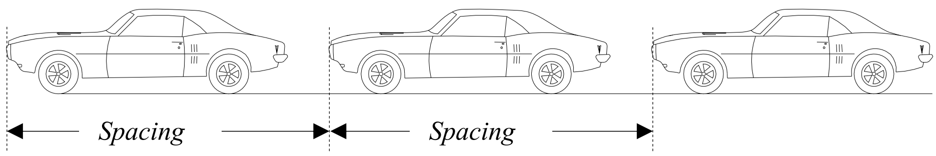


Figure 2-1: Spacing between successive vehicles measured from the front bumpers

Headway, which is a time component, is the time between successive vehicles as they pass a point on a roadway, also measured between common reference points on the vehicles. The use of these microscopic variables is of great importance in traffic flow analysis in that within a very short time, quite a lot of data (headway, spacing etc) can be obtained for vehicle pairs. Also, these variables in an aggregated form relate to density and speed (macroscopic variables).

2.4.2. Macroscopic Flow Parameters

The relationship between macroscopic flow parameters gives rise to the MFD out of which valuable information could be obtained to control demand-side policies to improve mobility in neighbourhoods (Geroliminis and Daganzo 2008). These parameters describe traffic stream for a given time interval by a single value of each - which applies to the traffic stream as a whole. The macroscopic variables that will be discussed under this section include: density, volume and speed.

2.5. Density

Vehicles fill up available road spaces gradually from time to time when moving to areas of traffic demand and according to Maerivoet et al. (2005), density, as a macroscopic parameter can be used to determine how crowded a section of a roadway is. This parameter can be used to assess traffic performance once a relation between density[1] and traffic flow is shown.

Density is defined as the number of vehicles that occupy a given length of a roadway/ lane and is generally expressed as vehicles per kilometre [veh/km]. The measurement of density is difficult but can be computed from the other macroscopic parameters (speed and volume) or estimated. The density (k) for a single lane traffic is defined as:

$$k = \frac{N}{D} \tag{2.1}$$

Where N is the number of vehicles on the length of road segment considered, and D is the length of road section covered by the vehicles. Since multilanes exist in the city of Almelo also, for which the MFD is being studied, density (k_l) for each lane (L) in a multilane is therefore summed up, thus:

$$k = \sum_{l=1}^{L} k_l \tag{2.2}$$

$$k = \frac{1}{D}\sum_{l=1}^{L} N_l \tag{2.3}$$

N_l is the number of vehicles present in lane l. Density can also be derived using speed and flow as:

$$k = \frac{q}{s} \tag{2.4}$$

Where k is the density in vehicle per kilometre [veh/km], q is the flow in vehicle per hour [veh/hr] and s, the space mean speed in kilometres per hour [km/hr].

According to McShane and Roess (1990), density is a very important parameter in terms of traffic demand because it relates to it directly. Based on that, an explanation given by them is that different land use types generate traffic and the trips produced from them produce density which in turn produces flow and speed. Not only does density relate to demand but also it measures the quality of traffic flow, as it measures the proximity of vehicles to one another and demonstrates the degree of freedom to manoeuvre within traffic streams (Highway Capacity Manual 2000). As per the explanations given on density above, it has become obvious how density as a parameter can help tell the performance of road networks because it simply gives an idea how many vehicles occupy a given distance of a roadway and by looking at performance, one can tell if the road network is able to cope with its demand levels.

2.6. Volume and Flow

To be able to derive valuable information from an MFD for transport planning purposes, a relation between density and flow that is established could be of help. Different land use types affect the number of trips produced and distributed between places and these trips characterise traffic flows.

[1] In this research, average traffic velocities were used instead of density which was proposed initially because traffic density data was not readily available. Since density and speed are related $\left(density = {}^{intensity}/_{speed}\right)$, the relation between flow and speed also gives rise to an MFD.

Traffic volume which is often used interchangeably as intensity, traffic flow, throughput, etc. is defined as the number of vehicles that pass a point on a highway or a given lane per unit time. Typical units of volume are vehicles per day [veh/day], vehicles per hour [veh/hr] or vehicles per second [veh/sec]. In planning, designing and the operation of road facilities, May (1990) explains that knowledge about traffic flow plays very important roles; and an instance where such knowledge can be applied is that: Flow measurements are used in origin-destination (OD) studies. The trips obtained from such studies come from the need to move from and to these origin-destination zones as a result of the land use activities that cause the demand to move to these zones. This also has effects on accessibility levels on networks linking the OD zone pairs, thereby making traffic flow an important parameter in the study of MFDs. Secondly, flow measurements are vital for spatial correlation or variation analysis between different areas since it will give an idea of how different areas correlate or show variations when flows on these different links constituting the different areas are aggregated over time (MFD).

Traffic flow (q), (in [veh/hr]) for a single lane traffic based on vehicle counts is given as:

$$q = \frac{N}{T} \tag{2.5}$$

Where N is the number of vehicles that passed a fixed point (detector) and T is the time considered for that flow. Once again in multilane traffic flow, the total flow is shown as the sum of flows of each of the L number of lanes, i.e.

$$q = \sum_{l=1}^{L} q_l \tag{2.6}$$

$$q = \frac{1}{T} \sum_{l=1}^{L} N_l \tag{2.7}$$

N_l is the number of vehicles that passed the detecting site in lane l, assuming that each lane has its own detector.

Peak flow rates are important parameters in capacity analysis (Highway Capacity Manual 2000). The Highway Capacity Manual(HCM), (2000) suggests 15 minutes interval for most operational and design analyses since flow rate variations for shorter periods are unstable, and are difficult to establish. This suggestion has been complied with in trying to establish the MFD by considering the relation between flow and speed over 15-minute intervals.

The 15-minute period of the ratio of hourly volume to maximum flow rate (this ratio is the peak hour factor, PHF) is given as:

$$PHF = \frac{Q}{4Q_{15}} \tag{2.8}$$

Where Q is the hourly volume ([veh/ hr]) and Q_{15}, the maximum 15-minute volume within the hour (in vehicles)

2.7. Speed and Travel Time

Speed (which is a very important parameter that can be related with flow to give an MFD for a given area) is defined as a rate of motion, expressed as distance per unit time. A typical unit is kilometres per hour [km/hr]. It is the inverse of the time taken to traverse a given length of roadway. Accessibility levels for neighbourhoods which can be enhanced by the use of MFDs can be determined by knowing the levels of speeds and travel times on such networks; and showing the relationship of the speed with flow. Speed and travel time are used as indications of the level of service (LOS) on road networks so can be used as network performance measures (May 1990).

Different vehicles travelling at different speeds on a roadway constitute a traffic stream, therefore a distribution of each of the vehicle speeds should be considered in speed analysis. From this distribution, McShane and Roess (1990) point out that an “average” may be obtained to characterise the entire traffic stream. Two ways of computing average speeds are the time mean speed (TMS) and the space mean speed (SMS). TMS is the average speed of all vehicles passing a point on a roadway over a period of time. This is given as:

$$V_{TMS} = \frac{1}{n}\sum_{l=1}^{n}\left({D}/{t_i}\right) \tag{2.9}$$

n is the number of observed vehicles, *D* is the distance traversed and t_i, the travel time for the *ith* vehicle.

The SMS shows the average speed of all vehicles occupying a given section of a roadway over a period of time. The average travel time in seconds (t_i) it takes the *ith* vehicle travelling at a speed v_i to traverse a given length of a roadway *D* is given as:

$$t_i = \frac{D}{v_i} \tag{2.10}$$

Therefore the average travel time t_{avg} for *N* vehicles will be:

$$t_{avg} = \frac{1}{n}\sum_{l=1}^{n} {D}/{v_i} \tag{2.11}$$

and the SMS will be:

$$V_{SMS} = \frac{D}{{1}/{n}\sum_{l=1}^{n}\left({D}/{v_i}\right)} \tag{2.12}$$

but speed (v_i) is given as D/t_i, therefore substituting this into equation 2.12 gives:

$$V_{SMS} = \frac{D}{{1}/{n}\sum_{l=1}^{n}\left\{{D}/{\left({D}/{t_i}\right)}\right\}} \tag{2.13}$$

$$V_{SMS} = \frac{D}{{1}/{n}\sum_{l=1}^{n} t_i} \tag{2.14}$$

$$V_{SMS} = \frac{nD}{\sum_{l=1}^{n} t_i} \tag{2.15}$$

2.8. The Fundamental Diagram

How effective a roadway system is can be evaluated based on a number of elements which include the number of vehicles that can travel on the road, the speeds at which these vehicles can travel, the density of vehicles along the roadway, the distances between these vehicles, the freedom to maneuver among lanes, etc. These qualitative and quantitative measures affect each other one way or the other and the derivation of the macroscopic parameters which relate to form the MFD has been shown below.

When vehicles move in a traffic stream, a relationship exists between spacing (s) and the density (k) of the stream of vehicles on a given length of a roadway. This is shown as:

$$s = \frac{1}{k} \tag{2.16}$$

Also, the headway (h) between these vehicles in a stream is the inverse of traffic flow (q), thus:

$$h = \frac{1}{q} \tag{2.17}$$

and the headway between two vehicles travelling at a spacing (s) with a speed (u) is given by:

$$h = \frac{s}{u} \tag{2.18}$$

Substituting equations 2.16 and 2.17 into 2.18; shows the relation between the macroscopic variables flow, speed and density. i.e.

$$q = uk \tag{2.19}$$

This equation represents the behaviour of one parameter with respect to the other and is the basis for the fundamental diagram since it involves a relation between traffic flow, speed and traffic density. The sub-chapters below show how each of these parameters relate to the other and what kind of information can be obtained from them. As part of this research, the application of data from loop detectors and probe devices have been analysed giving rise to the MFD. Based on the interpretation from the diagram; information obtained from it can be used by planners, traffic engineers etc to further plan traffic circulation within the city of Almelo.

2.8.1. Speed- Density Model

The development of a traffic flow model begins with a relation between speed and density (van Maarseveen, Zuidgeest et al. 2005). The relationship between these two parameters provides essential information for planning purposes, which is one reason why the MFD is being investigated for Almelo. In real life situations, a typical example of this relation is shown in figure 2-2. The graph shows that when a single road user uses the roadway he could drive at any desirable speed because density *(k)* is low and this is the free-flow speed *(u_o)* since the choice of speed is not limited by other road users. When more and more drivers begin using the roadway, density increases and the speed decreases significantly (because of the many interactions amongst vehicles) till the road capacity is reached. When the product of density and speed results in the maximum flow, the capacity is reached and this is referred to as optimum speed u_c (often called critical speed), (Highway Capacity Manual

2000). At a point in time, density becomes so high such that all vehicles stop and speed is now zero (this condition is the jam density, k_s). Information such as this from this diagram will aid the city authorities in planning the city by knowing how various land uses contribute to this diagram as a result of land use-transport interactions, what the city's free flow and critical speeds are etc and this is essential for planning, traffic management and safety purposes. Knowledge about the city's jam density helps to put in place effective measures to control traffic flow in the city so that the city's flows do not get to such high levels, if possible.

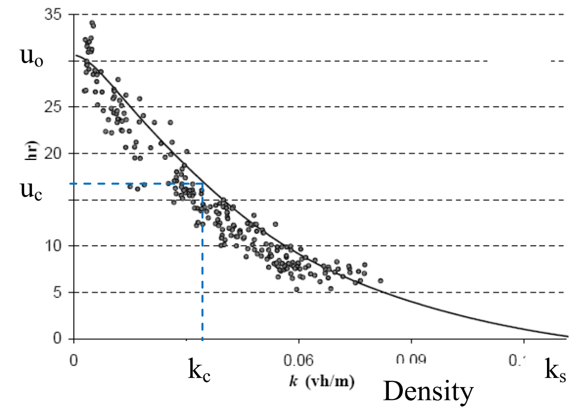


Figure 2-2: Speed- density relation for the city of Yokohama, Japan.

Source: (Daganzo and Geroliminis 2008)

This kind of relation can be shown theoretically as:

$$u = u_o\left(1 - {}^{k}/_{k_s}\right) \tag{2.20}$$

2.8.2. Speed- Flow Model

An aggregation of the average speed *(u)* and flow *(q)* of vehicles on the road network in the city of Almelo could establish a relation such as in figure 2-3, if the city has the overall traffic characteristics as such.

Density (k) can be derived from equation 2.20 as:

$$k = k_s\left(1 - {}^{u}/_{u_o}\right) \tag{2.21}$$

Substituting equation 2.21 into 2.19, the flow can be obtained as shown in equation 2.22

$$q = k_s\left(u - {}^{u^2}/_{u_o}\right) \tag{2.22}$$

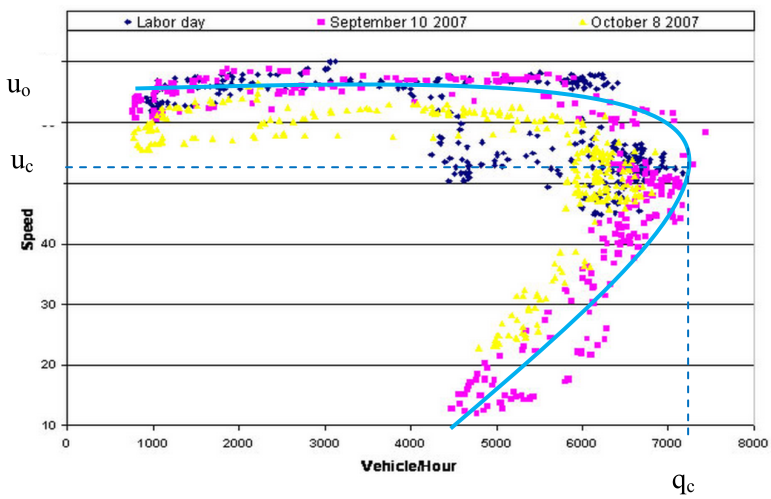


Figure 2-3: Speed/Volume Relationship observed on Northbound I-405 (Los Angeles), Three Mondays in September-October 2007

Source: (United States Department of Transportation - Federal Highway Administration 2009)

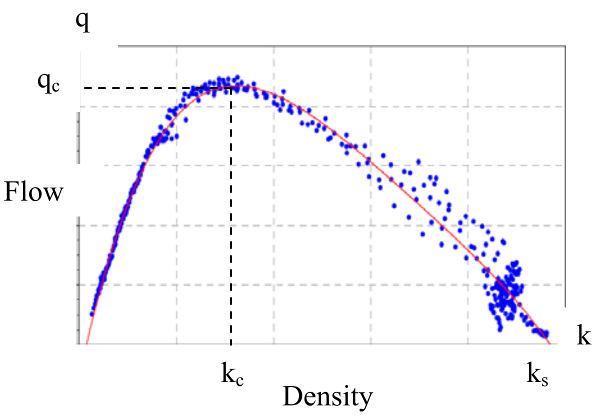
Through the study of the relationship between these parameters, one is able to interpret and know the kind of relation between land use and transport that contributes to this type of graph. Initially with no vehicles on the roadway, speed and flow are both zero. As the number of vehicles increases, the flow increases and speed decreases due to the vehicles interactions, until a capacity is reached; then flow decreases with decreasing speed. The capacity of the road is reached at this point. Also at this point, the maximum flow *(q_c)* and critical speed *(u_c)* can be known. These are vital information that can help engineers and planners further plan the city to meet the ever increasing traffic demand levels.

2.8.3. Flow- Density Model

The third model, which is a relation between flow on a network and the corresponding density, is a fundamental diagram of traffic flow. Theoretically, this graph can be obtained as shown in equation 2.23. It is derived by comparing equations 2.19 and 2.20. Thus flow (q) is obtained (equation 2.23) and is illustrated in figure 2-4:

$$q = u_o \left(k - {k^2}/{k_s}\right) \tag{2.23}$$

Some characteristics of an ideal flow-density relationship which serve as very useful information for planning purposes are that: when there are no vehicles on the road way (thus no flow), density is also zero. When the flow increases, density also increases till the road reaches its capacity when flows reduce because density is increasing. At this capacity, the critical density of the road can be known. From such graphs, it is able to determine what the jam density and maximum flow of the city are. Engineers can also deduce from the same graph at what density the city produces its maximum flow, and this is one of the objectives of investigating the existence of an MFD for Almelo. The terms as used in the relation are defined as:



q = flow
q_c = maximum flow
k = density
k_c = critical density
k_s = jam density
u = speed
u_o = free speed
u_c = critical speed

Figure 2-4: Relation between flow and density for the city of San Francisco network

Source: (Geroliminis and Daganzo 2007)

The discussions on the relationships between the three macroscopic parameters show that essential information required for planning and traffic operation purposes can be found in such diagrams. It is only after modelling and establishing such diagrams, that such information can be obtained to plan our city and road networks so as to be able to accommodate the ever increasing traffic demand. Once that is factored in planning purposes, mobility and accessibility will also be enhanced.

2.8.4. Level-of-Service (LOS)

Talking about the performance of road networks which can be studied by the use of the above described fundamental diagrams, the LOS concept also helps to describe a range of operating conditions on a particular facility. The LOS for each facility is measured by a measure of effectiveness and the three primary measures used by the HCM are speed and travel time, density and delay (McShane and Roess 1990). According to Papacostas and Prevedouros (2001), estimates of average delays for each vehicle using the road facilities determine the performance of the facility, with short delays resulting in good LOS and long delays resulting in poor LOS. LOS is described by six levels (A-F) and has been described extensively in section 2.9.3.4.

2.9. Road Network Performance

2.9.1. The need for traffic analysis

From Sumalee and Watling's (2003) point of view, the interactions between different components of a road network; such as the demand and supply sides (e.g. the link-flow volumes in the network), is the main mechanism that defines the state of the network. As these components interact, there can be variations in the link capacities of networks. The different forms of interactions have been summarised in figure 2-5 below. An aspect of this diagram (network reliability-section 2.9.2) has been looked into further detail under network performance indicators. The interaction which gives rise to different operational states of the network shows how the network performs with demand.

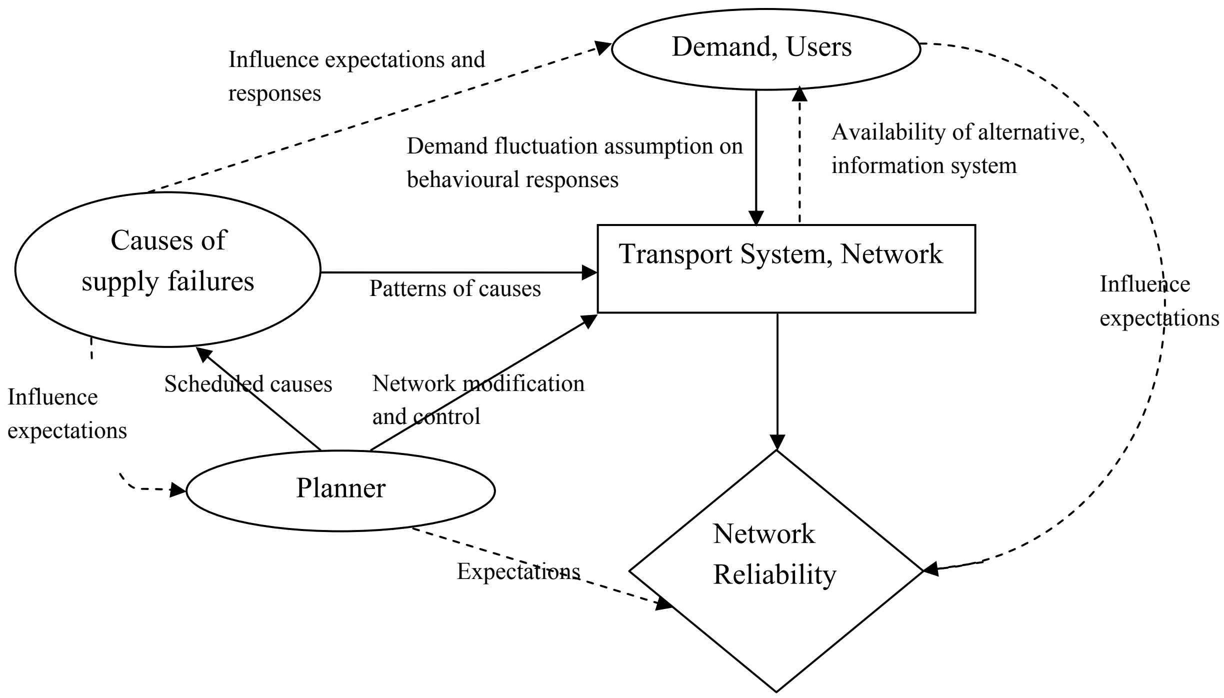


Figure 2-5: Conceptual framework for the analysis of transport network reliability

Source:(Sumalee and Watling 2003)

The performance of road networks is a key area that transport, traffic engineers and network operators pay great attention to. It is ideal to know how the road network has performed in the past, how it is performing now and how its future can be planned to meet increasing demand levels. The assessment of the performance of the network helps determine if the performance is meeting set strategic or operational goals. In traffic analysis studies, network operators need to know if they are achieving an efficient form of utilisation of the network from the capital investment made in the infrastructures provided. When traffic analysis is performed road network capacity upgrades can be planned in an effective manner. Traffic control measures can also be put in place to enhance the efficient movement of traffic on the network. This will therefore help reduce congestion, emissions of pollution etc, thus helping the economy in a way.

2.9.2. Network Reliability

How reliable our road networks are, is becoming an increasingly important attribute of road networks (Yin and Ieda 2001) and also a concern for planners and engineers in network design (Yin and Ieda 2002; Dimitriou, Tsekeris et al. 2007). This is because a network that is unreliable has effects on the lives of commuters and the economy of the nations, giving concern to studying the reliability of networks during area-wide studies. Bell an Iida (1997), define reliability from systems engineering point of view as the degree of stability of the quality of service that a system normally offers; and in a transport system such as a road network, travel demand flows and the physical network may contribute to how reliable the network is. A similar idea shared by Liu et al, (2004) is that "reliability, by its nature, implies something about the certainty or stability of travel time of any particular trip under repetition".

In road network reliability, Dimitriou et al. (2007), Sumalee and Watling (2003), share similar views that the level of stability of the transport network system can be related to its ability to respond and meet the expected demand levels under different circumstances (e.g. variability in flows and physical network capacities). A typical example where a network is reliable as shared by Ang and Tang (1990), is that the network should be able to cope with variations in demand over different days of a week by maintaining a constant average travel time between different origin-destination pairs (Ang and Tang 1990).

The focus of this research makes some recommendations as to ensuring that the road network in Almelo improves accessibility and mobility levels, thus reducing travel times and improving on its reliability, and that is what transport planners and engineers seek to do. Before improvements are made to the current network structure in terms of planning and engineering, network indicators will have to be used to assess present performance of the network. In view of that a look at different indicators has been considered of which the MFD promises to be very reliable according to research (Geroliminis 2008) and that is what this research seeks to investigate for the city of Almelo.

The next sub-chapter discusses some performance indicators that are applied at link levels of road networks. Although these indicators do not directly contribute to the study of MFDs in this research, they are worth discussing since they are used to assess performances of segments, which form the basis for MFDs, at an aggregated level. Just as these indicators determine how reliable segments are, they could be said to determine the performance levels of these segments and that is what the MFD seeks to do (by considering the segments at an aggregated level).

2.9.3. Traffic/ Network Performance Indicators

The performance of a country or region's economy, according to Lo at al. (1999), Chen et al. (2002) and Tang et al. (2005), depends heavily on an efficient and reliable transportation system to provide accessibility; and provide safe and efficient movement of goods and people. This same view is shared by the University of Applied Science Technikum Wien (2009), that the performance of transport systems has a crucial role for individual mobility and the welfare and economic growth of all nations. On the other hand, smooth traffic flow in a road network is often subjected to interruptions, so the need for the study of the reliability of a road traffic network (Lo, Yang et al. 1999).

As discussed previously, how effective a road system is can be evaluated based on a number of elements which include the number of vehicles that can travel on the road, the speeds at which these vehicles can travel, the density of vehicles along the roadway, the distances between these vehicles, the freedom to maneuver among lanes, etc. These are both qualitative and quantitative measures that could help us know how our road networks are performing in terms of meeting traffic demands.

An indicator, which helps to monitor and assess progress of work of a project, system etc can be used to measure the performance of road networks in terms of traffic flow. In this regard, Newton (2001), in chapter 2 of *Cities databook* confirms that performance indicators are essential because they could measure aspects of the performance of say, cities or road networks, and are intended to identify which sections of these entities are meeting desirable aims. Some of the network performance indicators that have been discussed for the purpose of this research have been enumerated below. Although these indicators may not directly contribute to the study of MFDs, their descriptions are of essence since they constitute some of the studies planners and engineers carry out to enable them determine the performances of road segments.

2.9.3.1. Travel / Journey Time Reliability

The Transport Research Laboratory (TRL) (2009) on their web page emphasise that there is a need for performance of road networks to be monitored over time so as to enable road managers to give attention to reducing congestion and improve travel time reliability. In the analysis of the reliability of road networks or transport systems, Lo et al. (1999),Chen and Recker (2000) point out the fact that although the analysis is of great importance, very little attention has been given to it (Chen et al, 2000 as cited in (Bell and Iida 1997)) . They define travel/journey time reliability as the "probability that a trip between a given origin-destination (OD) pair can be made successfully within a specified interval of time for a given level of traffic demand in the network". This makes travel time an important indicator of transportation systems but Nicholson and Du (1997), observe uncertainties of travel time reliability on road networks. These uncertainties they say stem from two sources: variations in demand flows or variations in arc capacities (Nicholson and Du 1997) as cited in (Chen, Yang et al. 2002). Hence two definitions for travel time reliability exist depending on the source of variability (Chen, Yang et al. 2002). The first, concerned with daily flow variations, is suitable for evaluating network performance under normal traffic conditions; whereas the second considers variations due to degradation and is suitable for both normal and abnormal traffic conditions.

As Sumalee and Watling (2003) put it, "the degree of stability of the transport network system can be referred to as the ability of the network to meet the expected goals under different circumstances (e.g. variability in flows and physical network capacities)". This therefore implies that travel time reliability can depict the stability of the system. In this instance, it is expected that the network should be able to cope with the variations in demand over different days of a week by maintaining a constant average travel time between the different OD pairs. The reliability of travel time is also observed as an important factor for trips; so it has a role to play in traveller's route choice procedures. For transport managers, if travel time reliability is enhanced, it will lead to better fleet management and may significantly reduce scheduling mismatches and lead to time and cost savings (Small, Noland et al. 1999) as cited in (Tu 2008).

2.9.3.2. Connectivity Reliability

Chen and Recker (2000) and Chen et al's (2002) studies on reliability measures of road networks define connectivity reliability as the probability that network nodes are connected. Terminal reliability (the existence of a path between a specific OD pair) is seen as a special case in connectivity reliability (Iida and Wakabayashi 1989). According to Chen and Recker (2000) and Chen et al (2002) , the condition that satisfies a network being successful is that for a given node pair, at least each path should be operational. A path consists of a set of roadways or arcs. In their separate papers, Chen and Recker (2000) and Chen et al (2002) state that even in situations like earthquakes, this form of reliability analysis may be ideal but there is an underlying inadequacy in that it only allows for either a state that operates at full or complete failure at zero capacity. This binary approach limits applications where arcs are performing between these two extreme conditions therefore reliability and risk assessment outputs obtained through this approach may be misleading for normal conditions (Chen and Recker 2000; Chen, Yang et al. 2002).

2.9.3.3. Capacity Reliability

Most of the existing reliability studies of road networks only focus on travel time and connectivity reliability which may not be sufficient for a network performance measure, according to Chen, Yang et al. (2002). Bell and Iida (1997), also share similar views with Chen et al (2002), because they emphasise that although it is very necessary to assess the reliability of transport systems, very few reliability studies exist (Bell and Iida 1997) as cited in (Chen and Recker 2000).

Capacity reliability is a new network performance indicator that has recently been introduced by Chen, Yang et al (1999) and Chen et al (2002). They define capacity reliability as the probability that the network's capacity can successfully accommodate a certain level of OD demand at an acceptable service quality (Lo, Yang et al. 1999; Chen, Yang et al. 2002), and that, it should be considered an important measure of overall system performance that is of interest to system managers (Lo, Yang et al. 1999). The capacities for network links may change from time to time due to various reasons such as the blockage of one or more lanes due to traffic accidents etc. Capacity reliability explicitly considers the uncertainties associated with arc capacities by treating roadway capacities as continuous quantities subject to routine degradation due to physical and operational factors.

Reliability of road network capacities depend on several factors of which demand levels is one. Road networks are designed to carry certain base travel demand levels and recent studies have shown that when demand levels are lower than the base demand levels, networks exhibit a very high level of reliability but once demand levels increase, capacity reliability deteriorates and fails completely when the levels go higher than the base levels (Chen, Yang et al. 2002) .

2.9.3.4. Level of Service (LOS)

The level of service concept has gone through a lot of developments as far back as the 1950s till now. Its formal introduction in the Highway Capacity Manual (HCM) was in 1965 (Highway Capacity Manual 1965). In the 1985 version of the manual, it was defined by six levels (A to F) in relation to several traffic conditions like a combination of travel time and the ratio of traffic flow rate to the capacity, because travel time was recognised as a dominant factor of the service quality (Highway Capacity Manual 1985) as cited in (Kita 2000). By Pecheux et al's (2000) opinion, finding effective ways to maintain acceptable LOS is critical in terms of user satisfaction and the protection of the environment, especially in current situations where congestion on our roads is increasing. The HCM serves as a "tool" to help traffic engineers, planners etc to monitor traffic conditions so as to make transport improvement decisions (Highway Capacity Manual 2000) but Choocharukul et al. (2004), are convinced that past researches provide evidence as to the difficult nature in quantifying the LOS concept and is one that "likely includes a complex interaction of many traffic parameters and road-user perceptions".

According to Zhang et al.(2004), previous editions of the Manual (Highway Capacity Manual 1985; Highway Capacity Manual 1998) defined LOS as "a qualitative measure describing operational conditions within a traffic stream and their perception by motorists and passengers" but the phrase "perception by motorists and passengers" was removed from the 2000 edition (Highway Capacity Manual 2000; Zhang and Prevedouros 2004). The 2000 version of the Manual defines LOS as "a qualitative measure describing operational conditions within a traffic stream, based on service measures such as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience". Although "perception" is no longer used to define LOS in HCM 2000, Zhang and Prevedouros (2004) are of the view that there is no doubt that LOS is a qualitative measure that needs to reflect user perceptions of quality of service, comfort and convenience.

Each of the six level scale definitions of LOS has been explained in the box below:

LOS A shows conditions of free flow where the presence of vehicles on the road do not greatly affect others in any way. The factors that affect vehicle operations are the geometric features of the highway and by driver preferences. Flows in this range do not affect speeds of travel and it is easy to maneuver (lane changes, merging and diverging movements) within the traffic stream. Spacing between vehicles is approximately 0.134 km at a maximum density of 12 passenger cars per mile per lane [pc/mi/ln] and minor disruptions to flow are easily absorbed at this level without a change in travel speed.

At LOS B, the presence of vehicles is noticeable and average speeds are the same as in the free flow level, but drivers have slightly less freedom to maneuver. Vehicle spacing is at an average of about 0.08 km at a maximum density of 20 passenger car per miles per lane [pc/mi/ln]. Still at this level, minor disruptions are easily absorbed, although localised deterioration in level of service will be more obvious.

The influence of traffic density on operations becomes vivid during LOS C and the presence of other vehicles begins to restrict the ability to maneuver within the traffic stream. At this level, average speeds remain at free flow states but drivers need to adjust their course to find gaps they can pass or merge. The average spacing of vehicles is reduced to approximately 0.06 km at a maximum density of 28 pc/mi/ln. Queues may form behind any significant traffic disruption and minor disruptions may be expected to cause serious local deterioration in service.

The LOS where average speeds begin to decline with increasing flows and the ability to maneuver is severely restricted; is LOS D. At this level, breakdowns can occur quickly in response to smaller increases in flow. Average spacing of vehicles is 0.047 km at a maximum density of 34 pc/mi/ln, so maneuvering within the traffic stream is now a bit difficult. Only minor disruptions can be absorbed without the formation of extensive queues and that leads to the deterioration of service to LOS E and LOS F.

LOS E shows operations at near capacity and there is very minimum spacing between the vehicles in the traffic stream. The limits for the level of service are approached and most disruptions will cause queues to form and service to deteriorate to LOS F. Maneuvering is difficult at this level of service.

At LOS F, which is the worst operating condition, queues are formed behind points of breakdowns such as accidents etc.

Sources: (McShane and Roess 1990; Highway Capacity Manual 1998)

Although LOS is identified as a qualitative measure that needs to reflect user perceptions of quality of service, comfort and convenience (Zhang and Prevedouros 2004), it does not do much when dealing with area or city-based performances, to reflect the quality of service provided by road networks. All the six levels of scale of the LOS denote the performance of road segments from time to time as vehicles fill available road spaces and these are to some extent confined to individual segments. In terms of area or city-scale performance of networks, an MFD has been recommended and is described in the next sub-chapter, since segment-based indicators (such as LOS) may not be sufficient in determining network performances, at area and city levels.

2.9.3.5. Macroscopic Fundamental Diagram (MFD)

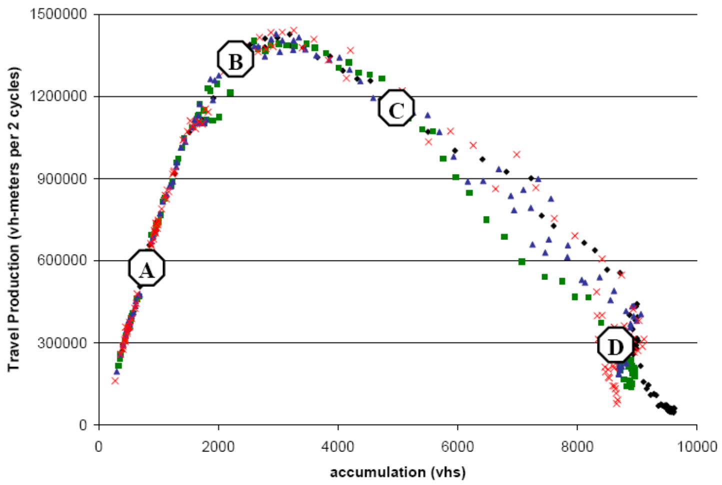
Macroscopic models common to traffic-related simulations have a long history, with the study of fundamental diagrams by Greenshields in 1935,(Greenshields 1935) as cited in (Muñoz 2004). According to Dixit and Radwan (2007), the measurements and relationships that exist between macroscopic variables (speed, density and flow) have been broadly studied for traffic streams theoretically and practically, (Edie 1963; Gazis 1974) as cited in (Dixit and Radwan 2007). Works by Wardrop (1952) and Smeed (1968) dealt with the development of macroscopic models for arterials, and were later extended to general networks (Wardrop 1952; Smeed 1968) as cited in (Geroliminis 2008).

Much work was also performed on how fundamental diagrams could be used to describe traffic patterns at signalised intersections or incident areas by Lighthill and Whitham in 1955, (Lighthill and Whitham 1955) and (Lighthill and Whitham 1955) as cited in (Lo, Chang et al. 2001). Again in 1974, the same authors (Lighthill and Whitham) looked at how vehicular traffic could be modelled macroscopically (Whitham 1974) as cited in (Klar and Wegener 2000).

It should be observed that most of the different performance measures described in the previous sub-chapters look at the performances at disaggregate link and intersection levels unlike the MFD which measures network performances at aggregated levels. This fundamental diagram serves as an indicator to measure the performance of the network during area-wide studies. All these performance measures are used worldwide but there is the need for "a consistent, reliable means to evaluate traffic performance in a network under various traffic and geometric configurations" (Williams 1996) and the use of the MFDs is a good option and the most promising out of the lot, according to recent studies (Geroliminis 2008).

The MFD is a diagram that shows the relation between average flow in the network and the network's average traffic density (Gonzales, Geroliminis et al. 2008) from which decision makers can use valuable information to evaluate demand-side policies for improving a neighbourhood's mobility (Daganzo and Geroliminis 2008). According to Magne, et al (2000), macroscopic models have advantages such as: input needs for macroscopic simulation are reduced and large scale city network modelling is easier, less computation time is required and their calibrations are easier . Geroliminis (2008), shows in his paper that several theories describing vehicular traffic movement in cities on an aggregate level have been proposed but these do not produce a macroscopic model (city-scale) with varying inputs and outputs that could describe dynamic rush hours.

Geroliminis and Daganzo's (2008) experimental findings show that MFDs can be used to control demand and improve mobility and accessibility within a city. This improvement is seen to enhance the performance of the road network (how the system responds to increasing travel demand levels (Williams 1996)). Once the MFD for a city is established and mechanisms are put in place to monitor the state of traffic flow, it is possible to know if the network is producing the desired accessibility levels at all times. By so doing, existing strategies can be refined to enhance the performance of the network and this is very vital for planners, in that the LOS that are provided to motorists, pedestrians etc could be monitored to assess the city's ability to manage growth (Williams 1996) . Since the performance could also be attributed to the way a city is planned, a typical MFD for a city may help explain if the city is well planned or not, or if some selected sections (of spatial interest) are performing better than others so as to know how to allocate resources for transport network improvements in an equitable manner.



As discussed previously, the MFD in itself has vital information which can be considered for planning purposes to enhance mobility and accessibility in cities. Typically, an MFD can be put into four phases (A, B, C, D) as shown and each of these phases shows the different state of the network with increasing traffic flow.

Figure 2-6: A typical MFD (for the city of San Franscisco)

Source: (Geroliminis and Daganzo 2007)

Phase A shows the condition when the system is undersaturated[2] and the average speed is about 25km/hr with an accumulation of about 952 vehicles. As demand increases the system moves to state B where the vehicle – miles travelled is near the maximum and the average speed is 17km/hr with an accumulation of 2143 vehicles. At this stage, engineers can tell at what accumulation the system experiences its maximum capacity, and this can be useful for planning purposes as well as knowing the land use activities that contribute to that accumulation. In phase C congestion is broad, long queues are observed and the average speed drops to 7km/hr (with an accumulation of 5337 vehicles). In state D output is near to zero (jam density) and the majority of vehicles are stopped (accumulation of 8943 vehicles). Once again, knowledge about the jam density could assist in putting in management measures to manage the overall flow within the city from getting to such high levels, thereby reducing congestion. Without such fundamental diagrams, some of this information will not be very evident making the MFD, a much promising indicator for determining performance of road networks.

2.10. Effects of Unreliable Networks

It is the hope of many engineers and road planners that network systems will be operating at ideal and at reliable conditions. Assessing the performance reliability of a road transportation network has become very crucial since this will help improve the quality of services delivered to commuters. Levels of unreliability have potential impacts on both individuals' lives and the efficiency of the economic system.

An unreliable network for example has an effect on travel time and this introduces uncertainty since commuters are never certain in trip journey times and this is an added cost of travel to them. Just as the travel time reliability indicator above, described, commuters' planned travel times experience a lot of superfluity so as to minimise the impact of unanticipated delays on scheduled activities which could lead to the degradation of the welfare of society as a whole. And this level of unreliability can result if roads are not planned and designed to meet demands, even during variations (capacity reliability).

Agencies in charge of transport planning of cities also experience the problem of unpredictability in transport costs due to the uncertainty in the transport system; hence the risk may be transferred to the price of commodities which is borne not only by trip makers but a lot of people in totality, one way or the other.

Connectivity reliability as described above brings to light about the fact that transportation systems are very essential components not only during our daily activities but also during the occurrence of natural disasters. Transport systems have therefore been identified by Nicholson and Du (1997), as the most important lifeline in the event of natural disasters (hurricanes, floods, earthquakes etc). While other lifelines (communication networks, electricity, water supply etc) can be restored in a relatively short period of time, the restoration of these systems depends highly on the accessibility to the failure points using the transportation infrastructure, therefore an unreliable network will hinder such a restoration process and increase not only economic loss but also fatalities that are difficult to quantify.

[2] The degree of saturation which is also referred to as the volume-to-capacity ratio (v/c ratio) shows the proportion of the capacity (supply) that is being used by the existing traffic volume (demand).

In this regard networks should be designed to be reliable by factoring in daily “disturbances” and should maintain an acceptable LOS even if certain links in the network are deteriorated. Chen et al. (2002), express their concern about the stability of road networks and say they should reflect the quality of service they would normally provide since a stable system would provide a competitive edge in global economy. Thus, the importance of a reliable transport system cannot be overemphasised (Chen, Yang et al. 2002).

To some extent, MFDs as performance indicators can describe the reliability of road networks. Just as recent studies demonstrate, valuable information from an MFD can be used to evaluate demand-side policies to improve a city’s mobility (Daganzo and Geroliminis 2008). When measures from such information are operationalised, they enhance mobility, accessibility and even, the reliability of the network. Although the other indicators apart from the MFD consider performances of transport systems at link levels, they constitute the numerous studies the Municipality of Almelo carry out to study the performance of localised road problems. But this research considers area-wide indicators and therefore looks at the feasibility of the existence of the MFD for Almelo.

2.11. Discussions

Some of the segment-based performance indicators that have been looked at in this chapter include connectivity, travel time, capacity reliabilities and the use of the MFD (area-wide indicator). Connectivity reliability is the probability that there is still a connection between a pair of nodes in the network when one or more links are closed. This type of reliability analysis may be suitable for abnormal situations and not for normal situations. A capacity reliability analysis may be suitable on very important links that are likely to fail. Both measures are interesting for network planners as well as for individual users but should be noted that capacities for a road network can change from time to time due to various reasons such as traffic incidents that may block one or more lanes, lane blockage due to construction etc. Quite recently, Yang, Bell et al. (2000), showed that the capacity of a road network does not only depend on arc capacities but also on demand level, congestion effect, and route choice. On the part of road commuters, travel time reliability is probably the most likely to be given attention to because it indicates directly the impact caused by the link degradation to the user. All these indicators consider performance of road network at link level but the MFD does otherwise by aggregating at network level and has essential information for road and city planning.

These segment-based indicators may not directly contribute to the study of MFDs in this research but they are seen as very essential during link-level studies because just as the MFD, they discuss the improved mobility and accessibility levels of neighbourhoods by determining if road systems are reliable or not (that is, if performance levels are enhanced or not). They could therefore form the basis for MFDs, since the MFDs upgrade from the segment-based indicators.

These segment-based indicators as described in previous chapters are essential in understanding performance levels of road segments but may not be enough for urban planning and management purposes of an entire area or even a city. This makes area-wide indicators such as the MFD, an appropriate indicator, which considers the performance of the entire city, selected parts of the city or trajectories within the city

2.12. Transport and Land Use Interaction

Land use and transport interaction is an area of study that has seen a lot of extensive research for several decades now, e.g. , (Lowry 1776; Hoyt 1939; Harris and Ullman 1945; Hansen 1959; Alonso 1964; Hägerstrand 1970; Wilson 1970; Boyce 1980; Anas 1982; Kim 1983; Anas and Duann 1986; Prastacos 1986; Kim, Rho et al. 1989; Landis and Zhang 1998; Landis and Zhang 1998); (Hirschman and Henderson 1990) as cited in (Shaw and Xin 2003) and (Garrison 1960; Maxfield 1969; McLoughlin 1969; Daniels 1975; Salau 1999) as cited in (Oduwaye 2007). This level of interaction is seen as quite complex but despite its complex, dynamic interactive process (Shaw and Xin 2003) , it is essential to always plan land use and transport interaction processes for cities.

Land use planning (LUP) has been defined and described in various literatures (Nnkya 1998) etc. A typical definition is that: LUP is "a programme of state intervention in land use and environmental change to mediate conflicts of interests over how land should be used, developed, and coordinate individual activities which if left to proceed otherwise would lead to an environment for living that is characterised by negative externalities, inefficient use of land and services, inequity and unfair distribution of resources" (Nnkya 1998).

The Working Group on Integrated Land Use Planning (WGLUP) formulated their basic understanding of LUP based on previous project experiences; and they defined LUP as an "iterative process that is based on the dialogue amongst all stakeholders aiming at the negotiation and decision for a sustainable form of land use in rural areas as well as initiating and monitoring its implementation"(Amler, Betke et al. 1999) . In all this, Nidumola et al.(2006), are of the view that LUP is required to be able to choose and put into practice those land uses that will meet present needs of the people in the best way, while safeguarding resources for the future (Nidumolu, De Bie et al. 2006). From these definitions, it is observed that LUP has to do with how our lands and resources are managed effectively. By so-doing, communities are able to set goals on how the community should grow and develop; and how these goals can be attained.

Different literatures continue to investigate transportation planning from diverse scopes and Banister (2002), concedes that it is evident to see the problems created by the increased demand for transport which gives rise to transport planning. According to Zuidgeest & van Maarseveen (2007), the Detroit and Chicago Transport Studies in the United States (in the 1950's) commenced urban transport planning, and this was used to inform decision makers of the nature of the transport system. The authors are of the view that this form of transport planning, analyses the transport system, gives forecasts on future performances and suggests measures to improve this performance where necessary, in order to meet desired demand levels (Zuidgeest and van Maarseveen 2007). In transport planning, a variety of disciplines are looked at such as the need to plan, design, maintain the transport infrastructure etc.

Land use and transport interaction as seen by Shaw and Xin (2003), is a dynamic process that involves changes over spatial and temporal dimensions between the two systems. Changes in land use systems can have effects on travel demand patterns and induce changes in transport systems. Land use changes affect travel demand and access to transport systems also has effects on land use due to the interconnection between land use and transport. The increase in demand to travel as a result of land use changes calls for the provision of additional transport facilities; and accessibility levels are enhanced with the provision of these facilities. This may also lead to the development of new land uses, leading to increasing demand and it feeds into the process again symbolising the need to really consider land use and transport planning in an urban planning process.

A look at this form of interaction shows that transportation accessibility influences land use locations/ patterns (Kelly 1994; Moore and Thorsnes 1994) like firms, households, recreational facilities, real estates, educational facilities; and land prices and density, (Alonso 1964; Mills 1967; Muth 1969) as cited in (Waddell, Ulfarsson et al. 2007). Waddell et al. (2007), note that the effects of transportation systems on land use have feedback results on the system performance as well. Also from a different angle, Brown and Affum (2002), point out that the investments that have been made into transport activities over the years have contributed to shaping urban growth and the form of settlements (Brown and Affum 2002) by way of planning different land uses.

On the basis of their interaction, transport plans that underscore the land use planning approach may influence settlement patterns so as to increase accessibility to shops, jobs, institutions etc, without the need to travel by car or by minimising the usage of cars and minimising the distance travelled. It may be noted that interaction patterns generated can vary between geographical locations and according to Shaw and Xin (2003), empirical studies have been performed to suggest this. The effects of transport system changes on land use and vice versa, not only occurs at varying spatial scales but also at varying temporal scales (Shaw and Xin 2003). Oduwaye (2007), also argues that the volume of traffic generated by different land uses varies during different periods of the day but there is usually a predictable pattern of such traffic volumes (Oduwaye 2007). This variation between geographical areas comes about as a result of the way we plan our cities. Planning helps decide where to put what and for what reasons etc. Parts of a city that are well planned and designed tend to attract jobs and investments better than areas that are less planned and this has effects on the flow of traffic within such areas.

Although LUT interaction has some positive feedbacks, negative feedbacks may also arise as a result of the level of interaction. Some cities' planning status takes shape along areas of well developed road networks which also increases the number of trips to those areas as a result of the improved level of accessibility. The trip patterns to those zones are as a result of demand from those areas, coupled with improved accessibility that lead to congestion on those links and junctions in the road network. This may call for further improvements to the road network. Over time, it becomes increasingly difficult for road controlling authorities to respond to the increase in demand for road travel due to the high costs of urban road schemes and the adverse social and environmental impacts of road building. Land fragmentation may also occur at areas where new roads are to be constructed to link newly developed locations to city centres. Changing traffic patterns can have effects on businesses etc. The types of these land use activities may change in response to altered traffic patterns and accessibility. Once there are limitations in accessibility, businesses and other related land uses may locate elsewhere. Another negative feedback is that land values are also affected and their prices may increase around areas which have improved road connections.

With this basis of LUT interaction, it is possible that an MFD for the city of Almelo will be affected by the different land use types in the city because these and other land use types generate and attract different trips at different types of the day; so information from such a diagram is expected to be channelled into further planning of the city so that accessibility and mobility levels will be enhanced. The study of an MFD for a city requires that consideration is also given to the land use component as well. This is because the level of land use - transport interaction for any city translates into traffic flow and as an obvious phenomenon land use and its related activities generate and distribute trips between places. These trips could (and often do) lead to the occurrence of congestion on our roads and the development of MFDs assist in obtaining information on how to evaluate demand-side policies to help reduce congestion. Studies into the spatial arrangement of different land uses and their transport components would then give an idea on how land use and transport interactions have influence on an MFD for a particular city. This is because the spatial arrangement could have influence on traffic flows which describe the state of performance of the city as determined by an MFD. Land use changes can have effects on travel demand patterns and induce changes in transport systems. Increasing demand to travel as a result of land use changes then calls for the provision of additional transport facilities; and accessibility levels are enhanced with the provision of these facilities. The mobility and accessibility levels in cities that arise as a result of land use transport relations can therefore be studied by the relevant information from an MFD established for the city.

2.13. Summary

This chapter commenced by looking at the transport activities within cities and how trips being generated and distributed between and within activity locations may on the longer-term change activity patterns and land-use patterns eventually (Zuidgeest 2005). It went further to demonstrate the need to consider appropriate indicators for area-wide studies for cities since segment-based indicators may not be enough for urban planning and management purposes, although they can serve other useful purposes. By virtue of this, the MFD was recommended as a typical example of such indicators that could help improve cities' accessibility and mobility levels according to recent studies. Before the MFD could be studied, the microscopic and macroscopic parameters whose relations give rise to an MFD needed to be understood, so the theory of traffic flow was considered extensively.

To be able to describe the states of road networks, traffic analysis should be performed and it can be deduced if such networks are effective and reliable or not. Together with such studies, indicators are required to describe the performance of the networks and examples of such indicators discussed in this chapter included travel/ journey time reliability, connectivity reliability, capacity reliability, LOS and the MFD. All, apart from the MFD consider road performances at disaggregate link and intersection levels. This makes the MFD, an appropriate indicator for the research purpose.

Once these indicators are established, planners and engineers are well informed as to how effective and reliable networks are. Unreliable networks have potential impacts on both individuals' lives and the efficiency of the economic system. Typical effects include uncertainties in travel time from origins to destinations, unpredictability in transport costs due to the uncertainty in the transport system, loss of lives and property during natural disasters when links lose their connectivity etc.

Next in that order was the interaction between land use and transport since this interaction could affect the shape of an MFD. Changes in land use systems can have effects on travel demand patterns and induced changes in transport systems. The increase in demand to travel as a result of land use changes calls for the provision of additional transport facilities; and accessibility levels are enhanced with the provision of these facilities. The effects of transport system changes on land use and vice versa, not only occurs at varying spatial scales but also at varying temporal scales (Shaw and Xin 2003). Traffic demand variations between geographical areas are as a result of the way cities are planned. Asides the positive feedback of their interaction, negative feedbacks arise as well and all these have been discussed in the concluding part of the chapter.

3. Study Area Description

This chapter gives a brief overview of the study area, Almelo, in The Netherlands. It describes its population dynamics over the years from 1960 to 2008, some economic activities and ends with traffic and transport statistics of the city.

3.1. Introduction

To perform spatial and temporal analyses; and further to the study of the MFD, the availability of data (such as traffic intensity and speed) for the city of Almelo in the Netherlands made it possible for the study to be conducted for the city. In addition to that, traffic and transport studies by Weijermars (2007), Thomas and Van Berkum (2008), Thomas, Weijermars et al (2008) etc have been conducted for the city of Almelo; so the study of the feasibility of the MFD and other spatial-temporal analyses add to the existing studies for the city of Almelo. This makes it interesting and appropriate since the study of traffic flows in the city has been approached from a different perspective in this research. This is also quite different from the existing studies for the city.

3.2. Location

Almelo, as shown in figure 3-1 below, is a medium sized municipality in the Twente Region, the most eastern part of the Netherlands, near the German border. Its geographical coordinates are 52°21'27.38" North and 6°39'49.54" East, and an average elevation of about 13 metres. It covers a total area of 69.40 km^2 (of which water covers 1.96 km^2 and land, 67.43 km^2) and has about 72,400 inhabitants, according to Statistics Netherlands (2009).

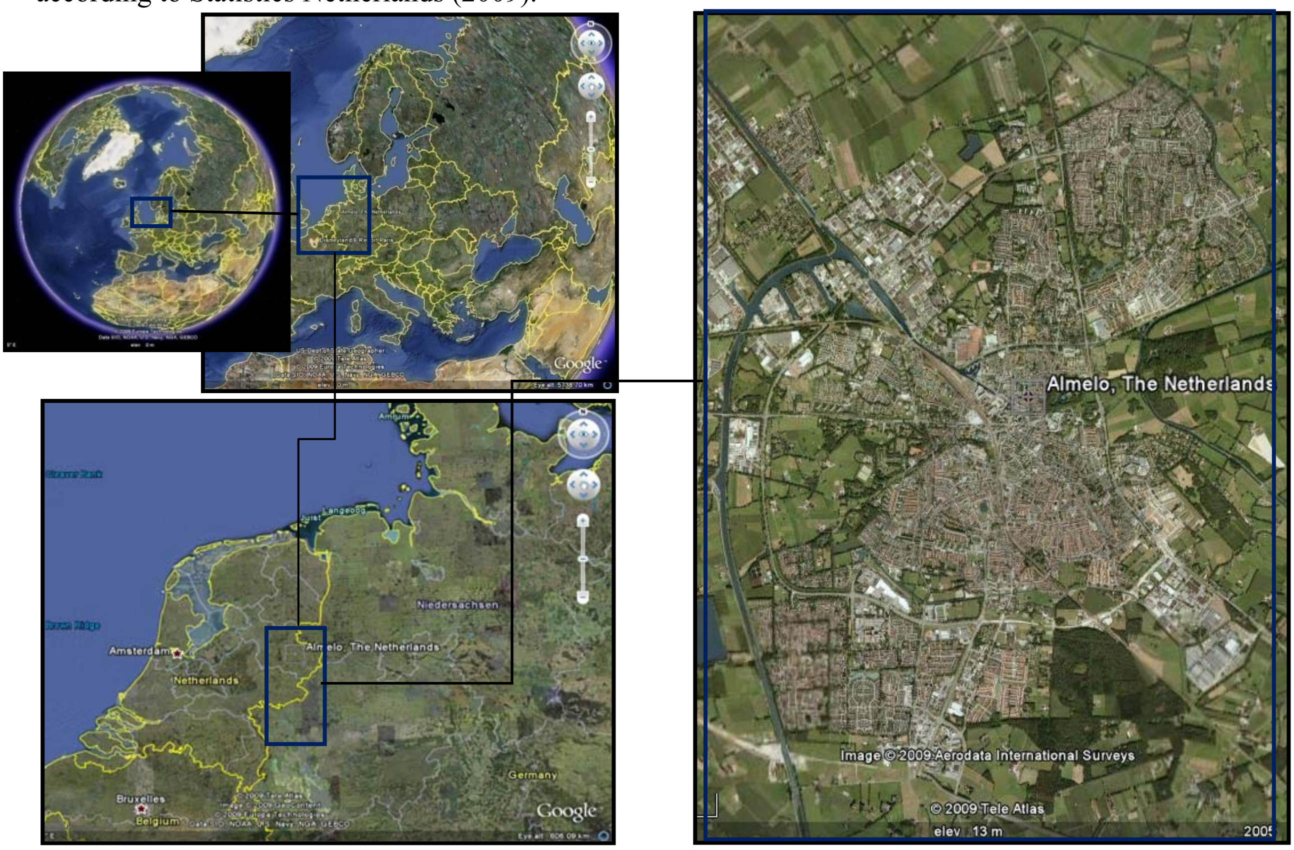


Figure 3-1: Study area location

Source: (Google earth, Aerodata International Surveys et al. 2009)

3.3. Population Dynamics

Figure 3-2 below shows the population dynamics for the city of Almelo from 1960 to 2008. Between January and December each year, there was at least an increase in population. Population increased steadily for the first 20 years, from 1960. From 1980 to 1990, there was a decline, then an increase again over the years from 2000 till 2008.

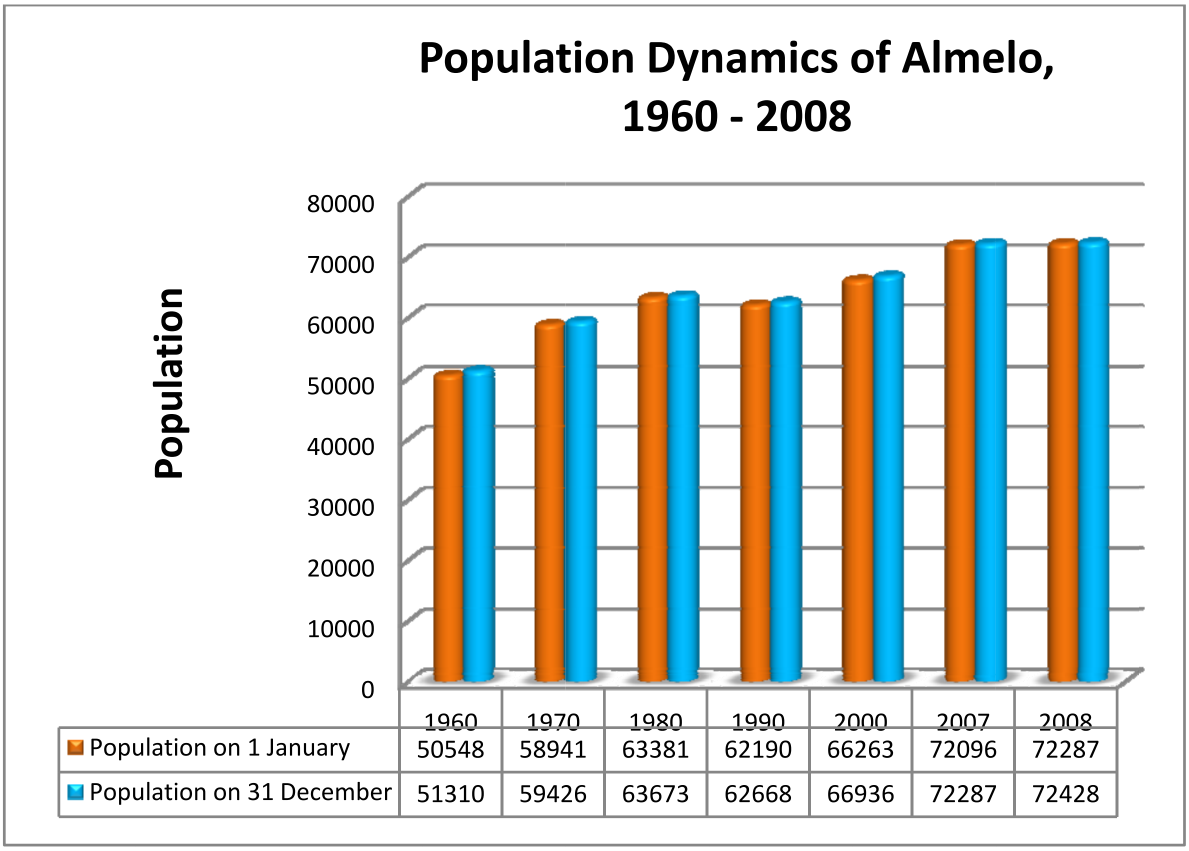


Figure 3-2: Population dynamics of Almelo (1960-2008)

Data source: (Statistics Netherlands 2009)

3.4. Economic Activity

Almelo is bordered by neighbouring towns like Hengelo and Enschede, and this enhances economic activities within the city. Almelo is an entrepreneurial city with high-quality companies supplying innovative markets worldwide. It also offers a diversity of shops, schools and businesses with about 8,434 people working in the industries.

3.5. Traffic and Transport Operations in Almelo

Recent studies (Thomas, Weijermars et al. 2008) for the city of Almelo show that variations on traffic volumes exist for the city. To better manage traffic and transport in the city, measures such as the collection of travel demand information is a prerequisite (Thomas, Weijermars et al. 2008). Currently, traffic demand information that is collected is used at localised levels for traffic management and safety purposes.

Public transport operations have also been given some attention for some time now. According to Hulleman R.(2004), public transport in Almelo was traditionally designed to cover the entire urban area with bus lines running through streets which were not suited for that purpose. This reduced traffic speeds, and delays were frequent. In that regard, public transport axes were designed to cope with these problems, with the axis connecting residential areas of Almelo to each other and to the city centre. Along the axis, important public destinations like the main hospital, a shopping mall and the soccer-stadium are located.

Based on the public transport axes, a new integrated public transport network was designed with the main objective of enhancing fast and frequent bus services, coupled with interchange opportunities and operating at a speed of at least 25 kilometers per hour [kph], compared to 18 kph in the existing network. The concept was geared towards making bus travels more attractive and this was achieved for some time till congestion problems as well as decreasing travel speeds were experienced. As a result of this, the City developed a comprehensive plan to upgrade infrastructure for buses, including traffic flow management and dedicated infrastructure, in 1995. This led to the design of bus lanes along some few road sections. This approach eased congestion to some extent and buses could travel with enough speed. To further provide solutions to ease congestion, traffic light controllers along bus routes in the city had priority systems installed in them which were connected to a central traffic light control system, enabling coordination of traffic management in the city and providing remote access to the controllers to ease maintenance and operation (Hulleman R. 2004).

In 1999, the Municipality of Almelo began to experiment with a new technology called SABIMOS[3] (Satellite Based Information Management Operating System), which is a new generation of vehicle detection technology. The experiment was performed using seven buses and three traffic light intersections. This technology consists of a combination of satellite navigation, through Global Positioning System (GPS) combined with various wireless communications technologies. It is an information system for both traffic management purposes and real-time data for information services. These services include the provision of information to passengers, to transportation companies and to contracting authorities and synchronising departure of vehicles, so that even when delays occur, passengers have a fair chance to make it to their connecting service. With this new concept, buses can monitor their locations, even when they are off route, by GPS. Sabimos basically has two main goals which are:

- Improving the flow of public transport
- Providing reliable real-time passenger information to the traveller so that public transport is more attractive.

Once buses are on specified locations, the on board computer is triggered to send a message to, for instance, the traffic light controller at the next intersection. A lot of information is provided by the transmission of this message by short range radio. The information includes the vehicle's actual GPS position, trip number, vehicle length, delay in minutes etc. Since its inception, bus reliability and punctuality have seen some improvement. The figure below shows one of the buses used during the implementation phase in the Twente region.

[3] http://www.sabimos.nl/

Figure 3-3: One of the buses used during the implementation phase in the Twente region.
Source:(Hulleman R. 2004)

3.6. Summary

With its medium-sized nature Almelo experiences an increase in population over the years, averagely. Such an increase does not rule out the effects of trips on the road network system. The cause of which has to do with increase in economic activities, improved transport services, the need to travel etc. It is observed that measures have been put in place to ensure efficient movement of goods and people within the city at localised levels but decision makers still have to consider further plans at area-wide levels so as to be able to meet demand levels at all times.

4. Research Methodology

This chapter identifies the data requirements for the research. The types of data and how they were collected, which is essential to help provide answers to the research questions are discussed in this chapter. The devices that were used in collecting the data and how these data were validated have been made mentioned in the chapter as well. Useful information can be derived from data after it has been analysed. A brief description of the analysis has therefore been made mention in the chapter.

4.1. Introduction

Prior to the analyses of the provided traffic and transport data a literature review was conducted regarding the research topic and research area; and to get acquainted with practices and methods by previous researches that are in line with this research and the study area. Some of these researches include *Public Transport, the comprehensive and cooperative approach of Almelo, the Netherlands, 2004 by Rob Hulleman, The Almelo Master Plan (2004-2030), Analysis of Urban Traffic Patterns Using Clustering, 2007 by Wendy Weijermars, etc.* A methodological framework that looks at the steps taken to analyse the data in this research was therefore devised and is shown below in figure 4-1.

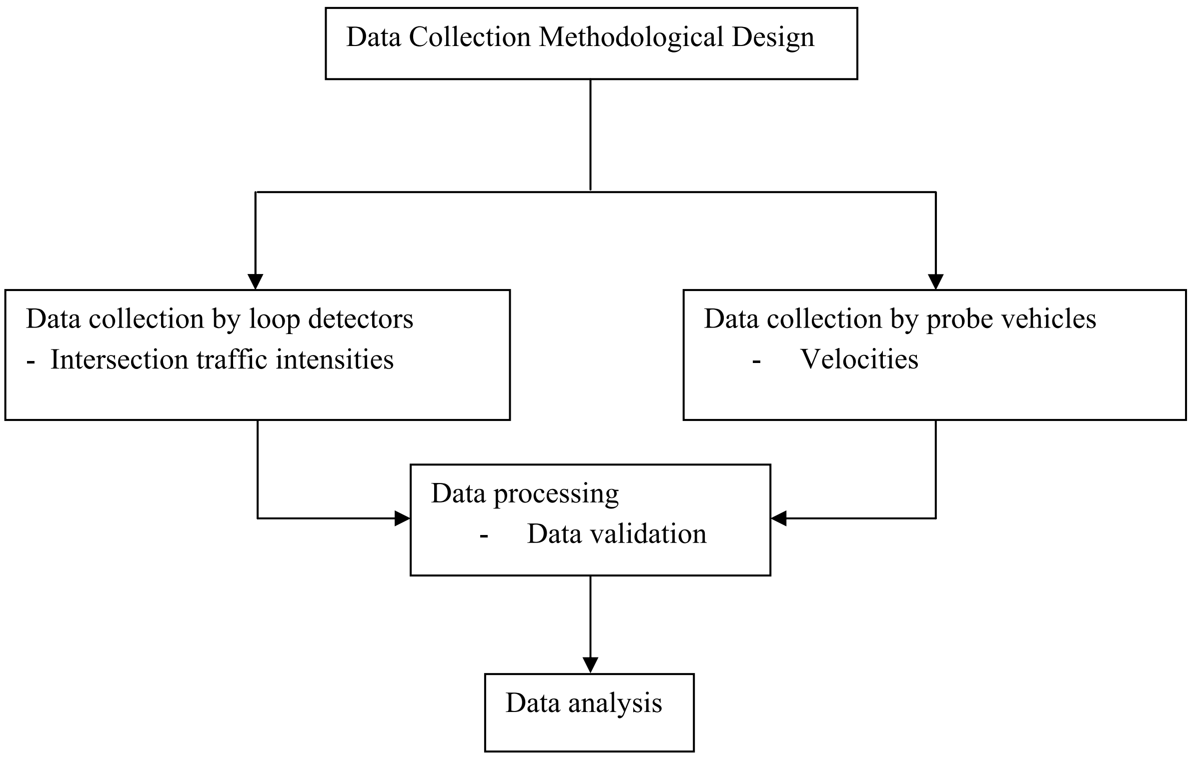


Figure 4-1: Methodological framework for analysing the data

4.2. Traffic Data Collection

Due to the nature of information required from the data and the limited time frame, it wasn't possible to personally collect primary data for this study. For example, traffic intensity data from loop detectors were required to be collected at different intersections over certain durations and at the same period and this was not possible to be collected by human efforts reliably. The same applies to velocity data collected by the probe vehicles.

In view of that, the researcher relied on secondary data collected by loop detectors[4] and probe vehicles[5]. Some other secondary data that were received as part of this research were reports and digital data sets as described initially. In addition to these a visit was made on the 16th of November, 2009, to some of the intersections where data was collected in the study area. This was to at least get acquainted with first-hand information of traffic flow pattern at those intersections. A meeting was also held with Drs. Rob Hulleman (of the Traffic and Transport Section) of Almelo Municipality on that same day, who gave an overview of traffic and transport related issues in Almelo.

According to Weijermars (2007), single loop detectors installed at signalised intersections for actuated signal control are used for collecting traffic data in most Dutch cities. These single loop detectors can only be used for the measurement of flows and occupancies, although algorithms can be developed from them for the estimation of speeds for analysis (Weijermars 2007). For the purpose of this research, intensity data from loop detectors via controllers positioned at some intersections within the network were used. The study area has some major intersections each of which is linked to one of these controllers and data (for each intersection) from the loop detectors are sent to the controllers for storage.

The traffic intensity data for this research was received directly after it had been prepared and validated from the raw data by Wendy Weijemars[6]. The data was collected over a year's duration from September 2004 to September 2005. The data received showed volume data for 19 intersections but some intersections that were very close to each other were considered as one so in effect the data covered 17 intersections over the entire network. Figure 4-2 shows the intersections where intensity data were collected and made available for this research.

For the traffic velocity data, speed profiles[7] have been derived by Tele Atlas[8]; by aggregating and processing GPS measurements from several devices that reflect actual consumer driving patterns. This consumer data helped to determine realistic average roadway speeds for different times of the day and different days of the week. Tele Atlas has speed profile coverage for 5-minute intervals for different countries out of which travel speeds on the Almelo road network were obtained for the research. This data was collected by the use of probe vehicles.

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[4] Details of how various techniques by which vehicles are detected and saved as data for traffic analysis are provided in Appendix 1

[5] The use of the probe vehicles in collecting data has been described under section 4.2.2

[6] Wendy used this same traffic volume data during her doctorate research work. She however used the data to perform the analysis of urban traffic patterns using clustering.

[7] The speed profiles represent changes in average speed behavior along a road element.

[8] Tele Atlas is a company which delivers digital maps and other dynamic content for navigation and location-based services, including personal and in-car navigation systems, and provides data used in a wide range of mobile and internet map applications. (http://www.teleatlas.com/index.htm)

Figure 4-2: Intersections where volume data was collected.

4.2.1. The use of Inductive Loop Detectors in Volume Data Collection

The most commonly used type of detector which is widely used by many agencies is the inductive loop detector (Kell, Fullerton et al. 1982; Eikvil, Aurdal et al. 2009) and has been in use for the detection of vehicles since the early 1960's (Potter and Reno 2005). Current technology typically collects data by the use of inductive loop vehicle detectors embedded in (or lying on) roadways (Eikvil, Aurdal et al. 2009). This vehicle detection device provides traffic flow information over time for a point in space.

Volume data for this research was collected by single loop detectors installed at signalised intersections for actuated signal control. As stated previously, the data was provided originally as ASCII files. Every record contains one traffic volume measurement for a certain detector for a certain time period on a certain day. A record contains variables such as date, intersection, detector, type of detector, start time of measurement interval, length of measurement interval, measured traffic volume etc.

Although loop detectors serve very useful purposes; threats to them come from road maintenance works. A schematic diagram of an inductive loop detector installation is shown below and by means of data processing techniques, traffic volumes and occupancy levels can be extracted from the signals that are picked up by the detector as vehicles pass over them (Weijermars 2007).

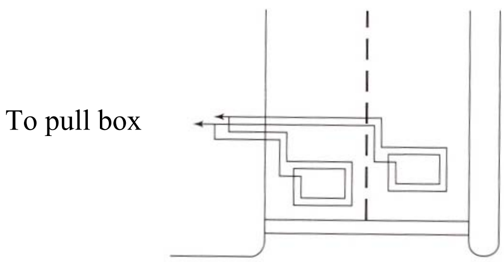

Figure 4-3: A schematic diagram of an inductive loop detector installation

Source: (Papacostas and Prevedouros 2001)

4.2.2. The use of Probe Devices in Data Collection

Probe vehicles are a more recent approach of using fleets of instrumented vehicles to collect data. The functioning of probe vehicles is explained in Taylor, Bonsall et al.(2000). The entire instrumentation involves the vehicle intermittently reporting its position, time (and perhaps other data including a recent speed history) back to a base or transmitting a signal which enables its position to be determined externally. Generally, the communication is by radio but other media such as infra-red might also be used. The vehicle's position is therefore estimated using a combination of triangulation from GPS[9] satellites or terrestrial beacons, dead reckoning using road wheel sensors and electronic compass, and map matching software (which corrects a triangulated or dead-reckoned estimate to fit the nearest road on a database in the on-board computer). These methods have become viable with the

[9] Probe vehicles are equipped with GPS receivers and two-way communication to receive signals from earth-orbiting satellites. The positional information determined from the GPS signals is transmitted to a control centre to display real-time position of the probe vehicles.

advent of mobile communications and of automatic vehicle location (AVL[10]) and automatic vehicle identification (AVI[11]) as an aid to fleet management and security.

The Tele Atlas speed profile product aggregated billions of anonymous GPS probe traces from millions of devices that reflect consumer driving patterns. These consumer driving patterns provide true average speeds on individual road segments. The growing number of these data points collected over the years determines average roadway speeds on a temporal basis.

4.2.3. Data Formats

Traffic intensity data received from the result of Weijermars's (2007) research were in text format *(txt)* but according to her, they were provided in ASCII formats originally. They have been converted to CSV formats for easy analysis. The records contain attributes such as; date, intersection number, link number, the measured traffic volumes, etc. The volume record has 288 records because it was aggregated to 5-minute intervals (1 hour =12 X 5 mins; 24 hours X 12 = 288).

Speed data from Tele Atlas was in a *shapefile* format. The original data cover the whole of the Netherlands but was pre-processed into obtaining the *shapefile* for Almelo which has several attributes such as: link names, link lengths, free flow speeds, weekday speeds, weekend speeds etc. In addition to that a *dbf* file containing the speed profile identifications, time slots and the relative speed profile values were obtained.

4.3. Data Preparation, Validation and Reliabilty Checks

Researches of this kind that have their data being collected by devices always have to be prepared and validated so as to deem them reliable since conclusions and recommendations will be made based on the data, after analyses. Series of operations have been performed on the secondary datasets so as to make them prepared for analysis in further stages. According to Weijermars (2007), the volume data was received from ViaContent System[12], which had to be processed[13] to be able to be used for further analysis since some records showed deficiencies. The volume measurements had already been inspected and invalid data, rejected by Weijermars and Van Berkum (2006). The errors in the measurement (e.g. by failures in the electronics or by miscounts in the number of passing cars) gave rise to invalid data and according to Thomas, Weijermars et al., (2008), certain criteria were used to detect the errors. Some of these criteria included: there should have been at least a 0 volume recorded, volumes should not exceed a certain maximum volume and 24-hour volumes should be larger than 0.

[10] This technique has mostly been used by transit agencies. Probe vehicles communicate with transmitters mounted on existing signpost structures.

[11] Probe vehicles are equipped with electronic tags. These tags communicate with roadside transceivers to identify unique vehicles and collect travel times between transceivers.

[12] ViaContent is a traffic information system that stores and processes traffic data (http://www.viacontent.nl/)

[13] Readers are referred to chapter 5, sections 5.3, 5.3.1, 5.3.2, 5.3.3- pages 67 -77 of Analysis of urban traffic patterns using clustering, (Weijermars 2007) for a detailed description of the validation and reliability checks performed on the data for Almelo.

The data received from Tele Atlas had also been prepared and validated[14] to clients' needs. Relational integrity analysis was performed to ensure road segments were in place. They also performed statistical analysis on the data for anomalies and outliers etc. Secondary data collected in the form of reports were used as references. The major tasks were to convert the data into required formats and platforms for data processing. The *shapefile* from Tele Atlas was in ArcGIS format so no conversions were required. However, the attribute table which was in *dbf* format was converted into a *CSV* format for analyses.

4.4. Data Limitation

Data collected by loop detectors face some limitations to some extent and the data for this particular research was no exception. Some detectors are very sensitive so they record vehicles on adjacent lanes. Also no intensity values are recorded for some intersections because some malfunctioned detectors had to be taken out of their loops due to road maintenance works, resurfacing works etc. In effect, some intersections had no intensity data. Due to the large nature of the datasets and the fact that intensity data were obtained in 5-minute intervals, algorithms had to be written to aggregate them to 15-minute intervals during some portions of the analysis, which also required so much time. These algorithms are shown in appendix 2.

Also with regards to the volume data, it was observed that not all the (major) intersections had volume data as can be seen in figure 4-2 above. This meant that although the research was being conducted at the city level primarily, the 17 intersections which had volume data were assumed to be representative of the whole city and this may have had an implication on the outcome of the research.

A similar observation was in the case of the speed data which had 60 profiles being used to represent the segments constituting the network. Apart from that, the profiles did not cover the entire network. Segments with profile number 0 were "unknown profiles" so segments with such profile numbers could not be analysed and this is shown in figure 4-4 below. According to Tele Atlas, they are able to prove that 59 curves is sufficient that any traffic behaviour can be mapped to one of these curves. Lack of data for the entire network may also have affected the results to some extent.

The speed data also had no attributes for the designed capacities of the roads. This could have served a very useful purpose of comparing designed capacities with currently existing capacities to find out if the trajectories are performing effectively or not.

[14] Readers are referred to section 1, page 8 Intelligent data for optimal routing, Tele Atlas Speed Profiles, Version 2008.10,(Tele Atlas 2008) for the verification process of the quality of the data.

Figure 4-4: Road segments with and without speed profiles

4.5. Data Analysis

The data was analysed in four phases. The first phase had to do with writing algorithms using Python (x,y) programming language to select and prepare the traffic volume data for analysis. Some sections of the data were further analysed in Microsoft excel, Arc GIS, SPSS and Grapher. The algorithms were required to:

- Extract the required attributes from the whole dataset and leave out the attributes that were not relevant to this study
- Aggregate the 5-minute data into 15-minute periods, for analysis.
- Reject 0 km/hr free flow speeds.

The aggregated data was saved into *CSV* format and the intensities averaged into daily flows per link for each intersection, for 15-minute durations. Some were also analysed in their 5-minute periods, especially when analysing them together with the percentage free flow speeds.

The second phase dealt with generating percentages of free flow speed data for each road segment at 5-minute intervals using the speed profiles given. Average speeds of the road segments, for the days under consideration were also generated from the speed profile data provided by Tele Atlas. These speed profiles show the behaviour of changes in average speeds during a given time period for a road element. The average speeds for each link were obtained by multiplying the percentage speed profile values for respective times by its corresponding free flow speeds.

The third phase looked at the performance of spatial and temporal analyses for selected trajectories or corridors based on the derived speed and volume data. Relationships between average percentages of free flow speeds and average volume were established for the city and selected parts or trajectories within the city.

Finally, the study of the feasibility of the existence of the MFD was performed by establishing relations between average speeds and average volumes.

4.6. Summary

This section has described the methods that were used in the research for the data analyses. Literatures by other researchers concerning the city of Almelo that were in line with this research were considered broadly. The volume and speed data collection by loop detectors and probe vehicles respectively have been described and these data were received in *shapefile, dbf* and *txt* formats. Data of this nature also need some amount of preparation and validation and the extensive processes that went into the data validation have been made mentioned of. The data validation had already been performed by the respective sources and reference has been made to them accordingly. Although the data had been validated, they needed to be processed into required formats for further analyses. The analyses were performed in different phases by writing algorithms, generating average speeds from the speed profiles and then establishing relations between the described variables for the city, selected parts or trajectories within the city. The limitations in the dataset have also been described in this chapter.

5. Analyses, Results and Discussions

This chapter discusses the various forms of spatial and temporal analyses that have been performed in this research. The spatial-temporal analyses cover the entire city and selected trajectories. Details of how the volume data were aggregated and analysed have been described. The derivation of the percentages of free flow speed as well as the average speeds for each road segment were obtained from the speed profiles, and are also described. As part of the analyses, speed-volume relations for the city and selected parts or trajectories of the city have been described. Results from the analyses have been shown and further discussed.

5.1. Preparing and Aggregating Volume Data

The original traffic volume data was built up of 5-minute duration intensity values multiplied by a factor of 12 indicating their hourly volumes. The analyses of the volume data commenced with the writing of algorithms to further divide each of these volumes by 12 to retain them in the original 5-minute volume bins. Another set of algorithms was written to aggregate these 5-minute volume data into 15-minute periods. This concept was adopted from the Highway Capacity Manual (2000) which suggests 15-minute intervals for most operational and design analyses since flow rate variations for shorter periods are unstable, and are difficult to establish. The algorithms have been shown in appendix 2 of this report. The aggregation of the volume data was based on the equation below:

$$V_{15} = \sum_{i=1}^{3} v_i \tag{5.1}$$

here V_{15} is the first 15-minute volume [veh/15-min] on the first link; this value is obtained by summing the first three 5-minute volume data (v). The next volume then comprises the next three 5-minute volume in that order till the last three. So in effect, the 288 (1 hour =12 X 5 min; 24 hours X 12 = 288) records of 5-minute data were reduced to 96 (1 hour =4 X 15 min; 24 hours X 4 = 96) in all.

Once this was in place, the next step was to look at the average volume for respective days throughout the year. An algorithm was therefore written first, to select each of the days of the week, that is, Monday, through to Fridays (intensity data was unavailable for weekends). The average volume for the city on a particular day ($V_{avg\ day\ i}$) for 15-minute periods was then obtained based on equation 5.2 below:

$$V_{avg_{day\ i}} = \frac{\sum_{i=1}^{n} v_i}{N} \tag{5.2}$$

Where v_i represents each of the day's volume at a particular 15-minute period, for a particular link belonging to a specific intersection, n is the number of the particular day in question (throughout the data collection period), with volume data and N is the total number of a particular day with volume data (say, all Mondays with volume data).

The initial idea was to use this approach for each of the given days so as to compare flows for each day but only Mondays and Tuesdays were looked at due to time constraint. Also, the spatial and temporal analyses were restricted to Tuesdays only and recommendations have been made so as to further consider analyses for other days.

5.2. Generating Travel Speeds

The spatial and temporal analyses required both volume and speed data. Studying the feasibility of the existence of the MFD for the city of Almelo also required a relation between speed and volume. This led to the generation of percentages of free flow speeds and average travel speeds on each of the road segments for the 24-hour duration. These speeds were generated from the given speed profiles (These speed profiles were for 24 hours on 5-minute intervals). In all, 60 different profiles were provided by Tele Atlas and this represented relative speeds on the network for Almelo. Each profile is applied to more than one segment so long as they characterise almost similar speed patterns throughout the day. Figure 5-1 below shows a typical example of a speed profile corresponding to a road link. The horizontal axis shows the time of the day, whereas the vertical axis represents percentages of free flow speed from 0-100% on that particular link. The higher the percentage of free flow speed on a particular segment at a particular time, the better its performance and vice versa. The percentages of free flow speeds were saved for further analyses (sections 5.3 to 5.6 and section 5.8).

This figure has been used as a demonstration of how average speeds on each segment were derived from the profiles. A typical applicable speed value on a road element is obtained by multiplying the speed profile value for a certain time of the day by its free flow speed at that time. The free flow speed corresponds to the average speed measured during the period of least traffic congestion; most often these reflect night time speeds. In the profile below, the speed of travel at the 17th hour is therefore 70 % of the free flow speed.

$$S_{17_{link\,i}} = Profile\ \%_{17_{link\,i}}\ x\ Free\ flow_{link\,i} \tag{5.3}$$

Where $S_{17link\ i}$ is the average speed of travel on link i at the 17th hour, *profile* $\%_{17link\ i}$ is the profile percentage value of link i at the 17th hour and *free flow link i*, is the free flow speed of link *i*. This same approach was used to generate all the speeds on all the road segments for each 5-minute over 24 hours.

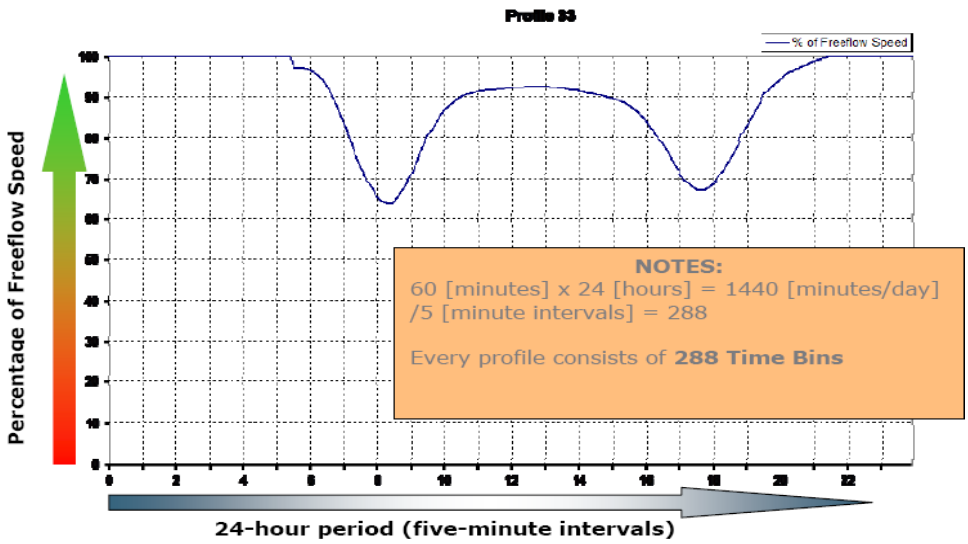

Figure 5-1: A typical example of a speed profile

Source: (Tele Atlas 2008)

After obtaining all the derived speed data using the above equation (5.3), a thorough look at the data was performed so as to get rid of invalid data. The search confirmed that some of the links were not assigned to any of the 60 speed profiles and were seen as “unknown profiles”. This meant those links had no speeds so they registered 0 [km/h] speeds throughout the 24-hour duration. As a way of ensuring data validity, algorithms were written to reject the 0 [km/h] speed values since they were going to affect the output. Speeds on the remaining links were aggregated to 15-minute intervals by finding the average of the first three 5-minute speeds, the next three etc, in that order. This was guided by the equation shown below:

$$S_{avg_{link\ i}} = \frac{\sum_{i=1}^{3} s_i}{3} \qquad (5.4)$$

Where $S_{avglinki}$ is the 15-minute average speed on link i, s_i is 5-minute speed on link i. To effectively work within an urban domain, some free flow speeds on the links were further rejected. Local roads and high ways were therefore rejected leaving behind speeds from 40-90 km/hr *(40 ≤free flow speed ≤ 90 km/hr).* Restriction to the 40-90 km/hr speeds was also with respect to the selection of the trajectories in question. Any speeds below or beyond these speeds will have omitted some of the segments of the main trajectories under study. The average speed data were saved for further analyses in section 5.7 (MFD).

5.2.1. Analyses With Reduced Data

Preliminary analyses were performed with the reduced data (aggregated volume data and generated travel speeds). This was to study the extent of speed and volume variations amongst the different days considered and also to find out what the morning and evening peak periods for the city are.

5.2.1.1. Volume Data

Analysis with the volume data gave rise to the average volume graph for the entire city for Mondays and Tuesdays, as shown in figure 5-2. These volumes show the15-minute intensity of all Mondays; and Tuesdays throughout the year from September 2004 to September 2005.

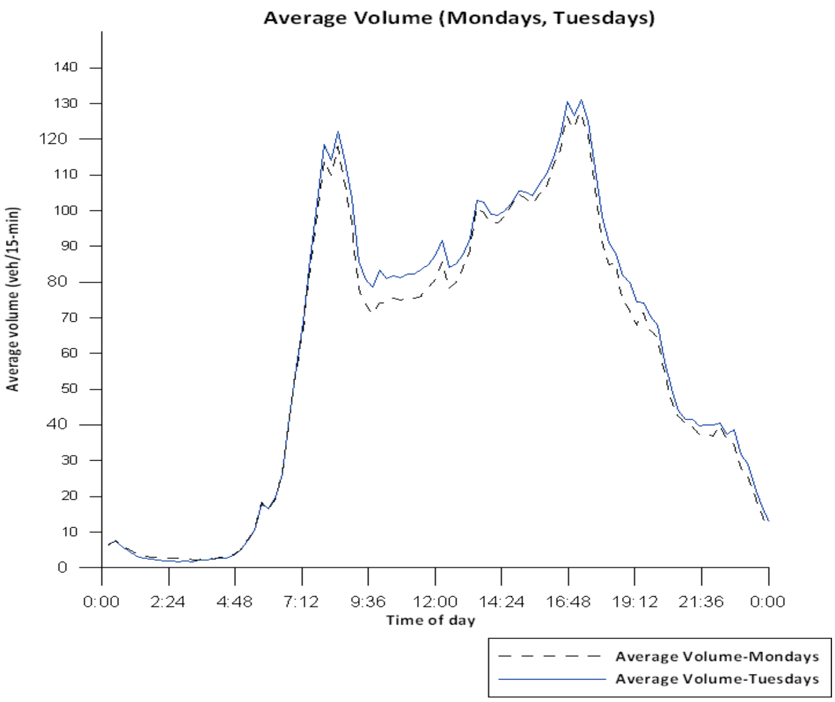

Figure 5-2: Average 15-minute Mondays' and Tuesdays' traffic volume (September 2004-September 2005).

This preliminary analysis of traffic flow suggests that the morning and evening peak periods for the city of Almelo are from 7-9 am and 16-18 hours respectively. It is observed that average volumes vary during the course of a 24-hour duration on a particular day. The average volumes on both days do not show much variation but slight distinctions made between both days are summarised in table 5-1 below. Evening peak periods record slightly higher volumes than morning peak periods on both days. Traffic volumes within the morning and evening peak periods are of great interest to traffic engineers and planners in design and operational analyses since roads to carry traffic are designed adequately to meet demand levels and these periods show the highest traffic flows throughout the 24-hour period.

Table 5-1: Summary of average volumes (September 2004-September 2005)

Day	Peak Period	Maximum average volume	Minimum average volume	Maximum Morning peak vol.	Minimum Morning peak vol.	Maximum Evening peak vol.	Minimum Evening peak vol.
Mondays	7-9 am	128	2	118	55	128	91
Tuesdays	16-18 hrs	131	2	122	56	131	99

The table shows that there were 15-minute volumes as high and low as 131 and 2 vehicles respectively. Also, evening peak periods record higher volumes on both days relative to morning peaks. Although both graphs show very little variations comparatively, Tuesdays seem busier days as compared to Mondays since higher volumes are recorded on Tuesdays than on Mondays, on the same road network. The analyses that follow were restricted to Tuesdays only, as a result of time constraint. (Also considering the fact that Tuesdays are busier days as compared to Mondays)

5.2.1.2. Speed Data

Since local roads and high ways were excluded, a time series analyses was performed with the remaining links *(40 ≤ free flow speed ≤ 90 km/hr),* the result of which is shown in figure 5-3 below. The graph shows that the maximum average 15-minute speed on Tuesdays was about 53km/15-min. This value remains constant till 5:30 am where a drop in speed begins as a result of an increase in the number of vehicles. The level of interaction of these vehicles causes speed to reduce further till 8:30 am. Speeds rise slightly again till 10:00 am, remains constant till 14:30 hours and drops marginally. From 17:30 hours, the speeds rise gradually till 21:15 hours. This is as a result of the fact that volumes reduce which causes an increase in speed values as a result of very little vehicle interactions. From 21:15 to the 24th hour, the speeds remain constant again at 53 km/15-min. This speed graph also suggests that the morning and evening peak periods are from 7-9 am and 16-18 hours respectively, as denoted by the volume graph.

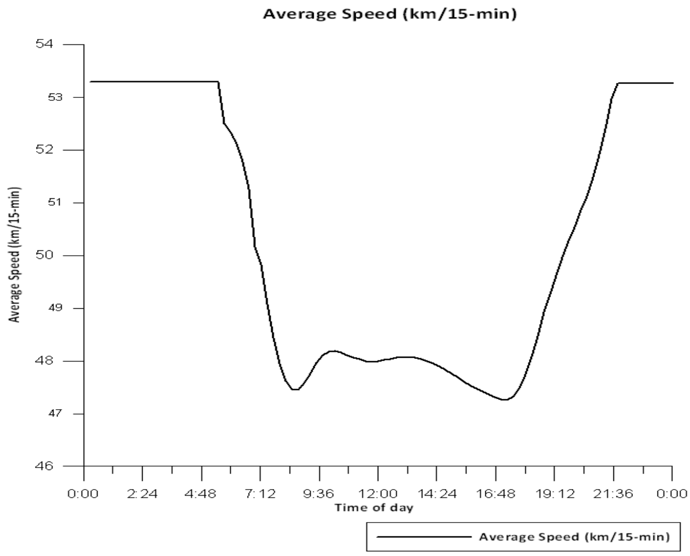

Figure 5-3: Average speed on links (40 ≤ free flow speed ≤ 90 km/hr)

The claim to the fact that the morning and evening peak periods of the city were 7-9 am and 16-18 hours respectively was further investigated and substantiated by considering all weekdays and all segments with speed profiles; since the initial analysis was based on only a single day. As a result of that, all volumes were averaged for all weekdays (Monday to Friday) and average speeds on all road segments with speed data were analysed and the graph below confirms the peak periods. These periods are sometimes estimated for design purposes, depending on several factors. The data in this case confirms such periods for the city of Almelo, which will serve as relevant periods for design and operational analyses.

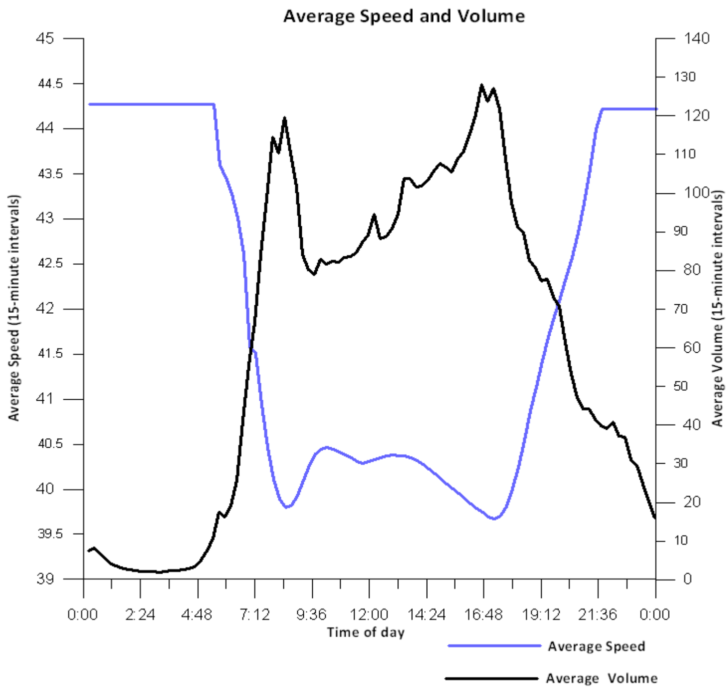

Figure 5-4: Average speed and volume graphs

The abscissa shows the time of the day starting at 12:00am to 24 hours. The ordinates show the average speeds on all segments with speed profiles; and the average volumes at all 17 intersections where data was collected. The speeds range from about 40-44.5 km/15-min, and volumes, up to 130 veh/15-min averagely.

With the concept of establishing relations between speed and volume, a much better platform was a requisite so as to compare performances of trajectories or areas, relative to one another, which is otherwise not possible due to different free flow speeds on different segments. A major finding was therefore attained by the use of the percentages of free flow speed which more or less normalises the speeds on the links. These percentages of free flow speeds were generated from the percentage profile values provided. Further relations between speed and volume were established using the percentage values, which is a rather new approach to establishing such relations.

In all, 60 profiles were provided, and a road segment corresponds to a particular profile number on a particular day at a particular time of the day. One profile could be applied to at least a segment in the network but percentage values may differ from time to time since percentage profile values range from 0-100%; with peak periods denoting lower percentages and non-peak periods recording relatively higher percentages. As stated previously, not all the segments had profile speeds, which was a short-coming in this research. The percentage profile value on a particular day of the week, for a particular link at a particular time of the day was therefore generated for the over 6,200 road segments provided. These were further generated for an entire 24-hour duration at 5-minute intervals for all links. The very large data set made it computationally intensive and very laborious, so the researcher restricted himself to Tuesdays only.

Once these data were in their required formats, the analyses that proceeded were in the order of:

Area-Based Profile Performance: The study under this theme was essentially to be able to perform an analysis that would enable the researcher to come out with specific geographic locations of the city where further analyses could be performed. This operation led to the performance of spatial clustering analysis which is contained in sections 5.3. The results of the clustering analysis were applied in section 5.4.

Profile Performance of Different trajectories: Next to that was the study of how different trajectories are performing in terms of their relative free flow speeds. This has been discussed in the entirety of sections 5.5 and 5.6 of this report.

Establishing the MFD: The final part was the study of the feasibility of the existence of the MFD for the city, where relations between average speed and volume have been established. In addition to that the performance of all the individual links (during the morning and evening peak hours) with speed profile was conducted. Details of that are indicated in sections 5.7 and 5.8 of the report.

5.3. Spatial Clustering Analysis - Classification of Intersections and segments to Form Geographical Areas

As part of the research objectives, area-based analyses needed to be performed to be able to determine how specific areas or trajectories are performing, relative to each other. According to Unwin (1996), patterns are those characteristics of the spatial arrangement of objects given by their spacing in relation to each other and this necessitated the performance of spatial clustering analysis so as to know which road segments belong to specific areas of the city. The clusters were formed on the basis of the percentages of free flow speeds on the segments, as well as and the distances apart between the segments. These were the most suitable criteria for the comparison, as compared to the other attributes of the speed data.

Spatial analysis which requires techniques to analyse spatial data was therefore part of the numerous analyses performed in this research. To begin with, an analysis of spatial clustering was performed in Arc GIS so as to be able to select those spots that had high and low concentrations of free flow speed percentages. In addition to these tools for spatial clustering analysis, one should also have a high local knowledge level of the city to be able to provide support to such analysis. The essence of this analysis was to be able to classify and select specific geographical areas as suggested by the data for further analysis.

Setting the platform for spatial analyses between selected locations was therefore a requirement since a part of the objective sought to compare traffic flow performance between selected areas of interest. Arc GIS uses the hot spot analysis (Getis-Ord Gi*) to perform this form of spatial analysis. The Getis-Ord Gi* identifies the spatial clusters of high and low values when given a set of weighted feature. The output from the analysis is a Z score and p-value for each feature and these values correspond to the statistical significance of the spatial clustering of values. In this analysis, the percentage free flow speed for each of the segments (40 km/hr ≤ free flow speed ≤ 90 km/hr) and their distances apart were considered. The clustering analyses were performed for the morning and evening peak hours and the outputs are shown in figures 5-5 and 5-6. A high Z score and small p-value (probability) for a feature suggest a spatial clustering of high values. A low negative Z score and small p-value indicates a spatial clustering of low values. The higher (or lower) the Z score, the more intense the clustering whereas a Z score near zero indicates no apparent spatial clustering. Since the network distance was not available as an option in this analysis (which would have been a preferred option), the Euclidean distance was used. A default minimum distance of 700 units was used because although changing the Euclidean distance value changed the output, there was not much significant difference. This value served as the minimum threshold distance to ensure that every feature had at least a neighbour. The Getis-Ord local statistics is given as:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - X \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{5.5}$$

Where x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$X = \frac{\sum_{j=1}^{n} x_j}{n} \tag{5.6}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (X)^2} \tag{5.7}$$

and the G_i^* statistic is a z-score so no further calculations are required.

Classifying the segments into many classes made it very difficult to distinctly select city parts. An "ideal" number of three classes was therefore chosen for the purpose of this research. The high, medium and low clustering of speeds are shown by the green, yellow and red colours respectively. This output was based on the percentage of free flow speeds for each of the morning and evening peak hours, and the distances apart between the segments. The results are as depicted in figures 5-5 and 5-6.

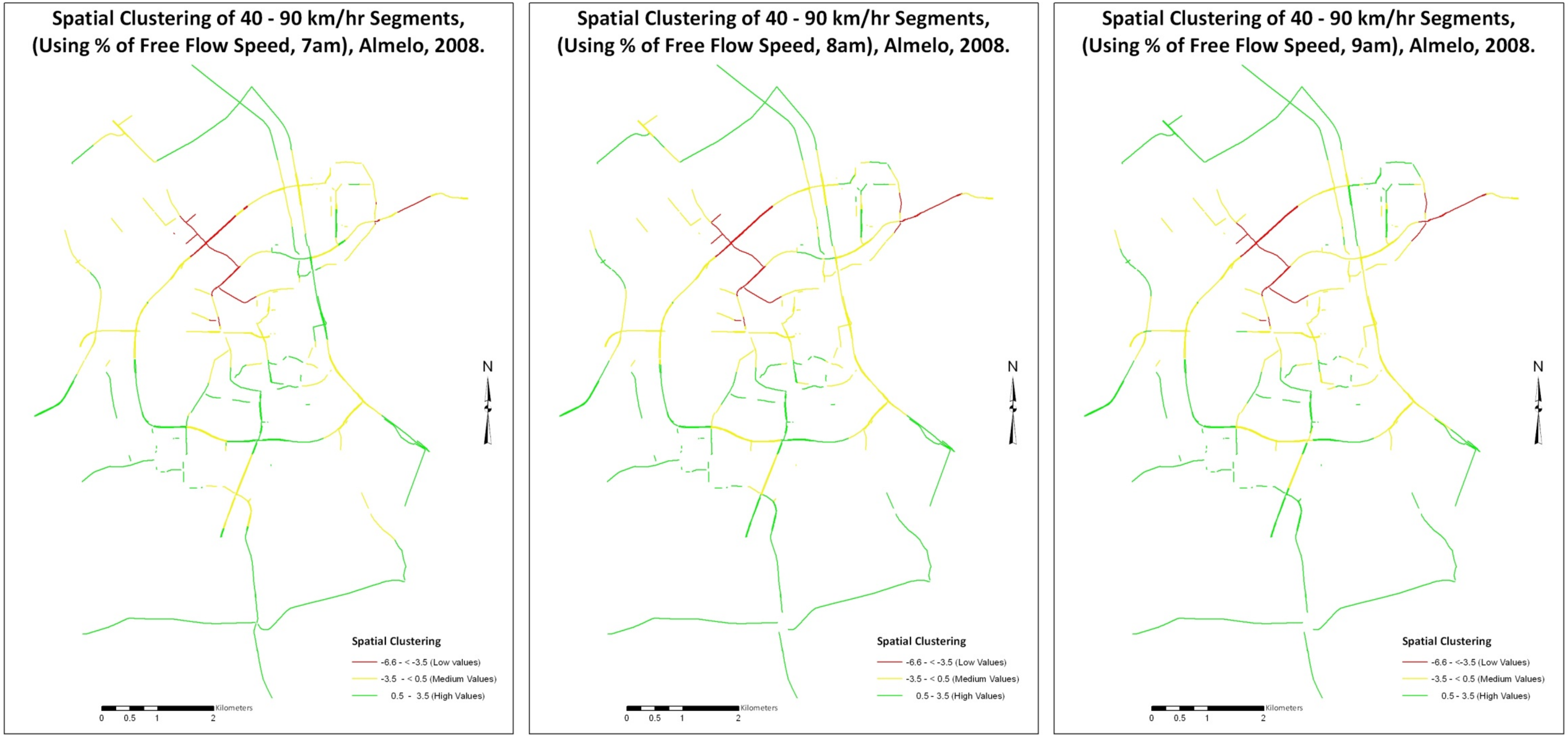

Figure 5-5: Spatial clustering of segments: 7, 8 and 9 am

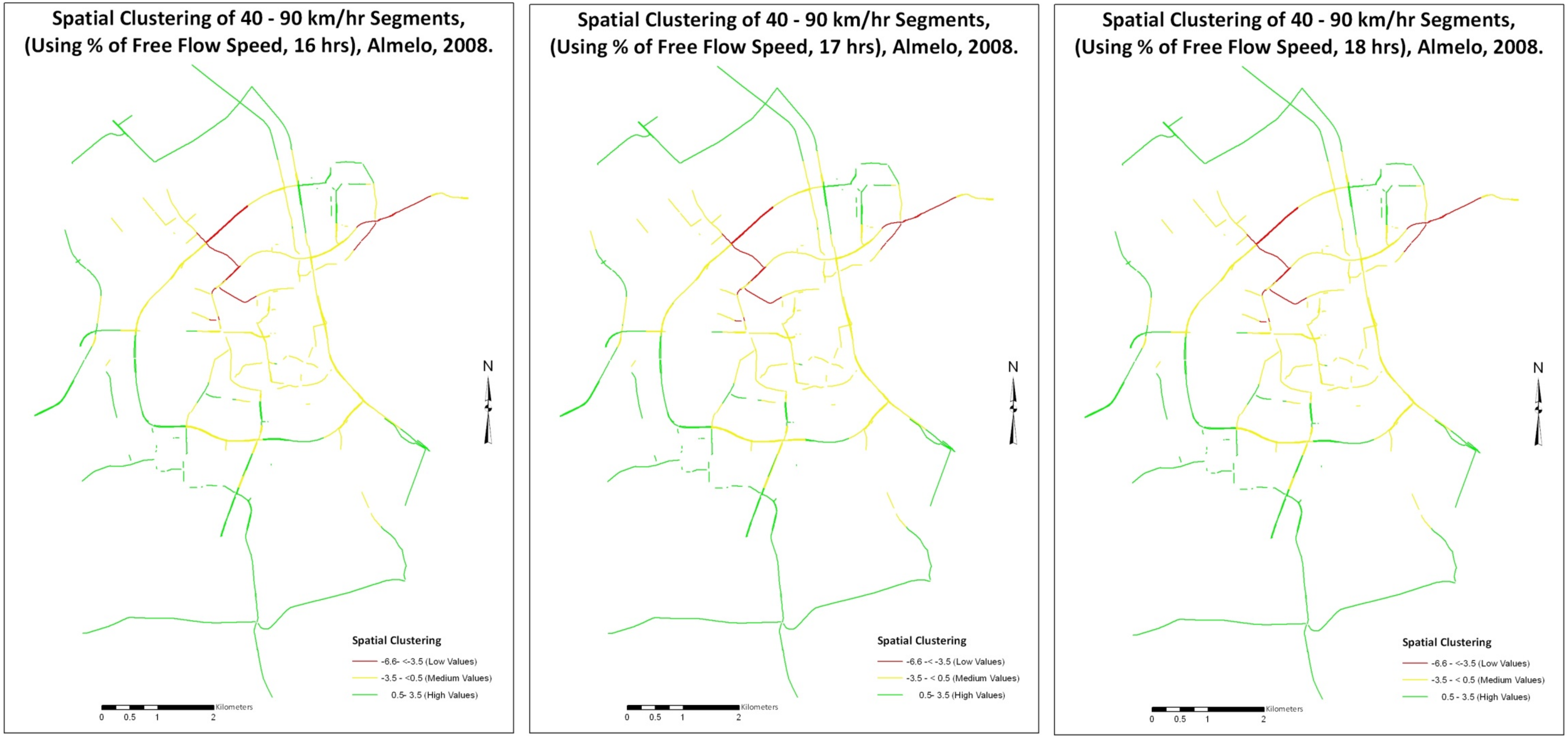

Figure 5-6: Spatial clustering of segments: 16, 17, 18 hours

5.4. Area-Based Speed-Volume Relationships

As part of the objectives of this research, how well different parts of the city perform in terms of traffic circulation was to be studied. Knowledge about such performance aids planners to know if that part of the city is performing well relative to the other or not; and results from these relations could be used as inputs for future planning purposes so as to know how to allocate resources and further plan the city. The analyses performed in this section were to be based on the selected specific areas under the spatial clustering study. Although the specific areas anticipated prior to the clustering analysis look very "patchy" as depicted by the maps (figures 5-5, 5-6) and may not be an ideal approach to compare the performance of distinct parts of the city, a demonstration of how the analyses would have been performed is shown below.

Figure 5-5 shows the clustered segments representing specific geographic locations during the morning peak period whereas figure 5-6 also shows the clustered segments representing specific geographic locations during the evening peak period. This was an intended approach to cluster the segments spatially since the same distinct areas run across all the peak periods (temporally). Spatial and temporal analyses were performed for two different parts of the city denoted by the red colour (north-western part of the city) and the green colour (south-western part of the city) but this approach was seen to have some shortfalls which affected the results. These were just preliminary analyses of the clustered regions to see how effective this approach was for clustering road segments and for further analyses depending on the effectiveness of the results.

The relations that characterise those selected city parts of the city are:

$$\% \ of \ free \ flow \ speed = -0.354 \ (Volume) + 100.9, \quad North \ West \tag{5.8}$$

$$\% \ of \ free \ flow \ speed = -0.377 \ (Volume) + 100.6, \quad South \ West \tag{5.9}$$

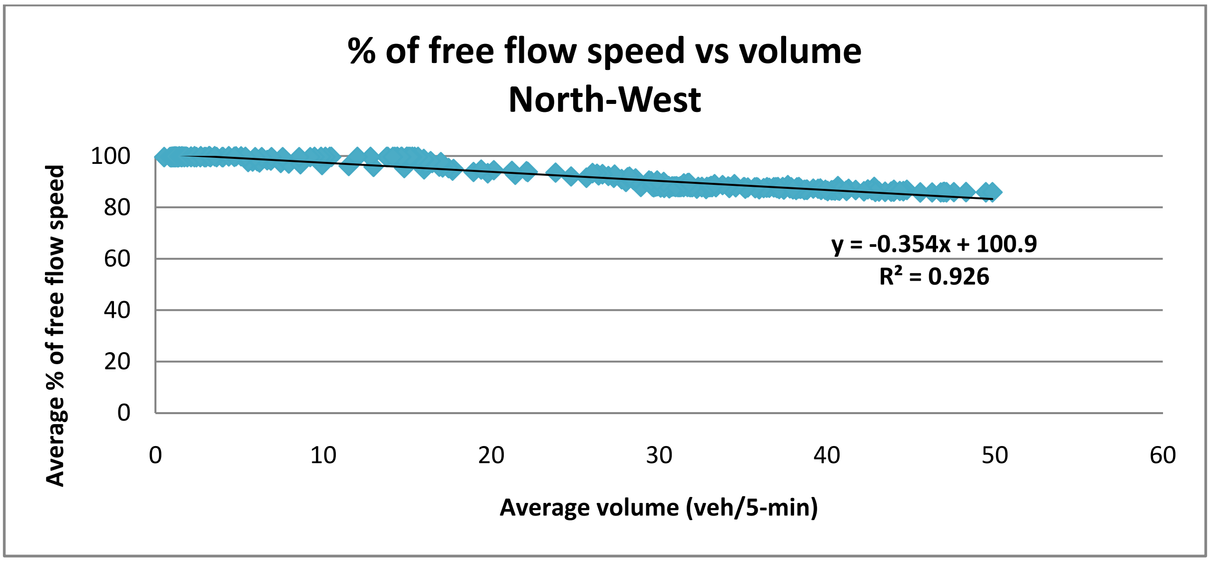

Figure 5-7: Percentage of free flow speed-volume relation (North-West)

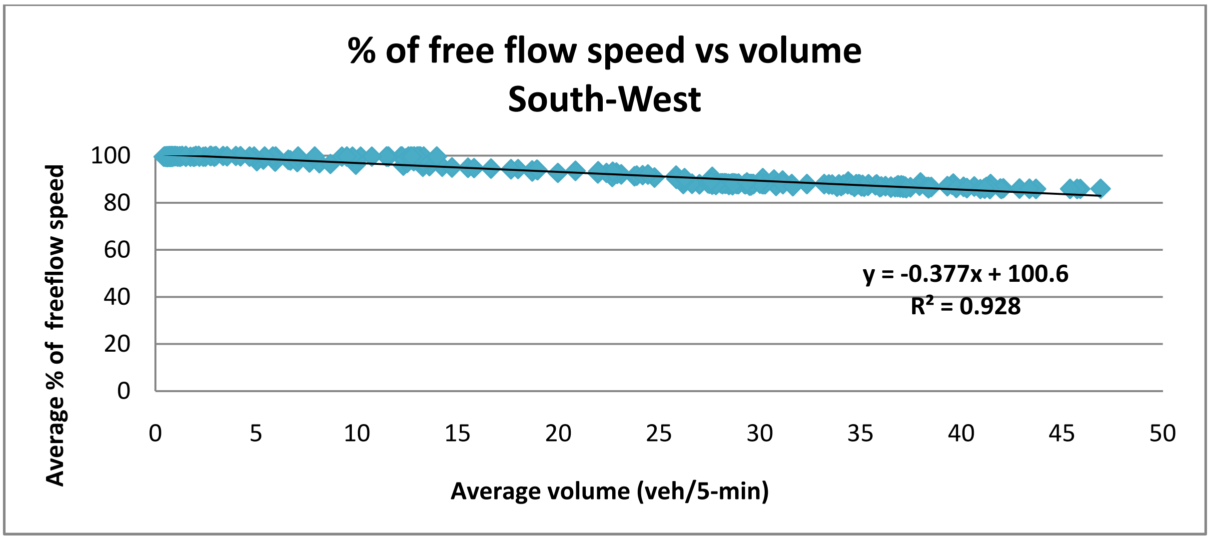

Figure 5-8 Percentage of free flow speed-volume relation (South-West)

Statistically, equations 5.8 and 5.9 could be said to be almost similar, which could imply that the two parts of the cities have almost the same characteristics in terms of traffic flow and may indicate the same performance levels during the peak periods, but this may not be so. For the same geographic areas, different results were obtained during a second attempt of selecting the same geographic locations.

Due to this limitation, it was therefore appropriate to rather consider the performance of road trajectories which was a better option to study spatial and temporal analyses in this research, as compared to the clustering of the road segments to form geographic areas. To further boost that, the comparisons were based on the performance of free flow speeds and not the average travel speeds (which is otherwise not possible due to different free flow speeds on different segments). The analyses performed on the road trajectories have been discussed in section 5.5 of the chapter.

5.5. Trajectories

This section describes the study of the performance of different trajectories. The need to study road trajectories was as a result of the fact that the clustering analysis does not work well due to the "patchy" formation of the relative speeds which gave rise to the study of trajectories instead. For simplicity sake, the corridors or trajectories were chosen to denote geographic areas for the spatial and temporal analyses. The trajectories were selected based on different criteria and these have been explained in the sub-sections below.

5.5.1. Criteria for Trajectory Selection

A critical look at the Almelo road network reveals several trajectories that belong to different geographic locations of the city and due to the nature of this study; emphasis had to be given to specific road trajectories that also comprise "important" roads on the network. In addition to the selection of particular trajectories, consideration was given to the data available (speed and volume) as well as the objectives of this research. With respect to the objectives of the research, it was therefore a requirement to consider all the segments and intersections that had speed and volume data respectively so that relationships between speed and volume could be established. With that subset of segment and intersection remaining, an observation made was that the intersections with volume data followed a certain path or trajectory. These intersections were found to be on the Western corridor of the city (the left part of the city's outer ring road), the inner corridor of the city (inner ring road) and the extension of the inner ring road towards the eastern corridor of the city.

The spatial-temporal analyses of the performance of these trajectories were looked at under two different scenarios. The first scenario considered the performance of the above-described trajectories. These trajectories are shown in figure 5-10. The second scenario looked at the trajectories with or without data at their intersections, as well as other areas in between those trajectories. The trajectories in the second scenario included: the outer ring road on the western corridor of the city, the inner ring road in the inner corridor of the city, the outer ring road on the eastern corridor of the city. The rest were: the outer ring road on the southern corridor of the city, the segments forming the central business district (CBD) of the city and finally, the segments between the inner ring road and the outer ring road bordered by the western, southern and eastern corridors of the outer ring road. These are illustrated in figure (figure 5-16). As stated initially, the performance levels were determined based on their relative free flow speeds in percentages. The next sections show the analyses under both scenarios.

5.5.1.1. Scenario 1

As stated earlier on, the first scenario considered how well or otherwise the trajectories below were performing with respect to their percentages of free flow speed.

- The outer ring road on the western corridor of the city (shown as yellow in figure 5-10 below)
- The inner ring road in the inner corridor of the city (shown as green in figure 5-10 below)
- The extension of the inner ring road on the eastern corridor of the city (shown as red in figure 5-10 below)

In view of that, the data had to be prepared to meet such objectives. Because the roads forming the considered trajectories have different characteristics such as different capacities, different designed speeds etc, it was necessary to have them on a common platform if their performance levels were going to be determined. A new and rather interesting approach which looks at the comparisons of the performance of road segments at an aggregated level using their percentages of free speeds was therefore utilised in this research. The use of average travel speeds was not feasible because different segments had different free flow speeds. Therefore the relationship established between speed and flow in further analyses was by the use of the relative free flow speeds in percentages and not the average travel speeds on the segments. Before that relation could be established, a selection of each of the links that constitute each trajectory was made. The average profile percentage at 5-miute intervals, for each of these trajectories over 24-hours was found using the formula below:

$$\%\,S_5 = \frac{\sum_{i=1}^{N} \%Profile_i}{N} \tag{5.10}$$

Where $\%\,S_5$ is the average profile percentage at a 5-minute interval for a particular trajectory, $\%Profile_i$ is the profile percentage of the i_{th} road element belonging to a particular road trajectory at a 5-minute interval and N is the total number of road elements belonging to a particular road trajectory at a 5-minute interval. So for each five minute, average profile percentages were derived for all the segments that constitute a particular trajectory.

Road Trajectory Performance:

The performance of the trajectories as suggested by the data is as shown below (figure 5-9). Although the trajectories were selected in line with the positioning of loop detectors at specific intersections where data was collected, these volume data did not form part of this analysis in determining the performance of the trajectories. The performance was solely based on the percentages of free flow speed.

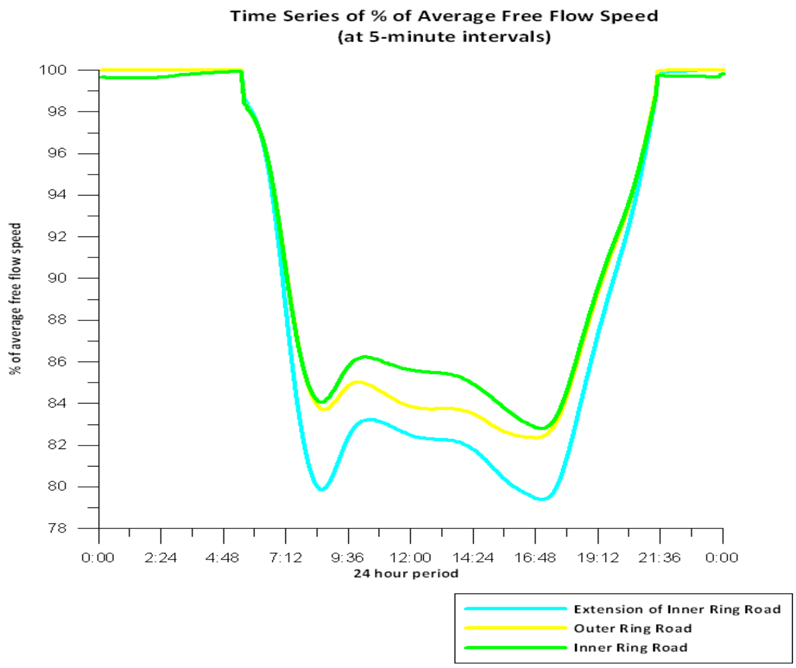

Figure 5-9: Time series of % of average free flow speed

The output shows how well each of the trajectories in question is performing in terms of the percentage of free flow speed it registers throughout the 24-hour period. The least indicated relative speed is around 79% and the best is 100%. All the trajectories record about 100% of their free flow speeds from 12am till around 5:30 am and from 23 -24 hours. The percentage free flow speeds drop during and in between the morning and evening peak periods. The morning and evening peaks are durations where relative percentage speeds are expected to drop due to the high levels of vehicle interaction. Although speeds during these periods cannot be expected to be around 100% during the other times of the day, traffic management schemes can be operationalised to enhance the performance levels during the morning and evening peaks.

Out of the three trajectories, it is evident from the analysis that the inner ring road performs best, followed by the outer ring road and then the extension of the inner ring road towards the eastern corridor of the city. These are shown in figure 5-10 as green, yellow and red respectively. During the morning peak where speed levels reduce on each trajectory, the inner ring records about 84 % of free flow speed, the outer ring, a little below 84% and the extension of the inner ring road, around 80%. A similar trend is observed for the evening peak period where the percentages are 83, 82.5 and 79 for the inner ring, outer ring and the extension of the inner ring respectively. In general, the greater the percentage of free flow speed on a particular trajectory at a particular time, the better the performance, and the lower the percentage of free flow speed, the worse the performance, relatively. One area of concern to planners will be how to put in place measures to at least enhance the performance level of speed on the worst performing trajectory (extension of inner ring road, in this case).

The map below shows that the inner ring road performed best in terms of percentages of free flow, followed by the outer ring road and then the extension of the inner ring road.

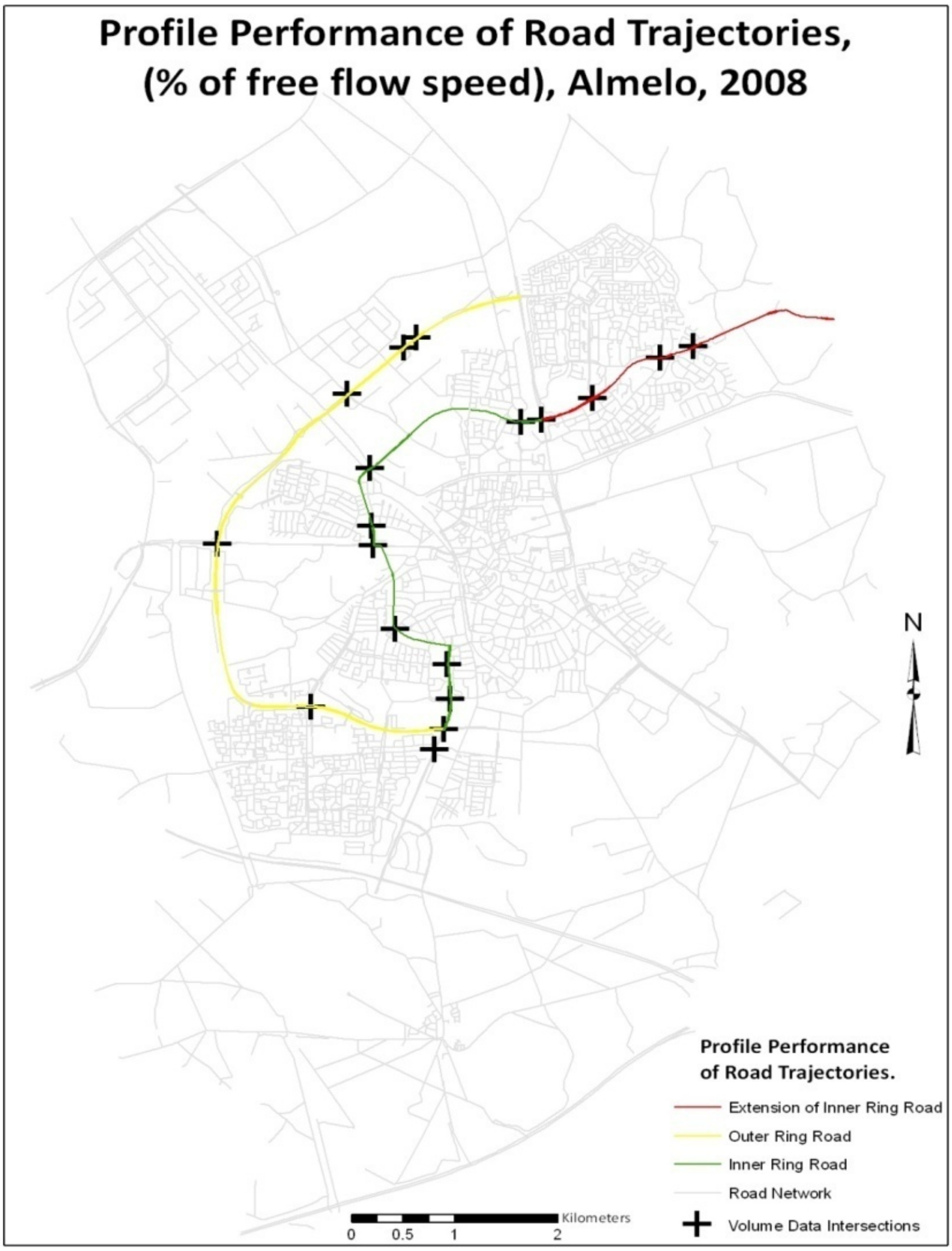

Figure 5-10: Profile performance of road trajectories[15], scenario 1.

[15] These trajectories show the volume data intersections located on them as described

Traffic Volume on Road Trajectories:

To be able to establish a relation between speed and flow, the volume data[16] also had to be prepared for further analysis. All the links for each trajectory were selected from the pre-selected segments with free flow speeds between 40 and 90km/hr and aggregated using equation 5.11

$$V_5 = \frac{\sum_{i=1}^{N} v_i}{N} \tag{5.11}$$

Where V_5 is the average volume at a 5-minute interval for a particular trajectory, v_i is volume on the i_{th} road element belonging to a particular road trajectory; at a 5-minute interval and N is the total number of road elements belonging to a particular road trajectory; at a 5-minute interval. A plot of the volumes on each of the considered trajectories is shown below in figure 5.11 where there are variations of traffic volumes on each trajectory throughout the 24-hour period. The peak periods as well as the periods between the peaks carry higher traffic volumes on all trajectories; and measures are required by planners to improve traffic management on these trajectories during such periods of the day. Further to that, the land use activities around the trajectories that contribute to such higher volumes during such periods can be studied. The results from such studies can be factored into further planning of the city.

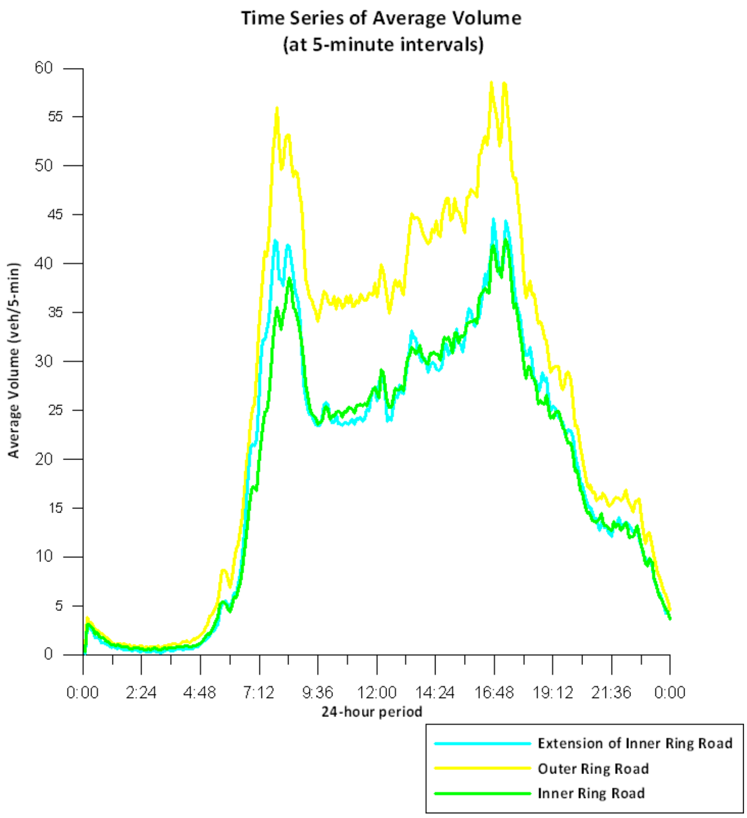

Figure 5-11: Time series of average volume

[16] It should be noted that the volumes at the intersections with volume data consisted of all segments forming the intersections; including perpendicular or adjacent segments. Volumes from all these segments contributed to the total volume at those intersections. And these total volumes were the volumes used in all the analyses that required volume data.

Speed-Volume Relations:

With the relative free flow speeds and average volume data now in the required formats, a relation was established for each trajectory and the results are shown in figures (5-12 to 5-14) below. The relations that characterise each of the trajectories concerning percentage free flow speeds and volumes, which were established, are as follows:

Outer Ring Road

$$\%\ of\ free\ flow\ speed = -0.387\ (Volume) + 101.3 \tag{5.12}$$

Inner Ring Road

$$\%\ of\ free\ flow\ speed = -0.505\ (Volume) + 101.1 \tag{5.13}$$

Extension of Inner Ring Road

$$\%\ of\ free\ flow\ speed = -0.591\ (Volume) + 101.3 \tag{5.14}$$

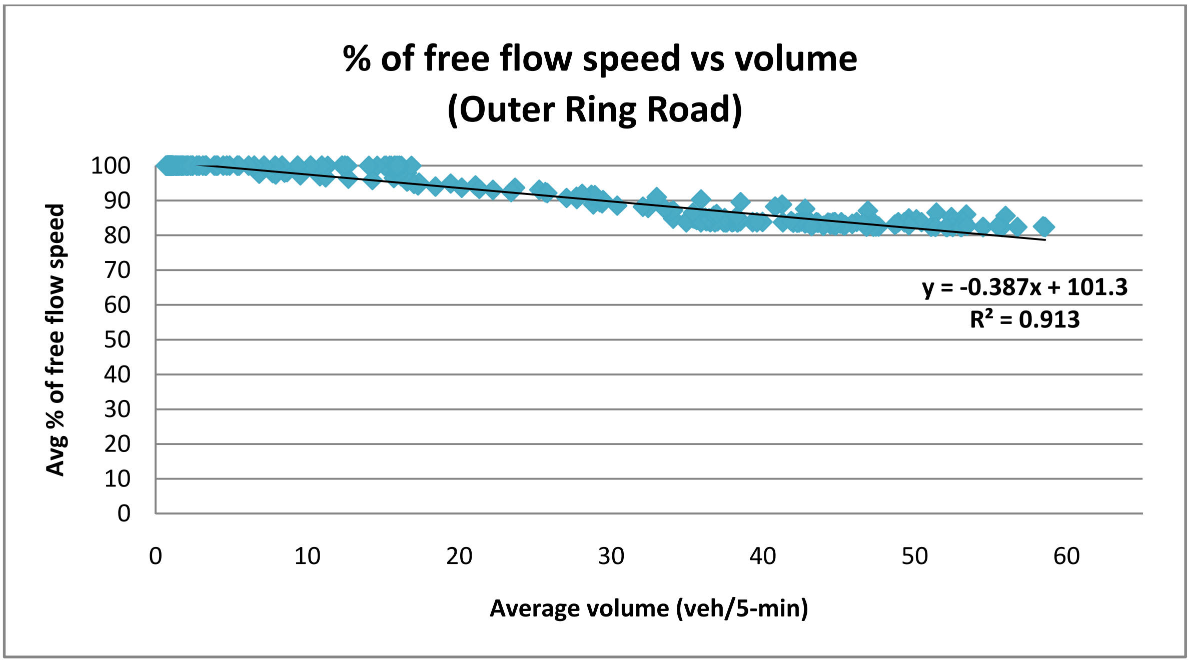

Figure 5-12: Relative speed-volume relationship for the outer ring road

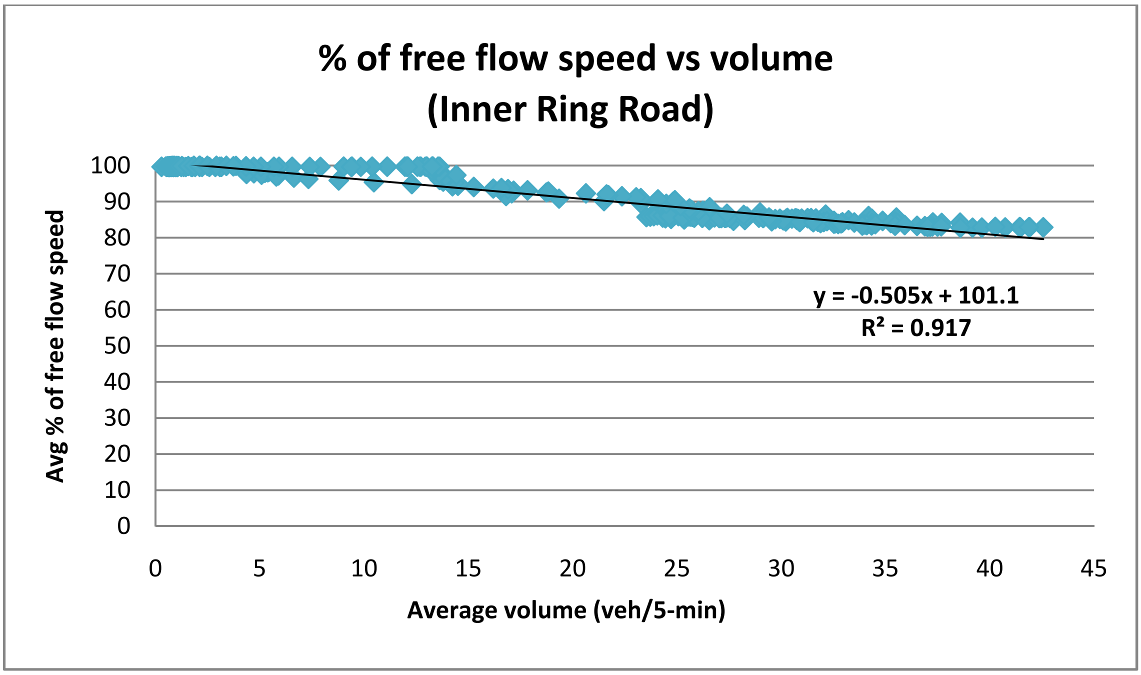

Figure 5-13: Relative speed-volume relationship for the inner ring road

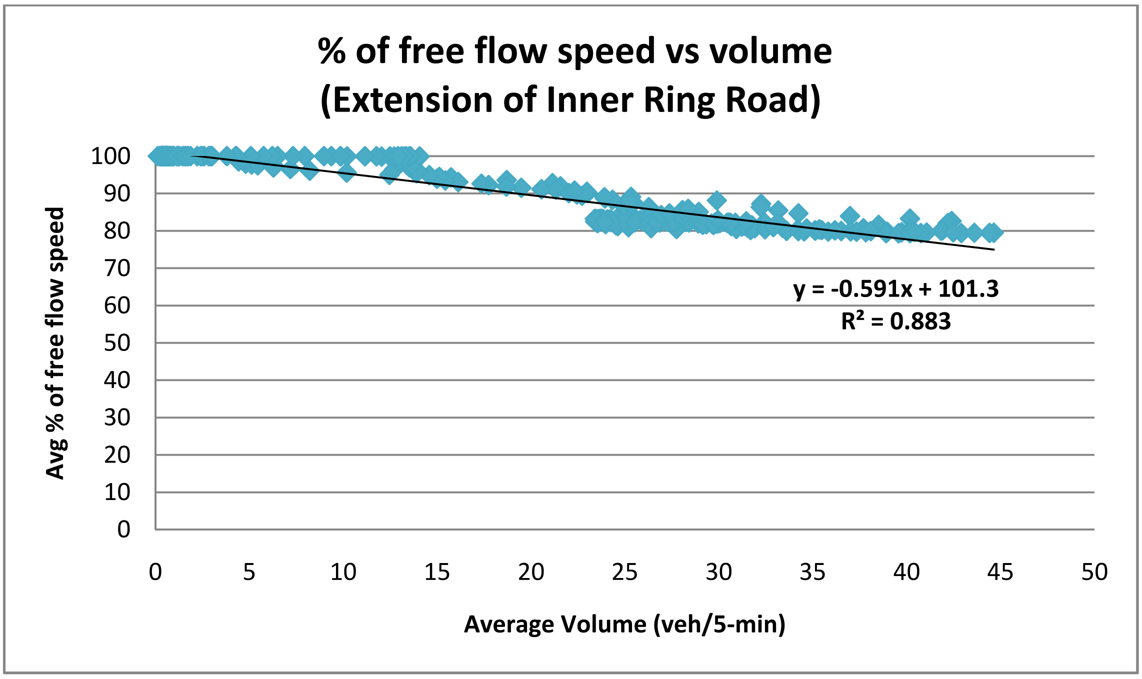

Figure 5-14: Relative speed-volume relationship for the extension of the inner ring road

Generally, each trajectory demonstrated the unsaturated regime of the fundamental diagram suggesting that as per the trajectories, area-based congestion was not really evident (at least in relation to current levels of travel demand). Strong negative relations between percentage free flow speed and volume exist on all three trajectories. A summary of regression coefficients is shown in table 5-2:

Table 5-2: Summary of regression coefficients

Trajectory	% of traffic volume that accounts for speed variations	Gradient
Outer Ring Road	91.3	0.387
Inner Ring Road	91.7	0.505
Extension of Inner Ring Road	88.3	0.591

On all three trajectories, a greater percentage of the traffic volumes account for speed variations on the respective segments as described by the different models, and they are seen to have different slopes as expected. A critical look at the slopes of these trajectories tells us how high or low their measured capacities are. A steeper slope has a larger gradient thereby, denoting a lower road capacity whereas a less steeper slope has a smaller gradient therefore a higher road capacity. In effect, the models suggest that the outer ring road has the largest “measured” road capacity, followed by the inner ring road, then the extension of the inner ring road.

The distribution of activities over space influence one way or the other, the number of trips generated and distributed between two or more zones. This greatly had an effect on the mathematical model derived for the different road trajectories. All 3 models indicate that over 88% of the volumes can account for the variations in the speeds indicating a very strong relation between speed and volume on the trajectories.

These results in themselves may not be enough to make management decisions. In that regard, the volumes and designed capacities are required and an illustration of this has been described in section 5-6 of this report. A management measure will then be to re-route a certain percentage of traffic volume from the extension of the inner ring road unto the inner ring road itself since the percentage of free flow speed performance indicated the inner ring road as performing the best of the three.

5.5.1.2. Scenario 2

The second scenario also looked at the performance of trajectories (inner and outer ring roads) with respect to their relative free flow speeds. In this scenario, no relations were established between speed and volume since not all the trajectories considered had volume data. Although the main idea was to look at trajectories, specific regions in between the trajectories which do not necessarily form trajectories were also considered so as to have an idea how those regions are performing relative to the trajectories.

In all, six trajectories were considered and are as follows:

- The western part of the outer ring road
- The southern part of the outer ring road
- The eastern part of the outer ring road
- The inner ring road
- The region between the outer and inner ring roads
- The CBD (region bounded by inner ring road and eastern part of the outer ring road)

The average profile percentages of the links that constitute each of these trajectories over 24-hours (at 5-minute intervals) were again determined using equation (5.10). The results of the analysis are shown in figure 5-15.

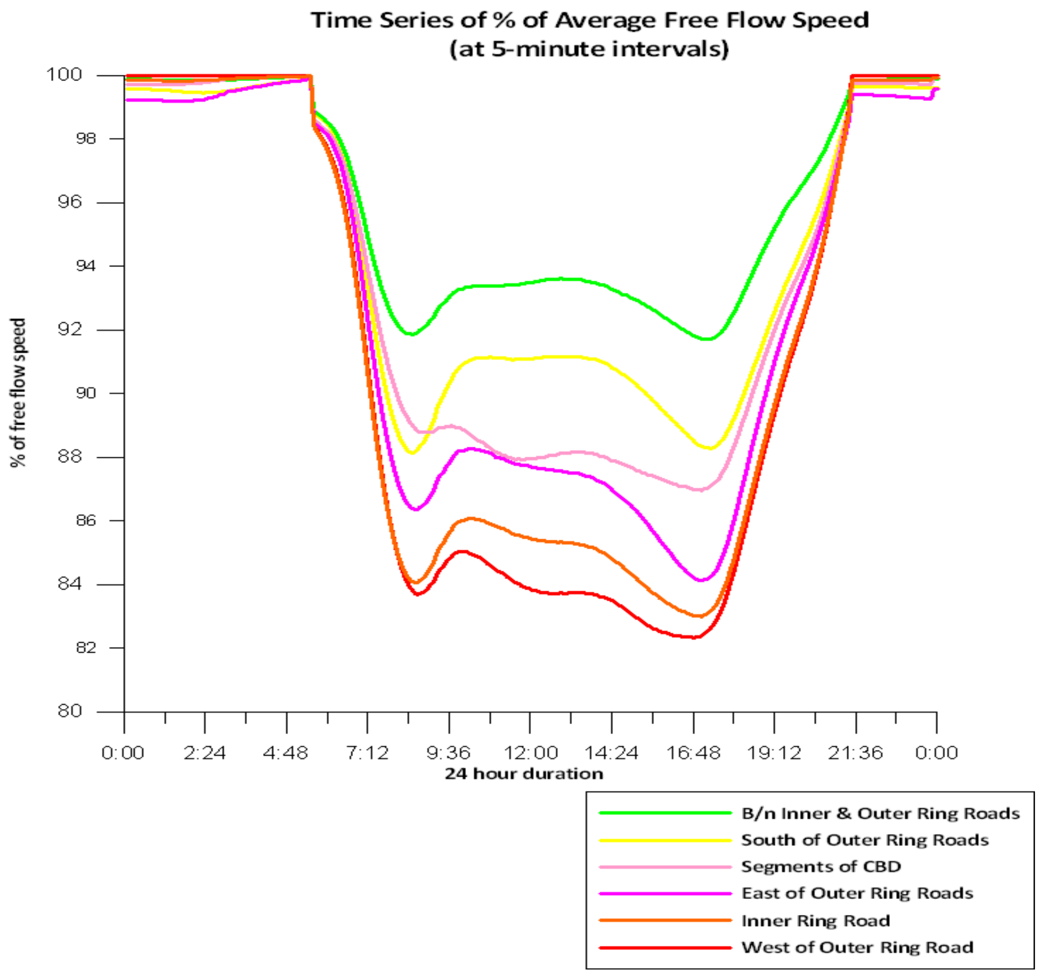

Figure 5-15: Time series of % of average free flow speed

The vertical axis of the graph shows the percentage of free flow speed from 0-100%. The higher the relative percentage speed, the better the performance and vice versa. Generally, all the trajectories are performing well since the least percentage free flow speed recorded was around 82% on the western part of the outer ring road during the evening peak. Although all trajectories are performing well, some do perform better than others. Their performance from best to worst is in the order of:

- The region between the outer and inner ring roads
- The southern part of the outer ring road
- The CBD (region bounded by inner ring road and eastern part of the outer ring road)
- The eastern part of the outer ring road
- The inner ring road
- The western part of the outer ring road

Considering the outer ring roads only, the southern part performs best, followed by the eastern part and the western part, especially during and in between the morning and evening peak periods. This may be as a result of the different levels of attraction on those corridors. The land use activities within those regions could also be factors contributing to the different levels of performance. Appropriate traffic management schemes can be enforced to help address some of these performance differences.

The segments between the outer and inner ring roads also perform better than those of the CBD which is expected because CBDs characterise areas of high traffic volumes and low speeds during peak periods due to their high levels of trip attraction.

At the very early and late hours of the day, there are slight variations in relative free flow speeds amongst the trajectories but these variations are quite higher between the morning and evening peaks. A “peculiar” behaviour is that of the southern part of the outer ring road which seems to perform better than the segments that constitute the CBD but getting to the morning peak period, the segments that constitute the CBD perform better than the southern part of the outer ring road.

Normally, a city’s CBD is characteristic of high concentration of traffic, high use of public transportation, high pedestrian levels etc because it is the geographical centre of the city where a lot of trips are generated and distributed. As a result of that, vehicular speed levels are presumably quite low at these locations.

In view of that, it was expected in the course of the analyses to see the percentage free flow speed of the segments that constitute the CBD performing worse but contrary to that, the CBD segments performed better than the eastern part of the outer ring road, the inner ring road and the western part of the outer ring road. As furtherance to this research, trips produced and generated by the different land uses within the catchment of the considered trajectories can be investigated to account for the variations in speeds as a result of the traffic flows on these trajectories. A map of the trajectory performance is shown in figure 5-16 below. Next to this analysis is a management measure that can be employed to enhance the performance of the “worse” performing trajectories by re-routing some amount of traffic and is in section 5.6 below.

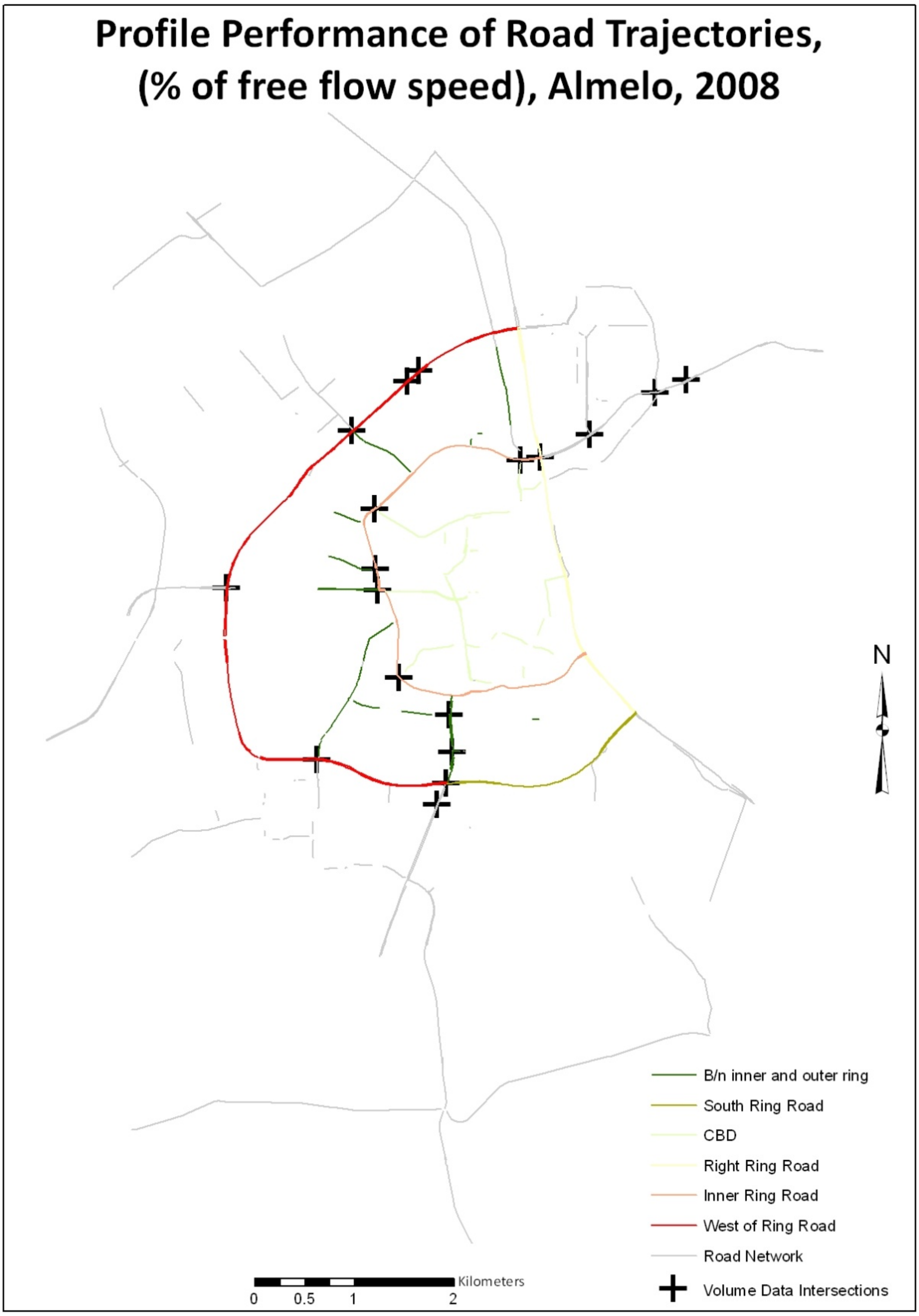

Figure 5-16 Profile performance of road trajectories[17], scenario 2.

[17] Some of the trajectories have volume data at intersections, others don't and others are regions classified as trajectories, for the purpose of this study

5.6. Traffic Re-routing

Practically, planners and engineers aim at minimising the utilisation of most heavily used links in road networks that tend to be congested during peak flows. Queuing delays on individual links increase significantly as link utilisation increases and this becomes a problem when appropriate measures are not put in place to address the situation. It has therefore become necessary to minimise link utilisation (especially on links that tend be congested often) throughout networks so that no bottleneck links will exist. Traffic re-routing is therefore a measure that can be instituted to help reduce congestion on heavily used links. This form of remedy reduces the amount of traffic flow on heavily used trajectories that experience high levels of congestion and re-directs them unto less likely used ones that are less likely to be congested, during the same time period. All these require extensive studies of the performance of trajectories. A look at figure 5-15 above indicates clearly that during peak morning and evening durations, traffic flows are high and speeds drop appreciably on each of the trajectories, but some trajectories perform better than others. So in effect, a measure to be instituted could be for example, to re-route some amount of traffic from the western part of the outer ring road unto the links between the inner and outer ring roads or distributing them unto other "better" performing trajectories, to further enhance the performance of the worst performing trajectory. In doing this, attention should be taken so as not to worsen the performance of the already "better" performing trajectories.

All this require carefully and well considered management measures and one would further ask: by how much volume should be re-routed unto "better" performing trajectories? Appropriate studies could have been further explored if the designed capacities of the road segments were known and then compared with the "measured" capacities of these trajectories as suggested by the data. An illustration of this is shown below.

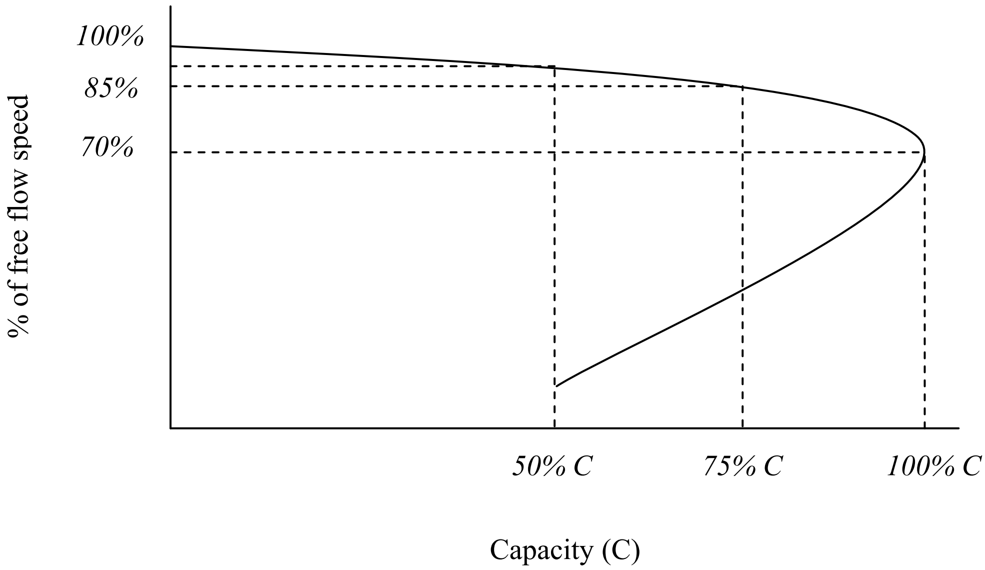

Figure 5-17: Schematic diagram of an MFD (% of free flow speed-volume relation)

Assuming the top part of the curve is a linearly decreasing straight line, and that the estimated capacity of the network is at 70% of the free flow speed (100% of capacity), it implies that at 85% of free flow speed, the network utilises 75% of its capacity etc. This same concept was applied to try to estimate how much of traffic volume should be re-routed from one trajectory to the other at peak durations to enhance the performance of the less performing trajectories. A closer look again at the models that characterise the outer, inner and extension of inner ring roads shows that:

Outer Ring Road

$$\% \; of \; free \; flow \; speed = -0.387 \; (Volume) + 101.3, \; R^2 = 0.913$$

Inner Ring Road

$$\% \; of \; free \; flow \; speed = -0.505 \; (Volume) + 101.1, \; R^2 = 0.917$$

Extension of Inner Ring Road

$$\% \; of \; free \; flow \; speed = -0.591 \; (Volume) + 101.3, \; R^2 = 0.883$$

To have a more robust estimate of capacity, the intercepts of the models can be fit at 100% because at 0 volume, free flow speed is reached. This transforms the equations into:

Outer Ring Road

$$\% \; of \; free \; flow \; speed = -0.352 \; (Volume) + 100, \; R^2 = 0.902$$

Inner Ring Road

$$\% \; of \; free \; flow \; speed = -0.463 \; (Volume) + 100, \; R^2 = 0.908$$

Extension of Inner Ring Road

$$\% \; of \; free \; flow \; speed = -0.542 \; (Volume) + 100, \; R^2 = 0.874$$

Restricting the analysis to the outer and inner ring roads only and putting in place some assumptions, the following can be deduced.

Assuming that the linear relations reach capacity at say 75% of the free flow speed and that both trajectories have the same designed speeds, it can then be inferred from the equations that:

Outer Ring Road

$$75 = -0.352 \; (V_1) + 100, therefore \; V_1 = \; 71 \; veh/5 - min \tag{5.15}$$

Inner Ring Road

$$75 = -0.463 \; (V_2) + 100, therefore \; V_2 = 54 \; veh/5 - min \tag{5.16}$$

In this regard, about 8 vehicles/5-mins can be re-routed from the outer ring road unto the inner road to ensure that both trajectories can have a flow of 63 vehicles/5-mins assuming all those conditions stated above hold.

Another way around it is that, assuming the capacities of both trajectories are reached at 75% of the free flow speeds and the measured capacities of the outer and inner ring roads are 60 and 45 veh/5-mins respectively at this free flow speed (figures 5-12 and 5-13), then it can be inferred that: 8 vehicles/5-mins can be rerouted from the outer ring road unto the inner road so that both trajectories can have a flow of 52 vehicles/5-mins assuming all those conditions stated above hold.

These are just hypothetical values trying to explain how much traffic volume can be re-routed unto other trajectories assuming their designed and “measured” capacities are unknown. Recommendations have been made to that effect so that further studies can be carried out once these parameters are adequately known.

5.7. Speed-Volume Relationship for Almelo (MFD)

The study in search for a macroscopic fundamental diagram for the city of Almelo, in the Netherlands commenced with various spatial and temporal analyses of corridors or trajectories within the city. The previous sub-chapters saw the development of relations for these trajectories which were considered under different scenarios. In these analyses, speed and volume data were prepared adequately to enable such relations to be developed. Next to that, is the speed-volume relation for the entire city of Almelo and this establishes the MFD. In this case, the average speeds of travel on the network were used instead of the percentages of free flow speeds.

After obtaining the average speeds and volumes for the city (equations 5.1, 5.2, 5.3, 5.4), a relationship between the two was established and the MFD for the city is as shown in figure 5-18. A full MFD as described in the earlier chapters shows about three states indicating less congestion (undersaturation), a state where the network reaches capacity and finally, a state of congestion (saturation). But the one developed for the city of Almelo, as suggested by the available data shows that there are no data in the congestion part of the diagram, thus there is little congestion in Almelo.

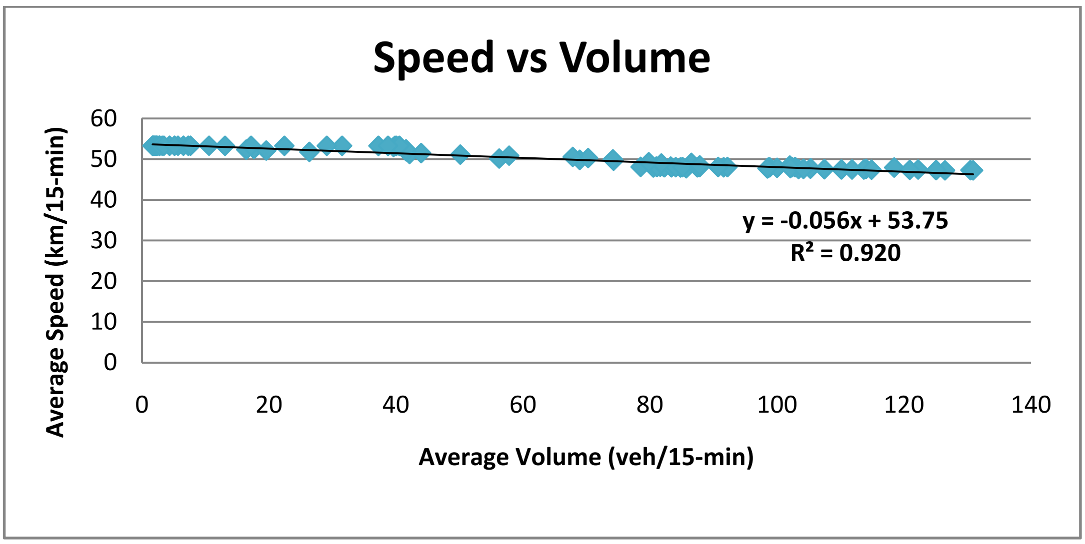

Figure 5-18: Speed-Volume relation (MFD for the city of Almelo).

Further analyses performed using these two variables have been summarised in the tables 5-3 and 5-4 below.

Table 5-3: Model coefficients

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	53.753	.127		422.141	.000
	Average Flow (veh/15min)	-.057	.002	-.959	-32.988	.000

a. Dependent Variable: Average Speed (km/15min)

Table 5-4: Model summary

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.959[a]	.920	.920	.708532386185733	.920	1088.212	1	94	.000

a. Predictors: (Constant), Average Flow (veh/15min)

The graph and tables show that the relation that exists between average speed and average volume for the city of Almelo can be modeled by the equation below:

$$Speed = -0.057\ (Volume) + 53.753 \tag{5.17}$$

The dependent (speed) and independent (volume) variables are average values for the entire city and occur at a 15-minute interval. This model shows the behaviour of traffic flow on Almelo road network and may not be applicable to other cities, even of the same dimensions as Almelo; because of the different network structures, design capacities of road, travel patterns etc. The tables also show that a very strong negative relationship (R^2 of 0.920) exists between the speed and volume. The R^2 value of 0.92 shows that for the entire city, the average traffic volumes can account for 92% of the variations in the average speeds and this implies that only 8% of the variation in speeds cannot be explained by the volumes in this model. Also, both regression coefficients are significantly different from 0, confirming the strong relation. The negative relation implies that each increase in the volume by say 10 vehicles causes the speed to decrease by 0.57. The traffic volumes used for this analysis consisted of all segments forming the intersections; including perpendicular or adjacent segments. Volumes from all these segments contributed to the total volume at those intersections.

A further analysis was performed by considering the intersections where volume data were collected and only those road segments with speed profiles, that form these intersections. The result from this analysis was compared with the initial one which made use of all the segments with speed profiles. Figure 5-19 and tables 5-5 and 5-6 show the output for the relation.

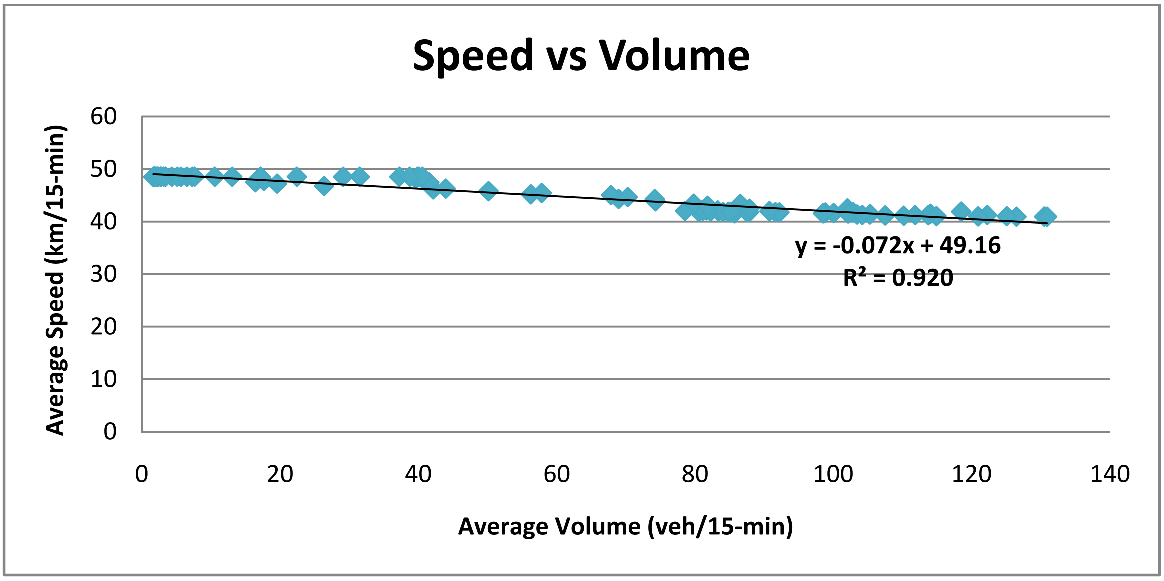

Figure 5-19: Speed-Volume relation (Speeds on only segments forming intersections where volume data was available were considered)

Table 5-5: Model coefficients

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	49.169	.162		303.070	.000
	Flow (veh/15-min)	-.072	.002	-.959	-32.936	.000

a. Dependent Variable: Average Speed (km/15-min)

Table 5-6: Model summary

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.959[a]	.920	.919	.90272773225438	.920	1084.780	1	94	.000

a. Predictors: (Constant), Flow (veh/15-min)

The graph and tables show a slightly different model as compared to that of equation 5.17 where the entire road segments were used instead of only those closer to intersections where volume data were collected. The relation is:

$$Speed = -0.072\ (Volume) + 49.169 \tag{5.18}$$

In this instance also, the undersaturated part of the MFD was obtained instead of the complete shape. Just as the previous relation, a strong negative relationship (R^2 of 0.920) exists between the speed and volume. Also, both regression coefficients are significantly different from 0, denoting a strong relation. The negative relation implies that each increase in the volume by say 10 vehicles causes the speed to decrease by 0.72.

Both graphs suggest that using any of those different combinations of road segments still show the linearly decreasing straight line relation between speed and volume, with a very high correlation between them.

An analysis performed by Thompson (1967) on the relationship between speed and flow in central London in 1967 showed a linear decreasing relationship between average speed and flow (Thomson 1967) as cited in (Geroliminis and Daganzo 2008). And this suggested that the streets in the data set were not very congested. These results are not different from what the city of Almelo is exhibiting, that a linear decreasing relation between average speed and flow exists, therefore suggesting that on the whole, Almelo experiences very little congestion. This is shown in the graphs (figures 5-18 and 5-19) where only the non-congestion part of the MFD is shown and this is in line with what Thomas and Van Berkum, (2008) wrote as "congestion is negligible in Almelo". Although the MFD exists for the city, the data suggests that Almelo does not yet have the overall traffic flow characteristics that will provide all the states of the diagram, and this shows how well the city is performing in terms of traffic flow, and how effective traffic flow is, at the city-scale level.

In addition to the above analysis where the MFD suggests that congestion levels in Almelo is low, a profile performance analysis was performed to check the congestion levels of the individual road segments within the city. Details of the analysis have been described in section 5.8.

5.8. Profile Performance

Another major finding was the use of the 60 profile speeds provided to prepare analyses leading to the production of "congestion" maps for the city. Although congestion denotes a state of traffic delay because the number of vehicles using a road exceeds the operational capacity of the network to handle it, these maps show the performance levels of each segment based on the percentage free flow speeds. This analysis led to the production of profile performance maps which show how each of the segments "scores" relative to the speed profiles provided. These profiles show the behaviour of changes in average speeds during a given time period for a road element. The profiles are in units of percentages. A zero profile percentage shows a worst percentage of free flow and the percentages rank better as the percentage of free flow speed approaches 100, with 100% being the best. In all, 60 different profiles were provided by Tele Atlas and this represented relative speeds on the network for Almelo. Each profile is applied to more than one segment so long as they characterise almost similar speed patterns throughout the day. The analyses were performed for the morning and evening peak periods and are shown in the maps below. The table showing the percentage profile values for the morning and evening peak periods is shown in appendix 3. This is a rather new approach at looking at the level of congestion on segments instead of the widely acclaimed (v/c) volume to capacity ratio on segments.

The speed–volume relation developed was at an aggregated level showing that Almelo is rarely congested. A further look at the performance congestion level of each segment was considered and studied using the profile speeds provided. The essence of this study was to be able to identify the individual inks in the network that experienced some level of congestion at specific times of the day so as to give recommendations on how to curb the localised congestion to further boost the performance levels of the city's network. The results are as shown in figures 5-20 and 5-21.

Generally, maximum flows are expected during rush hours or peak periods, and these flows lead to lower speed levels during these same periods. In analysing the profile performance, only the hourly periods from 7-9 am and 16-18 hours were considered since these periods reflect the peak durations.

The maps show the performance as depicted by graduating colours of green to red. Red and green show the worst and best performances respectively. During peak periods when traffic flows are high, with speed levels low, it is expected to see a high level of congestion on links but the maps show most of the links record percentages from 70-100% and very few are under 70%. The worst performed link records a speed of 44% of the free flow speed at 17 hours. These "congestion" maps help decision makers to know which individual links have certain levels of congestions during peak periods so as to put in management measures to ameliorate the effects at those localised levels. It is confirmed from the outputs that although very few segments had some localised congestion levels during these periods, Almelo in general does not demonstrate very high congestion levels and this also confirms the relation between average speed and flow as a decreasing straight line being demonstrated as the unsaturated part of the MFD.

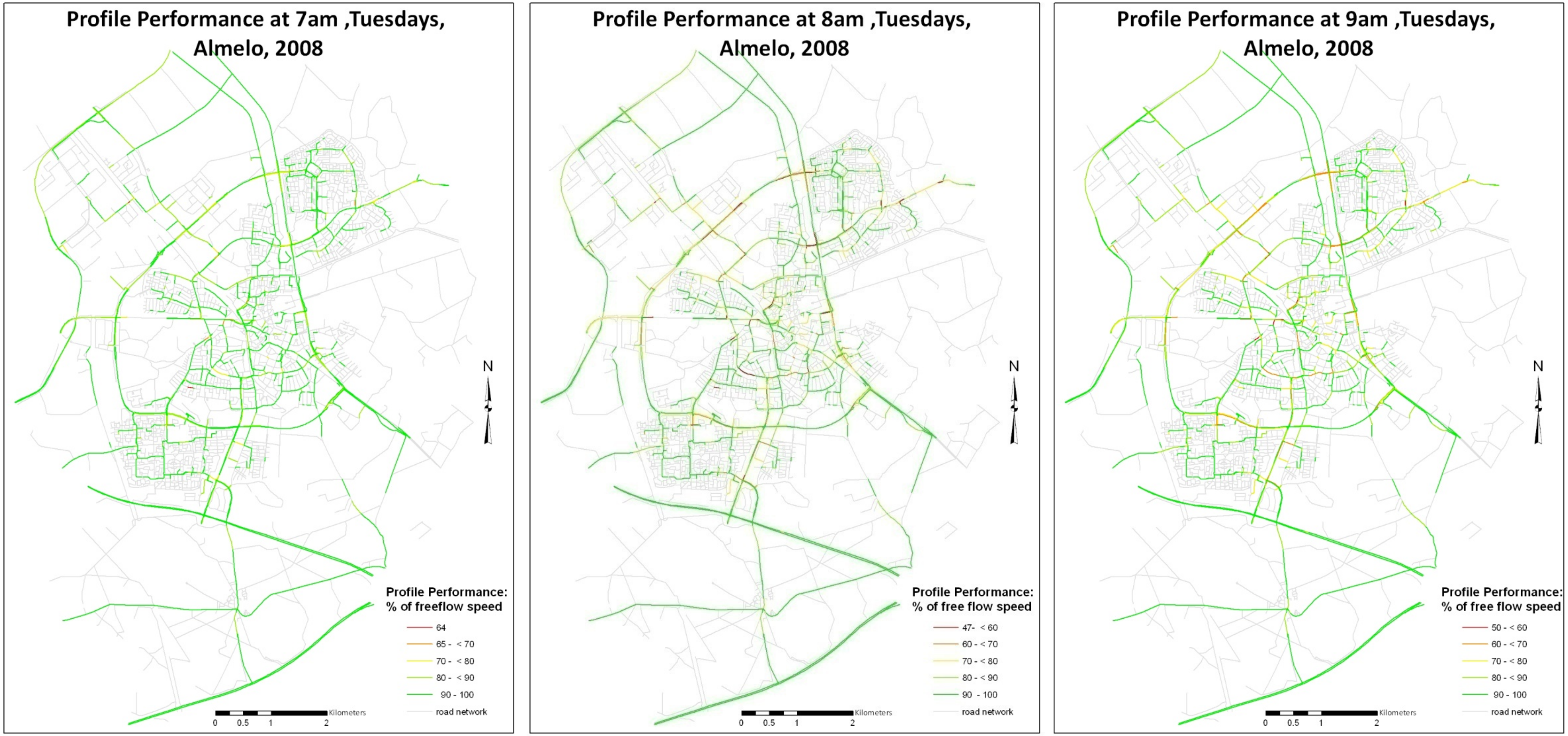

Figure 5-20: Profile performance at 7am, 8am and 9am

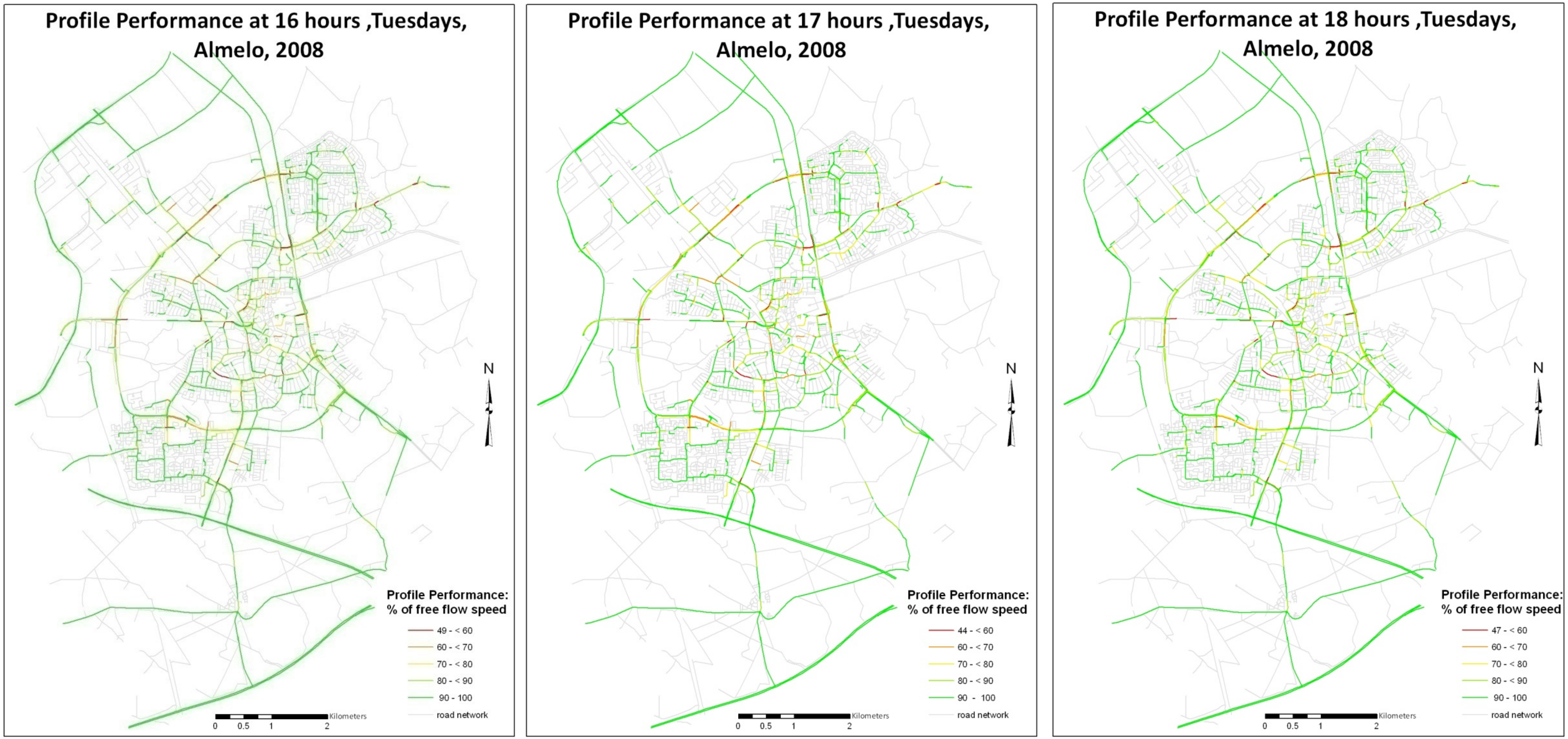

Figure 5-21: Profile performance at 16, 17 and 18 hours

A time series graph of average percentages of free flow speed of all segments with speed profile was produced in addition to the profile performance analysis. This graph (figure 5-22) shows that the worst performance level of free flow speed was around 89% during the evening peak period, attesting to the less-congested nature of the network in Almelo.

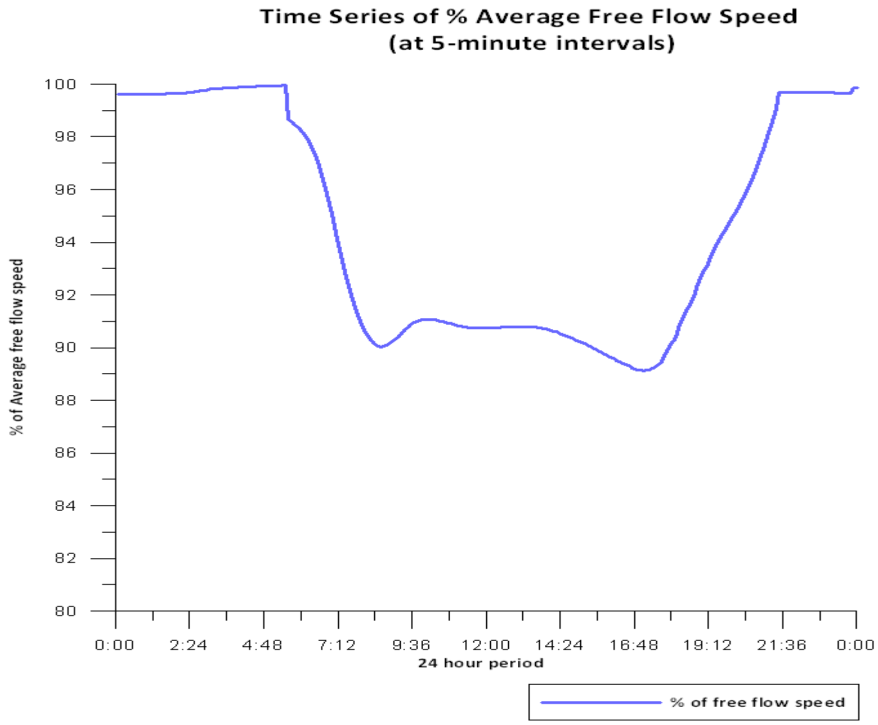

Figure 5-22: Time series of average free flow speed, Tuesday

5.9. Summary

Analyses that were carried out in this research have been described in this chapter. This enables relevant information to be derived from the data. The genesis of the analyses was with the preparation and aggregation of volume data to 15-minute intervals by writing algorithms. Average travel speeds have also been derived from the profile speeds; and the volume and speeds suggest the morning and evening peak periods are 7-9 am and 16-18 hours respectively. To be able to perform spatial analyses for geographic locations, spatial clustering analyses were performed to identify these zones but the clustered regions did not look quite encouraging so the concept of looking at different trajectories under different scenarios was used instead. Scenario one considered the trajectories with volume data collected at their intersections. The results showed that the outer ring road has the largest “measured” road capacity, followed by the inner ring road, then the extension of the inner ring road. The percentages of free flow speed data also suggested that the inner ring road performed best in terms of profile speed, followed by the outer ring road and then the extension of the inner ring road. An observation from further analyses indicated that traffic volumes accounted for a greater percentage of speed variations on the road segments in the city.

In a bid to minimise the utilisation of most heavily used links that experience congestion in road networks, so to avoid the formation of bottlenecks on links, traffic re-routing has been recommended. This helps to reduce the amount of traffic flow on heavily used trajectories that experience congestion during certain times of the day and directs them unto less congested ones. In re-routing care should be taken so as not to worsen the performance of the already better performing trajectories. It therefore becomes ideal if studies are able to show how much traffic volume should be re-routed. Once this is known, measures can be put in place to ensure that the effectiveness of all such trajectories.

For scenario two, six trajectories were looked at. The trajectories performed best to worst in the order:

- The region between the outer and inner ring roads
- The southern part of the outer ring road
- The CBD (region bounded by inner ring road and eastern part of the outer ring road)
- The eastern part of the outer ring road
- The inner ring road
- The western part of the outer ring road

The MFD suggested that the city does not experience any higher levels of congestion because the relation between average speed and average volume gave a linearly decreasing straight line. Similar results were obtained after choosing some segments out of the total number with speed profiles and even transforming the data.

Traditionally, the v/c ratio is used to determine the level of congestion on road segments. In this research, exploration has been made on how the profile speed percentages relative to free flow speeds can be used to determine degrees of congestion on road links. This approach can be used when determining the congestion levels on segments, if the capacities of road segments are unavailable and one has the percentages of free flow speeds available.

6. Conclusion

Finally this chapter gives a recap of the whole research by reviewing the aims and objectives that set off the thesis. It outlines the findings and achievements made in this research as per the research objectives. The limitations encountered in the course of the research have also been discussed, and lastly, some recommendations to planners, engineers, policy makers and possible directions for future researches have been enumerated.

6.1. Review of Aims and Objectives

This research aimed at performing spatial and temporal analyses of traffic flows in the city of Almelo in search for an MFD. This MFD was necessitated because segment-based indicators help to study performances of road segments but are not enough to study similar performance at area-based or city-based scales. The MFD gives an understanding of the general performance of the network for a city. Knowledge about the performance levels assist planners, engineers and policy makers into putting in place measures to enhance such performance levels, and this aids traffic flows within cities. To assist in accomplishing this, some research objectives were instituted and each of these objectives was made functional by series of sub-objectives and their respective research questions.

The first objective sought to perform series of spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo. This required data such as speeds and traffic volumes. Considering the aim of this research, it was not feasible to personally collect such data effectively so secondary data was relied upon. Speed data was provided by Tele Atlas and volume data, by ViaContent systems in Almelo. Also, discussions were held with Mr Rob Hulleman of the traffic and transport section of the municipality who assisted in providing other materials for the research. Other expert knowledge from the supervisors who are also familiar with traffic flow conditions in the city, assisted in the data acquisition process. The availability of the data commenced the analysis with the writing of algorithms, to help analyse the data due to its huge nature. Spatial and temporal analyses were then performed for selected parts of the city and selected trajectories under different scenarios, once the data were in their required formats. Basically, the spatial and temporal analyses under the first objective were by the use of the volume data and the percentage of the free flow speeds derived from the profile speeds.

Objective two then went into the study of the feasibility of the existence of an MFD for the city of Almelo. This was achieved by establishing a relation between average speed and average traffic volume for the entire city since an area-based indicator was required to determine the performance of the city's road network. It came out that Almelo at an aggregated level experiences little congestion although levels of congestion occur on some localised links. A negative but very strong relation existed between the speed and volume data pointing out the fact that traffic volume accounted for a greater percentage of speed variations on the segments.

The last objective was essentially to give recommendations on how such useful information from the established models (spatial and temporal analyses) could be used to better plan traffic operations in the city and this is contained in the discussions of chapter five.

6.2. Main Findings

This research was fundamentally aimed at performing spatial and temporal analyses of traffic flows in the city of Almelo, in search for an MFD; and series of analyses were performed to that effect. As per the specific research objectives (in bold), the following conclusions can be drawn:

To perform and study spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo.

The analyses showed that some level of variation existed between different trajectories within the city in terms of traffic flows and speeds. The speeds and volume showed a very high level of correlation; with the volumes accounting for about 92% of the speed variations on the network. Significant differences in the performance of trajectories were found when different trajectories were compared. This implies that some trajectories perform better than others in terms of their percentages of free flow speeds.

Under scenario one, the inner ring road in the inner corridor of the city performed best, followed by the outer ring road on the western corridor of the city and then the extension of the inner ring road on the eastern corridor of the city. On all three trajectories, performance levels were relatively bad during and between the morning and evening peak periods. From 11 pm till 5:30 am the following day, performance levels were the best at 100% of the free flow speeds. Generally, all trajectories performed well with above 78% of free flow speeds.

Scenario two also had all trajectories performing well at above 82% of free flow speeds. Although all trajectories had good performance levels, the best performing trajectory was the segments between the outer and inner ring roads, followed by: the southern part of the outer ring road, the segments of the CBD, the eastern part of the outer ring road, the inner ring road and the western part of the outer ring road, in that order. Just as depicted in the first scenario, performance levels on all trajectories were comparatively bad from 7am to 6 pm and very good (about 99% of free flow speeds) from 9:30 pm till 5:30 am the following day.

To study the feasibility of the existence of an MFD for the city of Almelo.

The series of analyses performed with the available data suggested that the macroscopic fundamental diagram exists for the city of Almelo. However, this particular diagram depicted the non-congestion phase of the “full” diagram, since there was no data in the congestion part of the diagram. This shows that very little congestion occurs in Almelo at a city scale since the city may not yet have the overall traffic flow characteristics that will provide all the regimes of the diagram.

By studying the MFD, a model that characterises the travel behaviour of Almelo was established (Equation 5.17). This model may not be applicable to other cities, even of the same dimensions as Almelo because of possible different city and network structures. The relation between average speed and average volume demonstrated that the average traffic volumes account for 92% of the variations in the average speeds and this implies that only 8% of the variation in speeds cannot be explained by the volumes in this model.

To give recommendations on how information from the established models can be used to better plan traffic operations in the city.

Some trajectories perform better than others according to the analyses. Engineers, planners and policy makers are advocated to put in demand-controlling measures to re-route some amount of traffic from these less performing trajectories unto the better performing ones so as to ensure effective flow of traffic in the city.

Although the city as a whole does not experience any higher levels of congestion, the research showed that some localised congestion levels (shown on the profile congestion maps, figures 5-23 and 5-24) were experienced at certain times of the days, especially during the peak periods. Measures are therefore to be put in place to help curb such congestion levels before they have serious effects on the network as a whole. These measures are justified in the sense that, although the city experiences no serious levels of congestion, a do-nothing situation may be appropriate for now but as population increases, economic activities, land uses are enhanced etc, the number of trips generated and distributed within and between zones may increase leading to an increase in traffic flow, and then congestion situations may set in.

Studies have shown that the MFD can be used to improve accessibility within cities (Geroliminis and Daganzo 2008). Although the MFD researched for Almelo did not show the complete regime of a typical MFD, information from a "complete" MFD can be channelled into enhancing accessibility levels to ensure effective traffic circulation within the city. This can generally be done with road pricing, rationing and/or perimeter control strategies based on neighbourhood accumulation and speeds, such as those proposed in (Daganzo 2007) and (Geroliminis and Daganzo 2007). Almelo may not be congested enough to be given such measures but these can be thought of and applied where necessary in future instances and as Geroliminis and Daganzo (2008) put it, "by knowing the MFD and monitoring the state of traffic continuously, transportation managers can now see whether their system is in a state that is producing the desired accessibility levels for all modes and at all times. Therefore, existing strategies can be refined".

The main findings from this research are thus:

Traffic volumes within the morning and evening peak periods are of great interest to traffic engineers and planners in design and operational analyses since roads to carry traffic are designed adequately to meet such demand levels. These periods exhibit highest traffic volumes and lower speed levels throughout the 24-hour period. Generally, these periods are estimated considering the work-trip patterns within a city. The analyses with the data suggested that the morning and evening peak periods for the city of Almelo are 7-9 am and 16-18 hours respectively. These periods were first established as a basis for all other analyses.

Generally, the evening peaks tend to show a slightly higher volume and a slightly reduced speed levels as compared to the morning peaks. It can further be investigated as to which land use activities within those corridors contribute to this variation. Such studies could enhance the effective distribution of resources in the city.

The clustering of road segments to form geographical areas was going to affect the results since a level of bias was detected by the selection of these parts of the city. Together with this approach, a strong form of local knowledge of the city could have aided in the selection of different city parts.

The research indicated that some trajectories indeed performed better than others even under different scenarios and this is very significant detail for planner and engineers to further plan traffic flow within the city. All the considered trajectories relatively performed worse between and during morning and evening peak periods. Performance levels were very good (≈ 100%) from 9:30 pm till 5:30 am the following day.

The research also demonstrated the existence of a macroscopic fundamental diagram for Almelo. This diagram as shown in previous chapters indicated the non-congested phase of the fundamental diagram (a linearly decreasing relation between speed and volume). The diagram, as well as the profile performance analysis suggests that Almelo at a city-scale level experiences little congestion, considering the available demand levels.

Speed and traffic volumes have a relation. The city of Almelo demonstrated a very high level of correlation between speed and volume and a model was established for the city demonstrating this level of relation. The model characterises the traffic flow in the city of Almelo and may not be applicable to other cities as a result of possible different city and network structures.

The strong relation also gave an indication that although other factors may contribute to speed variations on the network, traffic volumes accounted for the greatest percentage of variation of speed on the city's network.

A different approach to studying the degree of congestion on road segments instead of the conventional volume to capacity ratio was found to be that of the use of speed profile for the city's road segments. These percentages of free flow speeds could indicate the level of congestion on links. In Almelo's instance, although it showed that the city experiences little congestion, the individual links that are congested were distinctly identified, using the speed profiles.

Another finding was the use of the percentages of free flow speed in establishing relations between speed and volume. To be able to compare trajectories suitably, this approach is appropriate, instead of using the average speeds since different segments have different free flow speeds.

6.3. Limitations

Although the research has yielded some major results, it was faced with some limitations such as:

Not all the major intersections had loop detectors to record traffic volume. This gave rise to quite a smaller number of data points for the plots and this meant that the 17 intersections that had volume data were assumed to be representative of the volume for the entire city.

Secondly, the speed data had 60 profiles. Profile numbers 1-59 were those segments with speed data whereas profile number 0 was indicated as “unknown profile” so speeds on such links could not be analysed. In effect, not all the segments had speed data covering them so in this case as well, the segments with speed data were assumed to be representative for the entire city.

The speed and volume data came from two different sources. The volume data was collected from September 2004 to September 2005 as compared to the speed data which was collected differently and this shows some level of data variability. Volume and speed data collected within similar time frames could indicate a stronger relation among the variables and may enhance the results as well.

The designed capacities of the trajectories are unknown. This could have enabled further studies into the performance of trajectories by deriving their measured capacities from the analyses and comparing them to the designed capacities of the roads to cross-check if they were performing up to the designed capacities or underperforming. By this analysis, their degree of performance could have been well established.

The time constraint as a factor restricted the analyses to only Tuesdays, and in some instances, Mondays. Analyses for the other days would have created the platform for comparisons to be made among the different days of the week

6.4. Recommendations

Based on the observations and findings from the research, recommendations have been made and possible areas of extension for this research have been summarised below, as per the research objectives:

To perform and study spatial and temporal analyses of traffic flows in different parts of the city or corridors within the city of Almelo.

Volume data available for this research covered only weekdays whereas the speed data covered all seven days of the week. Due to time constraint, the researcher restricted his study to Tuesdays only and it is recommended that further studies should be carried out into the other days where traffic variations for these days could be determined and further explored. For instance, traffic variations could be studied between weekdays and weekends so that traffic circulation within the city would be well understood and appropriate steps put in place to enhance traffic flow.

Under this same theme, it is recommended that the designed capacities of the road segments are provided so that further analyses that pertain to comparing the performance levels of trajectories can be undertaken.

To study the feasibility of the existence of an MFD for the city of Almelo.

Furtherance to the study on the feasibility of an MFD for Almelo, the researcher commends that this type of study should be replicated in other cities so that the MFDs will serve as network performance indicators for traffic management purposes.

In addition to that, researches could be performed for different cities on how a city’s network structure (land use and transport planning) affects its MFD.

To give recommendations on how information from the established models can be used to better plan traffic operations in the city.

The level of interaction between land use and transport cannot be underestimated as deduced from other researches. This interaction is seen by Shaw and Xin (2003), as a dynamic process that involves changes over spatial and temporal dimensions between the two systems, and changes in land use systems can have effects on travel demand patterns and induce changes in transport systems. With regards to this, the researcher advocates that future researches in this domain will consider land use components and investigate how they influence or explain some of the results in this research.

It is also recommended that further studies are carried out into how information from the MFD could be used to enhance accessibility and mobility levels within cities.

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8. Appendices

8.1. Apendix 1- Automatic Detection of Vehicles

Data collection for traffic analysis comes in varied forms depending on several factors such as type of analysis, duration of survey, finance allocated for the survey etc. As discussed above, this research relied on already collected data by loop detectors and probe devices installed in vehicles t measure speeds of travel on road networks, and this chapter looks at the various systems that exist by which vehicles can be detected automatically for traffic planning purposes.

Detecting the presence of vehicles (counting them) on our road systems plays very important roles such as vehicle monitoring, traffic data collection for traffic planning and management purposes, accessibility analysis etc. This is a vital activity in the field of transportation systems considering the fact that it allows for the enforcement of traffic policies; with the information on traffic it provides (Cucchiara and Piccardi 1999; Eikvil, Aurdal et al. 2009). Different methods exist for carrying out this activity. Some cities in the developed countries use field based equipment such as cameras installed at fixed locations or weigh-in motion sensors on the pavements to monitor traffic (Gerhardinger, Ehrlich et al. 2005). Each of the different installations will consist of a detector unit, a decoder and a storage device and the sub-chapters below discuss some of the widely used detector methods and summarizes some of their characteristics (Taylor, Bonsall et al. 2000).

8.1.1. Inductive Loop Detectors

The most commonly used type of detector which is widely used by many agencies is the inductive loop detector (Kell, Fullerton et al. 1982; Eikvil, Aurdal et al. 2009) and has been in use for the detection of vehicles since the early 1960's (Potter and Reno 2005). Current technology typically collects data by the use of inductive loop vehicle detectors embedded in (or lying on) roadways (Eikvil, Aurdal et al. 2009). This vehicle detection device provides traffic flow information over time for a point in space.

The loops consist of fine wires that carry an electric AC (alternating current).The entire installation is made up of these loops which may be one or more turns of wire in a slot-cut slot in the street surface in the exact area where vehicles are to be detected. On the other hand, they can be stuck onto the road with a special tape and a bonding agent. The ends of the loop are then connected to an electronic amplifier usually located in the controller by the use of a cable. The principle by which vehicles are detected by the loop is by the fact that a vehicle passing over, or resting in the loop, will unbalance a tuned circuit which is sensed by the amplifier. Therefore there is a change in induction created by the presence of the vehicle. Different types of vehicles produce different induction "signatures" that are used to categorize them. This technology is therefore widely used in real-time traffic control systems and at automatic barriers, to count vehicles. Typical induction signatures are shown below (figure 8-1).

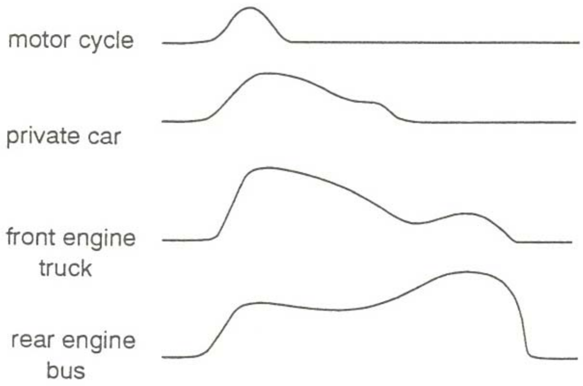


Figure 8-1: Typical induction signatures

Source: (Taylor, Bonsall et al. 2000)

Various patterns can be used when configuring the loops depending on the purpose for which they are going to be used. Typical examples of patterns normally used are parallelograms, diamonds, squares, rectangles, chevrons etc. Due to their very nature, care should b given when calibrating them. This is because the induction could be affected by vehicles in adjacent lanes or by a very wet surface, whenever they are calibrated to be too sensitive. On the other hand, if they too insensitive, they may not be able to detect bicycles or motorcycles. Once they are calibrated, a fixed loop installation can give rise to a stream of high quality data almost indefinitely with no more than infrequent checking and calibration. Although loop detectors serve very useful purposes; threats to them come from road maintenance works. A schematic diagram of an inductive loop detector installation is shown in figure 8-2.

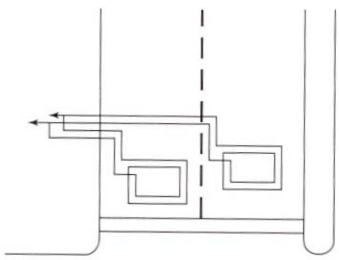


Figure 8-2: A schematic diagram of an inductive loop detector installation

Source: (Papacostas and Prevedouros 2001)

8.1.2. Pneumatic Tube Detectors

The principle of operation of this type of detector is based on the transmission of a pulse of air to an air switch when squashed by the passage of the wheels of vehicles, thereby counting the axles of vehicles. The detector consists of thick-walled rubber tubes mounted on the surface of the road. The vehicles traverse at their individual speeds so in order to avoid the tubes being whipped up by passing vehicles (thus triggering multiple signals each time the tube hits the road), they should be firmly fixed to the road.

The nature of this type of detectors makes it suitable for temporary surveys, especially on low flow roads e.g. a day to one month. Regular checks are required for such detectors to ensure that the tube has not become loosened due to the passage of vehicles. As a result of that they may be replaced after the passage of about 250,000 vehicles on a good road surface or considerably less than that on a poor road surface or in an extreme climate. Weather changes may also have effects on these types of detectors. Typical examples are that exposure to the sun denatures the rubber and high humidity can prevent effective operation.

Apart from these weather conditions, the tubes face the risk of prematurely being damaged by hard run wheels or animal traffic and so may be unsuitable for use in some developing countries. During traffic counts they should be located away from the reach of children who may stamp on them. They should also be located away from regions where vehicles may park on them to prevent the passage of air pulse. Calibration of the air switch is such that it is sensitive enough to detect all vehicles irrespective of their speed but not so sensitive as to pick up bounce signals in the tube. Figure 7-3 shows the cross-section of the pneumatic tube detector.

8.1.3. Switch Tapes/ Contact Strip/ Treadle Switch

This type of detector functions by completing a circuit whenever pressed together by the weight of a vehicle's wheel. It consists of a pair of metal contacts mounted in rubber and stuck to the road surface at right angles to the direction of flow of traffic. Just like other pneumatic tube detectors, their location, installation and maintenance are basically similar. The switch detector was noted for its poor reliability but this has been overcome with an improvement in design and manufacture but still have a shorter life than pneumatic tubes (Replacement is required after about 50,000 vehicles) (Taylor, Bonsall et al. 2000).

8.1.4. Multicore Cables

Muliticore cables have been developed as an alternative to pneumatic tubes and contact strips laid across the road surface (Taylor, Bonsall et al. 2000). The tribo-electric cable which consists of coaxial conductors separated by dielectric material; is the most commonly used. During its operation, a vehicle’s wheel that cross the cable causes the conductive material to rub the surface of the dielectric material thereby, causing a charge to accumulate and be transmitted to a sensor at the side of the road. These cables are normally on the road surface or held in special casing anchored in a slot.

There is also the piezo-electric cable which is also normally mounted on the road surface or held in special casing anchored in a slot just as the tribo-electric cable. It consists of coaxial conductors separated by polarized ceramic powder and are encased in a cable laid across the road surface. In its operation, the wheels of vehicles that cross the cable squash the ceramic powder thereby inducing a charge which is conducted to a sensor at the roadside.

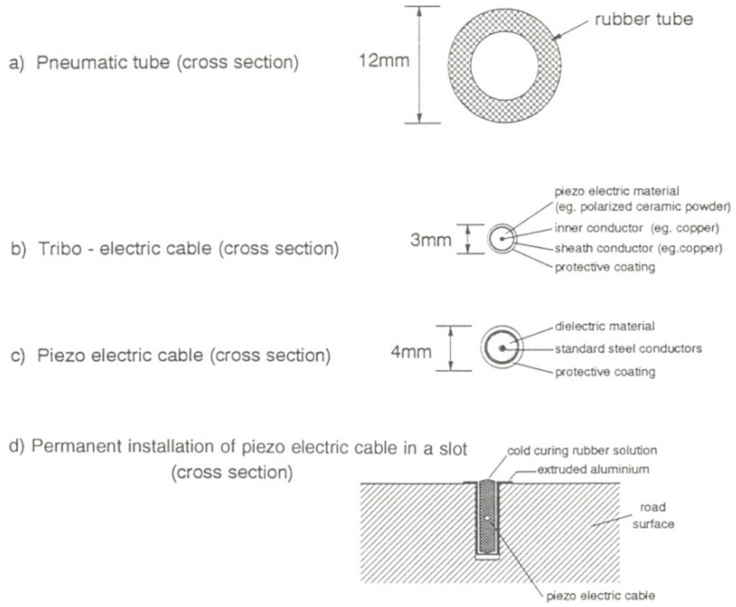


Figure 8-3: Cross-sections of the pneumatic tube, tribo-electric cable, piezo electric cable

Source: (Taylor, Bonsall et al. 2000)

8.1.5. Magnetic Imaging Sensors

The magnetic imaging sensors are quite recent and they work by developing magnetic imaging sensors which can detect interference to the ambient magnetic field caused by large ferrous objects entering a target area of about $2m^2$. It consists of a portable detector that can be fixed to the road surface or even buried permanently in the road. In order to tell if the cable and magnetic sensors should be placed in a groove or placed on the road surface, appropriate factors such as the duration of the traffic count and local conditions will have to be considered. Unlike the permanent fixing approach, the surface mounting is a quick process, cheaper and less disruptive to the traffic it has disadvantage by leaving the sensor exposed to wear and tear from traffic. On the other hand, if conditions like “bad” road surface, heavy traffic or a high amount of severe acceleration/deceleration in the vicinity of the site, a surface mounted detector may need re-fixing at frequent intervals.

After about 30 minutes, when they are fixed they are acclimatized to the magnetic field in the ambient region, they are able to detect any changes to this field, and given an appropriate software, they are able to count vehicles and classify them according to their length and speed. This approach is quite expensive in terms of monitoring flows on multi lane roads since each traffic lane requires a separate device.

8.1.6. Electronic Beams

The use of electromagnetic beams in counting vehicles does not suffer the drawback of disrupting traffic because they are not laid on the carriageway. Their applications are based on the principles of a beam (e.g. photoelectric beam), transmitted across a road being interrupted by the passage of vehicles. The number of times the beam is broken by the passage of vehicles shows the count for the number of vehicles passing. In trying to estimate the speeds and lengths of vehicles, the beams are positioned are specific intervals apart. To be able to classify the different types of vehicles, the beams are positioned at various heights so that larger vehicles break the beams at higher heights etc. The standard installation includes a transmitter/receiver on one side of the road and a reflector on the other. Vertically directed beams pointing down from an overhead gantry and reflected back from a detector on the road surface is used during multilane applications

At variance with this approach is the technique based on use of signals which are reflected back to the transmitter/receiver unit by the vehicles themselves. The presence, position and speed of vehicles can be determined by measuring the changes in the changes in the reflected signal. A moving vehicle will cause a change in the frequency of the transmitted signal and the Doppler Effect can be employed to deduce the speed with which the vehicle is travelling. The most widely used signals are microwave and infrared. Of the two, the microwave is cheaper and more tolerant to variable environmental conditions but the infrared deals more effectively with very slow moving traffic, as might be found in queues. Infrared and microwave have advantages where installation of a surface mounted detector would be difficult (e.g. on a motorway).

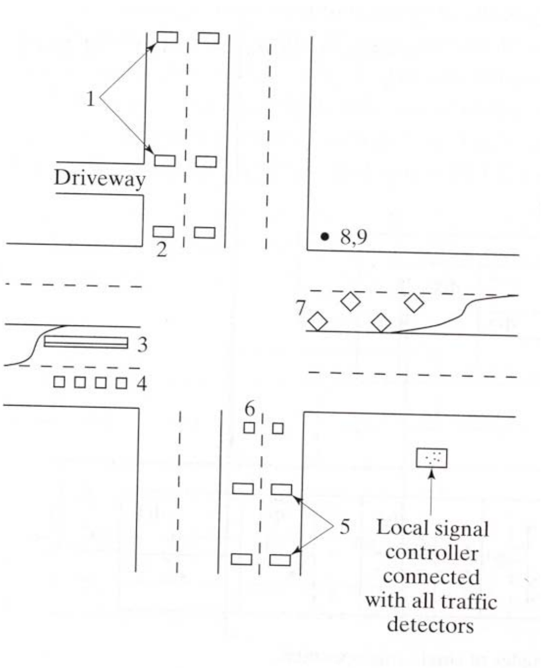
As can be noted, all the methods described above, apart from the electronic beam detectors involve installation of detectors in or on the road surface and this may cause some disruptions to traffic. The other methods that require that the detectors are laid across the carriageway (pneumatic tube detectors, switch tapes/ contact strip/ treadle switch and multicore cables) count the axles of vehicles rather than the vehicles. A conversion factor is therefore applied to get the number of vehicles counted. When installing the tubes, they are also installed perpendicularly to the direction of flow otherwise they will detect two wheels on one axle as if they were separate axles. If this is not done, he counts cannot be used for turning movement analysis. To be able to deduce the direction of flow from the resulting signals, the detectors should be installed in pairs at least 200mm apart, and if the speeds of vehicles and axle spacing are required, they are spaced two to five meters apart.

8.1.7. Functions of Vehicle Detectors

The two most important functions of vehicle detectors are passage detection and presence detection; although vehicle detectors serve several purposes (Papacostas and Prevedouros 2001). The passage detection is accomplished with a small loop that is occupied only briefly by a moving vehicle; and a short-duration pulse is generated to signal the vehicle’s presence. Some characteristics of such passage detectors are:

- High accuracy to be able to detect high speed vehicles
- Great sensitivity in detecting slow moving or stopped vehicles
- High accuracy to enable vehicle classification

Presence detection on the other hand is accomplished through a long loop or series of interconnected short loops, and that the detection zone should be long enough. The figure below shows a typical arrangement of detectors for both passage and presence detection.



Key:

1. Two sets of loops, 18 m apart for 50-55 km/ h speeds
2. Two 6 X 2.4 m loops to detect driveway activity
3. Long loop for presence detection
4. Four 6 X 1.8 m loops over 16 m length for presence detection
5. Two sets of loops 24 m apart for 60km/h speeds
6. Two 6 X 1.8 m loops for pulse operation
7. Diamond loops for presence detection
8. Pedestrian and bike crossing button
9. Pedestrian and bike crossing button

Figure 8-4: A typical arrangement of detectors for both passage and presence detection.

Source:(Papacostas and Prevedouros 2001)

8.2. Apendix 2- Algorithms Written for Data Preparation and Analysis

```
#divides each intensity by 12 to obtain a 5 min intensity for each intersection

import numpy as np
tel = 0
arr_intensity = np.zeros((6507,288))
file = r"D:\Almelo\dataalmelo\5minperlinkTT.txt" # define filename
f = open(file,'r') # open the file listfiles.txt
frow = f.readline()
frow = frow.split()
First_line = ''
n_col = 0
for i in frow:
  if n_col < 291:
    First_line = First_line + i + ","
  n_col+= 1
  First_line.strip(",") #removes final comma
First_line = First_line + "SUM INTENSITY"+ "\n"
header = 0
linklist= []
Fcol = []
for line in f:  # go through lines in file
  if header >= 0:
    hword = line.split() # split word; tab or whitespace separated
    link = (hword[0],hword[1],hword[2])
    Fcol.append(link)
    for i in range(3,291):
      arr_intensity[tel,i-3]=int(hword[i])/12
    linklist.append(np.sum(arr_intensity[tel,0:288]))
    tel+= 1
  header+= 1
f.close()

output_file = r"D:\Almelo\dataalmelo\5minperlinkTT_intensity_div_12.csv" # define filename for
output
f=open(output_file,'w')#open file
f.write(First_line)
n=0
for line in arr_intensity:
  line_string_intensity=""
  if n < len(Fcol):
    line_string_intensity=Fcol[n][0]+","+Fcol[n][1]+","+Fcol[n][2]+","
  for number in line:
    number=str(number)
```

```
        line_string_intensity+=number+","
    if n < len(linklist):
            line_string_intensity=line_string_intensity+str(linklist[n])+"\n"
            f.write(line_string_intensity)
    n+= 1
f.close()

#sums up the first 3intesities in that order to obtain 15 min intensities for each intersection

import numpy as np

arr_intensity_15 = np.zeros((6507,96))
input_file = r"D:\Almelo\dataalmelo\5minperlinkTT_intensity_div_12.csv" # define filename for
output
f=open(input_file,'r')
frow = f.readline()
frow = frow.split(',')
First_line = ''
n_col = 0
for i in frow:
    if n_col < 99:
        First_line = First_line + i + ","
    n_col+= 1

First_line.strip(",") #removes final comma
First_line = First_line + "SUM INTENSITY" + "\n"

header = 0
tel = 0
linklist= []
Fcol = []
for line in f:  # go through lines in file
    if header >= 0:
        hword = line.split(',') # split word; tab or whitespace separated
        link = (hword[0],hword[1],hword[2])

        Fcol.append(link)
        sum_15 = float(hword[3])
        for i in range(4,292):
            if (i-3) % 3 == 1 or (i-3) % 3 == 2:
                sum_15 = sum_15 + float(hword[i])
            else:
                arr_intensity_15[tel,((i-3)/3)-1]=int(sum_15)
                sum_15 = float(hword[i])
        linklist.append(np.sum(arr_intensity_15[tel,0:96]))
```

```
    tel+= 1
    header += 1
f.close()

output_file = r"D:\Almelo\dataalmelo\5minperlinkTT_15min_intensity.csv" # define filename for
output
f=open(output_file,'w')#open file
f.write(First_line)

n=0
for line in arr_intensity_15:
    line_string_intensity_15=""
    if n < len(Fcol):
        line_string_intensity_15=Fcol[n][0]+","+Fcol[n][1]+","+Fcol[n][2]+","
    for number in line:
        number=str(number)
        line_string_intensity_15+=number+","
    if n < len(linklist):
        line_string_intensity_15=line_string_intensity_15+str(linklist[n])+"\n"
    f.write(line_string_intensity_15)
    n+= 1
f.close()


# extracts only the peak 15 min intensities , out of the lot, for each intersection

import numpy as np

peak_intensity = np.zeros((6507,8))
input_file = r"D:\Almelo\dataalmelo\5minperlinkTT_15min_intensity.csv" # define filename for
output
f=open(input_file,'r')
frow = f.readline()
frow = frow.split(',')
First_line = ''
n_col = 0
for i in frow:
    if n_col < 11:
        First_line = First_line + i + ","
    n_col+= 1

First_line.strip(",") #removes final comma
First_line = First_line + "SUM INTENSITY" + "\n"

header = 0
```

```
tel = 0
linklist= []
Fcol = []
for line in f:  # go through lines in file
   if header >= 0:
      hword = line.split(',') # split word; tab or whitespace separated
      link = (hword[0],hword[1],hword[2])

      Fcol.append(link)

       linklist.append(np.sum(peak_intensity[tel,0:31]))
   tel+= 1
   header += 1
f.close()

output_file = r"D:\Almelo\dataalmelo\Peak_15min_intensity.csv" # define filename for output
f=open(output_file,'w')#open file
f.write(First_line)

n=0
for line in peak_intensity:
   line_string_intensity_15=""
   if n < len(Fcol):
      line_string_intensity_15=Fcol[n][0]+","+Fcol[n][1]+","+Fcol[n][2]+","
   for number in line:
      number=str(number)
      line_string_intensity_15+=number+","
   if n < len(linklist):
      line_string_intensity_15=line_string_intensity_15+str(linklist[n])+"\n"
   f.write(line_string_intensity_15)
   n+= 1
f.close()


# extracts only the peak 15 min intensities and finds sum, out of the lot, for each intersection

input = open('D:/Almelo/dataalmelo/5minperlinkTT_15min_intensity.csv', 'rb')
data= input.readlines()
list1=[]
listX=[]
output=open('D:/Almelo/dataalmelo/output.csv', 'w')
for line in data:
   line1=line.split(',')
   list1.append(line1[0:3])
   list1.append(line1[30:39])
```

```
    list1.append(line1[66:75])
    stringL=str(list1)
    stringL=stringL.replace('[','')
    stringL=stringL.replace(']','')
    stringL=stringL.replace("'",'')
    stringL=stringL.replace("'",'')
    output.write(stringL+"\n")
    list1=[]
output.close()
input.close()

output1 = open('D:/Almelo/dataalmelo/output.csv', 'rb')
output2=open('D:/Almelo/dataalmelo/SUMoutput.csv', 'w')
line1=output1.readline()
line1=line1.strip()
line1=line1.split(',')
heading=line1[0:3],line1[3:12],"Morning Peak Sum",line1[12:23],"Evening Peak Sum"
stringZ=str(heading)
stringZ=stringZ.replace('[','')
stringZ=stringZ.replace(']','')
stringZ=stringZ.replace('(','')
stringZ=stringZ.replace(')','')
stringZ=stringZ.replace("'",'')
stringZ=stringZ.replace("'",'')
final=open('D:/Almelo/dataalmelo/SUM_M_E_PEAK.csv', 'w')
final.write(stringZ)

line2=output1.readline()
while line2!="":
    listX=[]
    line2=line2.strip()
    List=line2.split(',')
    XList=(List[3:12])
    YList=(List[12:23])
    num =0
    num1 =0
    for i in XList:
        num+=float(i)
    for n in YList:
        num1+=float(n)
    listX.append(List[0:3])
    listX.append(XList)
    listX.append(num)

    listX.append(YList[0:8])
```

```
    last=str(YList[8])

    last.strip('\r\n')

    listX.append(last)
    listX.append(num1)

    stringX=str(listX)

    stringX=stringX.replace('[','')
    stringX=stringX.replace(']','')
    stringX=stringX.replace("'",'')
    stringX=stringX.replace("'",'')
    line2=output1.readline()
    output2.write("\n"+stringX)
    final.write("\n"+stringX)
output2.close()
final.close()

# selects only individual days throughout the year and sums

input = open('D:/Almelo/dataalmelo/Modified_SUM_M_E_PEAK.csv', 'rb')
head= input.readline()
data= input.readlines()
#listX=[]
output=open('D:/Almelo/dataalmelo/Tuesday.csv', 'w')
output.write(head.strip()+'\n')
for line in data:
    line1=line.split(',')
    line2=line.strip()
    if line1[0] == 'Tuesday':
        output.write(line2+'\n')
output.close()
input.close()

# gets rid of all segments with 0 free flow speeds

inputs = open('speed profile onlycsv.csv', 'r')
head= inputs.readline()
data= inputs.readlines()
#listX=[]
output=open('profile only.csv', 'w')
output.write(head.strip()+'\n')
for line in data:
```

```
    line1=line.strip().split(',')
    line2=line.strip()
    if line1[7] > '0':
        output.write(line2+'\n')
output.close()
inputs.close()
```

8.3. Appendix 3- Speed Profiles (Morning and Evening Peaks)

Table 8-1: Morning and evening peak speed profiles

PROFILE ID	Morning peak			Evening Peak			Average Profile % (Morning)	Average Profile % (Evening)
	7 hrs	8 hrs	9 hrs	16 hrs	17 hrs	18 hrs		
1	100	100	100	100	100	100	100	100
2	85	79	79	81	80	82	81	81
3	60	43	54	90	85	83	52	86
4	96	92	91	93	90	86	93	90
5	98	97	97	95	95	96	97	95
6	91	84	89	98	97	97	88	97
7	95	90	91	58	48	54	92	53
8	88	70	77	96	95	94	78	95
9	98	97	97	87	76	77	97	80
10	94	87	86	90	85	74	89	83
11	94	92	94	95	94	95	93	95
12	83	67	67	65	64	68	72	66
13	90	80	82	90	88	88	84	89
14	81	63	69	64	52	60	71	59
15	81	78	87	95	93	94	82	94
16	94	86	84	83	83	86	88	84
17	65	59	76	96	95	95	67	95
18	91	83	84	76	70	74	86	73
19	98	95	94	93	93	95	96	94
20	95	93	96	99	99	99	95	99
21	79	54	61	94	92	91	65	92
22	80	67	74	88	86	85	74	86
23	91	85	88	87	77	77	88	80
24	89	88	89	91	91	93	89	92
25	89	78	80	83	82	83	82	83
26	88	76	78	49	44	47	81	47
27	97	96	95	96	95	93	96	95
28	67	47	50	52	47	51	55	50
29	88	72	71	78	67	56	77	67
30	93	87	89	93	91	92	90	92
31	96	94	94	72	73	82	95	76
32	91	80	77	72	72	76	83	73
33	83	65	71	84	71	69	73	75
34	94	88	87	85	83	84	90	84
35	98	97	97	96	93	88	97	92
36	80	65	68	77	74	77	71	76
37	96	92	92	88	85	87	93	87
38	95	92	93	78	61	62	93	67
39	62	43	49	75	66	63	51	68
40	96	92	91	91	91	92	93	91
41	94	89	88	88	88	90	90	89
42	90	84	89	96	95	95	88	95
43	96	93	94	73	61	63	94	66
44	75	58	61	52	52	57	65	54
45	97	96	97	89	84	85	97	86
46	92	87	88	87	82	80	89	83
47	76	61	67	77	72	71	68	73
48	87	74	74	70	70	75	78	72
49	93	87	88	66	66	74	89	69
50	100	99	96	65	62	59	98	62
51	99	99	99	94	94	94	99	94
52	99	98	96	91	92	93	98	92
53	100	100	99	96	96	90	100	94
54	100	100	99	89	82	75	100	82
55	99	99	97	91	90	90	98	90
56	99	97	92	85	86	88	96	86
57	98	96	92	88	88	89	95	88
58	100	99	97	81	80	81	99	81
59	99	96	90	76	77	79	95	77