APPLICATION OF REAL-TIME TRAFFIC ADAPTIVE SIGNAL CONTROL ON THE R44 ARTERIAL, STELLENBOSCH

by

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DECLARATION

By submitting this thesis project electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualifications.

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ABSTRACT

The ever increasing level of traffic congestion experienced within and surrounding the town of Stellenbosch, South Africa, has been one of concern for many years. A large volume of commuter traffic creates a major influx of vehicles into and through the town during the morning peak traffic hour and, vice versa, a large outflow during the afternoon peak hour. These extensive traffic volumes exceed the provided capacity, thus creating an imbalance relating to the capacity vs demand ratio. This in turn leads to extended travel times, increased vehicle delay and a general inconvenience to the typical road user.

Considering this and understanding that congestion has a negative effect on the individual road user as well as on the economy in general, this research project investigates the potential feasibility of using a Traffic-Adaptive Signal Control (TASC) system to optimise and manage the flow of vehicles through a series of signalised intersections. Such a system relies on real-time traffic data input and a representative traffic model which simulates and tests several signalisation options and, based on the objective function of the optimisation method, results in a more suitable allocation of green-time shares within the network. This, in essence, *optimises* the flow of traffic on individual intersection level while at the same time *coordinating* the traffic flow on a network level.

The main objective of this research project, therefore, was to evaluate the applicability of a TASC system on the R44 arterial surrounding Stellenbosch in order to address the question of how applicable and effective TASC is in a developing world environment as a means to alleviate transport related problems on a traffic corridor. PTV Epics and Balance, proven to be successful in developed world application, is one such TASC system and was used within this study to address the research question.

In order to realise useful results, a calibrated and validated simulation environment had to be created. Modelling was firstly done within PTV Visum to create an underlying macroscopic model of Stellenbosch in general, after which another PTV Visum subnetwork model of the R44-specific study area was generated. The final model, a PTV Vissim microscopic model, represented the evaluative environment within which detailed results could be obtained for a number of different scenarios. These scenarios where firstly aimed at identifying whether the TASC system would bring any improvements at all and secondly under which level of TASC control, inclusive of different vehicle detection options, the best results were obtained. Different levels of TASC control refer to exclusive local optimisation, exclusive global coordination or a combination of both. Detection options included a suboptimal layout of the existing inductive loop detectors as well as more consistent TrafiCam x-stream virtual loop detectors.

Results comparison over a range of traffic flow parameters showed that the TASC system did indeed enhance the traffic flow. This was most notably found to be true under condition of the consistent camera detection and, predominantly, by using combined local and global TASC control. Based on the findings, this study recommends, with further study and continued expansion, the implementation of the TASC system on the R44 arterial, Stellenbosch.

OPSOMMING

Die steeds toenemende vlak van verkeersopeenhopings wat binne die omgewing van Stellenbosch, Suid-Afrika ervaar word, was vir baie jare 'n bron van kommer. 'N Groot hoeveelheid pendelverkeer veroorsaak 'n groot toestroming van voertuie na en deur die stad gedurende die oggend spitsverkeeruur, en omgekeerd, 'n groot uitvloei gedurende die middagspitsuur. Hierdie aansienlike groot verkeersvolumes oorskry die voorsiende kapasiteit, en dit skep 'n wanbalans met betrekking tot die verhouding tussen kapasiteit en vraag. Dit lei dus weer tot verlengde reistye, verhoogde voertuigvertraging en 'n algemene ongemak vir die tipiese padgebruiker.

As ons dit in ag neem en begryp dat opeenhoping 'n negatiewe uitwerking op die individuele padgebruiker sowel as op die ekonomie in die algemeen het, ondersoek hierdie navorsingsprojek die moontlike uitvoerbaarheid van die gebruik van 'n Traffic Adaptive Signal Control (TASC) -stelsel om die vloei van voertuie te optimaliseer en te bestuur deur 'n reeks gesignaliseerde kruisings. So 'n stelsel is afhanklik van intydse verkeersdata en 'n verteenwoordigende verkeersmodel wat verskeie signaliseringsopsies simuleer en toets. Op grond van die objektiewe funksie van die optimeringsmetode lei dit dan tot 'n meer geskikte toewysing van groentydse verdeling binne die netwerk. Dit *optimaliseer* in wese die verkeersvloei op individuele kruispuntvlak, terwyl dit terselfdertyd die verkeersvloei op 'n netwerkvlak *koördineer*.

Die hoofdoel van hierdie navorsingsprojek was dus om die toepaslikheid van 'n TASC-stelsel op die R44-arterie rondom Stellenbosch te evalueer ten einde die vraag te bespreek hoe toepaslik en effektief TASC in 'n ontwikkelende wêreldomgewing is as 'n manier om vervoerverwante probleme te verlig. PTV Epics en Balance, wat suksesvol bewys is in die ontwikkelde wêreldtoepassing, is een van hierdie TASC-stelsels en is binne hierdie studie gebruik om die navorsingsvraag aan te spreek.

Om nuttige resultate te realiseer, moes 'n gekalibreerde en gevalideerde simulasieomgewing geskep word. Eerstens is modellering binne PTV Visum gedoen om 'n onderliggende makroskopiese model van Stellenbosch in die algemeen te skep, waarna 'n ander PTV Visum-subnetwerkmodel van die R44-spesifieke studiegebied gegenereer is. Die finale model, 'n PTV Vissim-mikroskopiese model, verteenwoordig die evalueringsomgewing waarbinne gedetailleerde resultate vir 'n aantal verskillende scenario's verkry kon word. Hierdie scenario's was eerstens daarop gemik om te identifiseer of die TASC-stelsel enigsins verbeterings sou meebring en tweedens, onder watter vlak van TASC-beheer, met inbegrip van verskillende detektor opsies vir voertuie, die beste resultate behaal is. Verskillende vlakke van TASC-beheer verwys na eksklusiewe plaaslike optimalisering, eksklusiewe globale koördinasie of 'n kombinasie van beide. Detektor opsies het 'n suboptimale uitleg van die bestaande

induktiewe lusverklikkers ingesluit, sowel as meer konsekwente TrafiCam x-stream virtuele lusverklikkers.

Resultatevergelyking oor 'n reeks verkeersvloeiparameters het getoon dat die TASC-stelsel wel die verkeersvloei verbeter het. Dit blyk veral dat dit waar is onder die voorwaarde van die konstante opsporing van die TrafiCam x-stream kameras en veral deur gekombineerde plaaslike en globale TASC-beheer. Op grond van die bevindings, beveel hierdie studie, met verdere studie en voortgesette uitbreiding, die implementering van die TASC-stelsel op die R44-arterie, Stellenbosch aan.

ACKNOWLEDGEMENTS

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List of Acronyms and Abbreviations

.anm	Network data file
.anmroutes	Demand data file
.sig	Signalisation data file
ANM	Abstract network model
ASL	Advisory speed limits
CBD	Central Business District
CMF	Crash modification factor
CR	Commercial residential zone
CV	Connected vehicles
DHV	Demand hourly volume
DUE	Dynamic user equilibrium assignment method
E	Education zone
FCD	Floating car data
FTP	Fixed-time signalling plan
GPRS	General packet radio service
GUI	Graphical user interface
HBE	Home-based education trips
HBO	Home-based other trips
HBW	Home-based work trips
HC	Hill-climbing algorithm
HGV	Heavy goods vehicles
I	Industrial zone
ICA	Intersection capacity analysis assignment method
ITS	Intelligent transportation systems
KPI	Key performance indicator
LB	Local business zone
LFR	Less formal residential zone
LOS	Level of service
MB	Mid-block location
MR	Multi-unit residential zone
MU	Mixed use zone
NMT	Non-motorised transport

NVP	Network vehicle performance
NVTS	Nick Venter traffic surveying
O/D	Origin/destination
OSM	OpenStreetMap
PHF	Peak hour factor
PI	Performance index
PT	Public Transport
Rd	Road
Sat	Saturation flow rate
SC	Signal controller
SCATS	Sydney coordinated adaptive traffic system
SCOOT	Split, cycle and offset optimisation technique
SL	Stop-line location
SSML	Stellenbosch Smart Mobility Lab
St	Street
TASC	Traffic-Adaptive Signal Control
TAZ	Traffic analysis zone
TRH	Technical Recommendations for Highways
UCT	Urban traffic control
US	Upstream location
V2I	Vehicle-to-infrastructure communication
V2V	Vehicle-to-vehicle communication
V2X	Vehicle-to-other communication
VA	Vehicle actuated
VisVAP	Visual vehicle actuated programming

Chapter 1

INTRODUCTION

This chapter aims at introducing the underlying reasons for conducting this research study. The main focus of this chapter is to analyse where the need for this project arose, as well as to define further steps in obtaining a feasible solution to this need. The specific issues faced in the world currently, as related to the ever increasing number of vehicles on already oversaturated transport networks, are discussed and specific focus and attention is given to Stellenbosch as the testbed for this research investigation.

1.1 Problem statement

An effective and efficient, as well as economically and environmentally viable transport network is a key component in order for a town to develop its full potential (Sinclair, Bester and Van Dyk, 2012). Such a community is defined by sustainable interaction between the social, economic and environmental aspects of a vibrant, growing urban environment.

There is a heavy dampening effect on the functioning town when the transport network is not in a state of ideal performance. The underlying factor which causes such a lack of performance is the simple fact that the demand of vehicles on a certain segment of that transport network exceeds the capacity which it can provide, thus negatively affecting the road user. This is a major problem which rapidly developing towns are experiencing all around the world. The focus, therefore, is on oversaturated urban transport networks and understanding the pressure which is placed on this infrastructure, such that feasible solutions can be found.

There are a number of reasons why an unbalanced demand vs capacity comparison is often experienced. The main, and probably most obvious, reason is an ever increasing world population. The current world population is estimated at about 7.7 billion people (*World Population Clock*, 2018). The majority of this population live in urban centres, which in turn require a robust and capable transport network to handle the increase in traffic volume which inevitably accompanies an increase in population. The degree to which an increase in the number of vehicles on the road is related to an increase in population varies across the globe. Typically a higher relation is experienced in areas where there is higher private vehicle dependence. The relation of population density and economic growth to vehicle ownership also greatly impacts the total number of vehicles on the road (Dargay, Gately and Sommer, 2007). Considering the developing world, an often experienced lack of resources, as well as a lack of expertise in how to deal with increasing traffic, results in a problem not easily addressed in a developing world context.

It is often seen that available road reserve, or space available for road infrastructure expansion, is fully utilised when considering the urban environment. The option of increasing capacity of a segment in a transport network by adding lanes is therefore often not possible. Such a dilemma is often relatable to poor planning and foresight many years ago when the possibility of current high traffic volumes was not considered. In the case of a developing country, the road reserve might actually be available, but the funds to add the required infrastructure are often not. It might also not be economically viable to add the extra infrastructure. The consideration of latent or induced demand in the system is also one of importance. This refers to the demand which would like to make use of a specific road section during a specific time of day, yet does not do so due to sheer lack of capacity. As soon as the additional capacity is provided, via for example an additional lane, the same congestion levels, or even an increase, are experienced due to a higher actual demand than could be observed before the implementation (Henk, 1989; Cervero, 2002). Another solution to the problem, or sufficient additional capacity, needs to be found.

Another reason why there might be a sub ideal demand vs capacity relation on a transport network is that the resources which are present are not utilised and managed properly. If, for example, the traffic signal system is not updated, coordinated or adapted to changing traffic volumes, then the efficiency of the whole system is affected, having a negative effect on its capacity.

A number of direct negative impacts associated with a lack of capacity include congestion, increased travel time and increased vehicular emissions. In general, the cost of traveling experiences an increase and therefore a negative impact on the economy is also applicable. According to Glaeser (2011) traffic congestion, as a resultant problem of densification, negatively impacts the ability of city residents to connect with other people and thus also reduces quality of life. It is these resultant impacts, visible and obvious to the road user, that need to be counteracted in order to ensure a sustainable and liveable environment. If these impacts are not treated as indicators of the problem at hand, but rather are ignored and disregarded, then the future resulting problems might be far more severe and more difficult to counteract than the current situation.

The problem, therefore, is very simply that the demand on certain segments of a transport network exceeds the available capacity, leading to a number of undesirable consequences. The manner in which these affect the road user and how they can be counteracted is a challenge experienced all across the world.

1.2 Problems specific to South Africa and Stellenbosch

It becomes evident, when looking at this issue of demand vs capacity in a South African context, that there are huge challenges faced here. According to the TomTom traffic index, measuring congestion levels worldwide, Cape Town is the most congested city in South Africa with a congestion level of 35%. This is followed by Johannesburg with a congestion level of 30% (*TomTom Traffic Index*, 2018). This translates into 35% and 30% extra daily travel time respectively. This is an average value, with AM and PM peak values lying in a much higher range. So the problem is very much also one of adverse effects, such as congestion, resultant from an overloaded or inefficient transport network.

A major problem in South Africa is the lack of adequate formal public transport (PT). There have been many improvements in this area over the past years, yet the reliability and safety of the (predominantly informal) PT systems actually in place is often times questionable. There are a number of other factors which not only reduce the capacity of a road network, but also have an adverse effect on road safety. These include poor road infrastructure and maintenance, as well as a lack of non-motorised transport incorporation and limited traffic law enforcement (Sinclair, Bester and Van Dyk, 2012).

Another key contributor to congested roads in South Africa is the increasing rate of private vehicle registrations. This is naturally resultant from an increase in population, but also stems from the fact that owning a private vehicle is often seen as a status symbol. This means that a person will often purchase a vehicle as soon as he/she is economically able to do so (Moosajee, 2009). This trend has a very negative effect due to the obvious increase in traffic volumes, which in turn increases congestion. Providing adequate formal public transport would be one of the means to discourage this behaviour.

These issues have to be dealt with all across South Africa, to a varying degree of intensity. Stellenbosch, specifically, is a town faced with severe transport problems compared to other town of the same size. A number of reasons for this can be identified. Firstly, Stellenbosch is a University town with a growing student population of 31 765 students in 2018 (Stellenbosch University, 2018). This causes a large influx of vehicles into Stellenbosch with a significant portion of the students residing privately and commuting to town. Stellenbosch is also a sought-after tourist destination. With its many historical features in the city centre, as well as surrounding winelands and nature reserves, it is an ideal destination for tourists. With this comes an increase in heavier vehicles in the central business district (CBD), such as buses. Stellenbosch also attracts businesses and has a busy CBD and business park, Techno Park, attracting large numbers of vehicles.

The R44 arterial road through Stellenbosch is heavily affected by this ever increasing number of vehicles. It is the only arterial route through Stellenbosch, connecting with other arterials to several surrounding towns and communities. Figure 1-1 shows the R44 winding around the western side of main Stellenbosch. The most affected zone on the R44 is indicated in red.

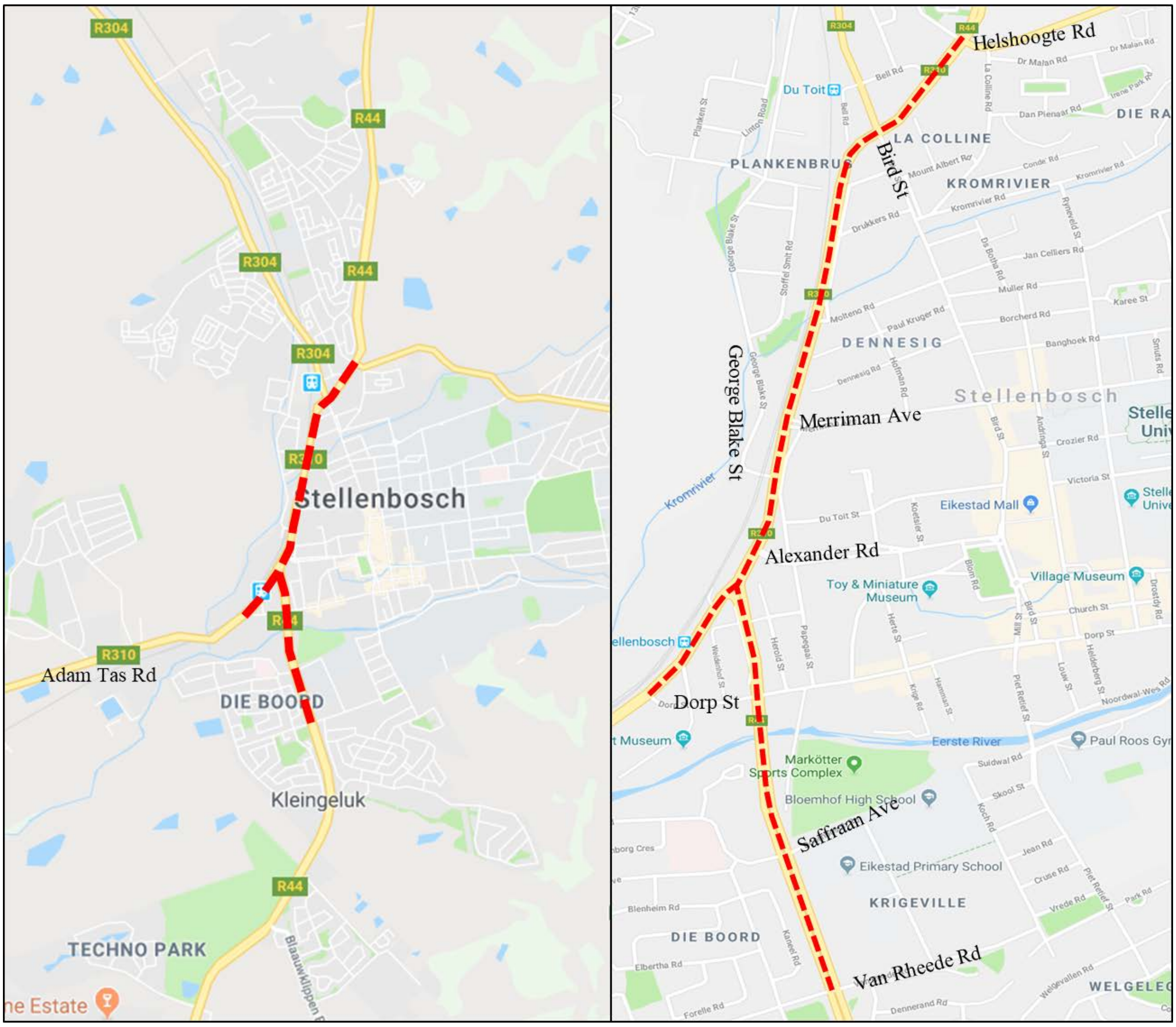

Figure 1-1: R44 arterial through Stellenbosch – specific study area indicated in red (www.google.co.za)

The R44 carries a lot of commuter traffic from the surrounding areas into Stellenbosch, mostly home-based-work (HBW) and home-based-education (HBE) trips. This high percentage of commuters is obviously aggravated by the lack of adequate PT. Not only is the R44 used as a means to get into Stellenbosch, but rather it also acts as a through route for a large number of vehicles into the surrounding towns. Typical desire lines are shown in Figure 1-2. Worsening this even more is the fact that a portion of heavy vehicles makes use of this route in order to avoid the weigh bridges on the N1 and N2 freeways (Sinclair, Bester and Van Dyk, 2012).

There is, therefore, a very high concentration of vehicular traffic on the R44 in Stellenbosch. A factor worsening the traffic problems on the arterial is that there are a number of access points within this most affected stretch of the R44. This obviously brings disruption to the traffic flow and has to be controlled by signalised intersections. The problem currently experienced with the signal plans is that they operate inefficiently, with a lot of room for improvement to reach optimal control of the intersections.

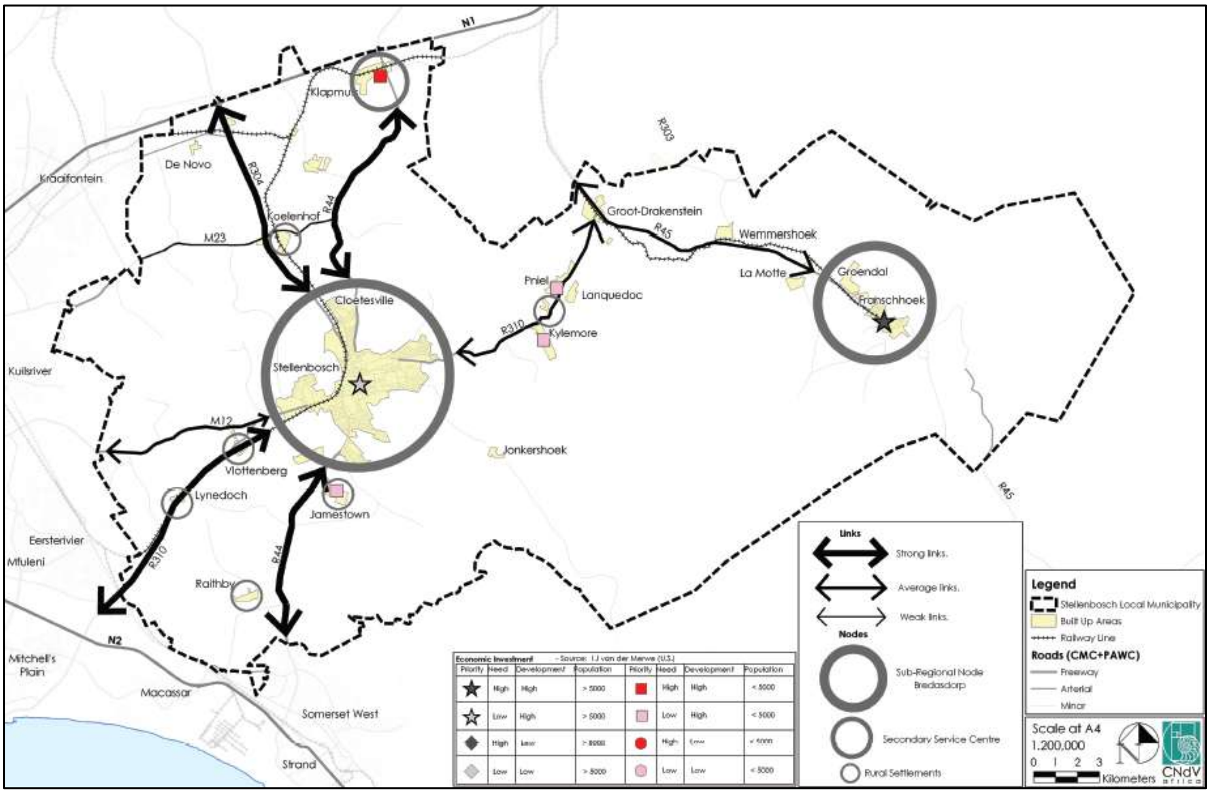

Figure 1-2: Stellenbosch desire line visualisation (Stellenbosch Municipality, 2012)

Considering, therefore, the high demand placed on the transport network of Stellenbosch, it is most obvious that something should be done before the situations worsens to such an extent that a future solution would be far more difficult to implement than what is currently possible. The R44 close to Stellenbosch is identified as a major bottleneck of the congestion problem and if the traffic conditions can be improved here, a positive effect would most definitely be visible in the greater picture of Stellenbosch.

1.3 Possible solutions

Having identified Stellenbosch, and in specific the R44 arterial corridor through Stellenbosch, as a major congestion zone, the next step is to address these problems and analyse specific solutions. A number of options are available in order to facilitate the alleviation of pressure on the transport network. Each will be briefly mentioned and ultimately one, or a combination of solution options, will be chosen to research in more detail.

Several main categories of solutions were identified to address the issue either directly or indirectly. These include the physical altering or addition of infrastructure to the road environment, changing business work schedules, improvement to the traffic flow management system and including heavy freight into said system more efficiently (Sinclair, Bester and Van Dyk, 2012).

When purely considering the addition of road infrastructure, the additional lane capacity can reduce congestion. It has, however, been found that this does not necessarily always bring about the desired positive change that is expected. This has been identified by Næss *et al.* (2014) in previous research relating to the concept of *induced traffic* and the *predict and provide* paradigm. Applying the concept of flexi-time work schedules to affected businesses could potentially spread the HBW traffic out over a longer time period, thus reducing congestion. School and university traffic would however not be affected by this. The more efficient regulation of HGV's and smaller freight vehicles as part of reducing congestion problems is potentially important to consider in an optimised transport network. Including heavy freight more effectively, or even restricting their movement during peak periods, could reduce congestion.

Improvement to the traffic flow management system in an urban environment such as Stellenbosch seems like the ideal place to start when wanting to improve traffic capacity. Actions such as traffic signal coordination and optimisation, turning movement control and specific access control to the main transport corridor can be considered. Continuously updated and coordinated signal plans would fall within this category. Another way to do this would be to implement what is known as Traffic-Adaptive Signal Control (TASC). This makes use of real-time traffic flow data to optimise and coordinate the signal plans by adapting the signal timing parameters to this data such that specific parameters are optimised according to predetermined objectives (Aslani, Mesgari and Wiering, 2017). The efficiency of such systems has especially been proven on major corridors where groups of signalised intersections can be coordinated (Pascale, Lam Hoang and Nair, 2015).

Additionally to the aforementioned solution options, the successful improvement of the public transport (PT) sector could reduce congestion drastically. Combined with this, especially in a place like Stellenbosch, should then be the more effective incorporation of the non-motorised transport sector (NMT). Other options, such as congestion charging, are also available, yet are very specific in their application approach.

Considering, then, the aforementioned solutions and their respective implications, as briefly discussed on a very broad and general basis, the focus of this research will be on making use of improved traffic flow management to address the transport issues on the R44 arterial, Stellenbosch. This would seem like the most obvious and first solution approach that should be followed. The specific solution approach will be addressing the traffic signal phasing and the improvement that can be brought about by implementing Traffic-Adaptive Signal Control (TASC). Various different TASC systems exist which could be utilised to achieve this and the process of defining the optimal system is presented later.

1.4 Research objectives

The main aim of this research is to evaluate the applicability of a TASC system on the R44 arterial through Stellenbosch in order to address the question of how applicable and effective TASC is in a developing world environment as a means to alleviate transport related problems on a traffic corridor.

Individual objectives are numbered for easier reference later in the document.

1) Individual TASC systems will be compared in order to gain an appropriate understanding of their differences and so that the most applicable to this environment can be evaluated in more detail as part of the literature study.

2) The specific environment of the R44 poses several challenges and an objective therefore is to evaluate the extent of how this affects the TASC system. Challenges include the merging of two arterials, the R310 and the R44 as part of a major affected intersection, as well as to understand the effect of incorporating an un-signalised, as well as a train actuated intersection into the system.

3) Seeing that TASC systems have not been extensively implemented in a developing country environment, this project focuses on how such implementation would compare to that of a developed country. In specific, the variation of traffic data availability, compared to a developed world, is of importance.

4) The different data sources will have to be evaluated in order to identify which is the most readily available and most accurate or which data sources can potentially be combined for maximum efficiency. The specific availability of floating car data (FCD) is taken into consideration as being a relatively untested addition to TASC regulation.

5) It is of utmost importance that the most accurate representation of reality is presented in the applicable simulation models which will have to be generated in order to test the TASC system extensively before the actual real-life implementation can be done. A specific objective, therefore, is to build an accurate simulation environment.

6) The evaluation, and ultimately the feasibility, of the TASC implementation will be based on traffic flow indicators such as queue length, delay time, average speed and travel time, compared before and after implementation using a number of different scenarios. This will then be utilised as a means to make applicable conclusions and recommendations.

1.5 Report contents

A short summary of all further report chapters as well as their contents is provided below.

- **Literature review:** The literature review is aimed at gaining an understanding into the concept of TASC as well as what is required to facilitate the proper functioning of such a system. A comparison between several different TASC systems is also provided, based upon which the further modelling and research is based.
- **Research methodology:** The research methodology lays out the various components within an appropriate research design. Specific research propositions regarding the possible outcomes of the study are also provided after which all envisioned data collection and processing as well as software analysis and results evaluation steps are presented.
- **Model components and information:** This chapter provides an insight into all the data components and model information utilised within the various modelling environments during this study. Reference is made to the sources and how the data was processed such that the use of this traffic data can be justified in leading to realistic simulation results.
- **Scenario development:** The scenario development chapter lays out all the different comparison scenarios with the help of which the TASC system will be analysed. Each scenario is briefly explained with reference to their signalisation, detection, analysis periods and levels of TASC control.
- **Software model development:** This chapter provides reasonably detailed description and discussion regarding the manner in which all the relevant software models were set up, calibrated and validated in order to ensure the highest achievable level of accuracy.
- **Results analysis:** The results analysis details all the evaluation criteria and lays out the results according to the different methods of comparison. Network performance, nodal and turning movement performance as well as travel time measurements are taken into account.
- **Conclusions and recommendations:** The final chapter of this report summarises the report contents as well as revisits the initial report objectives. Correspondingly, appropriate conclusions are drawn and recommendation are made. Lastly, future research ideas and topics are mentioned.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The aim of this literature review is to gain in-depth understanding into the concept of Traffic-Adaptive Signal Control (TASC) as a control mechanism to alleviate the traffic related problems in Stellenbosch. As part of this, an underlying understanding of signalised intersection control in general is first presented. Thereafter a detailed description of what TASC is and how it functions, with all of its advantages and disadvantages, will be provided. The manner in which TASC is utilised internationally, originating in a developed world context, and the current technological developments surrounding this concept, are also discussed. Furthermore, the applicability and feasibility of TASC to the Southern African context will be evaluated, identifying and discussing a specific control system to best suit this environment. Finally, a basic understanding of travel demand modelling is presented as an essential part of model-based TASC control.

2.2 Understanding signalised intersection control

Before the further evaluation and discussion of TASC can commence, an understanding into signalised intersection control needs to be established. TASC builds on the foundations of conventional methods of signalisation, yet provides a fresh approach to dealing with pertinent issues in the traffic regulation environment. Traffic signalisation, therefore, has to be understood in order to grasp the concept of TASC.

2.2.1 Origin of traffic signals

Signalisation had its beginnings in the railway industry as early as 1868 in London when a gas lamp was used to control the conflicting traffic streams at an intersection (Pašagić and Ščukanac, 1998). The first occurrence of a more modern type of electric signal was developed in Cleveland in 1914. A type of traffic signal relating very much to what is in use today was first installed in 1917 in Detroit, based on the designs and recommendations by William Phelps Fnou, an American accredited with being the first to address signal control from a scientific approach (Pašagić and Ščukanac, 1998).

As the demand for proper control of vehicular traffic increased with an increase in vehicles, the idea of the signalisation control measure was developed and furthered. Over the years a number of alterations and improvements have been made to this control type, especially as technological development progressed and computing power increased.

2.2.2 Traffic signalisation concepts

The basic concept of intersection control is to assign the right of way to different traffic streams in order to ensure a safe and orderly interaction between conflicting road users. Signalised intersection control facilitates this process by making use of displayed green, yellow and red lights to give sequential instructions as to who has right of way. Traffic signals are not necessarily the best solution when it comes to managing and controlling the traffic at an intersection, yet they do have many advantages and can increase safety as well as reduce delay if used under the appropriate circumstances (COTO, 2012). There are certain warrants that need to be fulfilled in order for signalisation to be considered at an intersection. These include several queue length factors as described in the South African Road Traffic Signs Manual (COTO, 2012), as well as a number of other factors such as peak hour traffic volume considerations, presence of school crossings, possibility of coordinated signal systems and crash experiences at the site (Transportation Research Board, 2010; Garber and Hoel, 2015).

2.2.2.1 Terminology

A number of terms are important to understand when wanting to follow signalisation logic. Some of the most important terms with definitions are listed below (Garber and Hoel, 2015; PTV Group, 2017b):

Controller: This is the device on-site which houses the necessary software and hardware to adjust the signal phasing.

Cycle: One cycle covers the entire signal control sequence from green start to green start for a phase or stage of an intersection. It has a specific duration in seconds.

Phase (Signal group): A phase comprises one or more traffic streams that are allowed right-of-way during the same time interval of a cycle. Figure 2-1 shows the typical cycle layout of a two phase traffic control plan.

Stage: A stage is a combination of phases/ signal groups that have allowed movement at the same time in the case of stage-based signal control. In other words, the green time start and end of all signal groups in that stage correspond to that of the stage.

Using signal groups and stages is another way of signal control compared to phases and split phases. Further discussion in this report will be based on the Signal Group/Stage combination rather than the Phase/Split Phase combination. There has been significant confusion regarding the use of terminology in the traffic engineering environment, specifically considering interchangeable use of the terms phase, signal group and stage. The definitions as given above are used in this report.

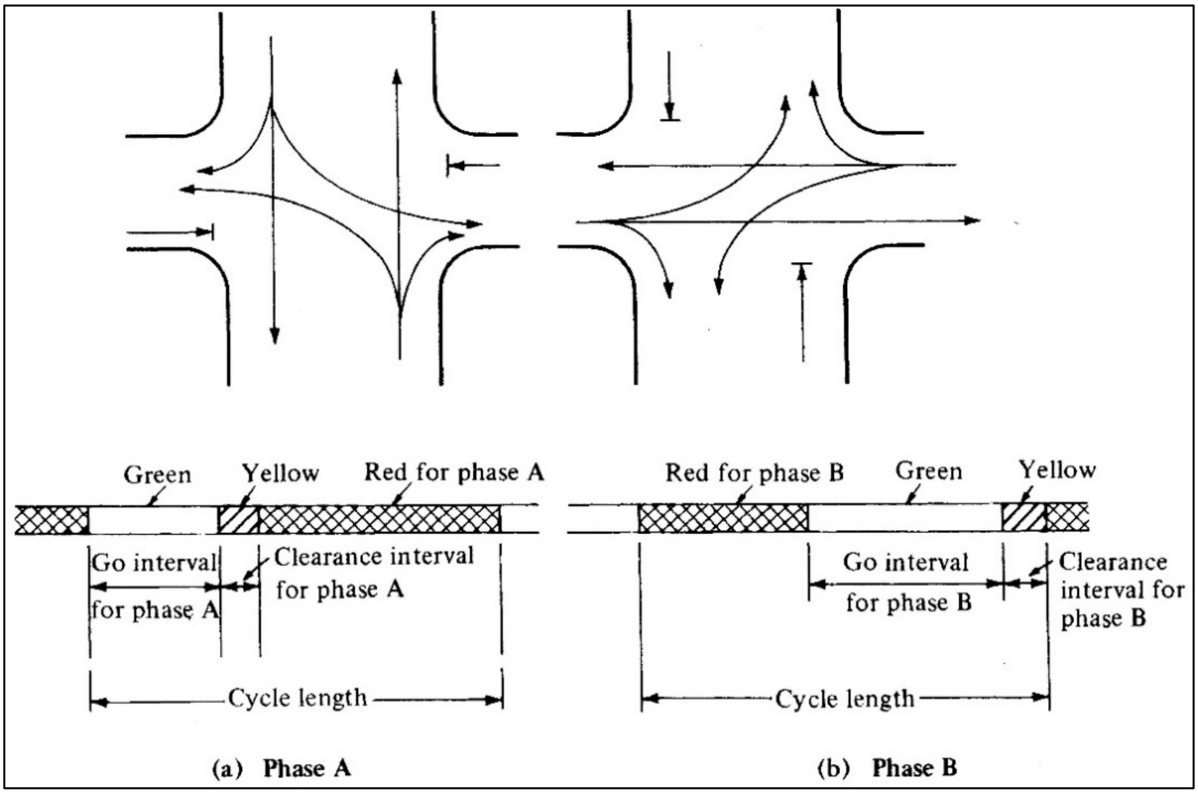

Figure 2-1: Two phase traffic control (Garber and Hoel, 2015)

Group-based control: This control method is linked to the definition and use of signal groups/phases only. If the intersection is relatively simple and phases are sufficient then this would be used.

Stage-based control: Stage based control is used when stages have been defined as a combination of signal groups. This type of control is more useful when the intersection movement options become more complex and different components of traffic streams have right of way at different times of the cycle.

Interval: The time period during which no change in signal indication occurs.

Change interval/ Intergreen: This is the total duration of the **yellow change interval** and the **red clearance interval** (All Red) and is a safety critical value with specified minimum durations.

Improper use of the yellow change interval can lead to what is known as a dilemma zone at an intersection. This is when the provided yellow time interval is not sufficient enough for the vehicle to safely stop or to pass the intersection safely without having to accelerate. This phenomena is seen in Figure 2-2.

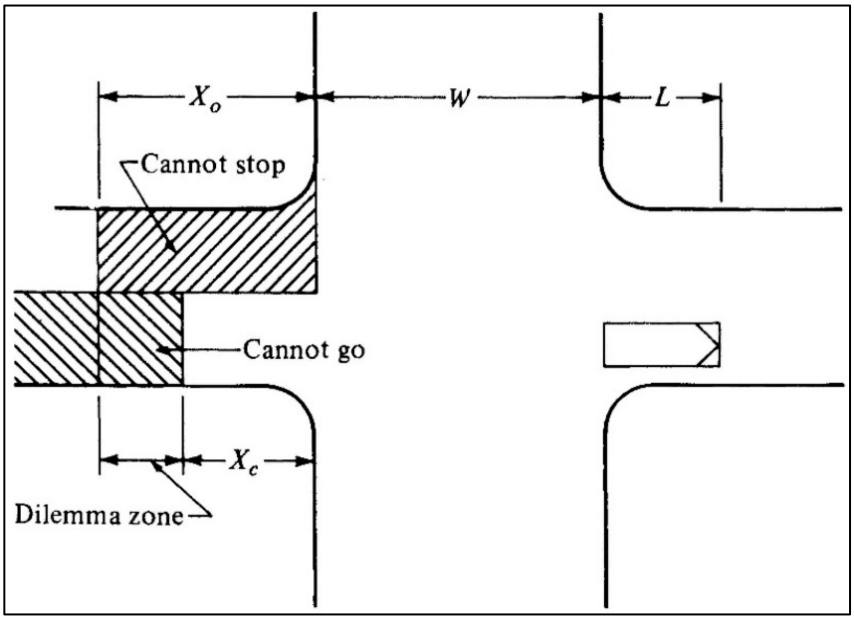

Figure 2-2: Dilemma zone at an intersection (Garber and Hoel, 2015)

The calculation of the yellow change interval is usually done separately to the actual signal control method calculation according to Equation 2-1 presented below. This is because this value is a minimum value that may not be violated such that the formation of a dilemma zone is prevented.

$$Y_{min} = \delta + \frac{W + L}{u_0} + \frac{u_0}{2(a + Gg)} \qquad \text{Equation 2-1}$$

With: W = width of intersection (m)

L = length of vehicle (m)

u_0 = vehicle speed (m/s)

δ = perception–reaction time (s)

a = constant deceleration (m/s^2)

Interstage: An interstage is the duration during which all signal state changes take place, if using stage based control, and corresponds to the change interval/Intergreen period except if a minimum green time enforcement is applied, which in turn extends the interstage to the end of the min. green of the next stage.

Peak hour factor (*PHF*): The peak hour factor is a measure of varying demand within the peak traffic hour and is calculated as seen in Equation 2-2. This factor can then be used in calculation of the demand hourly volume (DHV) as seen in Equation 2-3.

$$PHF = \frac{Volume\ during\ peak\ hour}{4 \times volume\ during\ peak\ 15\,\text{min}\ within\ peak\ hour} \qquad \text{Equation 2-2}$$

$$DHV = \frac{Peak\ hour\ volume}{PHF} \qquad \text{Equation 2-3}$$

Level of service (*LOS*): The LOS is a measure of quality as experienced by the road user when making use of, in this case, the signalised intersection. It typically ranges from **A** to **F** with **A** being the best and **F** the worst.

Adjusted saturation flow rate (*Sat*): The adjusted saturation flow rate is obtained by taking the base saturation flow rate (typically taken as 1800 *veh/h*) and adjusting this by taking into account several factors which influence the flow rate such as number of lanes, lane width, percent of heavy vehicles as well as grade percentage.

The aforementioned definitions are merely a collection of basic terms used in the signal control procedure. For a more detailed and in-depth description of terminology the reader is referred to the South African Road Traffic Sign Manual (COTO, 2012), the Traffic and Highway Engineering handbook (Garber and Hoel, 2015) as well as the Highway Capacity Manual (Transportation Research Board, 2010).

Different methods of operation have been defined when it comes to traffic signals. The most prominent and originally developed method is the *Fixed-Time control* method. Another option is the *Vehicle Actuated (VA)* control method which came into being as detection technology advanced. Lastly, the use of *Traffic-Adaptive Control* systems has become more prominent in recent years, with further technological advancement being the driving force behind this. Each of these methods are discussed in more detail in the following sections.

2.2.2.2 Fixed-time signal control

This method makes use of a preprogramed signal plan to regulate the traffic and is most effective when the vehicular flow is predictable and in under-saturated conditions. The *Traffic and Highway Engineering* handbook by Garber and Hoel presents two methods for basic setup calculation for a fixed-time control alternative (Garber and Hoel, 2015). The method by Webster and the Highway Capacity Manual method are described.

Webster obtains the optimum cycle length (C_0) for a signal program by means of total lost time per cycle (L) as well as the consideration of approach flow to saturation flow ratios for approaching lane groups (Y_i). The main aim here is to minimise delay. Lost time takes into account the all-red and yellow change interval times. From this, further, the green time shares per signal group or stage are calculated, also considering pedestrian movements, to present a complete pre-timed signal plan.

The HCM method uses a similar approach to Webster but rather makes use of the capacity (c_i), and thus the corresponding degree of saturation (X_i), to determine the optimal cycle length. Green time shares (g_i) are then also calculated appropriately using, inter alia, the cycle length (C), lost time (L) and volume-to-capacity ratios (X_i).

Treatment of right-turners at a signalised intersection can either be permitted, protected or a combination of both. This means that the turning vehicles are either only allowed as part of a main signal group and have to find gaps within the traffic stream to make the turn, or they are given a separate signal group where they are protected from conflict with other vehicles to make the turn safely. A combination of both would mean that the one is followed by the other, i.e. the protected phase can either be leading or lagging to the main phase.

Advantages to the fixed-time method is that it can be set up with relative ease and is very effective in periods with high traffic volumes. Regular updating, however, is required in order to ensure the efficient operation of the signal control. Fixed-time plans should also not be simply set up for one cycle in the peak traffic hour, but vary during the day to match specific time-of-day demands. If this is not done, a plan could be perfectly set up for a specific time of day but function sub-optimally during the rest of the day.

2.2.2.3 Vehicle actuated signal control

Vehicle-actuated (VA) control is where the signal controller has the ability to respond to the presence of road users at an intersection with the help of a detection system, thus allowing more flexibility when it comes to catering for current demand as part of the signal plan (Garber and Hoel, 2015).

The basic idea is to setup a “fixed-time” plan for the intersection with minimum and maximum phase or stage durations and then allow the flexibility within the signal plan to alter the specific phase durations to better match fluctuating demand. Cycle length is, therefore, adjustable and has to be limited properly to prevent an overly long duration. The specific limits for other factors of the VA control also need to be calculated properly in order to ensure adequate phase durations, even under minimum value conditions.

VA control can either be semi-actuated or fully actuated. Semi actuation refers to a scenario where vehicle detection only occurs on the minor approaches with major through flow thus having precedence unless minor flow detection occurs. Full actuation describes vehicle detection on all approaches to the intersection. This is usually done at intersections with large volume fluctuations on all approaches. Both methods can potentially have a great positive impact on traffic regulation.

VA control naturally, is a more expensive control procedure than fixed time control, yet it also has a number of advantages. A major disadvantage is the reliance this method has on accurate detection. If detection fails and no fall-back signal plan is established, major delays could occur.

2.2.2.4 Coordination

When a number of signalised intersections, in an urban environment, are found within a distance of not more than 1.2 km apart, then the concept of coordinating them becomes an option (Garber and

Hoel, 2015). Coordination is usually most suited to arterial routes. The idea is to create a "green wave" for a platoon of vehicles through the intersections. This would mean that travel time is reduced and general throughput of vehicles can be greatly increased. This can potentially lead to an enhanced operation of the signals in either one or both directions of travel.

One of the underlying considerations for such a system is that the cycle lengths of the included intersections have to be the same, or multiples of a selected common cycle time (half or twice the cycle length is acceptable). Without this it would be impossible to coordinate the signals as a consistent offset between the signals cannot be achieved. Usually, the major directional through phase is the coordinated phase from which the offset between intersections is measured. Generally thus, the **cycle length**, **offset** and **split** distribution are the most important parameters in a coordinated signal system. The split distribution refers to the portion of a cycle that is given to a specific phase, i.e. its maximum green time.

Important in such a coordinated system is the accurate setting up of a Time-Space diagram. Figure 2-3 shows such a diagram. It is used to evaluate the coordinated system and visually interpret changes to the phasing schedule. The vehicle speed is represented by the slope in the Figure. This can either be the desired 85th percentile speed or the prescribed speed limit.

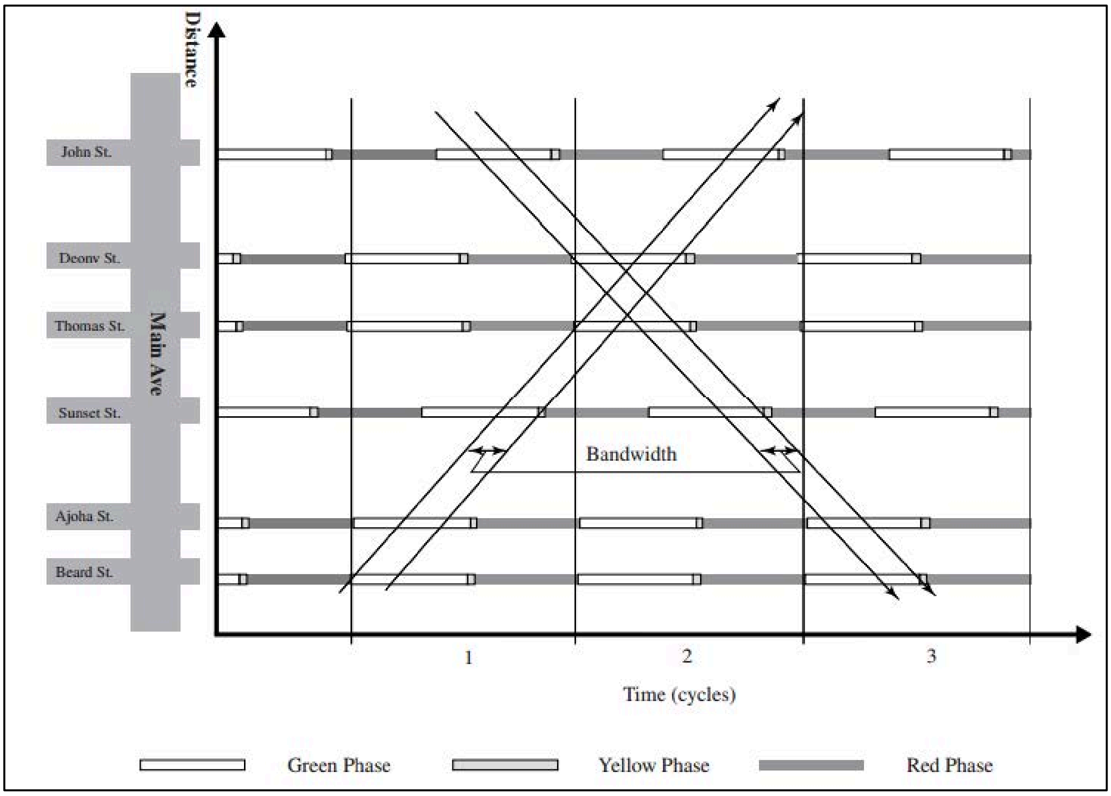

Figure 2-3: Time-Space Diagram showing bidirectional coordination (Garber and Hoel, 2015)

The **bandwidth** as seen in Figure 2-3 is a typical maximisation measure for optimisation. Maximising this measure, however, could lead to increased network delay by negatively affecting other parts of the network (Garber and Hoel, 2015).

2.2.2.5 Traffic-adaptive signal control (TASC)

This method makes use of predictive algorithms and real time detection to estimate the forecast traffic volumes and, with the help of a traffic model, establish the most appropriate signal plans. These plans are then implemented in real time and are adapted to the current traffic situation.

The main reason for wanting to make use of a traffic adaptive system is when a conventional method of signal control is no longer functionally efficient. This could be due to major traffic fluctuations, change in travel patterns due to changing land-use or an increasingly oversaturated network. Traffic-adaptive systems may provide a last resort measure of enhancing signal control before more drastic measures have to be implemented. Four main considerations have to be taken into account when using this system. Firstly, the traffic data needs to be accurately collected. A variety of sensor and detector options are available to be used, ranging from electromagnetic loop detection to highly specialised camera detection. Secondly, a programme needs to develop, in real time, alternative signalisation plans which, thirdly, have to be compared and evaluated according to a specific performance index (PI). Lastly, the most appropriate and useful signal control scheme then has to be implemented (Garber and Hoel, 2015).

The use of such a system has a vast advantage over fixed time signalisation, but only if the conditions are right. Otherwise the same results could have been achieved at a far lower cost. Traffic-adaptive signal control is only now starting to emerge as a usable control measure, mostly due to a previous lack of expertise and the high cost involved.

2.2.2.6 Traffic signalisation warrants

A number of different warrant have to be taken into account before the use of a traffic signal system can be justified at a specific intersection. This is mostly because the incorrect and unwarranted use of a traffic light installation can potentially do more damage than good. Traffic light systems are often seen as the best and only solution to alleviate all sorts of traffic related problems at an intersection, yet it is proven that this is not always the case and that incorrect use will degrade safety and increase delay.

The South African Road Traffic Signs Manual (COTO, 2012) defines that, firstly, the *minimum requirements for traffic signalisation* have to be met. Secondly, that *no viable alternative solution* can be implemented and, thirdly, that the specific *warrants for traffic signal installation* have to be satisfied in order for traffic signals to be justified.

The minimum requirements for traffic signal installations include a large number of factors, such as a maximum speed restriction of 80 km/h, as well as specific visibility requirements. The manual describes these in more detail (COTO, 2012). Alternative solutions which should be considered prior to signal installation include the redesigning of intersection geometry, provision of traffic circles or even grade separation (COTO, 2012).

When it comes to the particular warrants for traffic signalisation, the manual is very clear that installation should not commence without satisfying **at least one** of the warrants. The warrants are based on the measure of queue length on approaching lanes and are as follows (COTO, 2012):

- WARRANT 1: The average length of ANY individual queue equals or exceeds four (4) over any one hour of a normal day.
- WARRANT 2: The SUM of the average lengths of all queues equals or exceeds six (6) over any one hour of a normal day.
- WARRANT 3: The SUM of the average lengths of all queues equals or exceeds four (4) over each of any eight hours of a normal day (the hours do not have to be consecutive, but they may not overlap).

2.2.3 Traffic signalisation guidelines

Traffic signalisation is a very important part of effectively and safely regulating the behaviour of road users. In South Africa, the following guidelines and manuals are used in the design and implementation of traffic signal and can be consulted for further in-depth information. They include the South African Road Traffic Signs Manual, Volume 3 (COTO, 2012), the Traffic Flow Theory handbook (van As and Joubert, 2002) as well as the Highway Capacity Manual (Transportation Research Board, 2010).

Having considered the concept of traffic signalisation in more detail in this section, the idea of TASC can now be expanded on in Section 2.3 hereafter.

2.3 TASC operation

Before being able to understand how TASC is applicable to the specific environment of the R44 arterial in Stellenbosch, an intricate understanding needs to be established about how this signal control mechanism came to be. The very reason why and how this control approach was developed thus needs to be analysed and understood.

2.3.1 What is TASC?

The term TASC refers to *Traffic-Adaptive Signal Control*. It facilitates the description of the kind of signalised traffic control as discussed in Section 2.2.2.5. A number of different terms have been used in literature to describe this concept, yet TASC seems to be the most fitting and accurate to its application. Therefore this report will make use of the term TASC whenever referring to real-time control of signalised intersections even if a specifically cited source made use of another acronym.

2.3.2 History and origin of TASC

According to Wu and Ho (2009), TASC had its beginnings in 1963 when a new signal optimisation algorithm was proposed by Miller. Miller (1963), at the Highway and Traffic Engineering School; Birmingham University, considered the expansion of signal control from vehicle-actuated to a more traffic adaptive approach. At the time of his research, most signals were under VA control and the purpose of his research was to develop an accurate delay formula for traffic arrivals, utilising this to optimise the signal phasing. Seeing that most Performance Index (PI) calculations, related to identifying an optimal signal plan at an intersection, are based on at least the criteria of minimised delay, Miller's approach was taking the right angle and provided a stepping stone for further research.

The concept of TASC has been studied extensively since Miller's research was published and many different traffic adaptive control methods have been developed. The main aim of these being to address complex traffic situations and conditions and optimally enhance the throughput of vehicular traffic through those transport networks or corridors by implementing control mechanisms fitting to the current traffic loading.

The reasoning behind focusing on the development of these adaptive traffic control methods lies in the fact that, when applied properly, the results associated with such a solution have been known to bring improvements to traffic flow conditions, thus reducing congestion (Wu and Ho, 2009). The extent of these improvements are known to vary, depending on the specific traffic situation and conditions, whether it is considered on a network or corridor level or even just on an individual intersection level.

The need for addressing the negative effect of a constant increase in traffic volumes was recognised at an early stage. An increase in vehicular traffic inevitably leads to increased potential conflict points, not only between vehicles themselves, but also between vehicles and pedestrians. On top of this, there are a number of other negative effects associated with congestion, such as increased emissions and fuel consumption, which TASC has also been proven to reduce (Kwak, Park and Lee, 2012). TASC, therefore, originated from a need to address traffic related problems where conventional methods would be too costly, not effective enough or impossible to implement due to physical infrastructure restraints.

Together with an acceleration in technological advancements over the past half century, the application opportunities for adaptive traffic control systems in the transportation sector have increased drastically. TASC is a substantial and important part of the intelligent transportation system (ITS) environment (Aslani, Mesgari and Wiering, 2017; Islam and Hajbabaie, 2017) and is therefore highly linked with advancements in the computing capabilities and software related abilities of artificially intelligent systems. As this advancement therefore allows, the extent and feasibility of implementing TASC systems becomes more pronounced.

Some of the most prominent models that were developed in the 80's include the Sydney Coordinated Adaptive Traffic System (SCATS) (Sims and Dobinson, 1980) as well as the Split, Cycle and Offset Optimisation Technique (SCOOT) (Hunt *et al.*, 1982). Both of these methods were developed as alternative Urban Traffic Control (UTC) methods compared to the traditional fixed-time plans in use at that stage. They have undergone a fair amount of development and are still in use today all over the world. Over the years, a number of different mechanisms were developed to facilitate the process of adapting the traffic control to the current traffic loading. Most of the prominent models today make use of some sort of genetic or machine learning algorithm based on either a centralised, hierarchical or decentralised approach to signal timing (Islam and Hajbabaie, 2017). The SCATS system makes use of a hierarchical approach in which a strategic and tactical control level is realised on the regional and local area of implementation respectively. The SCOOT system, alternatively, makes use of a centralised approach where all the decisions relating to signal control are made by one central computer and then implemented. Section 2.5 of the literature study expands on the different methods of implementation.

Historically, therefore it can be seen that the implementation of such TASC systems originated in urban oversaturated traffic environments where the need for enhanced traffic control was recognised. A number of indicators are typical in sparking the consideration for such a TASC system. These, considering also the observed changes associated with them, are discussed in more detail in Section 2.4.

2.3.3 Current developments and scale of implementation

Pascale et al. (2015) noted that the management of traffic adaptive control systems involves a complex and somewhat unpredictable component, especially considering the rapid development of technological aspects pertaining to such systems. It has also been proven in literature that the implementation of TASC is not merely a 'plug-and-play' solution which is self-regulating and does not require any further thought after initial installation but rather requires an extensive and thoughtful validation procedure (Jhaveri Joseph Perrin *et al.*, 2003). If this validation process, however, is correctly managed then it has been extensively shown in literature that improvements in traffic parameters can be realised (Wu and Ho, 2009; Kwak, Park and Lee, 2012).

In light of the understanding that TASC is not a simple undertaking and is an especially fast developing and important area of traffic management, understanding the current developments and scale of implementation of such systems is very important in order to ensure successful use of adaptive control systems.

According to Wu and Ho (2009), most TASC models can be categorised according to either cyclic or dynamic control processes. In a cyclic traffic control model, the cycle length for signal control is decided a priori and assumed to be optimal. Other parameters can then be adjusted to formulate a traffic adaptive response. In models using dynamic programming, individual phase lengths are calculated and implemented given current traffic patterns which, subsequently, means that the cycle length is not fixed. Using this approach, the idea of traffic signal coordination becomes impossible. The individual intersection might very well be optimised, but to coordinate this optimisation across a corridor or network level becomes impossible. Also notable from Wu and Ho (2009) is that the specific module responsible for the timing decision of signal control can operate at different levels of real-time response to the environment. The control can be actuated, dynamic or traffic adaptive. The focus of present research is very much on the traffic adaptive level of control rather than actuated or dynamic.

Considering the centralised, hierarchical or decentralised approaches to signal timing, a considerable amount of literature is available concerning the current developments and the research focus areas of traffic adaptive control, as is neatly summarised by Islam and Hajbabaie (2017). Whether different algorithms or programming methods; computational developments or performance evaluation; levels of management and the pros and cons thereof; a lot of research has been invested into continually finding better ways of managing traffic in real-time.

When considering the extent of actual employment of TASC comparing developed and developing country environments, it is seen that the road infrastructure environment plays a major role in the successful operation of such systems (Weichenmeier, 2017). As shown by Weichenmeier (2017), the use of TASC in a developing country context can be extremely successful if the technology can be adapted to the environment, not with a copy-paste application approach compared to developed country use of the technology. It is however noted that employment of TASC has been prominent in European countries, simply because of the higher level of technological and infrastructural development. With the rapid advance of technology and the growth of developing countries in mind, however, it is expected that the use of TASC will increase, prominently in hubs of higher development. This can also be linked to an improving cost effectiveness and increasing technical expertise relating to the use of TASC systems (Garber and Hoel, 2015).

The idea of controlling and managing an entire urban traffic network with the help of TASC is one worth considering and has been the focus of many research investigations. Typical and most appropriate application of TASC has been on a corridor and individual intersection level. This is simply because of the relative ease of predictability of such systems. Pascale, Lam Hoang and Nair (2015) suggest that a network driven adaptive system is not as easily understood and managed as initially thought. This is especially true for oversaturated conditions in the network. The interaction of one intersection with its surrounding neighbours and the resulting dynamic network effects have not been well understood. In their research, Pascale, Lam Hoang and Nair (2015) address this issue by developing a network controlled traffic adaptive model to contribute towards the understanding of network interactions.

Several technological improvements of key importance to the development of TASC are the accurate detection of real-time traffic data, as well as other rising data sources such as floating car data (FCD), going hand in hand with faster and more reliable data transmissions. The ever increasing computing and processing powers of modern computer systems has a massive contribution to fast and accurate traffic modelling. Technologies such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) as well as vehicle-to-other (V2X) communications make the idea of a smart city environment feasible and place within reach an advanced mechanism of traffic management. All of these factors make it possible to better regulate traffic and find creative ways of addressing transport problems.

Another interesting, relatively recent, consideration of TASC is its combination with dynamic vehicle routing decisions through V2X technology. The idea is to consider the real-time routing information provision to vehicle users, thus reducing the overall network travel time (Chai *et al.*, 2017). Both dynamic routing as well as real-time signalisation have received a significant amount of research attention, yet the combination of them is not a commonly heard of theme. Chai *et al.* (2017) propose a Dynamic Traffic Routing (DTR) algorithm that functions alongside traffic adaptive signal control. They found a possible reduction of up to 27% in travel time within the network.

2.4 Reasons for TASC implementation

The development of TASC finds its roots in the efforts of researchers, traffic engineers and other concerned individuals alike to find better ways of managing motorised urban traffic. The deliberation towards a more efficient system is the driving force behind its advance. To be able to use the ever increasing technological capacity at our disposal in maximising the potential of existing infrastructure, such as traffic capacity, is an important aim of TASC. Some reasons for considering TASC as a solution option are expanded on in this Section.

When transportation systems experience congestion, it is either of recurring or non-recurring nature. Recurring congestion refers to the typical weekday traffic volume fluctuation during peak hour traffic, whereas non-recurring congestion refers to the non-typical fluctuation of traffic volumes linked to the unpredictable occurrence of accidents, adverse weather conditions, construction works or other abnormal events (Stevanovic, Dakic and Zlatkovic, 2016; Aslani, Mesgari and Wiering, 2017). The persistent presence of congestion is a tell-tale sign of an overly strained road network. This could be due to a combination of factors, usually a simple lack of capacity or a suboptimal signal strategy or a combination of both. Traffic congestion is directly linked to an increased travel delay to the road user, which, incidentally, is the main criteria to be minimised when it comes to TASC. Therefore, when a certain level of congestion is present, especially on a corridor level, TASC should be considered as a possible alternative signal control option. Additionally, if complex time-of-day (ToD) fixed-time or actuated signal phasing has to be present to somewhat cope with the problem, this is usually also an indicator that TASC should be considered due to the sheer inefficiency of the present system (FHWA, 2012).

Reasoning for TASC implementation can be considered on an environmental, economic and social level. When looking at TASC from the environmental perspective, a direct aim it meets is the reduction of greenhouse gas emissions. This is simply due to TASC's aim of minimising delay, thus also the number of vehicle stops, which immediately leads to lower fuel consumption and therefore less air pollution (COTO, 2012; Kwak, Park and Lee, 2012). If, therefore, a need for improved air quality is an issue to be addressed, then TASC can be a contributing factor to reaching that goal and should thus be considered as a substitute for the present system.

Economically, the benefits of TASC can be enormous when compared to other options that are aimed at reducing congestion (COTO, 2012; FHWA, 2012). Typically, other options would include the construction of additional lane capacity or even new roads/bypasses altogether which comes at a considerable cost. Potentially, the expensive construction of such infrastructure can be delayed by the installation of a TASC system having the same immediate results. The use of a TASC system could, for example, be a much faster, shorter term solution to the problem, providing the opportunity and time for detailed planning towards further, larger scale intervention measures to happen. Also, TASC might often be the only option available if other options are not feasible or possible at all. For example, if no road reserve is available for extra lane capacity, then TASC would immediately have to be considered as an option.

From the social perspective TASC can potentially also bring positive change. The general well-being of the community is an important factor to consider in any city or town. An insufficient and poorly functioning traffic system can be the source of a lot of frustration for people. To address this issue generally contributes to reducing the number of complaints relating to the traffic environment (FHWA, 2012). TASC should therefore also be seen as a tool to invest into the well-being of the public.

Generally, the difficulty of managing the traffic flow within a city or town increases as the density of urbanisation increases. Literature has shown that shorter block lengths favour the pedestrian but have a negative impact on traffic signalisation (Wu and Ho, 2009; Sevtsuk, Kalvo and Ekmekci, 2016). As soon as two intersections are too close to each other, the signal plans interact, often negatively, resulting in inefficient traffic flow. The use of a TASC system would greatly benefit such a situation due to its immediate coordination effect. TASC, additionally is seen as a means to eliminate the frequent retiming which is usually required for traditional signal control methods (Lidbe *et al.*, 2017). This would, naturally, make for a far more efficient system and reduce the chance of introduced errors or outdated signal timing.

The prioritisation of public transport within a complex network of road users is an important criteria to consider. The use of TASC can be very conducive to the integration of public transport due to its ability to give precedence to specific vehicle categories without losing its ability to coordinate and optimise the throughput of other vehicles in the system (PTV Group, 2017b).

A TASC structure can also be seen as a contributing factor to increasing safety along a traffic corridor or network. Due to increased mobility in a TASC system, the chance for crashes, especially minor accidents, is reduced based on a reduction of dangerous stops (Ma *et al.*, 2015). Thus, where a high indication of crash events is evident at a signalised site, studies have shown that TASC has the potential to reduce those figures. Research by Ma *et al.* (2015) has yielded an intersection Crash Modification Factor (CMF) of 0.83 for total number of crashes when installing a TASC system at that particular intersection. This is a significant reduction in the number of crashes and should not be disregarded.

An important justification to consider for TASC is the immediate, up-to-date availability of traffic data this will present. This would especially be true in a more developing country context where traditionally the gathering of useful traffic data is a strenuous and ever impeding part to any transport related project. Due to the constant detection that is required for such a system, the extraction of, especially, vehicle flow rate data is made possible without having to conduct expensive manual volume counts (COTO, 2012).

An additional important consideration for TASC is the stepping stone it can provide to a fully integrated network level traffic management system (FHWA, 2012). TASC is usually first implemented on a traffic corridor level which can later be expanded to network level control. The use of network adaptive signal control is not a very well understood matter yet, but it is envisioned that this will change in the future alongside advances in technology. To integrate such a system into network level traffic management scheme would then be the next step and having something like a TASC system in place is greatly contributing to this cause. The long term vision for traffic management within a town or city can therefore also be contributing to TASC justification.

On top of the aforementioned distinctively justifiable reasons for a TASC system, a number of “myths” have developed over time that can lead to wrong reasoning behind wanting to implement TASC (FHWA, 2012). A general misunderstanding within such a system is that it is seen as a “plug and play” or “set and forget” type of system. In other words, the mistake is to believe that TASC completely takes over and does all the work itself, making the traffic engineer redundant. Or, that the system will be able to cope on its own after installation and thus requires no maintenance (Lidbe *et al.*, 2017). These beliefs are incorrect and can result in improper motivation behind using such a system. Every TASC system needs proper initial setup and accurate data in order to function properly and efficiently. Regular maintenance and constant standby staff are also required in order to prevent and address system or detector malfunction.

2.5 Methods of TASC implementation

Brief reference was made in Section 2.3.2 to the different methods of implementation when it comes to TASC. The comparison of a centralised, a decentralised and a hierarchical approach to TASC is made. This section expands on the different methods and their typical advantages as well as disadvantages.

The methods of implementation as discussed in this Section do not refer to the actual signal control method, i.e. whether a group or stage based method is used, but rather refers to the way in which the TASC system itself is implemented. Together with this goes the specific control algorithms which are used to assert the system’s control logic. The signalisation control and TASC control levels work together, though, as the one will always have an effect on the other. On a software level the method of operation for TASC links with how this needs to be carried over to the actual signal controller. In other words, the TASC control is based on the preferred or currently utilised signal control.

When considering the way in which the control of TASC is applied, the idea of a local and global controller needs to be understood. A local controller indicates that the equipment is located at the physical location of the intersection and implements the signal phasing via the appropriate commands to the signal heads. This controller can either be self-sufficient or receive higher level communication from the global controller, if present (PTV Group, 2017b). The global controller therefore, refers to that side of the TASC system which has a bird’s eye view of the controlled area and can make decisions based on a globally optimised performance index (PTV Group, 2017a). The global controller can then send this information to the local controller. The communications aspect within such a system is of extreme importance as this ensures that the detected or available data is timeously and accurately received by the local or global controllers and corresponding decisions are then, in turn, also communicated to the rest of the system. The communications aspect of TASC is expanded on in Section 2.6 of this report, where the data requirement and detection aspects are discussed in more detail.

The distinction between rule-based and model based TASC control is also of importance to consider (PTV Group, 2017b). According to the guidelines for traffic light system, RiLSA (2010), rule-based control typically runs through a flow diagram every second and bases its decisions for the current state of signalisation on ‘condition vs action’ behaviour due to measured traffic flow parameters. The model-based control, on the other hand, makes use of a traffic model and corresponding control algorithm to test and evaluate various signalisation options and find the most optimal one based on the minimisation of the target function (RiLSA, 2010).

2.5.1 Centralised control methods

Centralised TASC control makes use of a global control setup which simultaneously optimises various signalisation parameters with the help of a mathematically defined process (Islam and Hajbabaie, 2017). This kind of technique is very commonly used today and provides optimised signal control due to its consideration of the entire signalised area.

The centralised control technique can be computationally strenuous and requires, correspondingly, the capable software and hardware components to make it function. From a hardware perspective this includes the need for a centralised computer terminal, on top of the local control hardware required at each intersection, as well as the corresponding communication infrastructure. Software requirements generally vary from one system to another as is specifically required. The use of a centralised, global optimisation approach has been proven to provide more optimal solutions than, for example, a decentralised approach (Islam and Hajbabaie, 2017). However, due to the fact that centralised optimisation is not scalable, it cannot be applied to wide network area optimisation.

Many different application techniques and approaches have been utilised and explored in the field of centralised signal control, as is neatly summarised by Islam and Hajbabaie (2017). Whether it has been the use of various algorithms and optimisation methods; bi-level programming; inclusion of various transport modes; proposed network optimisation or addition of route optimisation, a lot of research has been aimed at understanding and improving the centralised approach to TASC. The SCOOT system is an example of signalisation optimisation using a centralised technique of operation (Hunt *et al.*, 1982).

2.5.2 Decentralised control methods

The idea of a global control method is not utilised with the decentralised control approach, thus all levels of decision are implemented on the local level, whether it be for an individual intersection or an area with limited numbers of intersections. Global optimisation is therefore not used in this approach.

According to Islam and Hajbabaie (2017), the decentralisation of such a system makes it scalable, as opposed to a centralised system, which implies real-time implementation. However, because the overall global perspective is lost, the system may find suboptimal solutions for the signal optimisation problem.

Some examples of such a type of control method are the Cumulative Travel Time Responsive (CTR) algorithm by Lee *et al.* (2013) as well as the predictive microscopic simulation algorithm (PMSA) by Goodall *et al.* (2013). Several other types of decentralised control methods are indicated by Islam and Hajbabaie (2017).

2.5.3 Hierarchical control methods

Thirdly, the use of a hierarchical approach to TASC has been found in literature. This method utilises different decision levels within the control measure by allocating higher order decisions differently than lower order decisions. The differentiation between network level and intersection level decisions is made and allows the distributed computing of the respective level oriented objectives (Islam and Hajbabaie, 2017).

The challenge with this kind of TASC regulation is that it can potentially have interfering or contradicting optimisation function in the various levels of decision making. This in turn implies that a suboptimal signal timing results from the procedure. With this in mind the successful implementation of a hierarchical system can be a challenging one and has been the aim of a lot of research over the past years.

Once again, a number of different ways of hierarchical control have been developed with research areas shifting between different aspects of the control method as time progresses. Examples of this kind of control technique are the Sydney Coordinated Adaptive Traffic System (SCATS) (Sims and Dobinson, 1980), the Urban Traffic Optimisation by Integrated Automation (UTOPIA) system (Mauro and Di Taranto, 1990) as well as the Real-time Hierarchical Optimising Distributed Effective System (RHODES) (Head, Mirchandani and Sheppard, 1992).

2.5.4 Combined control and other aspects

A new focus of the current research lies in the combination of different control methods. The combined efforts of a centralised and a decentralised technique especially seem intriguing. This would overcome the problem faced with a centralised system of not having a scalable aspect towards network level control, as well as the problem faced with a decentralised system that loses the global perspective and thus cannot optimise efficiently. A combination of these would therefore create a far more optimised approach towards a TASC implementation.

Another important consideration is that the specific aim of the envisioned TASC system is largely determinant towards the method in which it will be utilised. If the focus lies on a single intersection, unsurprisingly a decentralised approach will be followed; a centralised approach naturally being more suited for corridor level operation. In other words, whether the extent of implementation is on network level, corridor level or intersection level requires different methods of dealing with a TASC system. Careful thought should therefore always be given to the anticipated use-case of the desired TASC operation in order to most optimally address the project needs.

The extent of implementation directly links to the specific data requirements needed to ensure useful operation. This is due to the way in which different control methods, especially in combination with other Urban Traffic Control (UTC) measures, requires different data input. Aspects such as advisory speed limits and dynamic vehicle routing, in addition to TASC, respectively require different data collection, as well as data communications approaches. Section 2.6 of this report expands on specific data requirements for different aspects of a TASC system and also looks at alternative, unconventional data addition to TASC.

2.6 TASC data requirements and detection

After having discussed the concept of TASC, its advantages, disadvantages as well as reasons and methods of implementation, the focus of this section lies on the specific data requirement needs pertaining to such a system, as well as the methods of obtaining those data components.

As has become apparent from the preceding sections, TASC requires the supply of real-time data. This can be in the form of various different data components, depending on the type and extent of adaptive control which is to be implemented, as well as the specific availability of data in the region. A possibility of the addition of newer, less well developed data sources is typically also an aspect of adapted TASC control to be considered, especially considering the developing world environment. The specific data requirements at different phases of the project might also vary somewhat.

2.6.1 Data components

The first data components required for a TASC system are the real-time measures of vehicle flow and queue lengths at an intersections (Weichenmeier, 2017). This is a prerequisite in being able to optimise network priorities. The specific distinction between types of vehicles is also of importance, additionally to the need for distinguishing between lane- and non-lane based traffic (Weichenmeier, 2017). The level of non-lane based vehicles at an intersection critically influences the type of detection to be implemented there, as certain means of detection are more prone to miss a proportion of non-lane based road users.

In the case of a model-based TASC system, as mentioned in Section 2.5, a base traffic flow model is required. Travel demand model requires intricate and detailed data components such as the road network, land-use and zonal information, travel demand data and the corresponding calibration and validation of the model. Without this accurate travel demand model, the necessary performance testing of the respective signalisation options cannot be done, resulting in a suboptimal signal plan selection.

According to Lidbe *et al.* (2017), there are a number of different data components that are more pronounced during different phases of the project lifecycle. During early planning and design, the most important data elements include the design traffic volumes, specific turning movement volumes as well as travel time observations. Also of importance, especially during design and installation, are the existing signal timing plans (Lidbe *et al.*, 2017). These are required as a base for optimisation to take place, on top of gaining an understanding into the current travel behaviour and the present regulation thereof. After installation, the most important data components are the continual monitoring of travel time changes and other TASC performance evaluation measures. Ultimately, the means of obtaining traffic volume counts from the detection system in place acts an important data source for future projects.

The addition of alternative data sources to the system, such as Floating Car Data (FCD), is a very promising endeavour. FCD refers to vehicle data collected from GPS enabled devices and can provide information including the speed, travel time and route choice for that vehicle (Weichenmeier, 2017). Seeing that it is impossible to have a 100% probe penetration rate on a specific road network, it is not possible to obtain exact vehicle volumes. Yet, FCD can act as a significant additional data source to TASC, especially in a developing world context (Ishizaka, Fukuda and Narupiti, 2005; Rao and Rao, 2012).

In order to allow for successful employment of a TASC system, careful consideration should be given to the minimum data requirements needed to gain the envisioned level of success from the system. This is important such that consideration can be given to what is available vs. what is required so that the necessary data infrastructure components can be established in time.

2.6.2 Data detection mechanisms and communication

A number of different mechanisms and methods have been developed to obtain the required traffic flow data. As technological advancements have progressed, these mechanisms have also been refined, changed and improved on. Important to consider is whether the detection is point detection or not, whether it is manual or non-manual detection and then whether these method are intrusive or non-intrusive to the transportation environment.

The original means of obtaining traffic data obviously lies with simple manual link volume and turning movement counts. Before extensive technology was available this was the only means available to obtain the data and it served its purpose well. A typical application area for this method, still often used in a developing country context today, is to obtain updated vehicle volumes at intersections for recalculation of signal timings. Also, the use of manual cordon counts to verify zonal traffic movements, or input this into a traffic model during calibration, is common.

The two main categories which non-manual vehicle detection can be divided into are intrusive and non-intrusive methods (Beyer, 2015). All the methods have advantages and disadvantages, considering the specific application area, required functionality and lifespan requirements. As summarised neatly by Beyer (2015), intrusive methods of detection include the typical electromagnetic inductive loop, pneumatic tubes, weigh-in-motion, piezoelectric and magnetic detection. On the other hand, non-intrusive methods are found to be video, radar, ultrasonic, infrared and mobile tracking.

Inductive loop detection has been widely implemented for vehicle flow and queue length detection. The use of video detection is becoming more popular as the technology becomes more readily available. When considering the specific requirements of a TASC system, the use of inductive loops and the additional video detection, where available, has been primarily found to be most effective. The idea of not exclusively making use of point detection, however, is becoming more pronounced. This obviously stemming from a search of potentially more readily available data sources within the traffic environment in less developed countries. This links into the use of Floating Car Data (FCD) as well as a Connected Vehicle (CV) environment.

Astarita *et al.* (2017) considered the use of FCD specifically in conjunction with TASC systems. The aim was to identify the applicability of such data additions to the system, as well as to create a basis on which new optimisation algorithms can be formulated. Shen and Stopher (2014), on the other hand, evaluated the specific use of GPS enabled methods of data collection in the context of travel surveys and data processing as a replacement for traditional household travel surveys. The use of CV communications in the specific context of adaptive signal control has also previously been researched. Seco and Bastos Silva (2017) proposed a Connected Vehicle Signal Control (CVSC) strategy to be used at an isolated intersection, this proving that the CV environment can have an outstanding additional optimisation impact on signalisation control. The combination of FCD and CV's in a TASC environment could potentially lead to increased use of advisory speed limits (ASL) (Astarita *et al.*, 2017).

A factor which is always important to consider, no matter what the specific non-manual detection mechanism, is how the detected data is communicated from detection device to recording or controller device. This is important because it can affect the accuracy and the time required for a response to be formulated, depending on reliability and speed of the data transmission. All round fast fibre connection would be the optimal scenario, yet is not necessarily always readily available. The use of a General Packet Radio Service (GPRS) connection has a lower initial cost expenditure, so is a more suitable option for developing countries. The use of a fibre connection in the long term is however always the preferred method.

2.6.3 Data challenges in developing world

When taking account of the different data requirements for a TASC system and the corresponding detection mechanism, it is important to address the specific data challenges faced in a developing world. This relates to the scope of this project in being able to apply such a system effectively in South Africa.

Weichenmeier (2017) investigated the applicability of a TASC system in developing countries. It was found that the high demand placed on the transport network, additionally to limited resources and often more pressing issues that have to be addressed, results in suboptimal traffic management. In other words, the lack of resources and expertise in these areas are a prime motivation to have a self-optimising signal control system in place. A challenge, however, is the supply of real-time data. This required infrastructure is often not available or not maintained and left to deteriorate. The challenge, therefore, is to identify what the minimum data availability requirements are for minimal system functionality and to find the most suited methods of collecting that data. This might be a challenge due to the specific travel behaviour in developing countries. The often unpredictable manoeuvring of road users can be difficult to detect as soon as non-lane based behaviour becomes apparent. The data detection mechanism has to be able to take into account such behaviour.

2.7 International implementation examples of TASC

The use of TASC systems in controlling signalised intersections elsewhere in the world is mostly focused around the developed country perspective. This is the original application area of TASC technology and also where the initial development took place.

As mentioned previously in this report, the use of SCOOT and SCATS systems has become widely known. These were some of the earliest models to be used and have found their way into numerous cities all across the world. A study done by Stevanovic (2009) into the principles and deployment of TASC systems in large cities found that at that stage most of the TASC implementations where either SCOOT or SCATS. Many other TASC systems, however, have also been developed over time and this section serves to highlight a few application examples before these different systems are compared more closely in the following section.

In the United States of America, the development of TASC systems has received quite a bit of attention over the years. The Federal Highway Administration (FHWA) invested into TASC system development, with systems such as OPAC, RHODES and ACS Lite resulting from this. According to Zhao and Tian (2012), the use of these systems is, however, still relatively low in the US and examples of their implementation are as follows: OPAC has been implemented, among others, in Chicago, Illinois as well as Vancouver, Washington. RHODES is in use in cities such as Tucson, Arizona and Seattle, Washington. ACS Lite on the other hand is visible in Houston, Texas and Bradenton, Florida. In the US, SCOOT has seen implementation in Detroit, Michigan as well as San Diego, California, whereas SCATS is operational in Park City, Utah. Elsewhere in the world, SCOOT is used in over 250 cities, most notably in London, UK. SCATS is naturally also evident in Sydney, Australia, its city of origin.

Other systems, such as PTV Epics & Balance, VS-Plus and In|Sync have also been used as TASC models. PTV Epics & Balance combine both local and global control as means to optimal traffic management with example cases of its implementation present in the Polish cities of Gdansk, Gdynia and Sopot as well as the city of Krakow (Weichenmeier, Hildebrandt and Szarata, 2015). VS-Plus, a traffic actuated control method, has been utilised in adaptive control systems in a number of areas in Switzerland such as in Basle, Berne, Lucerne and Solothurn (Verkehrs-Systeme AG, 2018). Many of the VS-Plus example installations have a similarity in that public transit is often integrated into these system. Another VS-Plus application is in the Chinese city of Heifei (Tian and Zhang, 2017). In|Sync, another traffic adaptive control system, has seen implementation in numerous cities, most notable being Columbia, Missouri and Farmington, New Mexico (Rhythm Engineering, 2018).

A few other noteworthy TASC system types that have been used internationally are TRANSYT-7F, Sitraffic Motion MX and UTOPIA. All of these have the same underlying method of addressing signal control in that they use an online traffic model to simulate the environment, predict into the future and assess possible control options and then implement the appropriate procedure based on an optimisation process.

Having mentioned a number of different TASC systems in use internationally, as well as a few of their application examples, the next step is to identify the most appropriate systems for comparison regarding the specific application area in Stellenbosch.

2.8 Different TASC systems comparison

For comparison purposes the specific systems which are to be evaluated were chosen to be the SCOOT, SCATS and PTV Epics & Balance systems. These were chosen based on their potential to be of use in the environment and conditions of the Stellenbosch use-case.

The criteria of comparison includes, inter alia, the different measures of vehicle detection required for the system to function. This comparison is based mostly on position of detection required for the optimisation process to function, i.e. whether stop-line (SL), midblock (MB) or upstream (US) detection. Also a criteria of comparison is whether the system responds in a proactive or merely a reactive manner to changing traffic conditions and what method of optimisation is specifically utilised for each method. The timeframe of implementing changes is also considered as a comparison measure, alongside the specific level of implementation, i.e. whether it is on a global (strategic) or a local (tactical) level. Important to consider is whether the TASC system is model- or rule-based and how they compare, as well as to what extent the system takes public transit prioritisation into account. Each TASC system is discussed in more detail after which Table 2-1 shows a more compact comparison.

2.8.1 SCOOT

The first of the three systems to be compared is the SCOOT system. Each of the seven comparison criteria mentioned earlier will be briefly discussed.

SCOOT has both a reactive and a proactive component to its response. It proactively adjusts splits and offsets, whereas it reactively adjusts the cycle length (Stevanovic, 2009). Three different optimisation techniques are used in SCOOT, the offset, split and cycle optimisers. Vehicle stops and delays are calculated on each link, with a subsequent performance index calculation resulting in incremental change in signal timing (Gordon and Tighe, 2005; Zhao and Tian, 2012). The basic principles of SCOOT are shown in Figure 2-4.

SCOOT relies heavily on accurate detection and thus also the correct positioning of the detectors. The SCOOT user guide advises detectors to be have two meter length in the direction of travel, can however also function with alternative existing detection. Placement of detectors should be at least 10 to 15 meters downstream of previous junction and 80 to 100 meters from the stop line on entry links (Siemens Mobility, 2016).

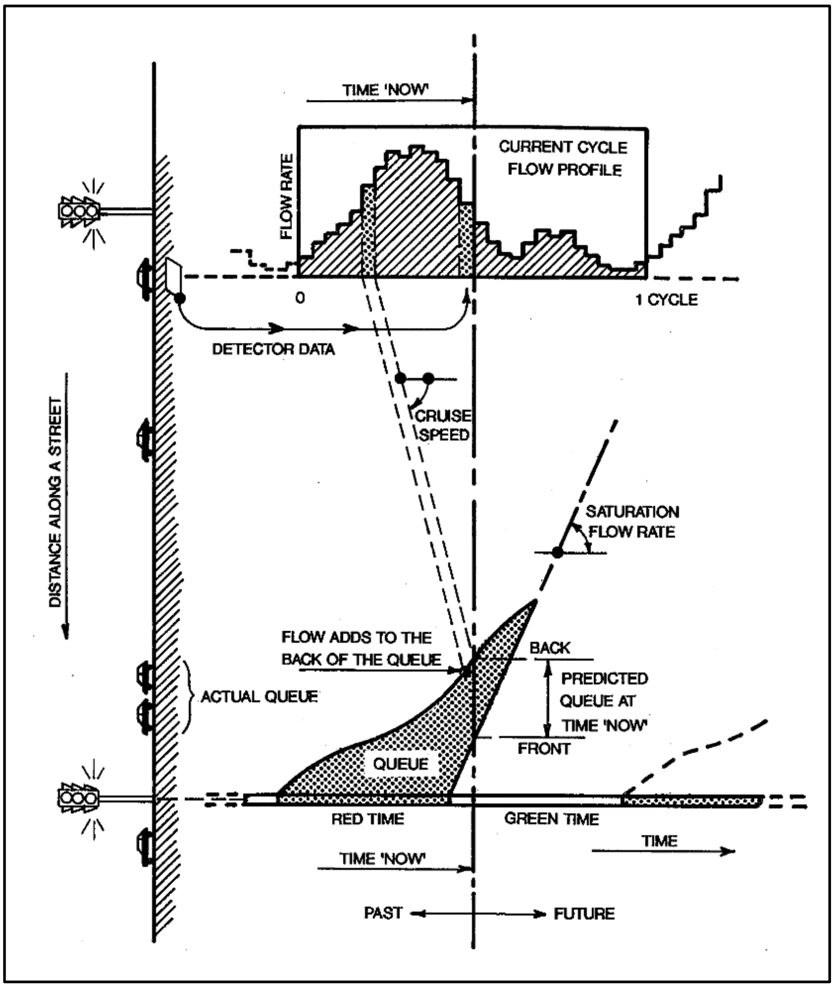

Figure 2-4: Principles of the SCOOT traffic model (Hunt et al., 1982)

The timeframe of optimisation is different for each SCOOT optimiser. Split optimisation occurs for every stage change, cycle time optimisation occurs every 2.5 or 5 minutes whereas offset optimisation occurs once per cycle (Siemens Mobility, 2016). Optimisation in SCOOT is model-based and occurs on a local and global level. As is the case with most modern TASC systems, the ability to include public transit prioritisation into its operation is also available in SCOOT.

2.8.2 SCATS

The SCATS methodology, as opposed to SCOOT, is not model-based, but functions solely on a reactive, rule-based level of response. This has been often thought to be its downfall, yet the system is still effective and in use all over the world.

As already mentioned earlier, SCATS follows a hierarchical level of control, with central, regional and local levels (Chen and Lu, 2010). This enables shared computing between the different levels in order to provide suitable configuration capacity for small, medium and large cities. Figure 2-5 shows a representation of the system.

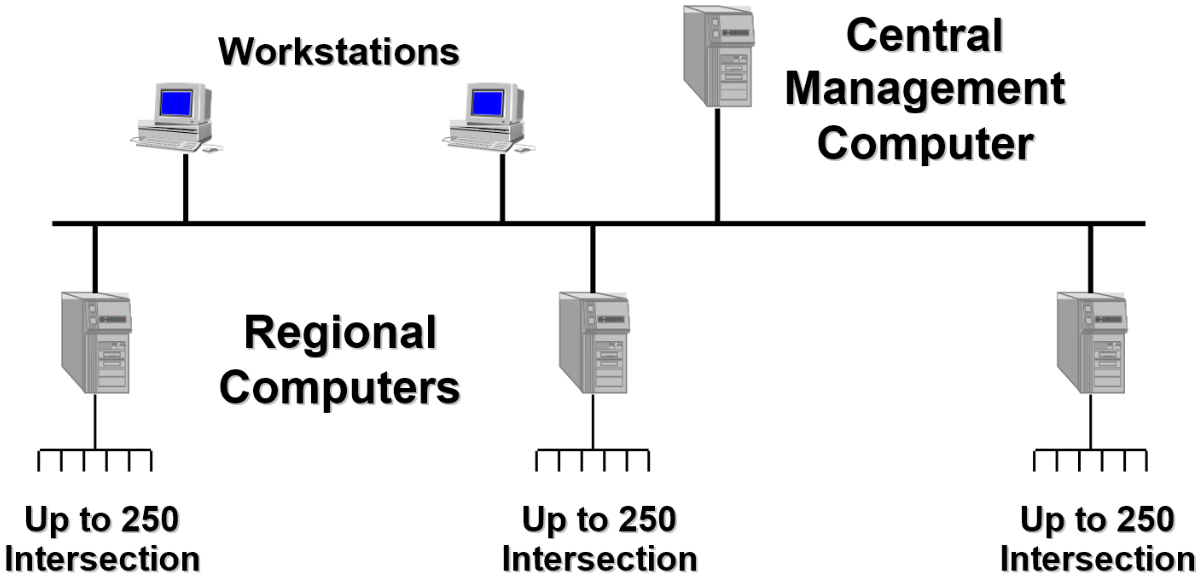

Figure 2-5: SCATS system layout (SCATS, 2018)

Detection for SCATS happens preferably on a stop-line basis (Gordon and Tighe, 2005; SCATS, 2018). This means that the system only makes use of detectors situated near-by the stop line and therefore does not have the capability to forecast queue lengths into the future. The response to such detection, seeing that proactive engagement is not enabled, is limited to predefined signal plan selection from a library of plans based on typically varying traffic conditions. The timeframe of such reactive optimisation is, in turn, only on a cycle interval sequence (Stevanovic, 2009).

Pubic vehicle priority in SCATS is an enabled functionality. It operates on three different levels of priority: high, medium and low.

2.8.3 PTV Epics & Balance

PTV Epics & Balance (PTV E&B) is a combination of both a local and a network level adaptive control module in conjunction with a traffic-model-based simulation environment. PTV Epics is the local control module, designed to operate on an individual intersection level and was originally developed by Joachim Mertz in order to address public transport priority regulation. PTV Balance is the network level control module which was originally developed by Prof Dr Bernhard Friedrich in the late 90's and was initially owned by GEVAS software GmbH (Weichenmeier, Hildebrandt and Szarata, 2015).

The traffic model based environment for PTV E&B is most suitably found in PTV Visum and Vissim, as PTV's different software components function very well together. Yet, the combination with other optimisers or modelling environments is not uncommon (PTV Group, 2017a, 2017b). Also, either PTV Epics or Balance can be utilised on their own and do not have to be used in conjunction with each other, which makes implementation very versatile. Typical conjunctive interaction of the different software component within the PTV Vision suite can be seen in Figure 2-6.

Detection for PTV E&B is very versatile. PTV Epics can function with any detector position, yet optimal detection is at a distance of about 50-80 meters in front of the stop line, corresponding to roughly 4 to 6 seconds travel time in a city (PTV Group, 2017b). Additionally, stop line detection can be added and is of some value, yet is not crucial for the successful operation of PTV E&B.

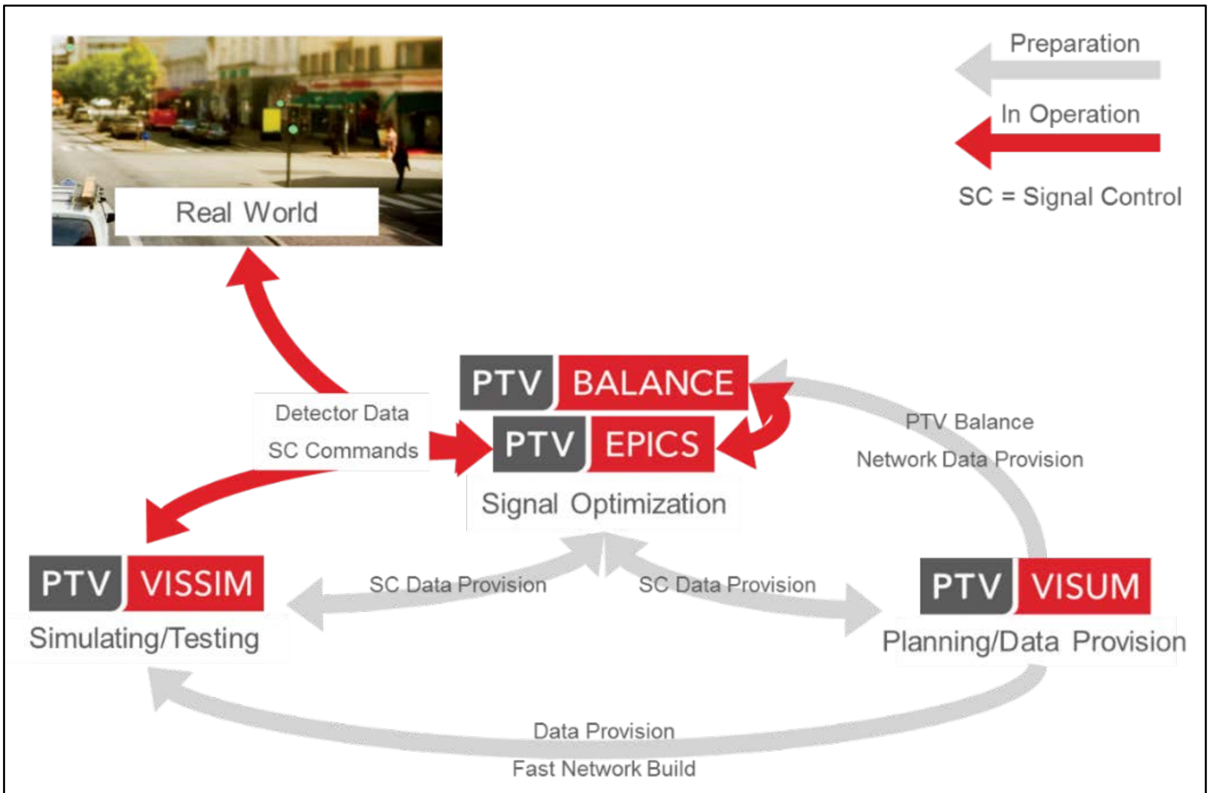

Figure 2-6: Integration of PTV Balance and Epics (Bruwer and Weichenmeier, 2017)

Optimisation in PTV Epics occurs in two steps, a time-ordered shortest way algorithm and a hill-climbing algorithm with optimisation of a performance index. This process happens every second. PTV Balance uses genetic algorithms to optimise splits and offsets to offer an optimal signal plan for implementation every five minutes (Weichenmeier, Hildebrandt and Szarata, 2015; PTV Group, 2017a). This makes the combination of PTV Epics and Balance both pro- and reactive.

Table 2-1 summarises the comparison findings of this section.

Table 2-1: Summary of TASC system comparison

Comparison criteria	**TASC system**		
	SCOOT	**SCATS**	**PTV E&B**
Detection	US*	SL***	SL/MB**(preferred)/US
Response action	Reactive/Proactive	Reactive	Reactive/Proactive
Level of operation	Local/Global	Local/Global	Local/Global
Timeframe	Stage/Cycle/5 min	Cycle	1 sec/5 min
Model or rule based	Model	Rule	Model
Optimisation method	Offset/Split/Cycle	Signal library	Offset/Split/Cycle
Public transit priority	Yes	Yes	Yes
Adaptability/Applicability	Medium	Medium	High

*Detection: ***SL: Stopline, **MB: Midblock, *US: Upstream*

Taking into account the above comparison of the mentioned TASC systems, the chosen method for this specific project is the PTV Epics & Balance system. This decision is based on the specific applicability of this software method to the developing world environment in conjunction with its extensive ability to be customised. PTV Group, additionally, is a lab partner to the Stellenbosch Smart Mobility Lab (SSML) where this project is undertaken, therefore the software is readily available under the existing partner agreement.

2.9 PTV Epics/Balance operation

Having identified PTV Epics & Balance as the preferred TASC solution for investigation in this research, PTV E&B is now evaluated and discussed in more detail. Specific functionality and manner of control is defined and the operation of the different software components is discussed in more detail. PTV Epics and Balance will be discussed separately in more detail after which the combined effort of the two PTV products is considered. A use-case scenario in the developing world context is also discussed.

2.9.1 PTV Epics

PTV Epics, as already mentioned, is the local control method in the traffic adaptive Epics/Balance combination. It is most optimally applied on a single signalised intersection level, yet can also be utilised on its own to coordinate "green wave" control (PTV Group, 2017b). The specific functionality and design of PTV Epics is discussed hereafter.

2.9.1.1 System functionality and objectives.

A distinct advantage of the PTV Epics control mechanism is that it makes use of a model-based environment. The typical application of a local control mechanism utilises a rule-based approach, i.e. a formulated response based on an often very complex "if-then" sequence (PTV Group, 2017b). This is then usually combined with global model-based control, yet this is not the case with PTV Epics which is model-based. Figure 2-7 indicates the model-based logic of PTV Epics.

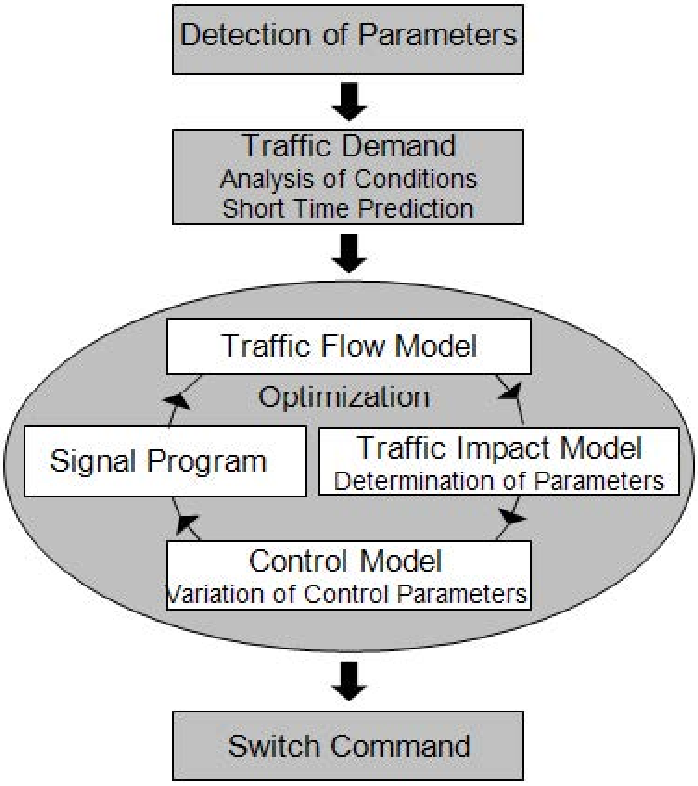

Figure 2-7: Model-based control method (RiLSA, 2010)

As compared to global model-based control, PTV Epics can run through its optimisation process in one second, based on its specific optimisation techniques. The performance index to be minimised in PTV Epics is made up of the weighted sum of total delay and number of vehicle stops. Delay is usually seen as the more important factor to be minimised.

It is the objective of the control model to establish the most suitable stage sequence to be implemented by means of a time-ordered shortest way algorithm, as well as to establish the optimised interstage starting times by using a simple hill-climbing algorithm (PTV Group, 2017b). It is possible for the optimisation process to take into account additional constraint information, such as minimum and maximum stage durations. Additionally to this, the performance index calculation can take into account the integration of a reference signal plan in order to ensure a signal time implementation that is as close as possible to the network optimised signalisation plan. Such a reference signal plan can be provided online through integration with a network optimiser, for example PTV Balance, or can also be provided offline by a traffic engineer. Equation 2-4 below is representative of the performance index calculation performed by PTV Epics.

$$PI(sp) = \sum_{sg \in SG} \alpha_{sg} D_{sg}(sp) + \beta \Delta (ref, sp)$$

Equation 2-4

With:

SG	= set of signal groups
sp	= signal plan to be valued
ref	= reference signal plan, e.g. from PTV Balance
α_{sg}	= weighting of the signal group *sg*
D_{sg}	= sum of delay at signal group *sg* over time horizon considered
Δ	= deviation of control alternative *sp* from ref
β	= weighting of deviation from ref

Due to the specific one-second optimisation timeframe associated with PTV Epics, and the fact that it is a model based optimiser, it can take into account all types of traffic, thus allowing for improvement in traffic flow over a wider range of road users. The weighting of particular traffic flows, however, is also possible in PTV Epics. This creates the opportunity to give preference to certain streams of traffic instead of just allowing for a general optimisation. This comes in handy when the inclusion of public transit is of importance as this requires higher priority than private vehicle traffic (PTV Group, 2017b).

Another advantage of PTV Epics is that it does not require any special controller hardware, when linking to most modern controllers. This eases the integration of the software into existing systems and minimises areas of conflict. Seeing that the Epics optimisation process is a relatively autonomous process, once set up properly, personnel efforts related to installation, maintenance and adjustments are typically lower than for similar rule-based optimisation systems. Particularly when the inclusion of public transport is considered (PTV Group, 2017b).

2.9.1.2 Data Provision

When bearing in mind the one second process of PTV Epics, it is apparent that the data provision for such a system also has to be completed on a one-second scale. The data that has to be available for PTV Epics to use includes the current signal image such that Epics can identify the current stage without which optimisation cannot take place. Also available has to be the current signal program to identify, for example, the cycle length. The current cycle second has to be available as fundamental means of being able to optimise. In terms of the detector data, specific events, occupancy times and failure occurrences have to be provided. Whenever a detector fails, and further optimisation thus fails, PTV Epics will revert to the reference plan.

The sequence of data provision for PTV Epics, especially considering the entire PTV Vision suite, allows for a unified process. Figure 2-8 represents this workflow provision. Step 1 incorporates the generation of a network travel demand model in PTV Visum (macroscopic) which forms the basis for testing various scenarios before generating the most optimal signal plan. For PTV Epics, step 1 is not a compulsory requirement as local optimisation at each intersection can still take place in PTV Vissim (microscopic) based on the local detection data (PTV Group, 2017b). Data provision for PTV Balance is represented using the same workflow, with step 1 as a compulsory requirement to ensure global optimisation.

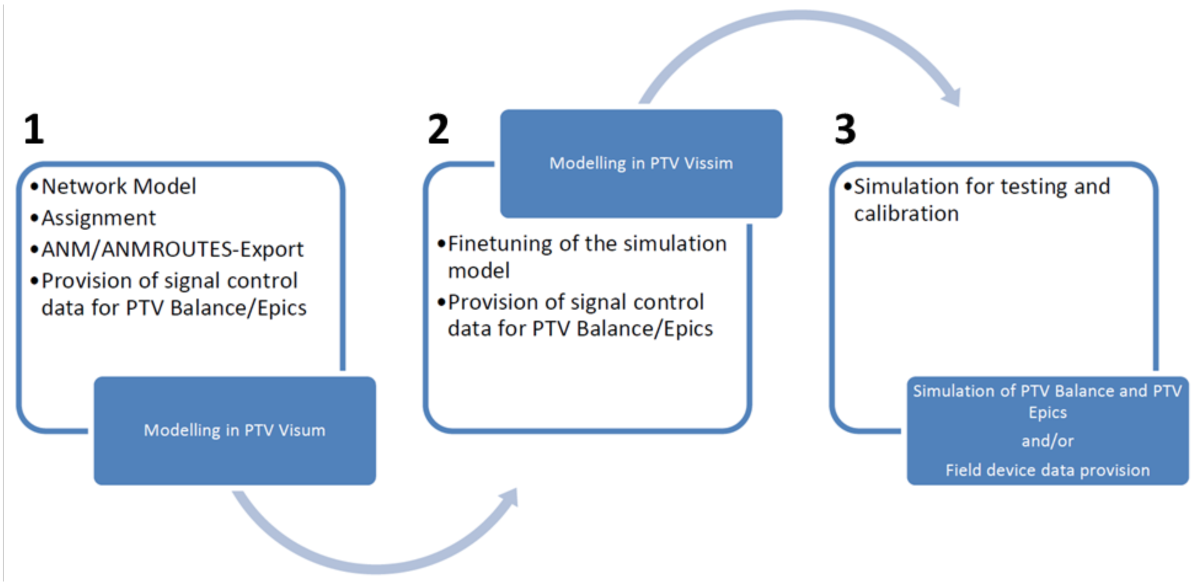

Figure 2-8: Data provision workflow for PTV Vision suite (PTV Group, 2017a)

2.9.2 PTV Balance

PTV Balance, as opposed to PTV Epics, is the global network control module in the adaptive traffic environment. This means that it is not focused on analysing and optimising traffic flow at a single intersection, but rather over the network or corridor level of the optimisation area. It is an abbreviation for "**bal**ancing **a**daptive **n**etwork **c**ontrol m**e**thod". Functionality and objectives of PTV Balance are discussed hereafter.

PTV Balance consists of a combination of components to ensure sufficient and successful optimisation of traffic on the network level. A macroscopic traffic model ensures an accurate estimation of current traffic flows in the network, forming the underlying base upon which further processes are established. A control model as well as a mesoscopic model are responsible for testing the effects of different signalisation plans over the network. Optimisation finally takes place with the help of optimisation algorithms (PTV Group, 2017a).

Reduction of delay in the system is processed on a network central level by coordinated green wave and offset optimisation. This is processed as the middle and long term area of adaptive-control application every five minutes, whereas one-second interval optimisation can be achieved by the local controller in order to adapt to the specific traffic flow fluctuations present at the intersection. It is, however, important to note that PTV Balance can also be implemented on a stand-alone basis and does not require the inclusion of a local optimiser such as PTV Epics. The controller, if able, would then simply implement the reference signal plan sent by PTV Balance as a fixed-time plan. Needless to say, implementation with local optimisation is always able to reach superior optimisation results (PTV Group, 2017a).

The macroscopic traffic model of PTV Balance can be replaced by a superordinate external traffic model in the case where this is present. The two superordinate systems which PTV Balance currently has the functionality to combine with are the PTV Optima as well as the DRIVERS (Gevas Software) models. This enables the formulation of signal plans based not only on the traffic state in the area of optimisation, but taking into account the traffic state over a larger city area. The extent of implementation for PTV Balance is, however, optimal in a subnet of up to 100 intersections. This subnet is then typically further divided into control groups of intersections which find themselves in an area of similar traffic related characteristics. This is to ensure reference signal program selection with adequate cycle lengths (PTV Group, 2017a).

The control system of PTV Balance, as illustrated in Figure 2-9, is categorised according to five main principles:

1. The collection and preparation of data
2. Traffic representation
3. Efficiency and control alternative evaluation
4. Creation of control alternatives
5. Data interfacing

Before the macroscopic model can be used to estimate traffic flows, the current traffic state of the road network needs to be represented as accurately as possible. This is achieved by accurate collection and preparation of the detector data. Here the detector positioning, as with PTV Epics, plays an important role. Also, all detector flow data is standardised to hourly volumes, due to the varying detection intervals, before being able to form the base for all further modelling.

Traffic representation in the traffic model is done on two levels: the macroscopic and the mesoscopic level. The macroscopic level approximates origin-/destination- relations for the subnet of controlled intersections via an OD estimation. This is then used in a traffic assignment procedure to assign traffic volumes to the respective links. The mesoscopic level of the traffic model generates periodic traffic flow profiles with help of the macroscopically generated parameters.

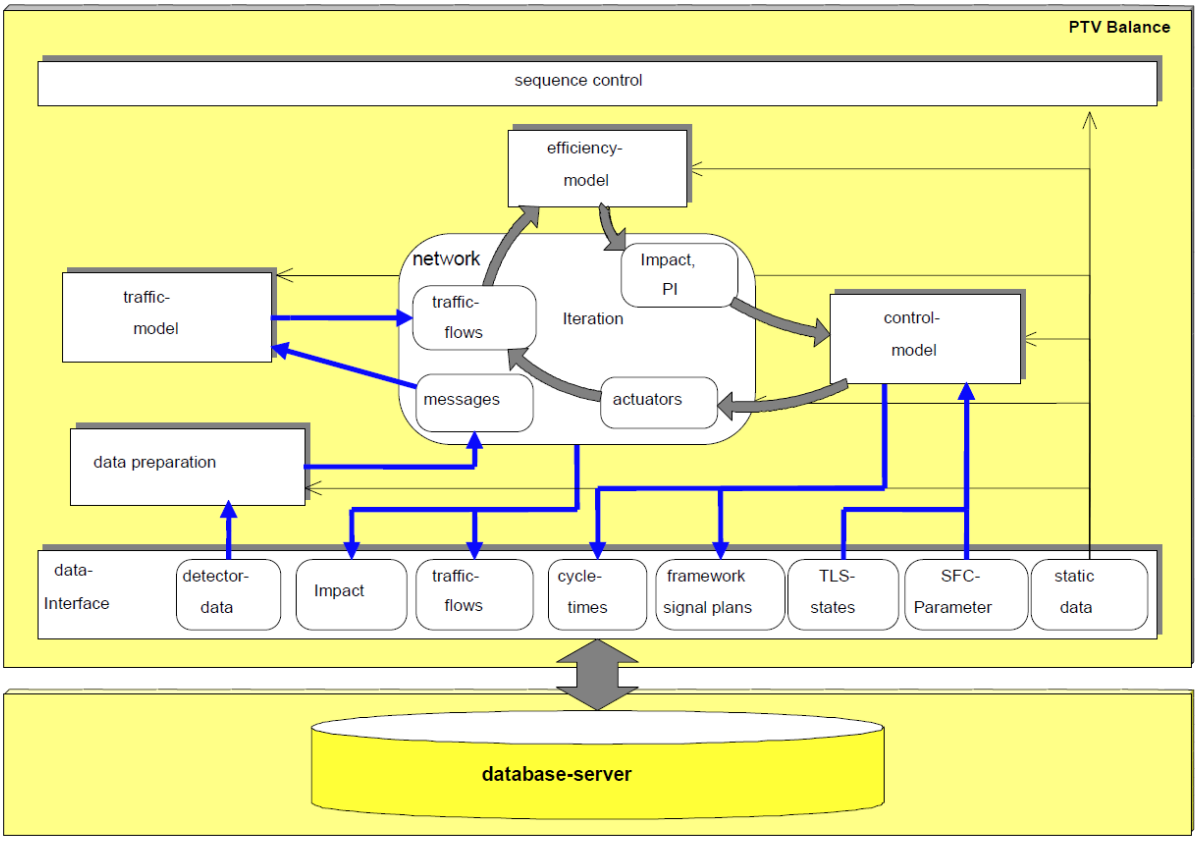

Figure 2-9: Block-diagram of the PTV Balance network control (PTV Group, 2017a)

During step 3 of the control process the performance index (PI) calculation as seen in Equation 2-5 is made use of. This requires the separate calculation of vehicle delay, number of vehicle stops as well as the queue lengths for each signal group *sg*.

$$PI(x,y) = \sum_{sg \in SG} (\alpha_{sg} D(x,y,sg) + \beta_{sg} H(x,y,sg) + \gamma_{sg} L(x,y,sg)) \quad \textit{Equation 2-5}$$

With:

SG	= number of signal groups in the subnet
α_{sg}, β_{sg}, γ_{sg}	= emphasis of delay/ number of stops/ queue lengths for signal group sg
D, H, L	= vehicle delay/ number of stops/ queue lengths for signal group sg
x	= vector of control variables
y	= vector of traffic related variables

For the creation of control alternatives, the split times, offset times as well as the cycle lengths are optimised in PTV Balance. This was originally done by only using a Hill-Climbing (HC) algorithm. Meanwhile, another algorithm, the genetic evolutionary algorithm was developed to operate in conjunction with the HC algorithm. The HC algorithm is far more computationally taxing, especially in combination with microscopic simulation, thus both optimisation algorithms are still contained within PTV Balance. Figure 2-10 shows the optimisation procedure for the genetic algorithm.

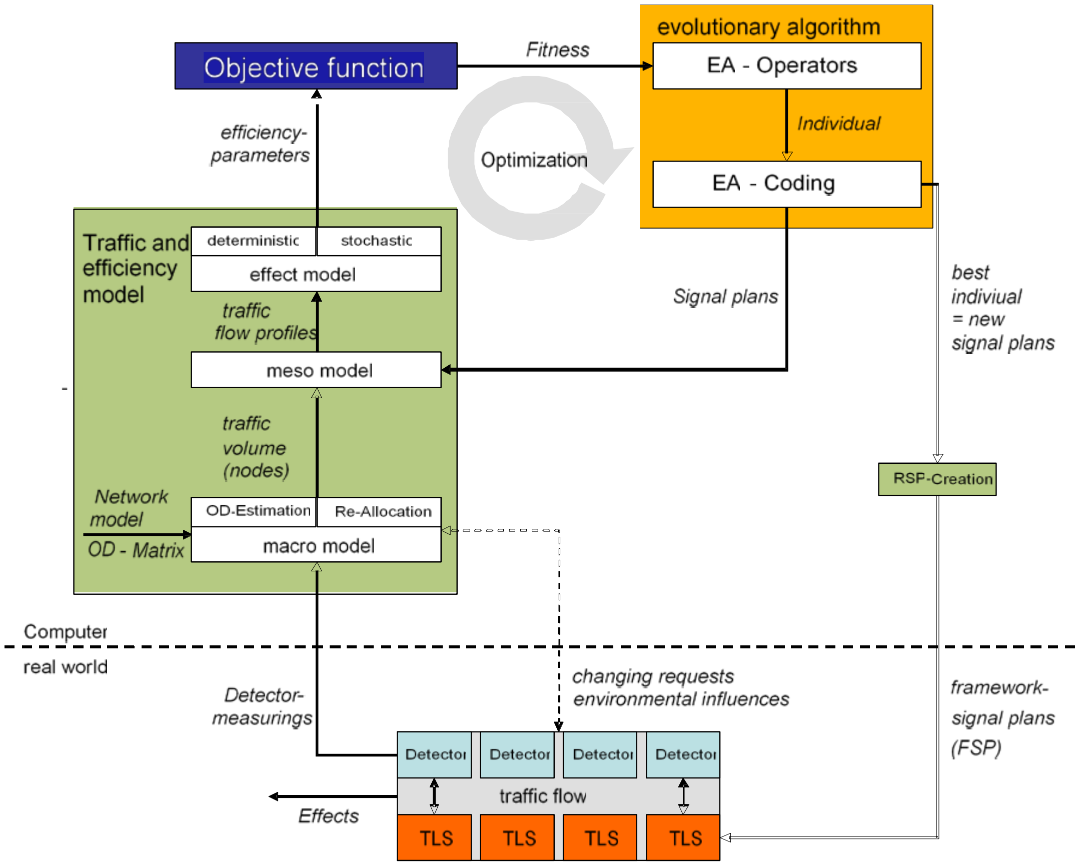

Figure 2-10: Genetic online optimisation procedure (PTV Group, 2017a)

The final step in the control mechanism of PTV Balance is then to interface the optimised control alternatives to the local controller in a manner in which it is usable and able to be implemented

2.9.3 Integration: Epics, Balance, Visum and Vissim

2.9.3.1 Integration aspects

The integration of certain components of the PTV Vision software suite is important when wanting to realise the best possible result from the system. The specific interaction between the different components, in the case of an adaptive control system, PTV Visum, Vissim, Balance and Epics, is previously indicated in Figure 2-6 and Figure 2-8. It is seen that in order to create a realistic, reliable output from the optimisation processes, the integration has to be carefully considered.

Important also to note, is that components such as PTV Epics and PTV Balance have the capability to function on their own, yet it has been shown that their combination is of immense value. Specific mention needs to be made of the fact that this combination is one where two model-based optimisers, on a local and global level, are integrated. This is not a typical method of approaching local optimisation and the potential application area for PTV Epics is therefore far extended beyond the usual rule-based optimisation (PTV Group, 2017b).

PTV Visum provides the macroscopic modelling capability of the system, whereas PTV Vissim provides the microscopic capability. The integration and replacement of certain components with other software tools having similar functionality is also possible within this system. This is primarily aimed at easing the application and integration into existing systems without having to completely replace it.

2.9.3.2 Simulation, calibration and operation

It is impossible to implement an effective adaptive signal control system without extensive and detailed simulation in a microscopic simulation environment such as PTV Vissim. This allows for the analysing and testing of relevant parameters in order to ensure that realistic traffic behaviour is achieved and modelled.

Simulation for both PTV Epics and Balance in PTV Vissim does not require major additional work on top of the setup of the actual PTV Vissim model. The setup of large networks is recommended in PTV Visum and is the standard procedure for PTV Balance use.

Before the calibration process can take place it needs to be ensured that the fundamental parameter provision is without mistake. The specific PTV Epics and Balance manuals refers to mechanisms of testing this step. Calibration is usually an iterative process and may take extensive tweaking and modification of the model to ensure that simulated vehicle behaviour reflects reality in all cases. Modern simulation environments, such as PTV Vissim, provide the user with a number of parameters that are indicative of uncalibrated model behaviour, yet careful consideration should always be given as to the actual movement of vehicles in the model. Once again, detailed steps of calibration are provided in the individual PTV Epics and Balance manuals (PTV Group, 2017b, 2017a). A specifically developed web-based GUI for PTV Epics and Balance eases this process of calibration by displaying simulation results in real time, thus allowing quick comparison to actual Vissim behaviour and therefore easier identification of discrepancies and inconsistencies.

When considering the operation of PTV Balance and Epics specifically, it is important to note that due to the systems' self-calibrating nature it potentially only has to be checked in detail over longer time interval periods than a rule-based system, yet the idea of "set-and-forget" is definitely not applicable. Periodic tests and checks have to be performed, detector data has to be validated and the detectors maintained, as with any other rule-based adaptive system also. Operation of the PTV Epics/Balance system is, also, not necessarily of higher labour and cost intensity as compared to other systems.

2.9.4 PTV Epics/Balance case studies

When considering areas of application for the specific use of the PTV Epics/Balance adaptive system, two cases are discussed in this section. Firstly, an implementation in a more developed country environment in Poland in the cities of Gdansk, Gdynia and Sopot as well as in Krakow. Then also a simulation implementation in a developing country environment in Delhi, India as well as a real-world test in Chandigarh, India.

In Poland, the Tristar system (Gdansk, Gdynia and Sopot) made a decision to update their signal control and utilise the PTV Epics/Balance combination in conjunction with the DRIVERS superordinate model. The system includes a total of over 150 intersections and operates in conjunction with the present MSR traffic controllers. Traffic jams were found to have decreased by more than 20% between 2010 and 2014 based on the system implementation (Weichenmeier, Hildebrandt and Szarata, 2015). Also in Poland, the city of Krakow implemented the PTV Epics/Balance combination on 30 controllers on four road stretches. The system includes Transit Signal Priority (TSP). Results were mixed for the different road sections, especially due to the difficulty of “before/after” comparison affected heavily by changing traffic conditions and characteristics. Results were in general, however, positive.

In India, in the city of Delhi, a test simulation study was conducted to indicate the possible positive implications such an adaptive control system could have in a developing world environment. The study was conducted on Lodhi Road across six signalised intersections. Use was made of a PTV Visum network model, as well as detailed simulation for calibration using PTV Vissim. Table 2-2 below indicates the potential results obtained from the detailed simulation comparison. As is evident, the results are overwhelmingly positive.

Table 2-2: Comparison of Delhi case study results after implementation of PTV Epics/Balance (Weichenmeier, 2017)

Parameter	**Change**
Travel time (seconds)	▼ 26%
Queue length (meters)	▼ 37%
Journey delay (seconds)	▼ 45%
Network speed (km/h)	▲ 27%
Network delay (seconds)	▼ 30%

The real-world implementation tested in the city of Chandigarh, also in India, proved similarly good results during simulation where network delay was shown to reduce by up to 48%. Implementation was done over three intersections, after which the actual average car delay was found to have a reduction of 40% (Weichenmeier, 2017). These developing country applications highlight the huge potential for these adaptive signal control technologies in such traffic conditions.

2.10 Applicability of TASC in South Africa

As previously identified by (Weichenmeier, 2017), the use of TASC can potentially be a solution option for heavily congested intersections in developing countries. This section aims at finding the specific applicability of TASC to South Africa in order to identify whether that same statement is true under the prevailing road conditions present there.

Firstly, the traffic patterns and behaviour under South African conditions have to be assessed. As already mentioned in Section 1.2 of this report, a problem which South Africa faces is that of heavy congestion, especially in urban areas of high development. This is relatable to a few factors, such as a high dependence on private vehicles due to a lack in adequate public transport. Many developing countries are observing this kind of trend. The general increase in private vehicles places a high pressure on existing transport networks, especially at signal controlled intersections.

Many traffic signals in South Africa are operating on FT signalisation plans, with generally infrequent updating of the timings. This in turn can be a major frustration for road users and, as mentioned in Section 2.4, has a negative impact on the social and economic aspects of a community, as well as on the environment. Considering the state of the present transport infrastructure, available resources, the demand placed thereon, as well as the increasing ease of real-time data accessibility, an ideal platform is created to see TASC being implemented in South Africa.

Generally speaking, there are a large number of potential application areas for TASC in South Africa which are satisfying the specific motivational reasons for such a system, as pointed out in Section 2.4 of this report. The whys and wherefores of TASC application in developing countries mentioned by Weichenmeier (2017) are all satisfied in the context of South African transportation needs.

2.11 TASC evaluation

This section aims to discuss the 6th research objective of this study, namely the effective evaluation of a TASC system in order to identify its feasibility and ensure optimal operation of the system. As noted by Lidbe *et al.* (2017), the evaluation of any TASC system is of great importance. This is due to the relative newness of such technologies and thus also the varying outcomes that have been identified in literature. Evaluation specific to the PTV Epics & Balance system will be taken into account as this was the system identified for use in this study. The initial, test-phase aspect of evaluation is required in order to understand TASC feasibility, yet a continuous level of evaluation once the system is in operation is also important to ensure consistently optimal output.

The idea is to use a comparative approach between the original, currently present, scenario of traffic regulation and the optimised TASC scenario in its various forms. Evaluation of TASC systems is usually done extensively in a microsimulation environment, as well as using in-field techniques. Field evaluation typically uses before-after evaluation methods, as mentioned by Kergaye *et al.* (2009), and serves the purpose of identifying either the positive or the negative impact of the newly implemented system physically on site. A usual problem found with a pure before-after field comparison is that traffic conditions change over the implementation phase of the project, making assessment of the TASC system difficult. Thus Kergaye *et al.* (2009) proposes the use of on-off evaluation, i.e. the system is tested under the exact same conditions as would have been present in the *off* state. On-Off evaluation is easily done using traffic simulation, which therefore calls for the extensive testing of TASC systems in such an environment before actually implementing the system physically. Ten simulation runs are typically enough to obtain reliable results (PTV Group, 2017a; Tian and Zhang, 2017). It is, however, also noted that a simulation can never obtain 100% reliable results and thus the move from simulated to real environment has to be carefully considered (PTV Group, 2017a).

Specific key performance indicators (KPI's) have to be used in order to facilitate this comparison, not only in the offline, simulation based comparison, but also in the online, real-world comparison. Many different traffic-related parameters have been utilised to measure change, including travel time (Lidbe *et al.*, 2017; Tian and Zhang, 2017), queue lengths (PTV Group, 2017a), number of vehicle stops (PTV Group, 2017b), traffic volumes (Kergaye *et al.*, 2009), total delay (Stevanovic, Dakic and Zlatkovic, 2016; PTV Group, 2017b), travel speed (PTV Group, 2017a) and even fuel consumption/emissions (Kwak, Park and Lee, 2012). For the case of this study, average vehicle delay will be the main criteria to be evaluated. This is because it is the central variable to be minimised during the PTV Epics and Balance optimisation.

Scenario management is another important concept to keep in mind when evaluating the effectiveness of a TASC system. Comparison does not necessarily only have to be made between base scenario and TASC-optimised scenario, but between a number of alternative TASC situations. Comparison can be drawn between base scenario vs global optimisation only, or base vs local optimisation only or base vs a combination of both global and local optimisation (PTV Group, 2017a).

2.12 Travel demand modelling

Since the TASC system of choice, PTV Epics and Balance, utilised a model-based approach to real-time traffic control it is important to understand the basic underlying principles of travel demand modelling. In essence, travel demand models are used to estimate the travel behaviour within an area for specific time frames, thereby estimating the traffic demand placed on the road network.

A number of different modelling approaches and methods have been used over the years. The classical and well-known 4-step method is still widely utilised and consists of **trip generation**, **trip distribution**, **mode choice** and **trip assignment** as can be seen in Figure 2-11. A network suitable for use with this method requires a zoning scheme containing data relating to land-use and household information (de Dios Ortuzar and Willumsen, 2011).

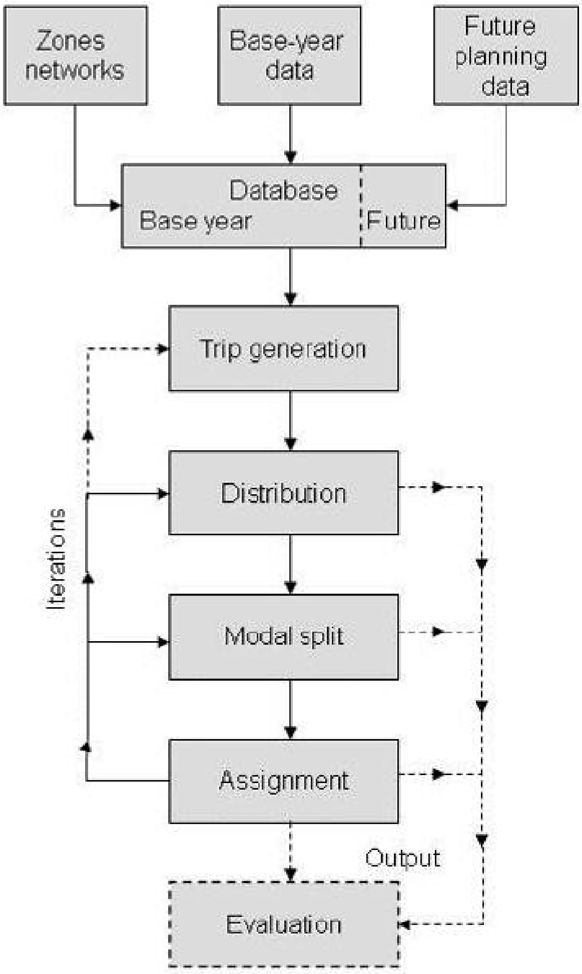

Figure 2-11: The classical 4-step transport model (de Dios Ortuzar and Willumsen, 2011)

Using the information contained within the network zoning scheme, it is then possible to estimate the total number of produced and attracted trips within each traffic analysis zone (TAZ). This is possible since it is known how certain zonal factors, such as number of dwelling units or development density, contribute to the generated traffic flow.

Trip distribution then uses the total productions and attractions within a choice model, based on measures of “attractiveness” such as trip distance and travel time, to define the number of trips going from one zone to another. This will result in an Origin-Destination (O/D) matrix between TAZ’s.

The mode choice step within the 4-step method aims to estimate the modal split between the TAZ’s. In other words, an estimation is made of which types of transport people will utilise. This is based on known travel behaviour, mode availability and other factors such as fare levels (de Dios Ortuzar and Willumsen, 2011).

Lastly, the trip assignment defines an estimation of the specific routes people will take to travel between zones. This calculation step can be based on different methodologies, but typically depends on factors such travel time, congestion levels or transit schedules.

Travel demand models can never be an exact representation of reality, yet have great potential in assisting with transportation planning decisions. Typically, travel demand models have to be validated regularly in order to ensure their continued relevance.

2.13 Literature review summary

The aim of this literature review was to facilitate an understanding into the concept of Traffic-adaptive Signal Control (TASC) in order to lay the foundation for relevant and meaningful research concerning its application in a developing world context.

First to be evaluated were the basics of traffic signalisation, as this is the foundational theory on which TASC is build and has to be understood if TASC wants to be fully grasped. Having covered these basics, effort was put into providing an overview of TASC itself; its history, origin and developments. Further discussion was then centred on the specific reasons why TASC is typically implemented, as well as the different methods of application. These factors were found to be wide-ranging and varying across different areas of application, yet all relatable to the basic idea of traffic-adaptive control.

Further points of discussion included the specific TASC data components required to make such a system function to optimal capacity, as well as how the availability of this specific data impacts the effective use of TASC. International implementation examples were mentioned, showing the proven usefulness of TASC, specifically in more developed country environments.

Following the aforementioned areas of discussion, a number of different TASC systems were compared and evaluated based on their focus areas of application and specific comparison criteria. The most appropriate and available system was identified for use in the Stellenbosch area. This system was the PTV Epics & Balance optimisation and coordination system, integrated with macroscopic and microscopic modelling tools, PTV Visum and PTV Vissim.

PTV Epics & Balance was then examined further, detailing its technical method of application. Applicability to the South African environment was also considered. Finally, the literature study identified best practice evaluation methods to ensure optimal functioning of the TASC system and guarantee continuously efficient operation.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

The definition and layout of an appropriate methodology is of importance in any research project in order to ensure that the objective outcomes and questions are answered in an efficient and optimal manner. Having discussed, in depth, the current standings of the research and application aspects of TASC as found in literature, the methodology for this project will be built upon the knowledge and understanding gained during that investigation in order to facilitate as ideal an approach as possible.

An important procedural aspect taken into account during the methodology definition is the specific research design required for this project in order to reflect credible, valid and reliable research outcomes. This is aimed at identifying key components of research to be completed during the study, as well as the order in which they have to be undertaken. Thereafter, specific action items are laid out regarding collection of data and general information, data processing and model development, which then leads into how the results will be evaluated so as to present useful conclusions and recommendations. In essence, this chapter aims at laying out a plan to be followed during the research period with the purpose of focusing the investigation on the project objectives.

3.2 Research design

The research design provides a framework as a means to ensure the smooth sequencing of the relevant research procedures which are followed, the data collection which is conducted as well as the data analysis which results. It adds structure to the research process.

3.2.1 Research process

The research process, as part of the envisioned research design, forms the underlying sequence within which the main action items are to take place. A specific objective in relation to this process is that it should lead the research in a way which results in acceptable outcomes. Specifically, to identify ways in which the overall research objectives are satisfied and fulfilled, addressing the research problem as originally defined. Figure 3-1 indicates the sequence of steps upon which this research is based.

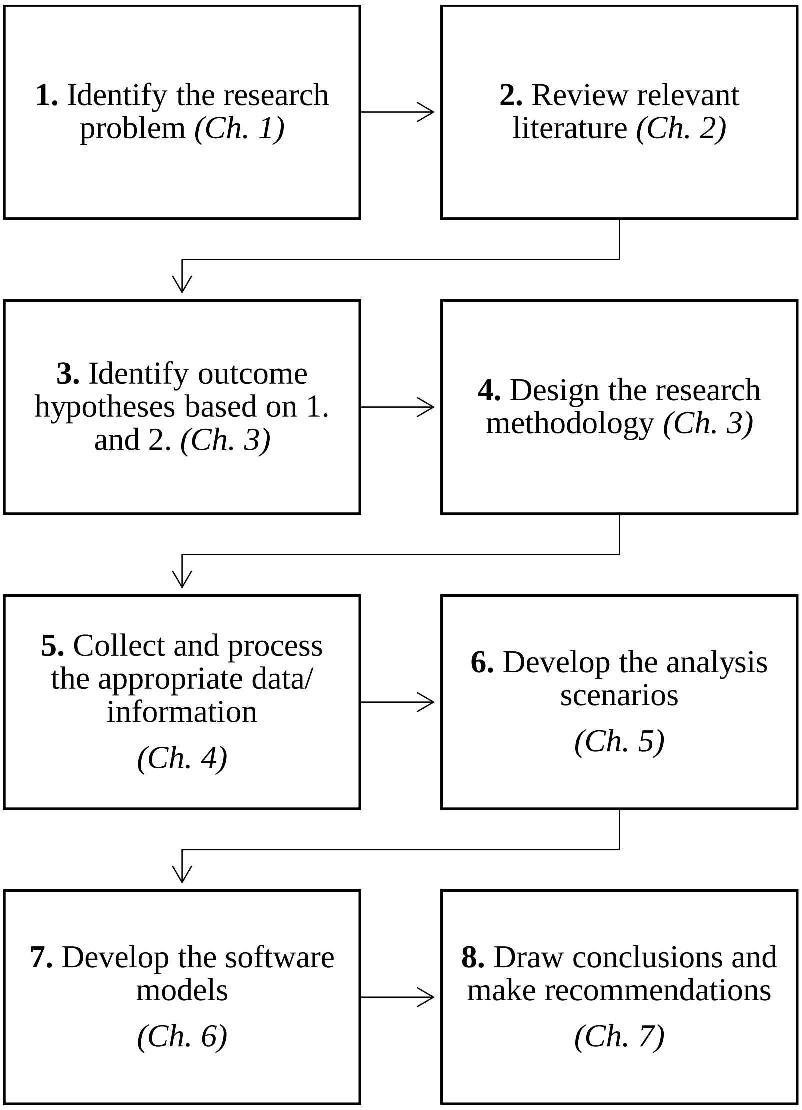

Figure 3-1: Envisioned research process

3.2.2 Research propositions

In order to create an expectation towards the outcomes of this study, several outcome hypotheses options are presented here. These are based upon the literature review and are tentative statements that can be proven either right or wrong.

The **first** proposition is that the system will function to an acceptable level, even considering possible lack of accurate detection options. This would be because of the ability of the system to improve on the current state of the network, under condition that at least some real-time detection information is available. The degree of successful optimisation thus would depend on the extent of accurate vehicle detection.

The **second** proposition is that the system would not be able to improve on the current network conditions due to a need for ideal and accurate detection requirements. The objective of the system to optimise, based only on limited real-time information, would then result in equal or worse conditions as before since the system believes it is optimising but is indeed not doing so representatively, creating a false ideal.

Thirdly and lastly, a proposition is that the system will not only bring improvements to network conditions which are adequate to motivate implementation, i.e. which would reflect proposition number one, but will create drastically improved traffic conditions. This would mean that even the slightest real-time data input will provide an exponentially greater ability to manage the traffic appropriately.

3.2.3 Research credibility, validity and reliability

The very essence of a credible, valid and reliable research project is defined by an apt research design. Specific points which need to be addressed are the process of data collection, the manner in which this data is processed and how the results are interpreted and represented. Important is that the entirety of the system with all its components and processes needs to be taken into account. It is easy to place exclusive emphasis on a specific aspect to highlight some preconceived idea of expected outcome. It is thus crucial to remove any bias from the process and ensure the inclusion of all reasonably conceivable scenarios in order to warrant acceptable conclusions. Also essential is the reasonably detailed explanation of all followed thought processes and procedures as backed up by extensive literature study.

3.3 Study area

Before any further discussion on the applicable research methodologies, final reference is made to the specific study area under consideration. Figure 1-1 on page 4 of this report provides a direct insight into the relevant section of the R44 arterial which will be considered in this project.

As can be seen in the figure, the study area ranges from the R44/Van Rheede Rd intersection to the R44/Helshoogte Rd intersection along the R44 arterial. Also incorporated into the study area is a small section of the Adam Tas Rd arterial from the Adam Tas Rd/Dorp St intersection to the Adam Tas Rd/R44 intersection. This section was included in order to take into account the extensive traffic input originating from the Adam Tas Rd arterial. Of importance to consider is the R44/Alexander St intersection. This is currently an un-signalised intersection, yet its signalisation is in planning (at time of research) and is thus incorporated as such in the network. The intersection is very close to the R44/Adam Tas Rd intersection making coordination essential. More detailed discussion regarding the greater study area of Stellenbosch can be found in section 1.2 of this report.

3.4 Data and model information

Collection of data and model information for this project, as detailed in Chapter 4, is defined by the specific modelling requirements and therefore also categorised according to the different phases of the modelling process (as discussed in Chapter 6). As evident from the literature review, two levels of modelling are required – macroscopic and microscopic.

3.4.1 Motivation for data supply chain

It is envisioned that a bigger Stellenbosch model is required on a *macroscopic* level which will feed into a smaller *macroscopic* model only considering the R44 problem area and its immediate vicinity. This is done in order to adequately supply the required Origin-Destination (O/D) movement patterns. The smaller *macroscopic* model will in turn feed into the corresponding R44 *microscopic* model where detailed testing can be done. Due to this, the majority of data collection will be required for the *macroscopic* level of modelling.

Theoretically, the adequate supply for a TASC system could be facilitated without the setup of an extensive Stellenbosch model if only a smaller section is to be controlled with the TASC system. This would however greatly increase the difficulty with which such a system could possibly be expanded to further intersections in the future. Also, the accurate macroscopic supply is more easily calibrated in a bigger model where relatively more traffic information is available. Seeing, also, that such a bigger model can be utilised for a number of other research projects, it is an obvious choice to set up this kind of model first.

3.4.2 Model name definitions

Since the data supply chain requires **three** different models, it is appropriate to define terminology referring to each of these models directly in order to ensure clarity.

Stellenbosch Model	This exclusively refers to the bigger PTV Visum *macroscopic* Stellenbosch model
R44 Model	This refers to **both** the R44 PTV Visum *macroscopic* and PTV Vissim *microscopic* subnetwork models
R44 Macro Model	This exclusively refers to the R44 PTV Visum *macroscopic* subnetwork model
R44 Micro Model	This exclusively refers to the R44 PTV Vissim *microscopic* subnetwork model

3.4.3 Stellenbosch Model data and information

Collection of data and other information for the **broader** Stellenbosch Model will include components such as land use patterns and other zonal information. Also, specific intersection turning movement traffic counts will be required to incorporate a calibration stage into the modelling process. Additionally, road classification and hierarchy needs to be known as well as the corresponding free flow speeds. This data will be obtained from the local municipality of Stellenbosch, where available, as well as from traffic counts conducted by *Nick Venter Traffic Surveying (NVTS)*. Local knowledge of traffic conditions will assist in setting up, calibrating and validating the traffic model.

3.4.4 R44 Model data and information

Data for the R44 Macro Model will then firstly include the Origin-Destination (O/D) supply data obtained from the Stellenbosch Model. Additionally, information such as detailed intersection geometry, currently used signal plans and controller information as well as detector information is required. This data and information will partially be obtained from the Stellenbosch Municipality as well as from Syntell (Pty) Ltd. Site inspections will also be conducted to obtain loop detector positions and verify geometric layout of the road network.

Information for the train route as well as for the signalised pedestrian crossings will only be added during the microscopic modelling stage within the R44 Micro Model. The train frequency will be obtained from the official train schedule and the pedestrian counts will be obtained from the Stellenbosch Municipality.

3.5 Data processing

Data processing will be done to ensure that data inputs are as accurate and reliable as possible. This will in turn make the calibration later in the modelling process far easier. Two specific aspects of data processing are incorporated and mentioned here. Firstly, data will be sorted according to relevance and accuracy as guided by local knowledge of the traffic environment. This will include most of the data processing, the extent of which will be discussed in Chapter 4. Secondly, where newer traffic counts are not available and the amount of current count locations is not sufficient, older counts will be adjusted using a growth rate.

3.6 Scenario development

Before software analysis can commence, the identification of comparable scenarios will be addressed. The idea is to identify different possible circumstances surrounding the control of traffic on the R44 corridor and package it in appropriate simulation scenarios. Detail will be given regarding the different detection possibilities, extent of signalisation and most importantly the comparison of different parts of TASC control. Another level of comparison will be made to distinguish between the original signal plans and some cycle, green split and offset optimised signal plans. Chapter 5 will discuss this scenario development process in relative detail.

3.7 Software model development

As mentioned, the software model development in Chapter 6 will focus on the Stellenbosch Model as well as the R44 Models. This part of the research project will incorporate all the specific modelling processes and procedures to ensure transparent and retraceable methods.

3.7.1 Stellenbosch travel demand Model

The Stellenbosch Model is where the setup of an acceptable and adequate simulation environment starts. This PTV Visum model of the main Stellenbosch area will not directly incorporate TASC measures but will be used to provide the supply network and demand. Reasonable detail as to the steps followed to create this foundational model will be discussed and analysed.

A specific point of discussion will be the use of the 4-step method to obtain AM zonal trip generation, distribution and assignment results. It is envisioned that the model will only include equivalent private vehicle volumes instead of complex modal split classifications in order to simplify the modelling process. Also, the use of matrix correction as a means to calibrate the model will be discussed, followed by the explanation of a PM matrix calculation. The model is anticipated to only include an AM and a PM modelling time frame to test the TASC system in these typical worst case scenarios. Statistical validation will be discussed as part of ensuring a representative model.

3.7.2 R44 Model with PTV Epics and Balance integration

3.7.2.1 R44 Macro Model

The R44 Macro Model is where the initial TASC modelling will take effect. PTV Balance- and Epics-specific modelling processes and parameters will be inserted and their modification will be explained. Detailed intersection geometry and signalisation control parameters will also be included at this stage of the modelling. The specific simulation approach and its parameters will be discussed and motivated in detail as well as a few challenges regarding our traffic environment and specifically their incorporation into the model will be addressed in this section of the report. Finally, the process of prepping and then exporting the macroscopic PTV Visum model to PTV Vissim is highlighted.

3.7.2.2 R44 Micro Model

After successful network generation via the import functionality from PTV Visum to PTV Vissim, the R44 Micro Model is where all the detailed simulations will take place to evaluate the operation of the road network. Before that, the final setup of the model will be explained in reasonable detail, including the fine-tuning of driving behaviour, train inputs, pedestrian modelling as well as a number of other factors. Ensuring that a realistic traffic environment is created will be a crucial part of the process at this stage. Seeing that only at this stage every individual entity is modelled, unrealistic behaviour will be easily identified and can then be addressed.

This model is where all the evaluations and results generation will take place. Therefore, the different scenarios will be created and evaluation parameters will be defined so that comparisons can be drawn.

3.8 Results interpretation and conclusion

Each of the various scenarios created in the R44 Micro Model will be simulated through 10 runs each with different random seeds to ensure sufficiently averaged result values. This data will include overall network delay, travel time and speed values as well as specific nodal and turning movement evaluations to obtain the change in average vehicle delay between some of the main scenarios of interest. Additionally, some corridor travel time measurements will be made and compared between scenarios.

This data will be processed and visualised using Microsoft Excel. The direct inclusion of several comparison criteria is important to exclude possible negative effects of one variable on another.

3.9 Limitations of the methodology

To increase the validity of the research project in general, it is important to identify and admit where limitations to the research are present and what the implications toward the outcomes are. In other words, to identify whether the limitations have a major effect or if the research can still be deemed successful and credible.

Firstly, there might be some minor deviations in terms of specific route choice options due to the nature of the data which was available for use during calibration. Nevertheless, these minor deviations should not in the least influence any comparative result evaluation between the different scenarios. It will still be fully evident which scenario carries best consequences.

The exclusive inclusion of only the AM and the PM peak periods might also be seen as a limitation. A fully developed daily model will however not be possible due to time and data constraints at start of modelling. Lastly, the use of only equivalent private vehicles in the model instead of a fuller range of vehicle types could be a limitation. Once again, the comparative approach to evaluation rules out any unreliability regarding the final verdict.

3.10 Research methodology summary

With the help of a properly formulated research methodology it becomes easier and more manageable to engage in the process of obtaining appropriate project outcomes that can be seen as credible, valid and reliable. This methodology laid out a research design and proposed a set of possible project outcomes. Thereafter, definition was given to the envisioned methods for data collection and processing, as well as for scenario development, software analysis and results interpretation. Finally, some possible limitations to this methodology were identified.

Chapter 4

MODEL COMPONENTS AND INFORMATION

4.1 Introduction

This chapter details the data and information with the corresponding sources which are to be used for the setup of the different modelling components. As mentioned in the Methodology, the model supply can be categorised according to the requirements for the Stellenbosch Model as well as the R44 Models, both Macro and Micro. **The way in which these components are then used and assembled to formulate a TASC system is explained in Chapter 6 of this report**.

4.2 Stellenbosch Model components and information

4.2.1 Background

Any macroscopic travel demand model requires specific components. These are basically included in **1)** a link and node structure representing the traffic network, **2)** a zonal system containing land use and population information and then **3)** some calculation process where the land use and population data is used to obtain zonal origin-destination (O/D) matrices for specific time periods. Brief reference will be made regarding the model components and data parts of the Stellenbosch Model as linked to these three steps.

4.2.2 Link and node structure

Regarding the link and node structure, the following information is required:

- Transport network
- Link type classification
- Intersection/Node type classification
- Link capacities
- Free flow speeds

The required link and node structure can typically be created from scratch or some third party provider can be utilised to generate a reasonably accurate network rather quickly. OpenStreetMap (OSM) (*OpenStreetMap*, 2017) was utilised in this case and the network structure can be seen in Figure 4-1. Link capacities are required for such a model and were based on general South African values, as well as the extensive experience of industry professional, Evan Roux, who assisted with the model setup. The aerial view background image was supplied by Bing Maps. Also required is an updated link classification scheme to represent the South African road classification and hierarchy standards. This was obtained from the Stellenbosch Municipality Roads Master Plan as well as the classification scheme presented in the TRH 26 (COTO, 2019).

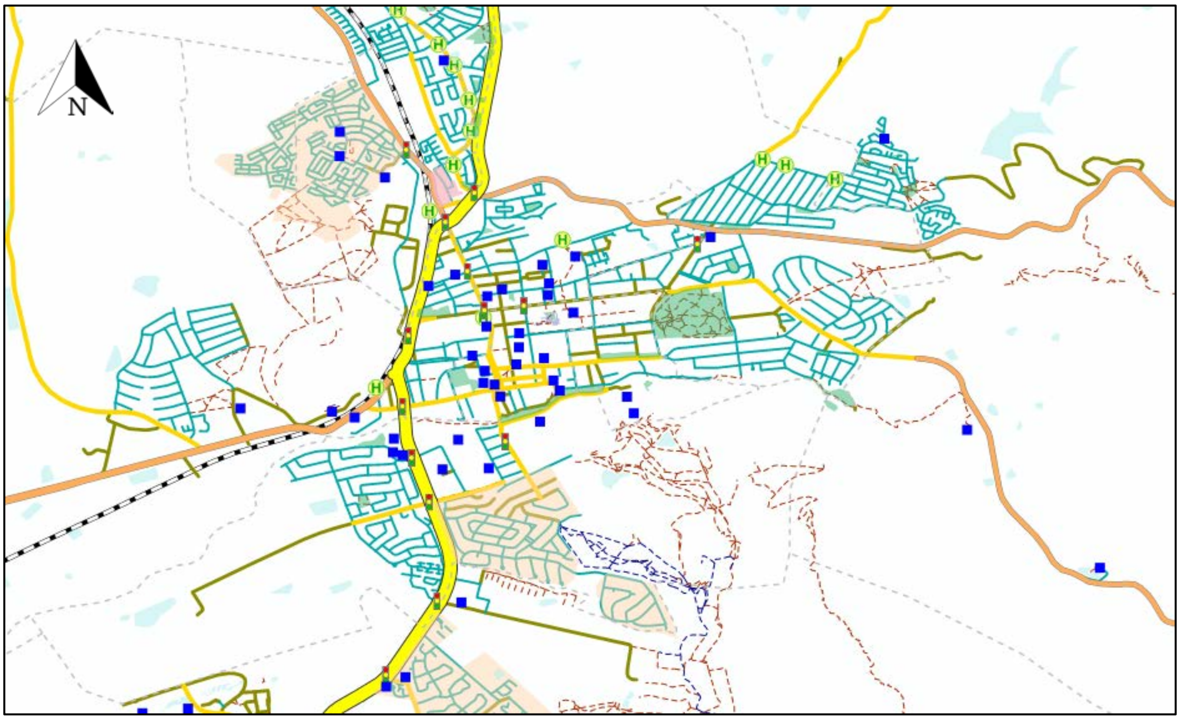

Figure 4-1: Unadjusted Stellenbosch OSM import

Also needed are the free flow speeds associated with each link, used to define Volume-Delay functions during model setup. These were obtained from TomTom and Figure 4-2 shows some of the free flow speed values within the network.

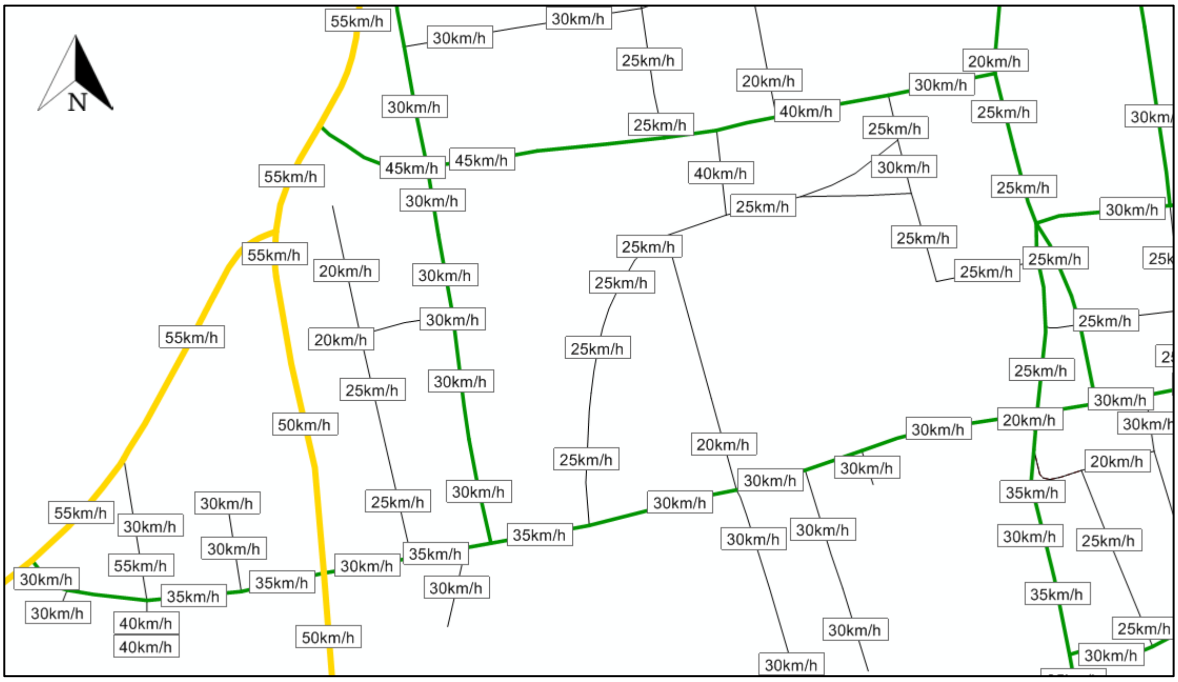

Figure 4-2: TomTom free flow speeds extract

TomTom data is described as Floating Car Data (FCD). Essentially what this means is that TomTom collects their traffic data from GPS probe devices in the traffic stream. Data collection is therefore not limited to one specific location but can span bigger traffic networks. This data can be processed in different ways including custom travel time analysis, custom area analysis, custom probe counts and speed profiles. The free flow speeds in specific are determined during the middle of the night when there is minimal traffic (TomTom, 2014).

4.2.3 Zonal system

The following zonal components are required for model setup:

- Land use zoning scheme
- Aggregated zones/ Ward zones

Regarding the zonal system for this project, the direct need was for specific zonal-based household-, land use- and population data. This information was provided by the Stellenbosch Municipality in the form of several shape files containing the Stellenbosch zoning scheme. Broader ward boundaries and information was obtained from Wazimap (Wazimap, 2019).

4.2.4 Calculation procedures

The following basic components are required for the setup of the calculation process within the Stellenbosch Model:

- 4-Step Method information
- Traffic counts for matrix correction
- Peak hour traffic periods

Data required for the 4-Step Method includes the factors used during trip generation, the utility function specifics used during trip distribution as well as trip assignment inputs. Required for the calibration of the model during matrix correction are counted turn-specific traffic volumes on every intersection in the R44 subnetwork. The counts were provided by Nick Venter Traffic Surveying (NVTS) and Figure 4-3 indicates the locations for the available AM and/or PM peak traffic counts, inclusive some in the wider Stellenbosch area.

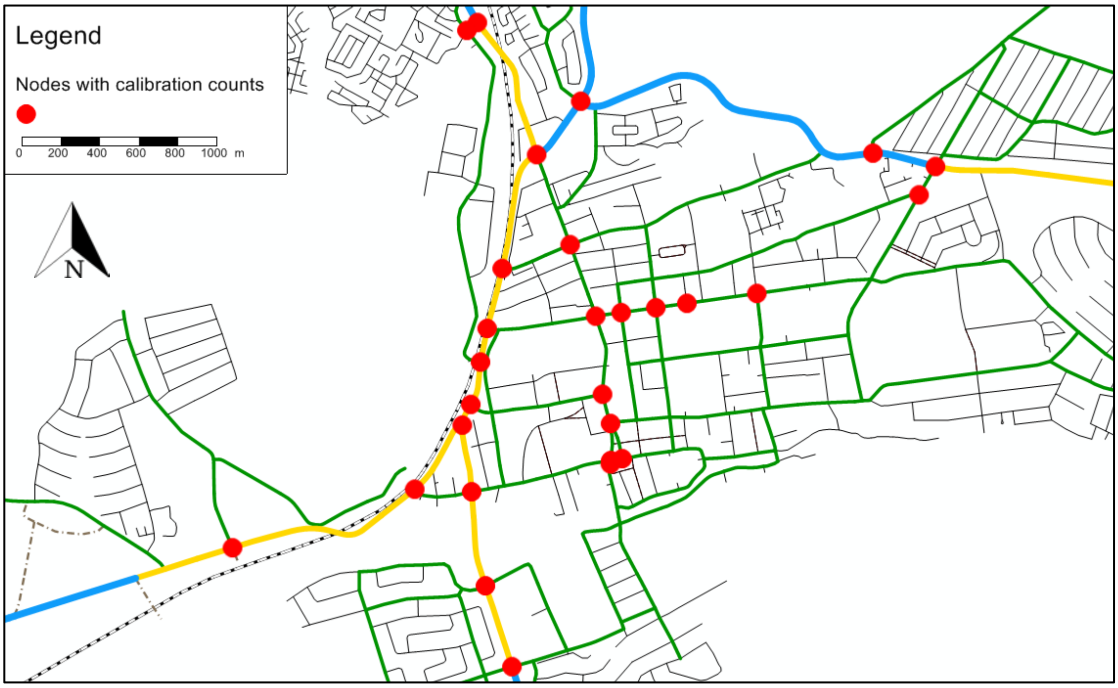

Figure 4-3: Locations for traffic counts utilised during calibration

The peak hour periods, for which the calibration counts are to be inputted and for which the AM and PM peak hour matrices will be calculated, were determined from all-day count distributions done by NVTS during October 2018 at the locations seen in Figure 4-3. The peak periods were found to be 07:00-08:00 for the AM and 16:30-17:30 for the PM peak. Figure 4-4 indicates the count distribution per 15 minute interval for the full R44/Van Rheede Rd intersection, showing the defined peak periods. Further distribution graphs can be seen in Appendix A, Figure A-1 to Figure A-4.

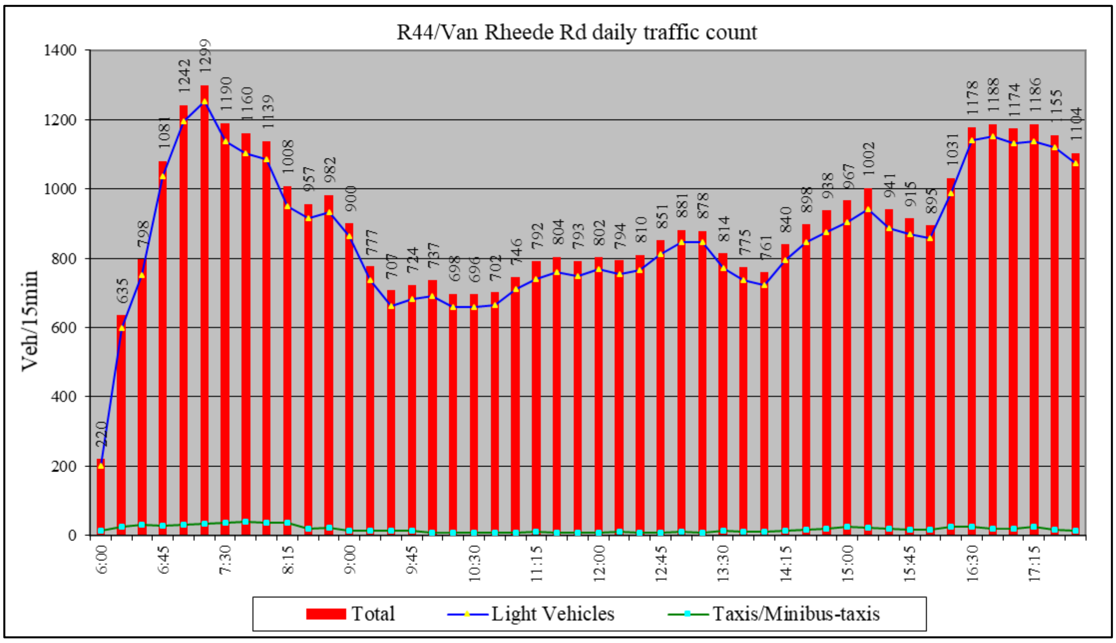

Figure 4-4: R44/Van Rheede Rd daily full intersection traffic count, October 2018 (NVTS)

4.2.5 Summary

Table 4-1 below summarises the data components and other information required for the setup of the Stellenbosch Model.

Table 4-1: Stellenbosch Model data components and sources

Modelling Step	Model Component	Source
1. Links and Nodes	Network	OpenStreetMap
	Link types	TRH 26/COTO
	Link capacity	COTO/Field experience
	Free flow speeds	TomTom
	Background	Bing Maps
2. Zones	Land-use SHP files	Stellenbosch Municipality
	Ward SHP files	Wazimap
3. Calculation	4-Step Method info	Field experience
	Calibration counts	NVTS/ Stellenbosch Municipality/ WSP

4.3 R44 Model components and information

4.3.1 Background

The R44 Models will span over two different spheres of modelling, namely macroscopic and microscopic. The nature of the data supply as required for PTV Epics and Balance specifically calls for this kind of setup, as explained in the literature study. This stage of data supply correspondingly sees a split as related to the data and information source classification required for the model setups. One supply side will be taken straight from the broader Stellenbosch Model, whereas the other side will originate from manual input definitions.

4.3.2 R44 Macro Model

For the setup of the macro part of the R44 Model, the following data components are required:

- Subnetwork
- Hourly Origin-Destination matrices
- Geometric layout of each junction
- Current signal plans and related info
- Current and planned detection info
- Peak period calculation intervals

The subnetwork as well as the O/D matrices are PTV Visum-based data inputs from the Stellenbosch Model. The geometric layouts, current signal plans, detection info and peak period calculation intervals are based on manual inputs.

4.3.2.1 Stellenbosch Model data supply

Seeing that the R44 study area will only be a subarea of the greater Stellenbosch Model, use will be made of the subnetwork generator to obtain this subarea. Figure 4-5 shows the required subnetwork area. The O/D information will be calculated separately for each hourly AM and PM peak hour in the Stellenbosch Model and then exported and imported also into the smaller R44 Macro Model. These hourly matrices form the underlying time slices upon which the system will be built and can be seen in Appendix A, Figure A-5 to Figure A-7, with corresponding zonal definition.

Figure 4-5: R44 subnetwork location within the town of Stellenbosch

4.3.2.2 Manual data supply

The level of manual input into the R44 Macro Model will be quite extensive and various data components are required. Firstly, junction geometry information will mostly be taken from field measurements of the area, as well as from Bing Maps aerial imagery. The measurements of importance required for this are the number of lanes, lane widths, turning movements, stop line and signal head positions, channelised turns as well as median widths and auxiliary lane lengths.

Also required are the signal control measures as these will also form part of the export/import parameters. The definition of the signalisation will firstly require the current signal plans. These were provided by Syntell (Pty) Ltd via the Stellenbosch Municipality. The aspects of importance, to be extracted from the signal plans, are listed hereafter:

- Signal groups with lane turn definition
- Stages as a combination of signal groups
- Inter-green values (all-red and yellow intervals)
- Cycle lengths
- Signal programs with stage sequences (AM and PM)
- AM and PM peak intervals

The larger peak period **intervals** to be used in the signal plans will be based on the current peak hour signal plan distribution used by the Municipality. These are from 6:30 – 9:00 in the AM interval and from 15:30 – 18:00 in the PM interval, 2.5 hours each.

Lastly, vis-à-vis the manual data input, all information relating to vehicle detection is required for the model. This includes the previously used and current type of detection, the position of detectors relative to the stop line as well as the upgrades to newer methods of detection. Specifically required is the positioning of older inductive loop detectors, whether they are still functional as well as whether they are set up as *per lane* or *per several lane* detection. At the time of this research the municipality was upgrading the intersection detection method to use TrafiCam X-stream camera detection. All related information is therefore also required. This detection information was either accessible via the Municipality of Stellenbosch or obtained during site visits.

4.3.3 R44 Micro Model

The R44 Micro Model requires the following data and information components for setup:

- Network export data
- Demand and route data
- Shared signalisation files
- Train schedule
- Pedestrian input volumes

The network data (.anm file) and demand data (.anmroutes file) is required for import into PTV Vissim for the stipulated time intervals. These files will incorporate, in the case of this project, data supply and simulation results all the way back to the Stellenbosch Model.

The externally saved signalisation files (Vissig/.sig files) that will be created during the R44 Macro Model definition, are also required for the R44 Micro Model. All changes and adaptations to the signal plans for various scenarios are discussed in Chapter 6, section 6.3.3. Official train schedule times are required for the necessary inclusion of the train line within the R44 Micro Model (CTTRAINS, 2019). Location of this train crossing can be seen in Figure 4-6. The last important data supply aspect to the R44 Micro Model is the required pedestrian volume at the two separately signalised pedestrian crossings, also indicated in Figure 4-6. Supply of these volumes was taken from counts done by WSP Consulting, via the Stellenbosch Municipality.

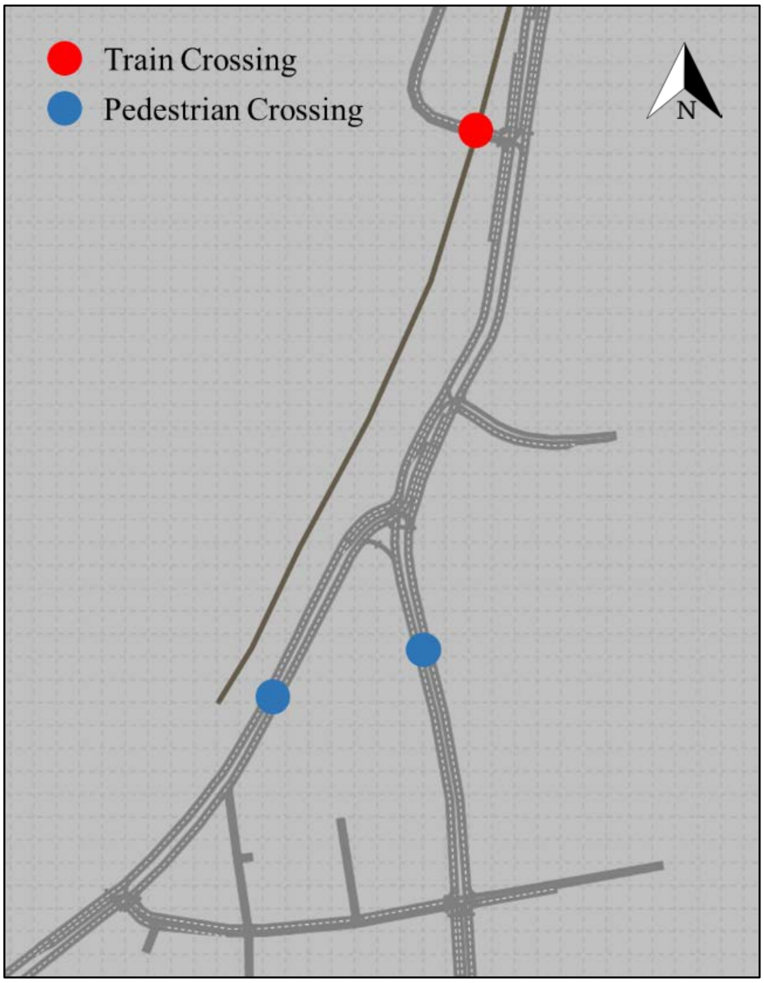

Figure 4-6: Location of train crossing and signalised pedestrian crossings

4.3.4 Summary

Table 4-2 below summarises the various data and information components, as well as their respective sources, required for the R44 Model setup.

Table 4-2: R44 Model components and sources

Modelling Sphere	Model Component	Source
1. R44 Macro Model	Subnetwork	Stellenbosch Model
	Hourly O/D matrices	Stellenbosch Model
	Junction layouts	Site surveys/Bing Maps
	Signalisation aspects	Syntell
	Detection data	Stellenbosch Municipality/Site
2. R44 Micro Model	Network export data	R44 Macro Model
	Demand and route data	R44 Macro Model
	Shared signalisation data	Vissig files
	Train schedule	CTTRAINS
	Pedestrian inputs	WSP Consulting

4.4 Model components and information summary

This chapter served the purpose of informing the reader of the various model components, data and information aspects, together with their sources, required for adequate model setup. Reference was made to the broader Stellenbosch Model as well as the subnetwork R44 Model, being split into the PTV Visum R44 Macro Model and the PTV Vissim R44 Micro Model. Each model's components and data requirements were summarised in table format in sections 4.2.5 and 4.3.4 respectively. Detail was given as thought to be sufficient in providing an adequate underlying understanding of the model components required for the model setup explained in Chapter 6. Further information can be found in Appendix A – Model Components & Data, as well as by contacting the author directly.

Chapter 5

SCENARIO DEVELOPMENT

5.1 Introduction

Having defined the extent of all required model components and information in the previous chapter, proper definition needs to be given to the way in which differing scenarios are set up to ensure adequate results comparison. This scenario development is set up and explained prior to the actual model set-up (Chapter 6) so that a better understanding is created regarding the TASC system and its various components.

5.2 Scenario sets

Three sets of scenarios were defined, each controlled by a different set of signal plans, as well as different vehicle detection conditions. Also, each scenario was executed for both the AM and the PM peak period. Each scenario included the signalised pedestrian crossings as well as the actuated train crossing without any alteration between scenarios. The three "sets" of signal plans can be summarised as follows and are then explained thereafter.

Scenario-set 1: Using plans adapted from the original plans to enable TASC control.

Scenario-set 2: Using exclusive inductive loop detection as opposed to the camera detection.

Scenario-set 3: Using the original plans (do-nothing scenarios).

5.2.1 Scenario-set one

The first set includes the bulk of the scenarios, 16 scenarios in total, as it is expected that the optimal scenario will be found in this set. This was an assumption, yet the inclusion of the other two sets of scenarios will prove this either wrong or right.

Scenario-set one incorporates signal plans which are slightly adapted from the original plans to provide equal cycle lengths for ease of coordination as well as some minor logical plan changes to accommodate the difference in operation between different signal control software (such as the removal of duplicate stages, which is not acceptable in Vissig). This set of scenarios included various control mechanisms: either fixed-time, only local control, only global control or a combination of local and global control, using either no detection or TrafiCam X-stream detection (as defined in Chapter 6). Also included in these plans is the optimisation of either only the offsets between the signal plans or an optimisation of the offsets and the green split times within each signal program. A scenario is also added to test individual cycle length optimisation and the effect it would have on TASC control.

Each scenario, for the AM and PM peak respectively, is discussed hereafter.

5.2.1.1 Scenarios 1&2

Scenarios 1&2 applies the signal plans for this scenario-set in purely a fixed-time manner, implicating worst-case traffic conditions in a fully loaded network. Also included is an offset optimisation.

5.2.1.2 Scenarios 3&4

Scenarios 3&4 use the same signal plans as scenario 1&2 i.e. also fixed-time, with the exception that they include a green split optimisation additionally to the offset optimisation.

5.2.1.3 Scenarios 5&6

Here the plans for *scenario-set one* are applied with PTV Epics local optimisation only, using the TrafiCam X-stream vehicle detection and inclusive of the offset optimisation.

5.2.1.4 Scenarios 7&8

Scenarios 7&8 as opposed to scenarios 5&6 only use PTV Balance global optimisation, also with the TrafiCam detection and offset optimisation.

5.2.1.5 Scenarios 9&10

Scenarios 9&10 make use of a combination of local and global control, PTV Epics and Balance, with TrafiCam detection. Important to note is that only offset optimisation is used here and not green split optimisation also.

5.2.1.6 Scenarios 11&12

Scenarios 11&12, then, are a copy of scenarios 9&10, except that this set includes green split optimisation on top of the offset optimisation and camera detection.

5.2.1.7 Scenarios 13&14

These two scenarios are special cases as they exclude any sort of signal control at R44/Alexander St. intersection. Currently this intersection is controlled by a points-man and thus very difficult to simulate. The signalisation of this intersection is in planning and thus all other scenarios include this signalisation, yet the unknown effect of a two-way stop controlled intersection as part of a TASC system warranted this scenario from a research perspective. Apart from the exclusion of Alexander St. these scenarios are copies of scenarios 11&12.

5.2.1.8 Scenarios 15&16

Scenarios 15&16 also represent copies of scenarios 11&12, except that they include an individual intersection cycle length optimisation to test the effect of unequal cycle lengths on a TASC system.

5.2.2 Scenario-set two

The second scenario-set only includes 4 scenarios, based on the envisioned best scenarios of *scenario-set one*. In essence, *scenario-set two* uses the same signal plans as set one, except that the entire detection method is changed from the camera detection to the best representation of what the presently functional inductive loop detection would be. The reason why this was done, was to test what such a TASC system would do if the detection were not uniform and specifically if the detection incorporated non lane-based detection.

The assumption was that the best results of scenario-set one would be obtained from either scenarios 9&10 or 11&12. Thus, the change in detection configuration was only applied to these signal plans.

5.2.2.1 Scenarios 17&18

Scenarios 17&18 thus made use of PTV Epics and Balance TASC control, based only on the inductive loop detection and still including offset optimisation, yet not green split optimisation (based on scenarios 9&10).

5.2.2.2 Scenarios 19&20

Scenarios 19&20, conversely, had the same setup, except that green split optimisation was also incorporated (based on scenarios 11&12).

5.2.3 Scenario-set three

The third scenario-set was one that could not be excluded. This scenario-set included, as best possible, the very original, currently used signal plans. This means they do not include equal cycle lengths, making it impossible to effectively coordinate. This was in essence the base-scenario which the best scenario would be compared to in identifying the change in certain traffic parameters after TASC implementation. Important to note here is the inclusion of signalisation at R44/Alexander St. intersection even though there is no signalisation currently present. This is to create a comparatively equal platform between different scenarios as the inclusion of said signalisation in one and the exclusion in another scenario would render them incomparable. Signalisation at R44/Alexander St. was modelled after the R44/Merriman Ave. signal plans seeing that they present near identical geometrical layouts.

5.2.3.1 Scenarios 21&22

These last two scenarios, then, include a simple fixed-time representation of the current signal plans, implying the worst-case scenarios during peak hours, excluding offset, green split or cycle length optimisation.

5.3 Scenario development summary

The scenario development chapter focused on providing insight into the different comparison scenarios and the motivation behind them. This is discussed prior to in-depth model setup to ensure a better understanding regarding the TASC system. Table 5-1 below provides a summary of all applicable scenarios.

Table 5-1: Summary description of the different evaluation scenarios

Scenario no.	Scenario description (AM & PM)
1 & 2	Fixed-time signal plans including minor changes to base plans + offset optimisation
3 & 4	Fixed-time signal plans based on 1&2 + offset and green time optimisation
5 & 6	PTV Epics local optimisation based on 1&2 + offset optimisation (Cam detectors)
7 & 8	PTV Balance global coordination based on 1&2 + offset optimisation (Cam detectors)
9 & 10	PTV Epics + Balance control based on 1&2 + offset optimisation (Cam detectors)
11 & 12	PTV Epics + Balance control based on 3&4 + offset + green time opt. (Cam detectors)
13 & 14	PTV Epics + Balance control based on 11&12 without Alexander St signalisation
15 & 16	PTV Epics + Balance control based on 11&12 + individual cycle length optimisation
17 & 18	PTV Epics + Balance control based on 9&10, only offset optimisation (loop detectors)
19 & 20	PTV Epics + Balance control based on 11&12, offset & green time opt. (loop detectors)
21 & 22	Base signal plans in fixed-time format without any optimisation

Chapter 6

SOFTWARE MODEL DEVELOPMENT

6.1 Introduction

This chapter highlights, in reasonable detail, the process and methods followed during the setup of the various modelling components in order to motivate and justify the reliability of the resulting output values. The entire modelling process is not explained in full detail as it is not the scope of this research. However, reference will be made regarding additional information that can be obtained if further understanding into the process is required.

As already evident from the literature study and the model components chapter, the data supply chain included the PTV Visum macroscopic Stellenbosch Model feeding into the PTV Visum subnetwork R44 Macro Model which in turn provides data supply to the final PTV Vissim R44 Micro Model. Each step of this modelling process is explained in reasonable detail.

It is important to note that the setup of the comprehensive Stellenbosch Model was not purely intended for this project but feeds into the research of other projects as well. Work on the model was therefore partially tasked to the author as well as Dominique ter Huurne, a PhD candidate at the Stellenbosch University. This was additional to the input and experience of industry professional, Evan Roux, who assisted with the model setup.

6.2 PTV Visum Stellenbosch Model

Following the layout as found in the model components chapter, the modelling process is briefly explained according to the following categorisation: Network link and nodal structure, zonal system and calculation procedures. Since the work effort regarding this model was shared and not of main focus in this thesis, the possible omission of explaining some steps in detail is probable.

6.2.1 Link and node Structure

From the OpenStreetMap (OSM) network structure imported into PTV Visum, the base network was obtained. Several simplifications, corrections and definitions had to be made.

6.2.1.1 Simplifications and corrections

Firstly, all unnecessary link types were removed from the import and the network was cut down to a more manageable size. This was then followed by specific simplification of the directional link designation. One link per direction was altered to one for both directions. This reduces, directly, the number of defined nodes and makes the modelled intersection control more realistic, as can be seen in

Figure 6-1 below. Also, since the OSM import is not perfect, small alterations were made, such as the side of driving and the addition of some minor omitted links.

Figure 6-1: Simplification of the original OSM network import in terms of the directional link designation

6.2.1.2 Definitions

After some simplifications and corrections were made, several network definitions were incorporated. Specifically, the different node types, i.e. signalised, roundabout etc., were given. On nodal level attention was given to the specific turning movements which were open or closed. An example of such alteration is at R44/Dorp St. intersection were two right turns are closed and thus had to be defined accordingly.

This was when the link classification was also added. An alteration which was made to the Stellenbosch Roads Master Plan classification scheme was the classification of Merriman Ave. which is currently classified as a Class 3 arterial, but is in fact a Class 4 collector road, as defined according to TRH 26 standards. Relating to links also, the number of lanes and the associated capacity values were checked and corrected were applicable.

Figure 6-2 shows an extract of the model with updated link classification. Figure 6-2 also shows the different intersection control types required within the network.

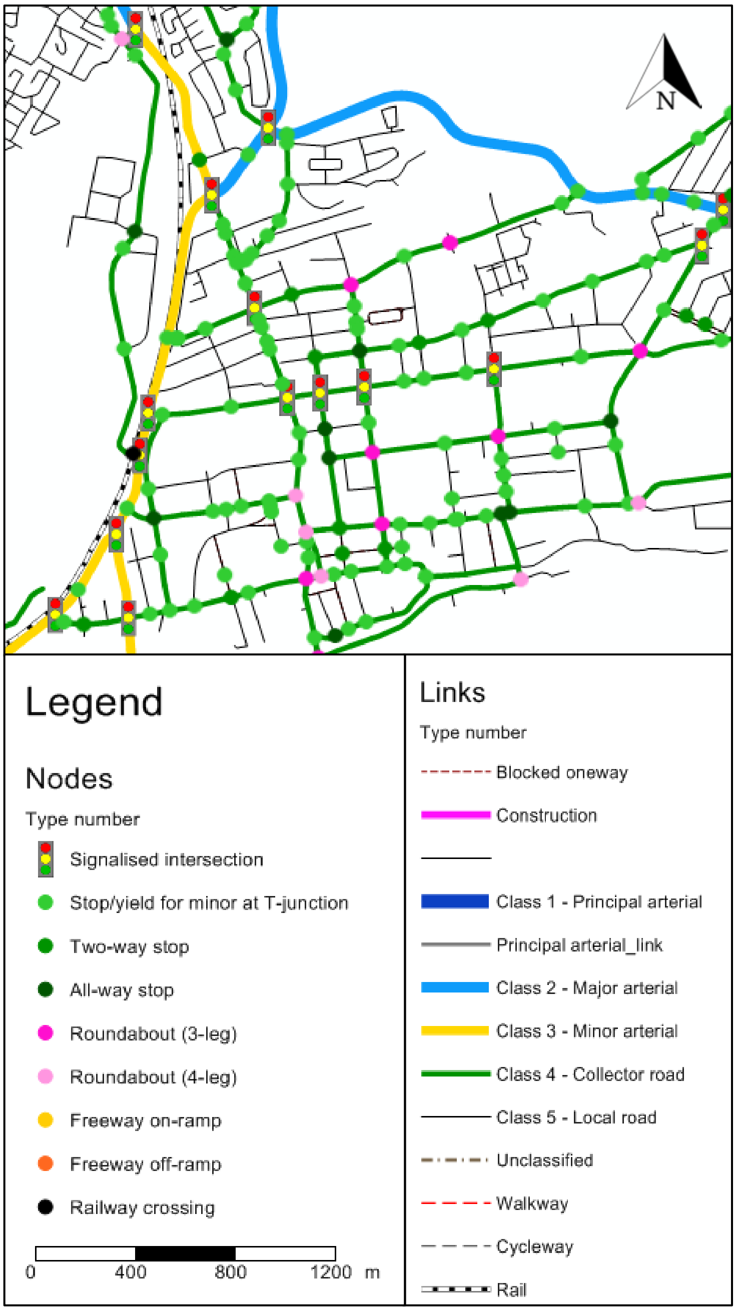

Figure 6-2: Extract of the model link classification (bottom right) and intersection control types (bottom left)

6.2.2 Zonal system

The zoning scheme and ward shapefiles were imported, inclusive of their zone-specific data. This consists of property zones aggregated into manageable and referenceable traffic analysis zones (TAZ's), which in turn are combined to match the ward boundaries. The property zoning types are differentiated into a number of categories. Of importance are the conventional residential (CR), less formal residential (LFR), multi-unit residential (MR), local business (LB), mixed use (MU), industrial (I) and education (E) zones. The important information included in these zones was either the number of units or the area related to the land use type to be used in the calculation process. Figure 6-3 displays the progression of zonal detail from ward level to TAZ level all the way down to individual property level. Where the zoning scheme definitions were somewhat inaccurate or not relatable to the actual land-use, changes were made. It becomes obvious thus, that the local knowledge of an area is very important in defining a travel demand model, especially were data is not always as readily available or well defined.

An important part of the zonal system is the sensible definition of connectors between a zone and the road network. Essentially, any number of connectors can be defined per zone with a given percentage share of the zone-related traffic volume flowing via each connector. The appropriate placement of where these connectors attach to the network was important to keep in mind since this influences the way in which traffic "flows" between zones.

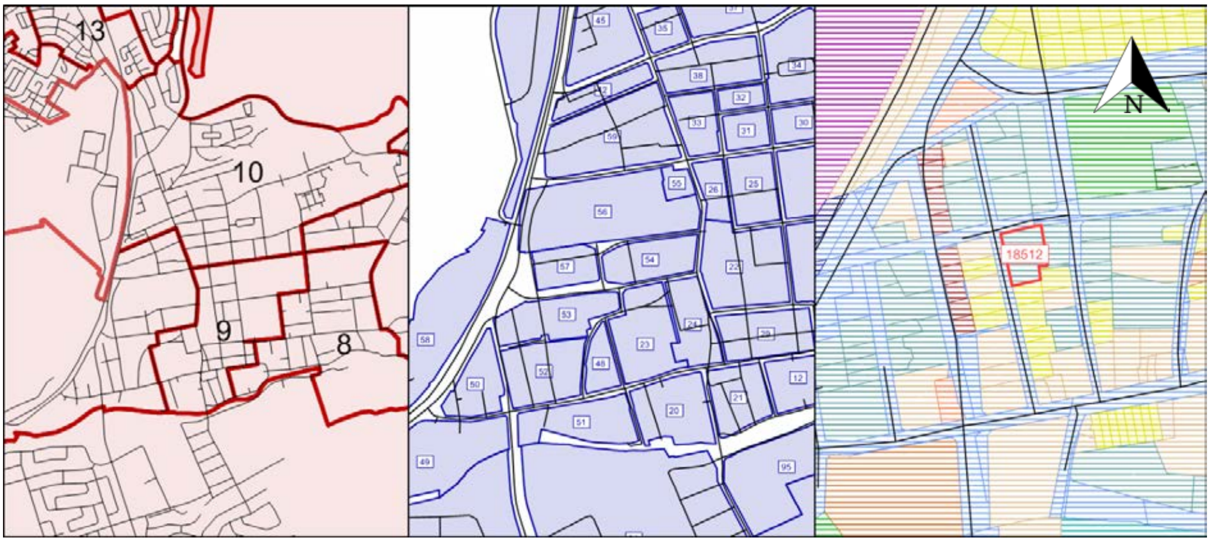

Figure 6-3: Progression of zonal system from ward level to traffic analysis zones (TAZ's) to property zones (left to right)

6.2.3 Calculation procedures

The calculation procedure is where all the previous definitions and model components were combined to obtain useful turn- and link- based traffic volumes relating to a calculated O/D matrix. Several parameters had to be set and defined. The simulation run containing the calculation sequence follows a so called procedure sequence.

6.2.3.1 AM peak procedure sequence

The method used during the calculation process was the well-known 4-Step Demand Model. In essence, these 4 steps are defined as trip generation, trip distribution, modal choice and trip assignment as explained in section 2.12 of the literature review. In this model the assumption of equivalent private vehicles was made, once again for simplicity's sake, which negated the need for the modal choice step. Other demand model options are available such as the EVA passenger demand or tour-based models, yet for the type and availability of the obtainable data, the 4-Step Method was seen as most applicable.

Within the 4-Step Model itself, further detailing and stratification of person groups and activity pairs could have been achieved, given sufficient time and data availability.

Trip generation requires a calculation formula by which the number of attractions and productions in person trips are obtained for each zone. The setup of each of these formulae was facilitated by industry professional Evan Roux. Additionally, the attraction values had to be balanced to the total productions so that the total productions equals the total attractions, which is a requirement. Balancing is always done to the productions since they are generally based on more accurate data.

Trip distribution, then, used the productions and attractions within a choice model based on trip distance and travel time to define the number of trips going from one zone to another. Once again, the setup of this choice model was assisted by Evan Roux. Essentially after this trip distribution, the O/D matrix is obtained. During the trip assignment step, this previously calculated matrix was then assigned to the network in a realistic manner, identifying specific route choices people would make to get from one destination to another and yielding specific traffic volumes within the network.

Calibration is the most important step in any traffic model. Without calibration it would be impossible to know whether the assigned traffic volumes are actually representative of reality or not. In this case calibration was done with the help of the available traffic counts. An iteration loop was set up, allowing for a certain maximum change within the matrix, to alter trip distribution and assignment in the model until a satisfactory level of correlation is achieved between the modelled vs the counted traffic volumes. Needless to say, if the initial trip generation was way off, it becomes extremely difficult to properly calibrate a model. As seen in Figure 4-3, the available counts were well placed in the area of interest and thus a satisfactory calibration would mean that the subsequent use of generated O/D matrices over that corridor can be sufficiently motivated in terms of accuracy. Figure B- 1 in Appendix B indicated the goodness of fit between the modelled and the counted volumes after calibration took place. To be noted is that both the slope and the statistical R^2 values are very close to 1, which is ideal.

6.2.3.2 PM peak procedure sequence

Having completed the calibration of the AM matrix, a subsequent PM matrix could then be generated. The easiest and most sensible option to be used here, in absence of any other, more accurate information, was to simply transpose the AM matrix and set up another iterative calibration loop using the respective PM traffic counts. This is a relatively easy operation and the goodness of fit between the counted and the modelled values can be seen in Figure B- 2 in Appendix B. Here once again the slope as well as the R^2 values are close to 1.

6.2.4 Subnetwork generation

After the AM and the PM calculation procedures were completed and the calibration had yielded acceptable results, it was necessary to define a clear split between the greater Stellenbosch Model, with all other projects related to it, and the R44 TASC project. For this to take effect, the specific subnetwork in consideration for the TASC application had to be cut out of the model. This was done by defining a subnetwork area and then exporting this subnetwork area of the model inclusive of the calculated demand matrices. These new matrices where then no longer based on the TAZ's, but rather on new input zones; zones created at all the input points to the network between which the trip distribution was defined, as can be seen in Appendix A, Figure A-5. This process of exporting new demand from the Stellenbosch Model could be repeated for the AM and PM peak whenever small changes were made in the bigger model. This workflow is rather convenient as the demand modelling does not have to be repeated in the R44 Model again.

6.3 R44 Macro Model with PTV Epics and Balance integration

Allowing the supply process to flow via the macroscopic level of modelling greatly reduces the level of difficulty associated with creating a microscopic model. This is due to the fact that the PTV Vissim model does not have to be built from scratch but a big part of it is generated using the export/import functionality provided in PTV Visum/Vissim. Another reason why the supply follows a route via the macroscopic modelling sphere is that PTV Balance in principle obtains its data supply from PTV Visum. This was expanded on in the literature review.

Essentially, the R44 Macro Model is where the TASC modelling starts to take effect. A number of different parameters had to be defined, as well as a specific modelling sequence was required in order to make this system work.

6.3.1 General considerations and parameters

Some general considerations need to be kept in mind when working on such a model. First and foremost, the aim is to create a realistic traffic representation and if to achieve that some "unrealistic" alterations need to be made to the network this is justifiable. One such alteration was too extend the input links leading into the network longer than in reality in order to allow realistic inflow of vehicles into the model.

Another aspect to bear in mind is that this network needed to be suitable for the abstract-network-model (ANM) export to PTV Vissim. The following was important:

- Connectors must not be connected to nodes that represent a physical intersection
- No node may have more than one connector per direction
- No zone may have more than one connector per direction

For these reasons it is beneficial to have imported the demand matrices as described in section 6.2.4 and to have the data supply defined as it is. One of the many parameters worth mentioning is to set the assignment to "*save paths as connections*" in order to save the assignment routes to the .anmroutes file, also required for the export.

6.3.2 Junction editing

First focus in the R44 Macro Model was given to the appropriate definition and editing of each junction within the subnetwork. Here, initially, the proper layout and number of lanes and lane turns were checked as well as the consistent definition of allowed traffic systems between the lanes and their consecutive lane turns (i.e. whether they are open to Car, Bus, HGV etc.). This should already be contained correctly in the subnetwork from the Stellenbosch Model. Attention was given to the definition of auxiliary lanes, slip/channelised turn lanes and, where applicable, median presence. All these lane lengths and median widths were either based on the Bing Maps background lengths or measured out in person where discrepancies were visible. Also added to the model were crosswalk locations at all intersections. These were, however, not utilised during evaluation except for the individually signalised pedestrian crossings mentioned in section 4.3.3.

The next part of junction control was to define an external signal control of type "Epics/Balance local" for each intersection. Within these signal files (.sig files) at this stage only the signal groups (as seen in example Figure B- 4 in Appendix B) were defined. This was so that the signal groups could be linked to their respective lane turns within the junction editor.

Additionally, an important step during junction editing, was the correct placement and description of all the various detection options. As mentioned in section 4.3.2.2 the original inductive loop detectors as well as the envisioned camera-based vehicle detection was to be tested and evaluated. All these detectors were placed at their respective distances from the stop line, allocated to a signal controller and given a channel number for reference in the .sig files. The envisioned TrafiCam detectors were all placed at a consistent 5m and 20m upstream of the stop line per lane as can be seen in Figure 6-4, a PTV Vissim-equivalent representation of the R44/Van Rheede Rd. intersection. Actual TrafiCam detection data could not been incorporated at the time of this research, yet the exact positioning was adopted to use simulated values generated within to modelled environment to test the TASC system based on this detection mechanism. A typical real-life layout of the TrafiCam configuration can be seen in Appendix A, Figure A-8.

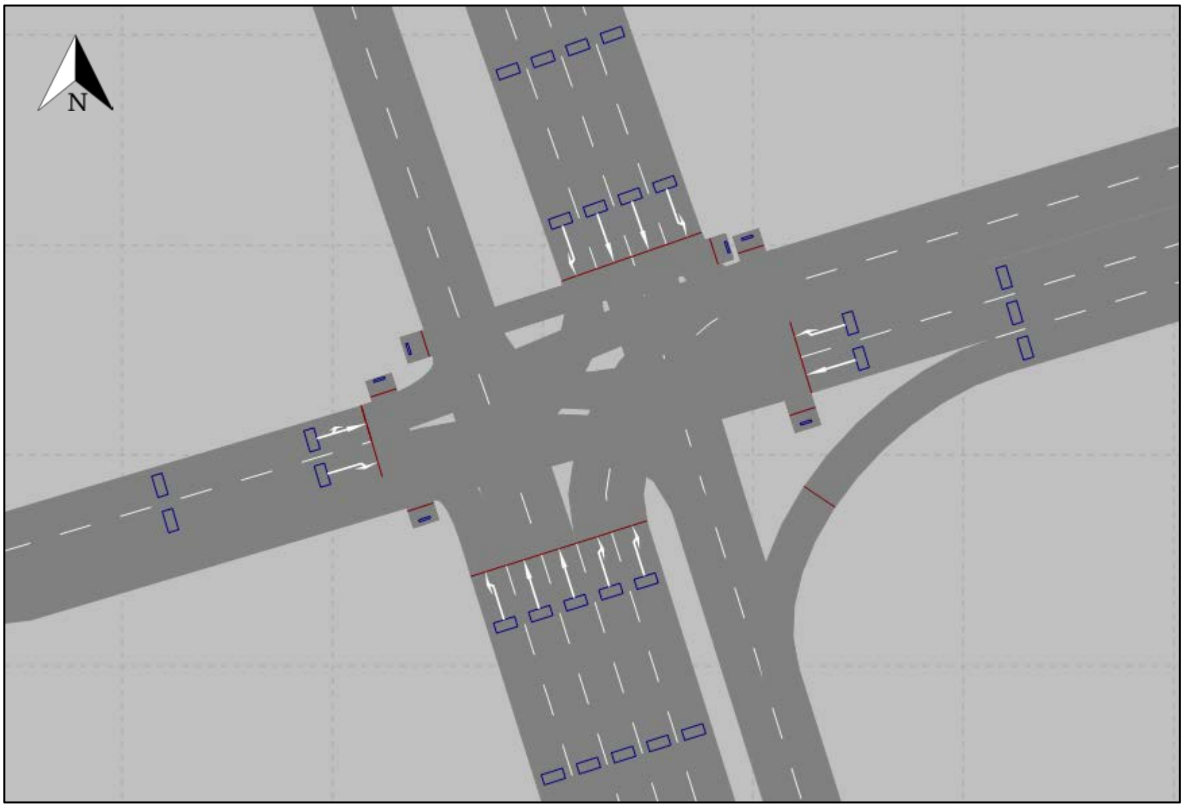

Figure 6-4: PTV Vissim equivalent layout representation of the TraffiCam detector positions at 5 and 20 meters (blue rectangle)

6.3.3 Signal control editing

After adequate junction layout, special attention was given to the correct setup and further editing of all signal control data. A number of different signal control pieces had to be put together and were added to the .sig files, all in accordance with the signalisation specifics allocated to each evaluation scenario given in Chapter 5. Many of the default definitions and values were obtained from the Syntell plans.

Firstly, already having allocated each intersection's signal groups, the intergreen matrices between the signal groups had to be formulated. This essentially entails the summation of the yellow time and all-red time intervals between the groups in order to ensure that the intersection clears before a new stage starts. It is a safety-critical value and may not be violated by any optimisation procedure. The majority of the original Syntell plans were based on an inter-green value of 5 seconds, i.e. 3 seconds yellow time and 2 seconds all-red, except for a few longer turning movements. Following this, the stages where defined as a sensible combination of signal groups. These stages were in turn expressed within a sequence to define a signal program. In between the stages within the signal program sequence, Vissig, the PTV external signal control program, automatically creates so called interstages. These interstages enforce the previously mentioned intergreen values.

The green split definitions which were used in the signal programs were also taken from the Syntell plans. However, because PTV Epics and Balance start their local and global optimisation from the base of a fixed-time plan and the original plans were provided in an actuated control format (i.e. minimum and maximum values for the green splits were given) it was necessary to assume the worst case scenario and use the maximum green splits. This is a very justifiable decision as signal timing measurements during the peak hours yielded the exact maximum green splits at all monitored intersections.

Using these same maximum green splits within the signal program definitions yielded a cycle length value of 144 seconds for 7 of the 10 intersections. Based on this, and referring back to the scenario definition in Chapter 5, the decision was made to use an equal cycle length of 144 seconds over the corridor in order to allow for more effective coordination between intersections. This was then applied to the set of signal programs used in scenario-set one. The different signal plan optimisation techniques (offset, split and cycle) applied to the different scenarios are discussed during the procedure sequence definition hereafter, as well as in the R44 Micro Model description.

Remaining, then, to be set up within the .sig files were the PTV Epics- and Balance-specific parameters. Essentially, here the minimum and maximum allowable alterations to the signal programs are specified and it can be chosen which interstages are used, i.e. time and duration constraints of stages and interstages are specified. Vissig generates default values here which are based on the given signal program and thus acceptable for use. Most importantly, at this stage, it must be defined whether the signal program is altered by exclusive local optimisation, i.e. PTV Epics, or by exclusive global coordination, i.e. PTV Balance, or by the extent with which both PTV Epics and Balance work together. The degree of local vs global control can be configured to create varying levels of control options. In the case of this project, different signal programs were created to be either purely local control or purely global control or a combination of both, which was set up to have a relatively medium PTV Balance influence of 3/5.

For the train and pedestrian crossings, it was necessary to define two signal groups and set the “actuated” group, i.e. train or pedestrian actuated, to non-cyclical. This means that the signal group is only activated when triggered by train detection or via the pedestrian push buttons. Usually one would use VisVAP (Visual Vehicle Actuated Programming) to define such actuated control within the PTV Vision Suite, yet the Epics/Balance signalisation control eases this setup by allowing non-cyclical signal group allocation.

An aspect that was initially set up within the .sig file were *daily signal program lists*. This is a necessary addition when applying such a system over the entire day. However, as this model only focused on AM and PM peak comparisons this was not necessary.

Lastly, and also importantly to be defined, were the signal coordination groups. Initially it was thought to split the subnetwork into several coordination groups but seeing that the network is relatively small and intersections are within minimum distance separation requirements from each other (section 2.2.2.4), one coordination group was assigned to all the signalised intersections and the cycle length family of 144 seconds was used.

A typical layout of signal groups, stages and their sequences can be found in Appendix B, Figure B- 4 for R44/Helshoogte Rd. Figure 6-5 shows the graphical representation of a stage-based signal program layout after input of all the relevant information into PTV Vissig.

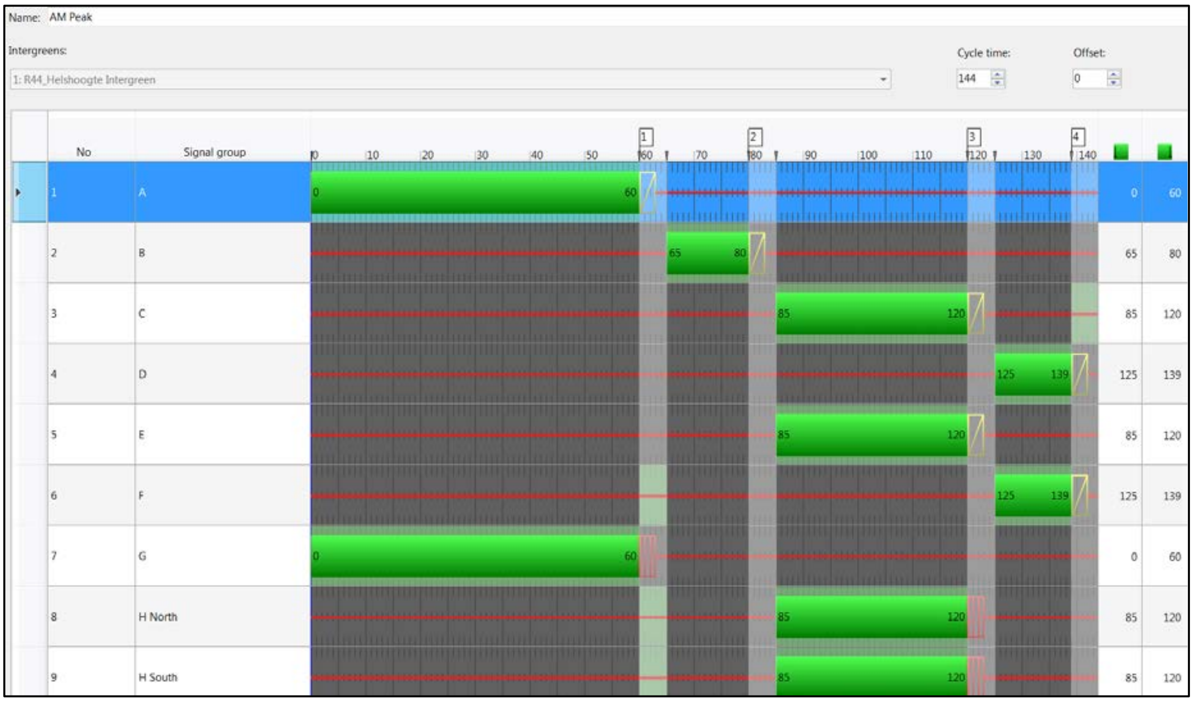

Figure 6-5: Graphical signal program representation

6.3.4 Procedure sequence definition

Once proper definition has been given to all junction layout and signal control aspects and all other imported data is available, the procedure sequence can be added. However, before this procedure sequence was formulated, it was important to ensure that indeed everything was supplied and defined correctly. A built-in check system provided in PTV Visum is the “network check”. This will run through a check list for anything from checking for logical network consistency to ensuring consistent parameter definition for assignment or export settings. All the checks were run, with emphasis placed on the checks relating to the viability for intersection capacity analysis (ICA), viability for ANM export and the viability for a PTV Balance/Epics supportive network. After several initial warnings and corrections all these checks were satisfied.

The aim of the procedure sequence is to take all the data, run a specific sequence of traffic assignment options in order to create the .anm (network file) and the .anmroutes (demand file) for the export to PTV Vissim. A number of PTV Epics- and Balance related, as well as ANM export related steps were taken into consideration during this procedure of which the first, and very important step, is the

"Preprocess Balance/Epics" step. This enables all PTV Epics- and Balance related parameters and creates the attribute BalanceSatFlowrate (Balance saturation flowrate) which is used to define the turn-based saturation flow rate used in the network. These values were manually specified for the pre-process step as can be seen in Table 6-1, based on local knowledge of the Stellenbosch traffic and compliant with typical South African values (COTO, 2012). This pre-process step is the very first step that has to be present in the sequence.

Table 6-1: Balance saturation flowrates defined during preprocess Balance/Epics

Location/turn-type	Veh/h per lane
Links	1800
Straight-(main) turns	1900
Left-(main) turns	1750
Right-(main) turns	1800
U-turn-(main) turns	900

The way the rest of the procedure sequence was set up, 3 main procedure categories were created. The initial assignment **(1)** was an equilibrium assignment present to allow for basic signal optimisation, if required. Then to follow was an assignment with ICA **(2)** with additional option for signal optimisation followed by a Dynamic User Equilibrium (DUE) assignment **(3)** for anmroutes export. The reason for each step and their sequence is explained hereafter.

Two aspects of importance regarding the specifics of the assignment methods which were used relate to the impact of signal control which needs to be taken into account as well as the time validity of the demand which needs to be considered. The impact of signal control needs to be incorporated by means of turn capacities in the network, either within an assignment with ICA or using those turn capacities from the assignment with ICA in another assignment method. It is important to consider the signal control because a difference in impedance at the nodal level needs to be realised.

Regarding the need to incorporate the time validity requirements connected to the demand; this is necessary to be able to alter demand over time within PTV Vissim and PTV Balance. A static assignment would only be able to represent a fixed time period demand in the same time interval after export, however would not be able to incorporate an assignment with ICA (which requires hourly demand matrices as an input) nor represent changes in demand over time. For this purpose a DUE assignment was utilised. This can however not take into account the impact of signal control on the turn capacities.

In essence the final setup of the procedure sequence was then defined to have an optional procedure group for initial signal optimisation, a second group for the assignment with ICA to generate the required turn capacities which were then used within the third group, the DUE assignment used for the

ANM export. In this way demand longer than one hour could be represented while still taking into consideration the impact of signal control. This also leaves room in case a fluctuating demand needs to be represented at some stage. A snippet of the actual procedure sequence can be found in Appendix B, Figure B- 3.

Specific mention needs to be given to the signal optimisation procedures available within the PTV Visum procedure sequence and to which extent each of these was actually utilised. Firstly, a "*signal, cycle and split optimisation*" technique is present which can be used to quickly generate sensible signal plans for a large network where no other information is present. In conjunction with the second optimisation method in use, the "*signal offset optimisation*" technique, this would provide relatively satisfactory signal plans to base the PTV Epics and Balance optimisation on. However, since the currently used plans from Syntell were available, the signal, cycle and split optimisation procedure was not used within PTV Visum. An initial attempt was made to see if any improvements to the plans during this optimisation would be present, however, these were so minimal that this was discarded as insignificant. A different split optimisation procedure is available within PTV Vissim and is discussed in section 6.4.7. This procedure uses a far more detailed approach and was eventually utilised to bring some improvements to the plans and represented in various scenarios as defined in Chapter 5.

The *signal offset optimisation* procedure within PTV Visum was utilised to generate the appropriate time offset values between intersections. To this end a reference signal control had to be specified, which was set to be the R44/Bird St. intersection as it is one of the main intersections leading into town.

6.3.5 Export specifics

Once the procedure sequence was properly defined and executed, the generated data had to be exported in the appropriate file format in order to create the R44 Micro Model as well as to assign the applicable supply files to PTV Balance.

The PTV Vision software suite is designed in a manner by which certain files can be used equally by different software components. This however requires that the same file directory needs to be specified within which all the files are stored. This can potentially become a bit messy, yet is very worth it considering the ease of inter-software file management. File types that can be used interchangeably like this are the signalisation files (.sig), the network export files (.anm) and the demand export files (.anmroutes).

Of importance in the export are the ANM and the ANMRoutes files. The ANM file contains all data elements relating to the network, such as information on transport systems, nodes, links, turns and number of lanes. Also, elements such as the signal head and detector positions are present. In essence, everything involving the "physical" geometric layout of the network and all its components. The

ANMRoutes file, on the other hand, contains all information relating to the actual traffic demand. This data is saved in a route coordinate format or a demand matrix format. During the export it is important to define the simulation time interval for which the demand is exported. I.e. if the AM peak period sequence is run then the simulation time interval needs to be from 06:30 – 09:00. Additionally, it is important that the saturation flow for links and turns is specified for the export and import into PTV Vissim. This is defined by the parameter BalanceSatFlowrate as described earlier.

For initial import to PTV Vissim both the ANM and the ANMRoutes files are needed. These are also both required for PTV Balance. Upon alteration to the demand structure, such as a change in the Stellenbosch Model, which requires new subnetwork matrix generation and importing into the R44 Macro Model, which in turn requires new procedure execution there, this new demand then also needs to be exported again (.anmroutes file) to be used in the R44 Micro model. Instead of having to export both the ANM and ANMRoutes files again and start the microscopic modelling from scratch again, PTV Visum allows for co-ordinate based route export. This creates an ANMRoutes file based on co-ordinates which can be imported in PTV Vissim in an easier manner.

6.4 R44 Micro Model with PTV Epics and Balance integration

Having discussed in reasonable detail the modelling and management of the R44 Macro Model, as well as the required export procedures and files, focus is now placed on the most important modelling part of the project – the PTV Vissim R44 Micro Model with integrated TASC control. All previous models and data provision flows into this model and this is where all the detail simulation, testing and evaluation takes place. The aim is to create an accurate representation of the actual real-life traffic environment over the corridor, modelling each entity and integrating the concept of TASC.

6.4.1 General considerations and parameters

There are a few general considerations that need to be mentioned regarding the model setup as relating to its purpose and the available data supply chain. Firstly, the resulting R44 Micro Model is a static microscopic model. This is the case because of the way in which the demand is imported into PTV Vissim, i.e. route-based. If use had been made of a demand matrix configuration within PTV Vissim, theoretically a dynamic model could have been defined. This, however, introduces another level of variance and complexity into the model and its outcomes which is not ideal when trying to do a comparative analysis between different scenarios.

Secondly, and relating to the above, it is to be noted that the model setup of an ANM imported PTV Vissim model is different to one which is created from scratch. Since the routes, vehicle inputs, links and connectors (to name but a few) do not have to be defined manually, it becomes viable to have a complex static microscopic model which manages these, in essence, on its own. In other words, had this model been created from scratch it would have been easier to go the route of a dynamic model. Specifically the route definition as generated after import would not have been possible to create manually due to its complexity.

Thirdly, it is important to note that the network generated after initial import into PTV Vissim is not perfect, at least not from an aesthetic perspective. If all important parameters where defined correctly in the underlying R44 Macro Model, these should be present in the resulting R44 Micro Model, however, it is impossible to simply export, import and then have a perfect model. Typically, large intersection and links feeding into the network with central medians need to be checked.

A specific parameter worth mentioning as an important parameter when setting up any microscopic model is the "Diffusion time" parameter. This defines the allowed time interval which a vehicle may be stationary in a network before it is removed. If this parameter does not align with the magnitude of the general signal cycle length, then vehicles are just going to disappear in the model. The alteration and adaption of many such "minor" parameters to the model-specific environment will ultimately define whether the model is representative of reality or not.

6.4.2 Import specifics

The import into PTV Vissim has already been touched on in earlier sections of the report. Essentially, the ANM and ANMRoutes files are used to generate a runnable microscopic simulation model. Either only the ANM file can be imported on its own and checked for any mistakes, after which the ANMRoutes file is then imported, or both can be imported at the same time. In the case of this project both were imported at once.

It was helpful to generate the imported network and then scour it for any obvious mistakes that had to be corrected in the R44 Macro Model and would thus require a re-export and import. A few mistakes that were picked up on were wrongly closed turns, misplaced detector positions and the omission of a signal head. These were all factors that would affect the assignment results in PTV Visum and thus had to be eliminated first.

An important aspect of the import to be aware of is that PTV Vissim generates so called PANM and PANMRoutes files. These files are basically a copy of the initially imported ANM and ANMRoutes files and are used to compare and manage additionally imported data to the original data. PTV Vissim uses these internally and therefore they also had to be specified during the import.

Since the initial modelling of this project was started in an earlier version of both PTV Visum and Vissim, and these did not support the co-ordinate based route export and import yet, it was challenging to manage separate, altered or additional ANMRoutes files without having to do an entirely import and generate a new PTV Vissim model. This challenge was thankfully overcome with the co-ordinate based route functionality in the newer versions.

6.4.3 Network alterations

After the "import, identify mistakes and re-import" routine was done several times and no obvious mistakes were present in the R44 Macro Model anymore, effort was directed towards establishing a final network representation of the model in PTV Vissim. In other words, the ANM file would not be imported again. The ANMRoutes files, naturally, will alter between various scenarios and their various forms will be discussed in section 6.4.8, Scenario Management.

The first changes were visual, aesthetic changes that do not necessarily affect the simulation in any major way. This includes, amongst others, realigning the spline points of links and connectors to create a more realistic view of the network. Figure 6-6 shows the difference between a directly imported network and an aesthetically altered network.

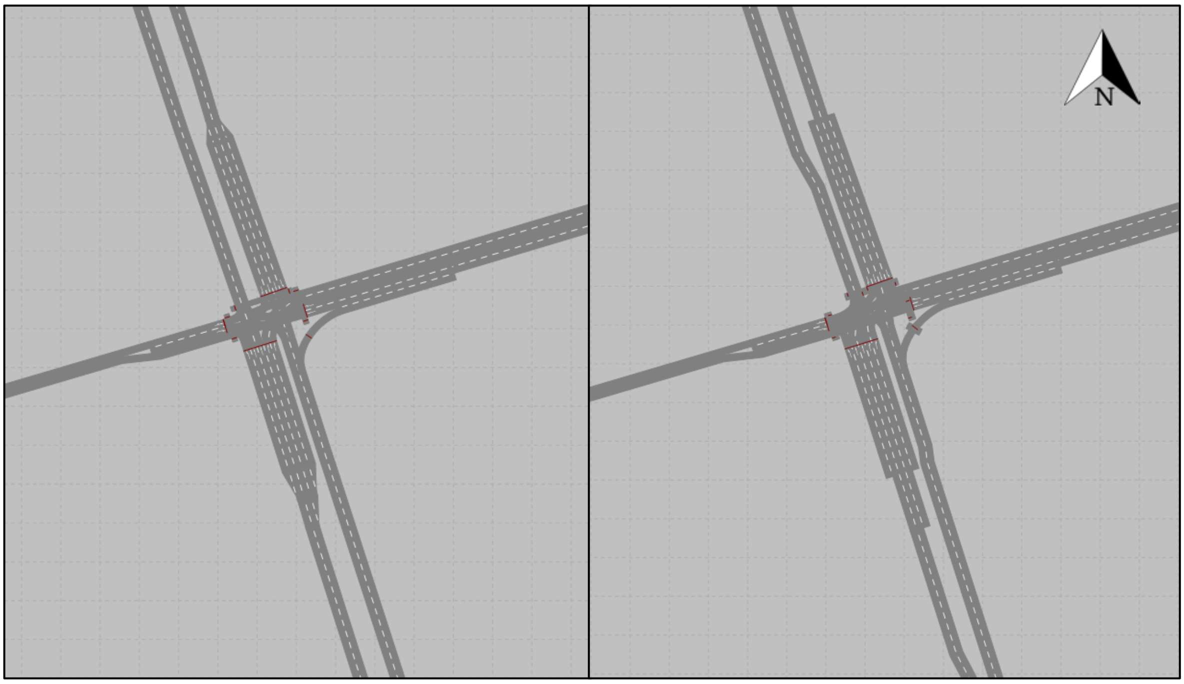

Figure 6-6: Aesthetically altered PTV Vissim network vs directly imported network

Next, changes were made that are important to ensure smooth, realistic driving behaviour. It is important to understand that these are changes which will affect the simulation outcomes. One such parameter was the *emergency stop distance* prior to specific turning movements. This ensures that a vehicle wanting to turn but not able to enter the correct lane early enough will come to a standstill at the appropriate distance thus simulating the correct queueing behaviour, i.e. at auxiliary lanes. Another parameter was the *lane change distance*. This ensures a sufficient travel distance before a turning movement at which a vehicle wanting to turn is prompted to start its lane change manoeuvre in order to get into the correct lane. Where additional lanes after an intersection are reduced it is important to ensure a small enough lane change distance to allow vehicles to use the additional lanes. Also related to turning movements was the correct modelling of the auxiliary lanes. Here, sufficient funnelling had to be ensured in order for vehicles to correctly flow into the auxiliary lanes and not behave jaggedly.

Other modelling components that had to be added and altered where applicable were the conflict areas. These ensure that right-of-way is given to the correct traffic stream were they are in conflict with each other. At all signalised intersections it was checked that all the signal heads were linked to the correct signal groups in the signal plans. This had to be modified at some of the signal heads, especially in cases were two allowable signal groups had to be allocated to the same signal head. The alteration of all these parameters and modelling factors was aimed at recreating realistic driving behaviour within the model.

Lastly, and importantly, was the addition of all train- and pedestrian related inputs and network objects. The train was only added to the model at this stage because of its ease of inclusion within the microscopic model. The aim was not to model the train traffic in its utmost detail inclusive of passenger boarding and alighting, but to ensure sufficient representation of the train crossing's effect on the TASC system. To this end both the Stellenbosch and the Du Toit stations with the official train departure times between these two were added to the model. Public transport detectors were added to the rail line which were used to trigger a non-cyclical signal group at the train crossing (marked **A** in Figure 6-7) to ensure its pre-emption, as well as to trigger a non-cyclical signal group at the nearby intersection (marked **B** in Figure 6-7) to ensure that traffic is cleared from the train crossing.

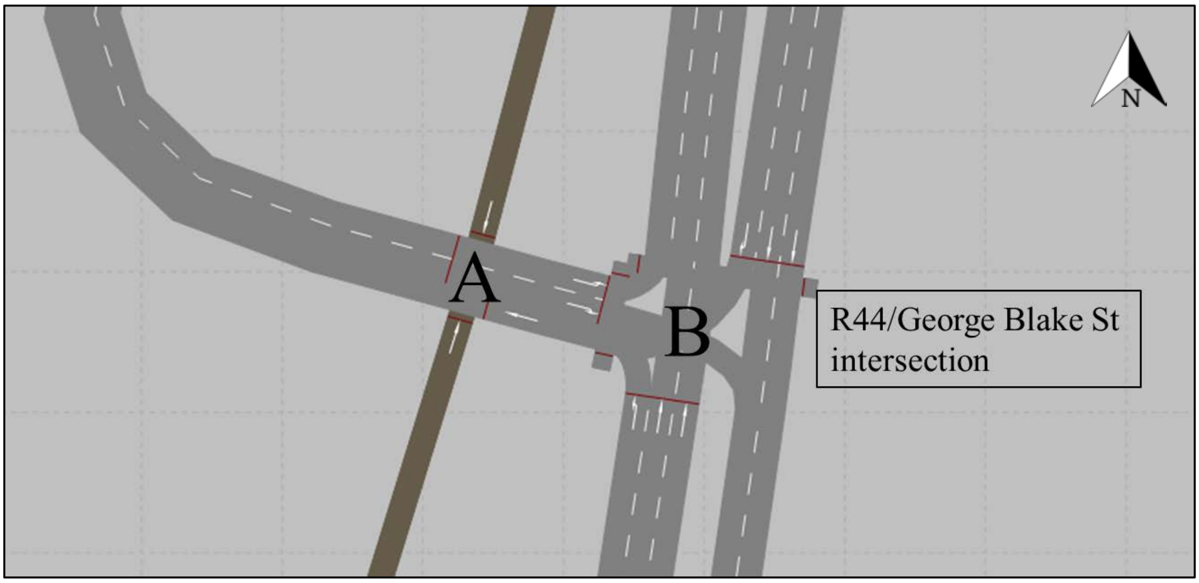

Figure 6-7: Indication of the rail crossing and nearby intersection, R44/George Blake St

The pedestrian inputs, as previously mentioned, were only added at the separately signalised pedestrian crossings. Here the appropriate input volumes, waiting areas, routes and pedestrian detectors (push-buttons) were created, also linked to the corresponding non-cyclical signal group with a given weighting of 5 (as opposed to a weighting of 1 for a private vehicles).

6.4.4 TASC parameters

Most TASC related parameters were already defined within the signalisation plans during their configuration in the R44 Macro Model. This means that all PTV Epics and Balance related parameters within the .sig files themselves were appropriately allocated and arranged in their correct relation to each other.

The one major feature of PTV Balance control which still had to be added was the *Balance-Central* controller. Just like all other signal controllers have an *Epics/Balance local* control type and function as the local instance of TASC at each intersection, the global instance of TASC still had to be created. This was then the Balance-Central controller which requires the ANM and ANMRoutes files as input in terms of data supply. Several individual Balance-Central parameters can be altered or specified, such as the method of optimisation. These were left at the default recommended settings.

6.4.5 Calibration

A very important step during the R44 Micro Model set-up was the calibration. The calibration step does not refer to the calibration relating to traffic demand, which was already handled in the Stellenbosch Model, but rather refers to the calibration of the model in terms of realistic driving behaviour and accuracy of modelling technique. The output of the model will only be as accurate as the level of calibration towards reality is.

The main exercise within this modelling step was to run and rerun the simulation with one random seed until satisfactory results and behaviour were achieved and then only start to alter the random seed with which traffic is fed into the network. In other words, it is an iterative process and requires small changes each time so that the corresponding effects of the changes can be seen. Initially the simulation was run without any optimisation, i.e. not TASC control, until useful modelling outcomes were realised. After this the optimisation was added.

During this iterative calibration process several techniques were used to ensure satisfactory results. Firstly, reliance was placed on visual observation of the simulation. Often an error can be easily spotted if the simulation is observed and something seemingly wrong is identified. Then troubleshooting starts until the problem is solved. Additionally to this, both PTV Epics and Balance can be switched to *debug* mode. This means that a whole array of log files are generated with detail relating to the simulation. Of specific use were the *Epics_MainLog* files for each intersection as well as the *Balance_output* log file. Log levels 4 and 5 could then easily be identified, indicating problems either having a negative effect on optimisation or preventing it altogether. The debug mode also means that a web-based graphical user interface (GUI) is opened, representing results and internal data components mostly relating to PTV Balance, but also some for PTV Epics. It is useful for calibration in that it allows direct insight into how PTV Balance represents the traffic environment and whether it is in agreement with the PTV Vissim representation. Figure 6-8 shows the same network view in the web-GUI and in PTV Vissim and indicates the agreement between them in terms of real-time queue modelling.

Figure 6-8: PTV Epics modelled queue lengths shown in the web-GUI (purple) vs the PTV Vissim modelled queues

Another useful calibration technique is to additionally visualised signal times table data. Figure 6-9 shows the actual signal group state along with the PTV Balance frame signal plan as well as the queue which PTV Balance estimates. This can be used to identify possible discrepancies or problems between the TASC control and the actually realisation signal control.

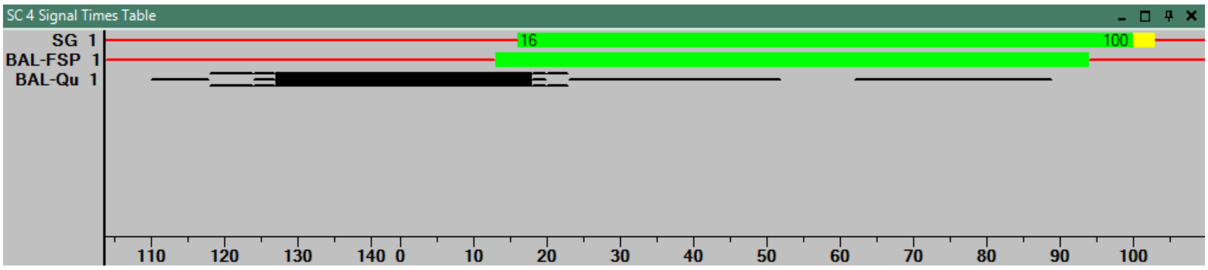

Figure 6-9: Signal times table showing the actual signal state, the Balance frame signal plan and the Balance queue estimation

6.4.6 Validation

A validation step was also included after the calibration step in order to ensure that the calibrated model relates sufficiently to reality when tested against another traffic data source. This reduces the possibility that the calibration was skewed due to faulty or inaccurate data. The data which was used during the R44 Micro Model validation was obtained from TomTom floating car data (FCD).

Four different route-based average speed measurements were used for comparison between the modelled data and TomTom data. These average speed values were calculated within the R44 Micro Model and then compared to the same measurements in FCD format obtained over the same route sections. The routes which were used can be seen in Figure 6-10 below.

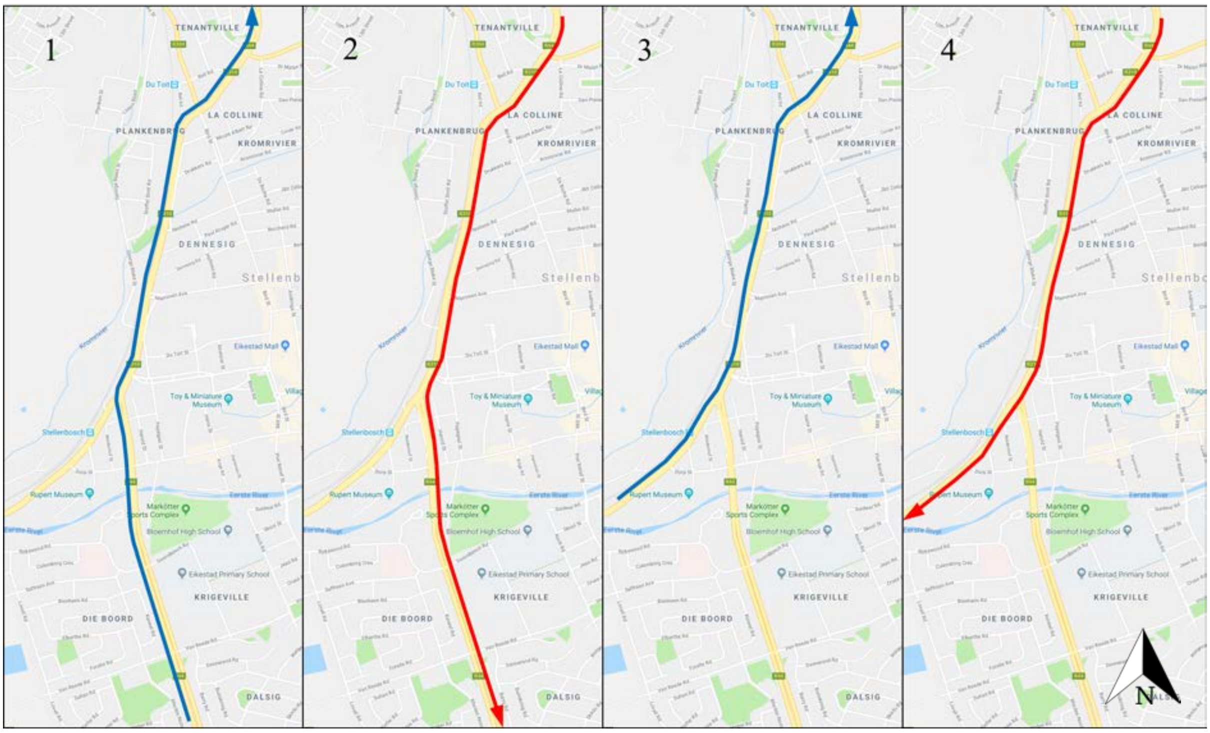

Figure 6-10: Average speed route sections used for model validation

Table 6-2 shows the change from the R44 Micro Model speeds to the TomTom FCD speeds. As is evident, none of the routes have a variation of more than 5 km/h between the modelled and measured values. This is also illustrated in Figure 6-11 where all four modelled route speeds fall within the allowed 5 km/h deviation.

Table 6-2: Average speed model validation results

Route		PTV Vissim Average speed (km/h)	TomTom Average speed (km/h)	Difference in average speed
1	R44 northbound AM	12.1	17.1	+ 5.0 km/h
2	R44 southbound PM	18.6	16.8	- 1.8 km/h
3	Adam Tas northbound AM	14.7	18.7	+ 4.0 km/h
4	Adam Tas southbound PM	15.8	15.4	- 0.4 km/h

From these results, therefore, it can be concluded that the PTV Vissim R44 Micro Model is sufficiently representative of the real traffic environment. This ensures credible, valid and reliable comparison of the various resulting model outcomes.

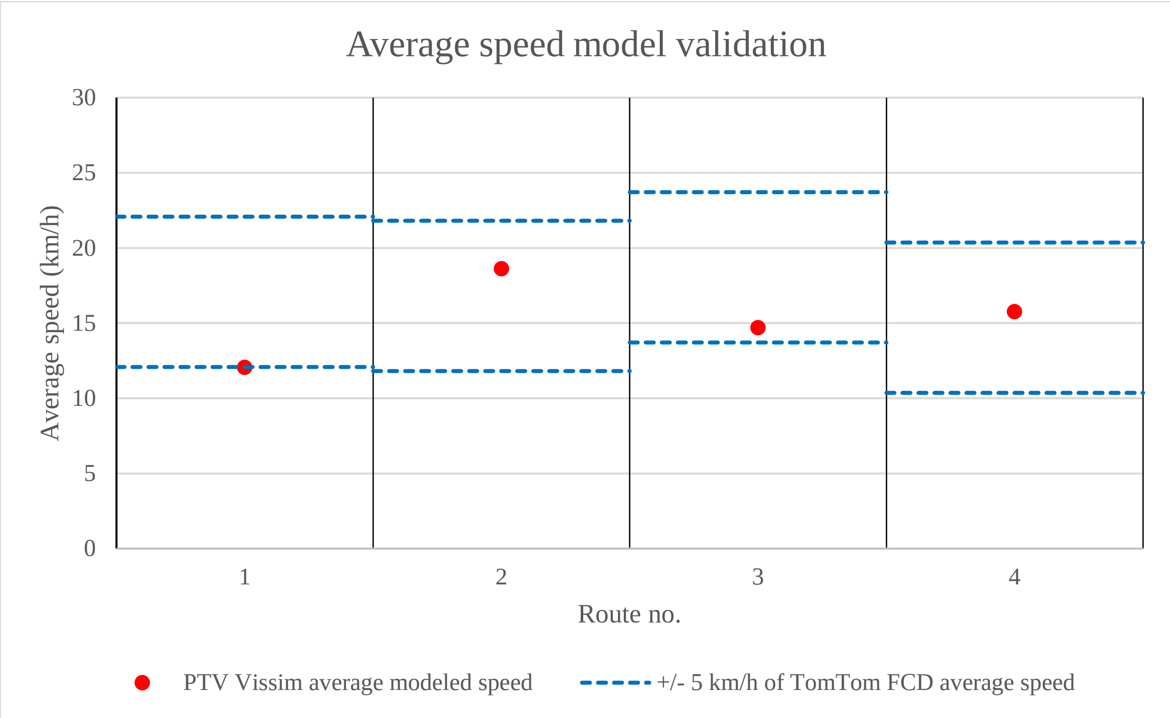

Figure 6-11: Average speed model validation

6.4.7 Green time optimisation

Once the model was sufficiently calibrated and validated it was essentially ready for simulation. However, before the different scenarios for simulation could be defined, an important part of the signal split optimisation had to be performed. As mentioned in section 6.3.4, the signal, cycle and split optimisation procedure within PTV Visum was found to only be suitable for generating new signal programs from scratch rather than optimising already defined signal programs effectively. It was therefore decided to apply the *green time optimisation* technique, available in PTV Vissim, to the signal programs requiring this for their respective scenarios. This technique is far more detailed than the one available in PTV Visum as it is based on the microscopic model.

The method works by repeatedly calculating simulation runs of the entire network with all signal controllers (SCs) switched off, except for the one currently being optimised. This prevents upstream intersection interference. Basically, the optimisation runs will continue up to such a point where changes to the green time allocations between stages no longer yield an improvement relating to volume throughput or a decrease in delay at the intersection. The changes in green time are made by taking one second off the best stage in the program and adding it to the worst stage until no more transfers of green time between any stages can be made which would lead to improvements.

6.4.8 Scenario management

Scenario creation and management was where the very essence of the research-focused aim of this project was realised. Scenario management allowed the comparison and evaluation of various different TASC measures and signal control alternatives as were defined and discussed in Chapter 5.

Essentially, once a project is placed under scenario management, a base network is created upon which all the scenarios are built, using modifications. This is the implicit approach to scenario management and means that scenarios are modified directly. It is also possible to build scenarios entirely from modifications by creating and modifying the modifications first and then building scenarios as combinations of modifications. This is the constructive approach to scenario management. In the case of this project the implicit approach was utilised.

Since the AM and PM peak period demand is not a factor of change between the scenarios, the first two AM and PM based scenarios were created and the corresponding final ANMRoutes file for each was imported via the coordinate-based approach. After the demand import it was important to ensure the correct route placement. Due to the initial non-coordinate based import it was found that a few routes were not complete or cut off inappropriately. This was easily fixed within the model itself due to specific warning messages generated during the import. All further scenarios were duplicates of these initial two AM and PM scenarios (no. 1 and 2), in terms of the network and demand, with the appropriate changes made to the signal plans in use, the type of detection or optimisation assigned to the signal plans, the level of TASC control as well as the inclusion or exclusion of the Alexander St intersection. During the process of assigning all these parameters to the different scenarios, a finalisation of all signal plans was undertaken, i.e. all the parameters were checked and ensured to be consistent.

During scenario setup some parameters were assigned to multiple scenarios at once. These include the specific simulation and evaluation parameters as discussed in the next section. Scenario management, essentially, makes it easy to keep track of the changes made to a base scenario and then to obtain simulation results for each. During the discussion of the result outcomes a summary of all scenarios is provided for ease of reference during analysis of the data.

6.4.9 Simulation and evaluation parameters

In order to obtain sensible and scientifically justifiable simulation results, the approach to each simulation as well as its evaluation need to be appropriately defined. The simulation parameters control aspects such as the simulation time, the number of runs and the random seed increments. Evaluation factors ensure that project-relevant result attributes are calculated, such as nodal results, as well as the time interval within the simulation period during which these attributes are obtained.

For the simulation parameters, firstly, it was necessary to ensure all AM scenarios were run from 6:30-9:00 and all PM scenarios from 15:30-18:00, the peak periods intervals. Each scenario had to be run 10 consecutive times, as indicated in the literature review (section 2.11), with a singly incremental random seed starting at 42. The average values over the 10 runs were then used to represent results.

Evaluation was defined on a network level and a nodal level. Network evaluation was ensured by choosing the *Vehicle network performance evaluation* output and nodal evaluation was selected at the *Nodal evaluation* output. For nodal evaluation, the nodes themselves had to be defined in the network first. Additionally to the network and node evaluation, some travel time measurements were selected for evaluation as well. Once again, the points between which the travel time evaluations were to be obtained had to be defined within the network first. For the AM peak the specific hourly time period of evaluation was specified to be from 7:00-8:00 and for the PM peak this was from 16:30-17:30. Evaluation was only done over these peak hours, as defined in section 4.2.4, in order to obtain comparative results over the actual peak hour and not just the general peak period. It was still very useful to build the model for the general peak period as this ensures that the network is fully loaded at start of evaluation. All the specific performance indicators which were extracted from these evaluation results for comparison are discussed in detail in Chapter 7.

6.5 Model development summary

Chapter 6, the model development chapter, gave insight into the process of traffic modelling which was followed as well as the necessary decisions and assumptions that had to be made within this process. Specific reference was made to the setup of the PTV Visum Stellenbosch Model, the PTV Visum R44 Macro Model and, most importantly, the final PTV Vissim R44 Micro Model which was used to simulate and evaluate a number of different scenarios. The results thereof are discussed in the following chapter.

As already stated, the extent of given detail within this section was based on the envisioned level of detail and understanding into this process as desired by the reader. Most certainly only a relatively condensed version of the actual modelling process was provided here and further information can be found in the specific PTV manuals (PTV Group, 2017b, 2017a), as well as in the appendices or by contacting the author directly. Relating to the direct correlation towards the research objectives, however, it was attempted to provide all necessary and applicable information.

Chapter 7

RESULTS ANALYSIS

7.1 Introduction

After the reasonably detailed discussion within the preceding model development chapter, it is now time to analyse the output results obtained from the PTV Vissim R44 Micro Model, based on the different scenarios which were utilised. This chapter therefore aims at laying out all applicable simulation results in a clear and concise manner.

Essentially, four different means of comparison and analysis are discussed in this chapter. Firstly, a short summary will be provided regarding the data available within the web-based PTV Balance graphical user interface (GUI). This will give a first glance at the network level success or failure of the system. Then, in more detail, some network vehicle performance (NVP) measurements are discussed, followed by a few nodal and turning movement evaluations and concluded by four different travel time measurement comparisons. Effort was placed into identifying the scenarios of importance on network level and then to perform any further results comparisons only between these scenarios in order to simplify the results representation.

A summary of all scenarios is provided in Table 7-1 for ease of reference during the results analysis.

Table 7-1: Summary description of the different evaluation scenarios

Scenario no.	Scenario description (AM & PM)
1 & 2	Fixed-time signal plans including minor changes to base plans + offset optimisation
3 & 4	Fixed-time signal plans based on 1&2 + offset and green time optimisation
5 & 6	PTV Epics local optimisation based on 1&2 + offset optimisation (Cam detectors)
7 & 8	PTV Balance global coordination based on 1&2 + offset optimisation (Cam detectors)
9 & 10	PTV Epics + Balance control based on 1&2 + offset optimisation (Cam detectors)
11 & 12	PTV Epics + Balance control based on 3&4 + offset + green time opt. (Cam detectors)
13 & 14	PTV Epics + Balance control based on 11&12 without Alexander St signalisation
15 & 16	PTV Epics + Balance control based on 11&12 + individual cycle length optimisation
17 & 18	PTV Epics + Balance control based on 9&10, only offset optimisation (loop detectors)
19 & 20	PTV Epics + Balance control based on 11&12, offset & green time opt. (loop detectors)
21 & 22	Base signal plans in fixed-time format without any optimisation

7.2 PTV Balance web-GUI

The PTV Balance web-GUI provides an insight into the way in which PTV Balance optimises the flow of traffic and what the parameters and variables are which it uses to do so. This tool is typically used for real-time management in actual industry application. Before the actual, detailed network performance evaluation is described and discussed in the next section, some of the "real-time" outputs obtainable from this analysis tool are shown here as a first indication of potential network level success. For the sake of brevity these will only be presented for one of the envisioned best scenarios using PTV Balance, the AM peak hour scenario 11. A number of data analysis variables are obtainable from the interface, as can be seen in Figure 7-1 below.

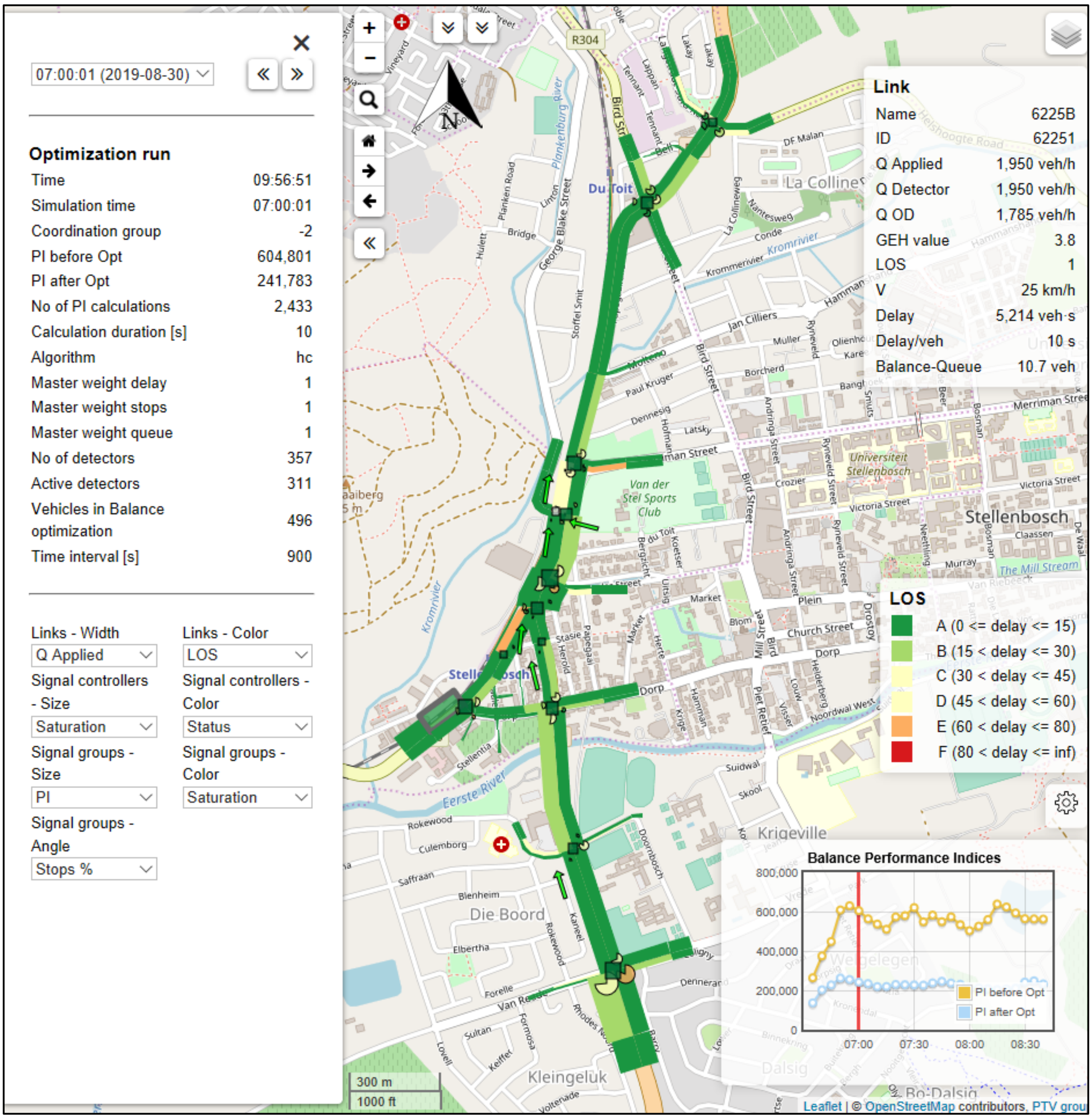

Figure 7-1: Indication of available analysis data within the PTV Balance web-GUI

The PTV Balance web-GUI firstly provides a summary of every optimisation run performed during the simulation. These are calculated on a 5-minute basis and any one of those optimisation runs can be analysed separately. Information in this summary includes the performance index (PI) before and after optimisation, as well as the number of performed calculations. The PI over the entire simulation run is visualised in a before-and-after graph to indicate the level of improvement within the network. As can be seen in Figure 7-1 on the previous page, the PI is drastically improved over the entire simulation period and thus, within the PTV Balance GUI, a definite network level success can be seen. Detail regarding the PI calculation can be found in section 2.9.2 of the literature review.

Additionally, a number of different calculation results can be visualised for different network objects such as links, signal groups or entire intersections. Figure 7-2 below shows an example of this for a specific signal group at the R44/Van Rheede Rd intersection. As can be seen, the flow profile of that signal group is also visualised and shows, for each second of the cycle, what the signal state is, as well as the number of vehicles either waiting at the stop line of flowing through it. In this case the queue length formed during the red state of the signal group adds up to about 47 vehicles, yet these are sufficiently served during the green state. The PTV Balance web-GUI is found to be a useful tool to ensure coherency between the different modelling spheres linked to the TASC system and adds another layer of management and understanding. It is used during real-world deployments.

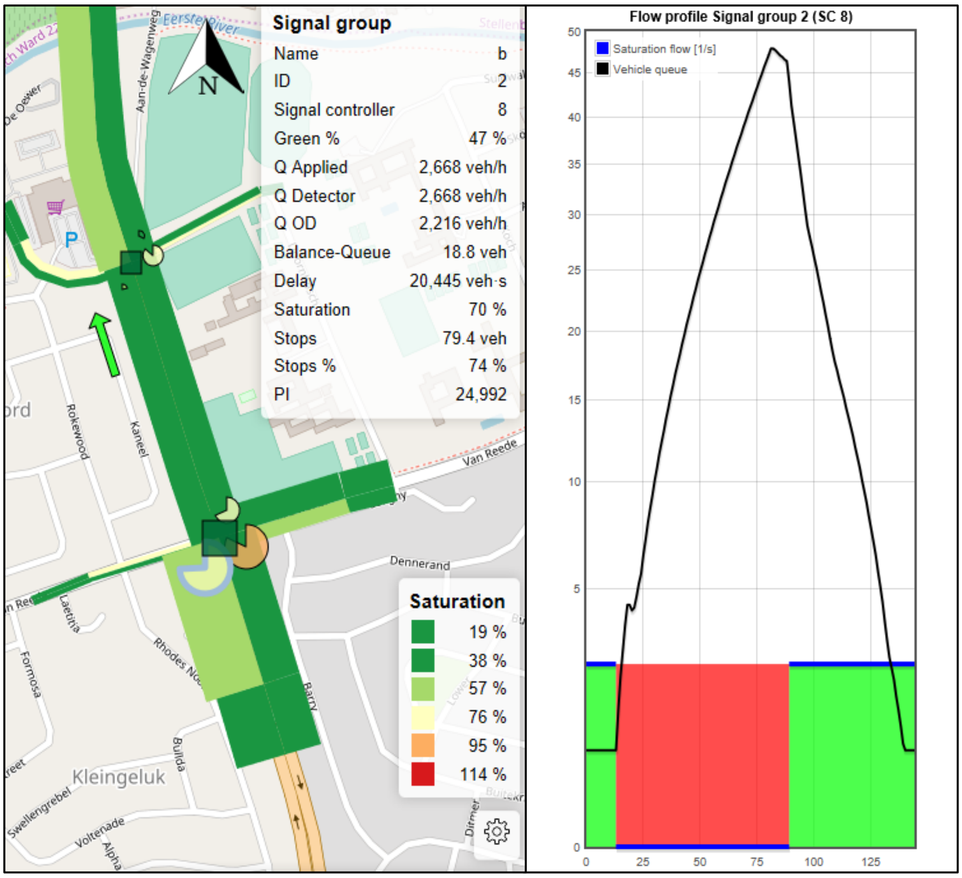

Figure 7-2: PTV Balance web-GUI calculation results visualised for a signal group

7.3 Network vehicle performance evaluation

After initial indication of network level success, as indicated by the performance index within the PTV Balance web-GUI, more detailed network level analysis is done. Network vehicle performance (NVP) evaluation provides an averaged indication of several performance measurements over the entire network. It is important to include this in the results analysis chapter because it needs to be known what the overall effect of the TASC system is. This, however, cannot be the only measurement criteria since a network level improvement could possibly hide an intersection level problem. Thus, the NVP evaluation is an important indicator of success and in a simple network this generally means overall success. In slightly more complex networks, however, more analysis is required.

7.3.1 Process of results evaluation

The following key performance indicators (KPIs) were used during analysis: average vehicle delay, number of arrived vehicles, average speed, average number of vehicle stops and total travel time. For the average vehicle delay measurement all the scenarios are compared against each other. The most pertinent and important scenarios are then identified and further measures of comparison are made between these select scenarios only. This was done because delay is the main factor to be minimised during the TASC optimisation and the most important scenarios can therefore be identified using this evaluation criteria. A summary of the overall network results in percentage difference between the current base scenario and the best scenario can be seen in section 7.3.4 for both the AM and the PM peak hour periods.

7.3.2 Description of key performance indicators

In order to fully understand the manner in which the scenarios are compared it is necessary to understand the way in which the KPIs were defined and calculated. For each KPI a short description is provided.

The **average vehicle delay** is the delay per vehicle calculated as the total delay divided by the sum of the number of vehicles in the network plus the number of vehicles that have arrived. The total delay in essence is the summation of the delays per time step. These are the parts of each time step that must also be used by vehicles due to the difference in actual vs desired speed and is summed for all current vehicles in the network plus the already arrived vehicles. Delay is considered to be the most important KPI in this study.

The **number of arrived vehicles** is simply the number of vehicles that have completed their desired journey within the network and have arrived at their destination. The comparison of this can indicate the level of congestion in a network.

The **average speed** is equal to the total distance travelled divided by the **total travel time** in the network. Both of these are a summation for all vehicles currently in the network or already having left it and are calculated between the point of entry into the network and the point of exit. The **average number of vehicle stops** is simply the total number of stops divided by the sum of vehicles in the network plus vehicles already having left the network. A stop is counted if the speed of the vehicle at the end of the previous time step was greater than 0 km/h and then equals 0 km/h at the end of the current time step.

7.3.3 Results discussion

As indicated, the delay comparison between **all** of the different scenarios is shown here in Figure 7-3. The current base scenarios are the last two, scenario 21 and 22, and base scenario lines have been added to the graph for quick reference regarding the change in delay.

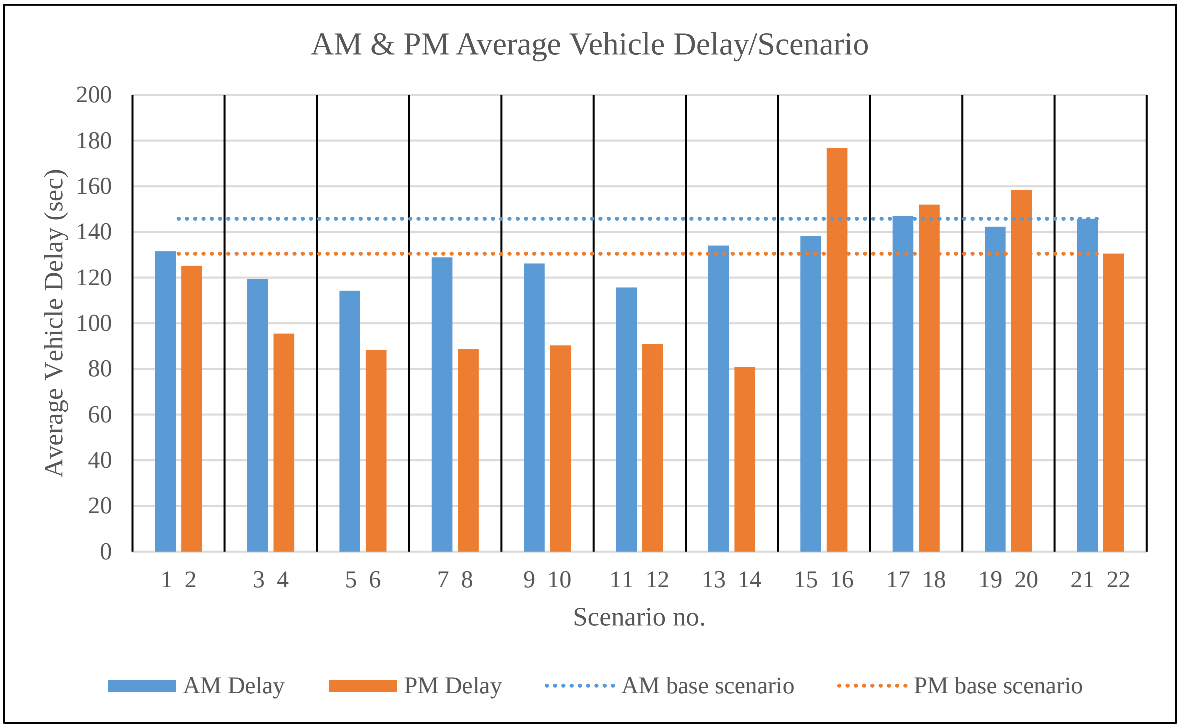

Figure 7-3: AM and PM peak hour average vehicle delay/scenario (all scenarios)

As can be seen in the above figure, the best improvement in the **AM** is seen when compared to scenario 5 (local optimisation) at 22% (31.5 seconds) as well as scenario 11 (local optimisation and global coordination) at 21% (30 seconds). Interestingly, the use of exclusive global coordination in scenario 7 (PTV Balance) had less of a positive effect than only local optimisation (PTV Epics) did. This indicates that the network under consideration is less suitable for coordination than initially expected. The reason for this is relatable to the relatively short distances between intersections as well as the "triangle-like" configuration of the Adam Tas Rd/Dorp St, Adam Tas Rd/R44 and the R44/Dorp St intersections, naturally breaking up the coordinated flow of vehicles.

When looking at the **PM** peak hour, it is seen that scenario 14 boasts the best improvements at 38% (50 seconds) rather than the expected scenario 6 or 12 as based on best AM results. This is easily understood when considering that scenarios 13&14 are the scenarios excluding traffic signals at the R44/Alexander St intersection. For AM traffic flow (generally higher volume northbound) these signals would be beneficial because of the high volume of right turners from the R44 onto Alexander St. However, in the PM peak traffic this would not be as beneficial as expected, especially using the current plan configuration. This is because vehicles are more prone to find a gap in traffic when turning left onto the R44 and thus a signalised intersection would slow them down. Considering this situation and the possibility to improve it by changing the PM signal plans, the biggest sensible improvement in the PM peak is realised in scenario 6 at 32% (42 seconds).

When considering scenarios 15 to 20 it is evident that especially in the PM peaks a worsening of traffic conditions is experienced. For the AM peaks the delay stays relatively equal to the base plan. Scenarios 15&16 are the individually optimised cycle length scenarios and it makes sense that they are worse, seeing that the effort to coordinate such different plans will fail. Interestingly though, for scenarios 17 to 20 the conditions were also worsened although the only difference to the best scenarios was that instead of the predictable TrafiCam x-stream camera detection, these scenarios used the inductive loop configuration were it had been present. This proves that the TASC system cannot function on vehicle detection that is not placed in a *per lane* configuration or only sporadically available, but rather requires predictable detection per lane and at constant distances to the stop line. Also to be noted though is that some intersections such as the R44/Van Rheede Rd and the R44/Alexander St intersections did not include any inductive loop detection because none were present in the real world and this could have worsened these scenarios unrealistically. However, this would also indicate that if some intersection in the network do not include vehicle detection, then the TASC system will not be able to function properly.

Also interesting to note, in both the AM and the PM peak, is the difference between scenarios 21&22 and 1&2. 1&2 refer to the scenarios were all cycle lengths were equalised and the plans given an offset value, additionally to some minor plan changes. Furthermore, it is evident that adding the PTV Vissim green time optimisation to the signal plans decreases the delay even further (scenario 3&4), however not as good as real-time optimisation would.

Based on the average vehicle delay findings it was decided to provide a more condensed insight into the further network performance evaluation. The scenarios which were chosen for further evaluation were numbers 5&6, 11&12, 13&14, 19&20 and 21&22. The scenario without the Alexander St signalisation was included to provide further insight into the effect this has on the TASC system. The best inductive loop scenario is also still included. For the equivalent graphs including all the scenarios, reference should be made to Appendix C, Figure C- 1 to Figure C- 4.

Figure 7-4 below gives an indication of the number of arrived vehicles in the network at the end of the simulation interval. It can clearly be seen that these results agree with the average vehicle delay results in Figure 7-3. Scenarios 5&6 and 11&12 give best results when compared to 21&22. As expected also, the inductive loop scenario was very close to the base scenario. Interestingly though, scenario 14, although having lower average delay than 6&12, has a near equal number of arrived vehicles in this comparison.

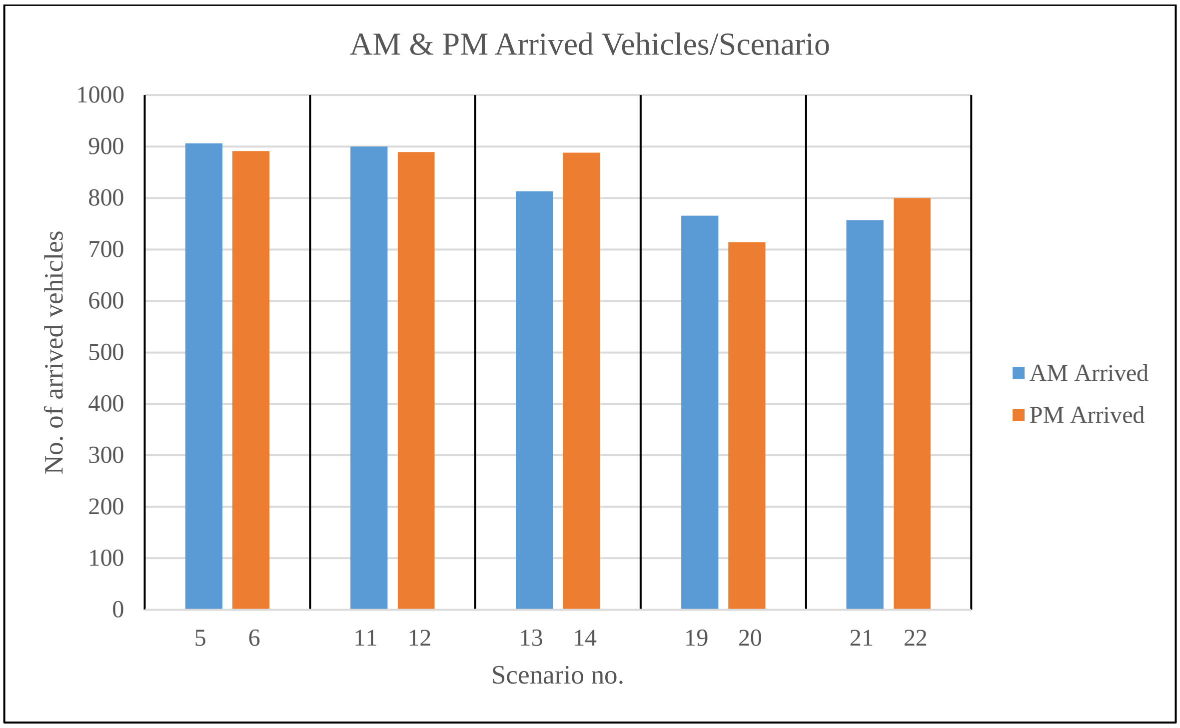

Figure 7-4: AM and PM peak hour number of arrived vehicles/scenario (selected scenarios)

When analysing Figure 7-5, showing the average speeds distribution in the AM and PM, it can be seen that scenarios 5&11 again bring the best improvement during the AM peak and scenario 14 brings the best improvement in the PM peak. This ties in with the previous network evaluation results, especially the average vehicle delay results.

The average vehicle stops analysis given in Figure 7-6 gives an interesting insight into how the objective function of the optimisation procedure in the TASC system favours the minimisation of delay rather than the number of vehicle stops. In the AM peak period a slight increase in stops is observed after TASC implementation. The increase is, however, only by a maximum of 0.5 average vehicle stops, making it a rather minute difference.

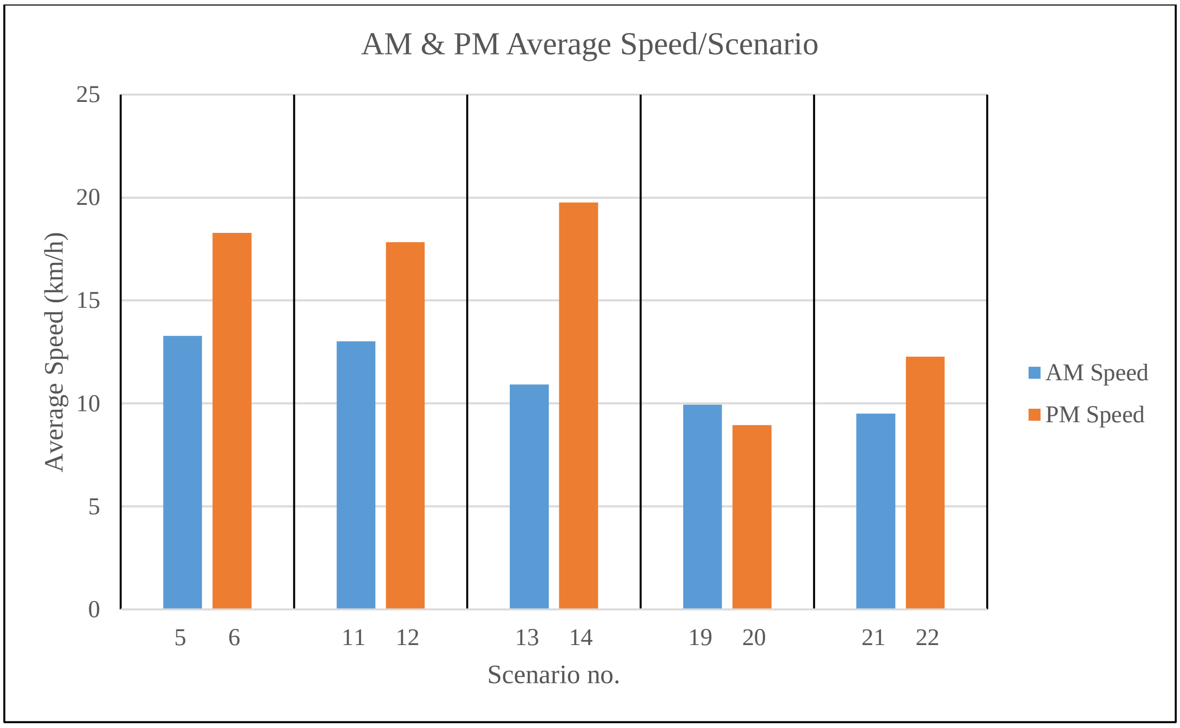

Figure 7-5: AM and PM peak hour average speed/scenario (selected scenarios)

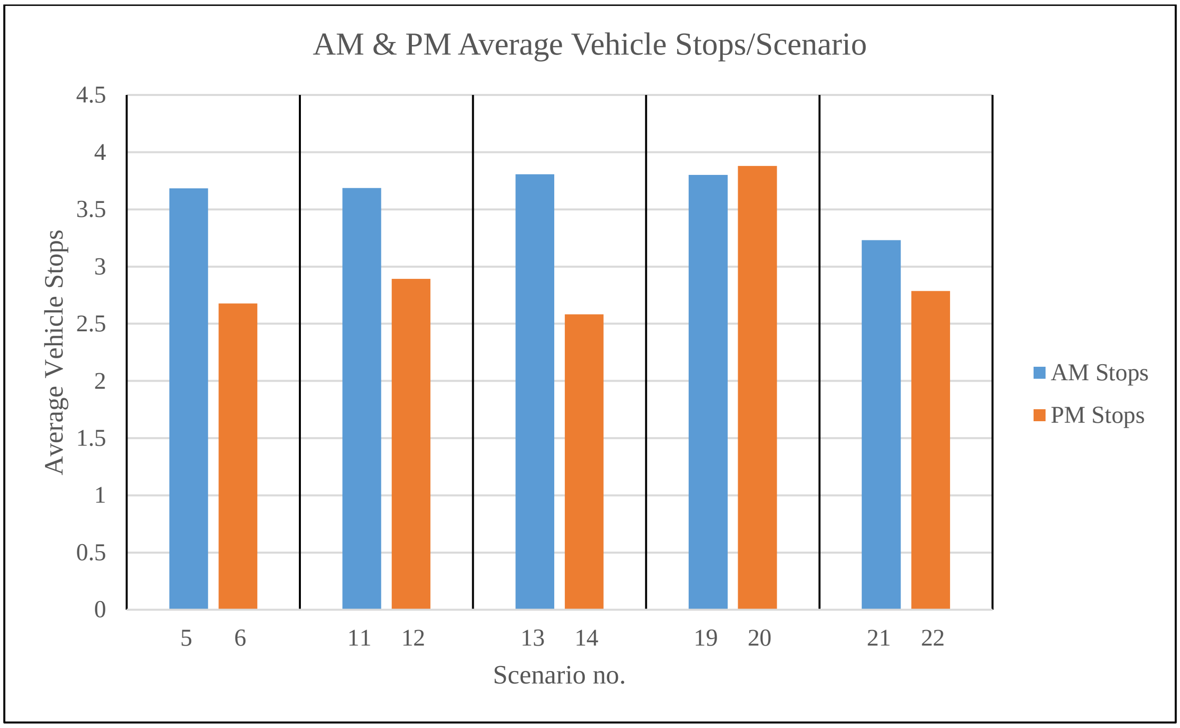

Figure 7-6: AM and PM peak hour average vehicle stops/scenario (selected scenarios)

Figure 7-7 shows the total travel time comparison between the main scenarios. Here once again the same general picture can be seen. Scenarios 5&11 bring best improvement in both the AM and PM, assuming that the PM signal plan could be adjusted at Alexander St intersection to the point were equal PM improvement figures are observed in these scenarios as in scenario 14. Further recommendations regarding this can be found in Chapter 8.

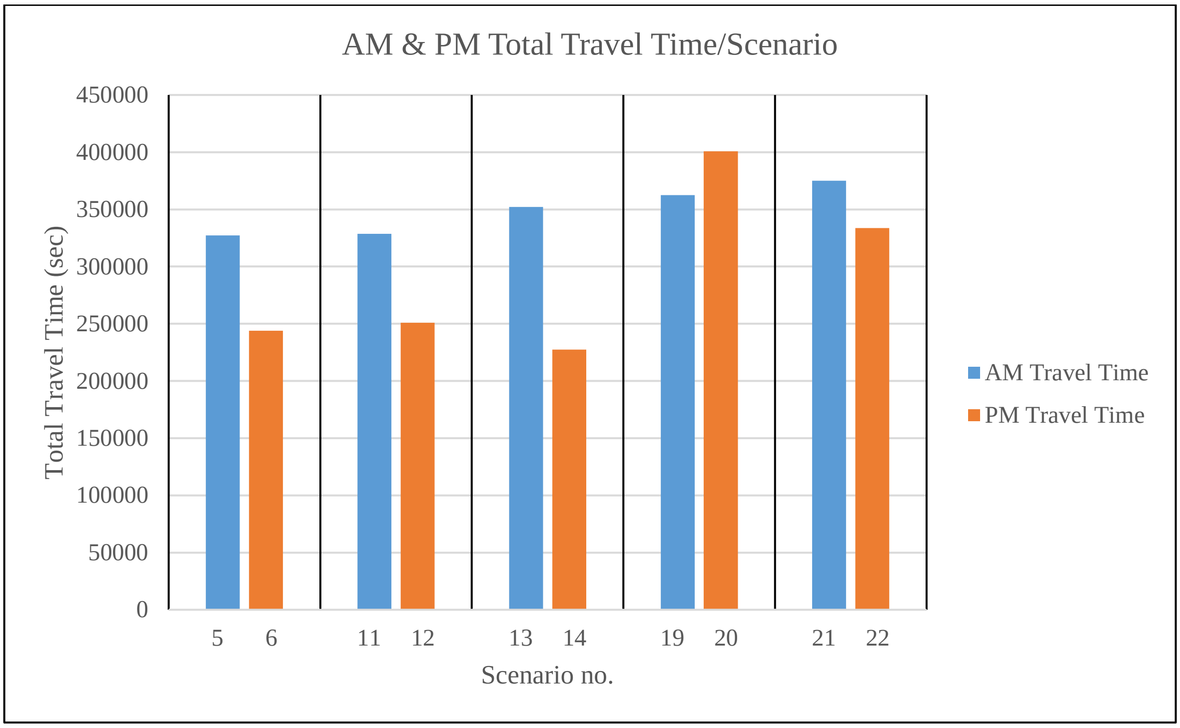

Figure 7-7: AM and PM peak hour total travel time/scenario (selected scenarios)

7.3.4 Network vehicle performance summary

Important for the network vehicle performance evaluation was to determine whether the results were consistent over a range of different performance indicators. This was the reason why five different KPIs were evaluated. It was found that in all cases, except for the average vehicle stops evaluation, scenarios 5&6 can be regarded as the most beneficial scenarios. This also takes into account the exclusion of scenario 14 in the PM period, as explained on page 95. Table 7-2 provides a percentage difference between the base scenarios 21&22 and the best scenarios exclusively using local optimisation, numbers 5&6.

Table 7-2: Network vehicle performance evaluation summary; percentage difference results representation

Parameter	Scenario 5	Scenario 6
	Change (AM peak hour)	**Change (PM peak hour)**
Average vehicle delay (seconds)	▼ 22%	▼ 32%
Arrived vehicles (volume)	▲ 20%	▲ 11%
Average vehicle speed (km/h)	▲ 40%	▲ 49%
Average vehicle stops (number)	▲ 14%	▼ 4%
Total travel time (seconds)	▼ 13%	▼ 27%

7.4 Nodal and turning movement evaluation

Having identified the best case scenario from an overall network perspective, it is important to take the analysis a step further and evaluate the main scenarios of concern on a nodal and turning movement level. This was done in order to minimise the possibility of a one-sided or skewed results analysis.

7.4.1 Process of results evaluation

The evaluation process was firstly aimed at analysing 4 different intersections of concern in the network after which a specific set of opposing turning movements at those same intersections was further evaluated and discussed. The main criteria by which the nodes and the turning movements under consideration were chosen was based on local understanding of the traffic and specifically the knowledge of potentially congested movement groups. Also to note, many other turning movements or intersections could have been evaluated yet for the sake of a concise and sensibly summarised report only the following, as seen in Table 7-3, are discussed.

Table 7-3: Nodal and turning movement evaluation locations

Node no.	Intersection name	Turning movements	
		AM	**PM**
1	R44/Helshoogte Rd	*Left turn*, R44 north onto Helshoogte Rd east	*Right turn*, Helshoogte Rd east onto the R44 north
2	Adam Tas Rd/Dorp St	*Right turn*, Adam Tas Rd south onto Dorp St east	*Left turn*, Dorp St east onto Adam Tas Rd south
3	R44/Van Rheede Rd	*Right turn*, R44 south onto Van Rheede east	*Left turn*, Van Rheede Rd east onto the R44 south
4	R44/Bird St	*Right turn*, Bird St north onto R44 west	*Left turn*, R44 west onto Bird St north

This section makes comparisons based on vehicle delay, averaged per node and per specific turning movement. This is done since delay is the main factor to be minimised during TASC optimisation. Scenarios 5&6, 11&12 and 21&22 are compared, based on the best network performance results comparison.

7.4.2 Description of key performance indicator

For the nodal and turning movement evaluation, **average vehicle delay** is calculated differently than for the network performance calculation. Here, vehicle delay is obtained by subtracting the theoretical (ideal) travel time from the actual travel time. The ideal travel time is what could have been achieved if no reason for stopping was present, such as when there are no other vehicles and/or signal controls. The vehicle delay was obtained at the end of each simulation time interval (every 300 seconds) per turning movement or node. The delay was then averaged over the entire simulation run and then again averaged over the 10 consecutive simulation runs to obtain the final value per scenario.

7.4.3 Nodal results discussion

When considering the previously discussed outcomes of the network performance evaluation, a similar trend is expected at the intersection level. It was however found that this was not always true and certain deviations from those expected outcomes were seen. The first two of the evaluated nodes fit the expected picture, with an overall decrease in delay for all TASC scenarios, whereas the other two showed somewhat alternative results.

From Figure 7-8, it can be seen that a definite reduction in delay is observed when comparing scenarios 5 and 21 (10 seconds, 9.5%). This aligns with the network results, indicating that exclusive local control has a bigger impact than local and global control combined. In the PM peak it can be seen that the combination of local and global control has the best result with scenario 12 indicating the lowest delay (decreased by 28%). An overall improvement on average of 10% is realised at the intersection, regardless of the level of TASC implementation.

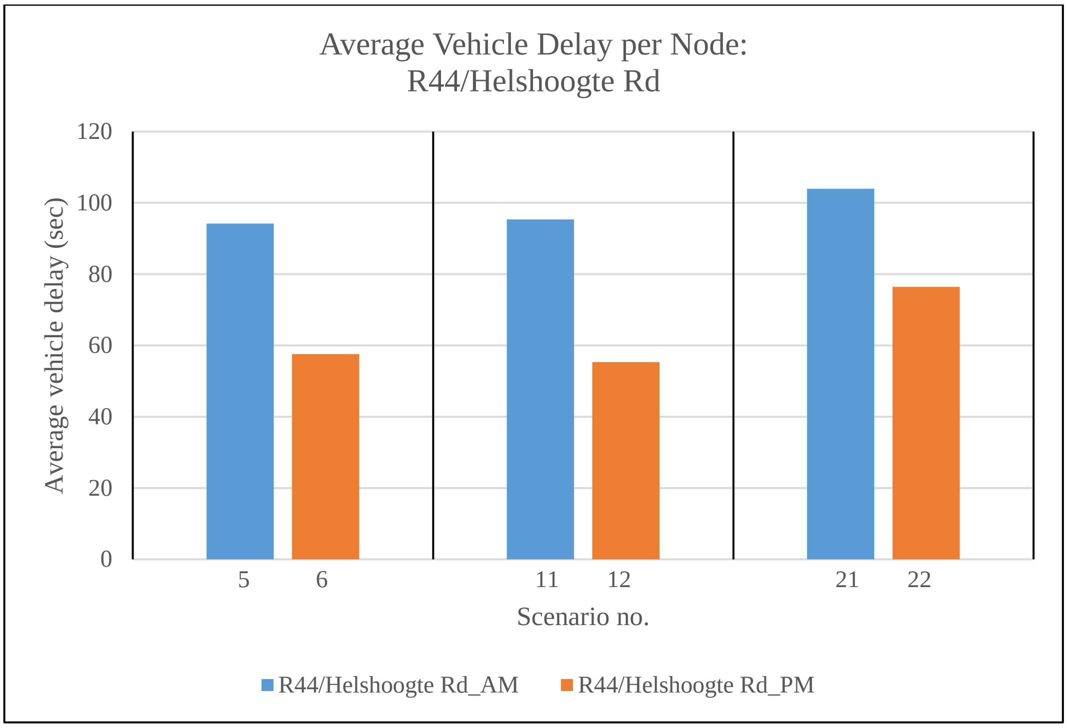

Figure 7-8: Average vehicle delay per node at the R44/Helshoogte Rd intersection

For the AM peak, Figure 7-9 also indicates a definite improvement of 18% decrease in delay (9.4 seconds) for scenario 11 where both local and global control are executed. The use of only local control in scenario 5 also delivers a good improvement in the order of 14% (7 seconds). For the PM peak hour, scenario 12 decreased delay by 5 seconds (14%). Here it can be seen that even if scenarios 5&6 dominated at network level, for this particular intersection scenarios 11&12 were found to be better.

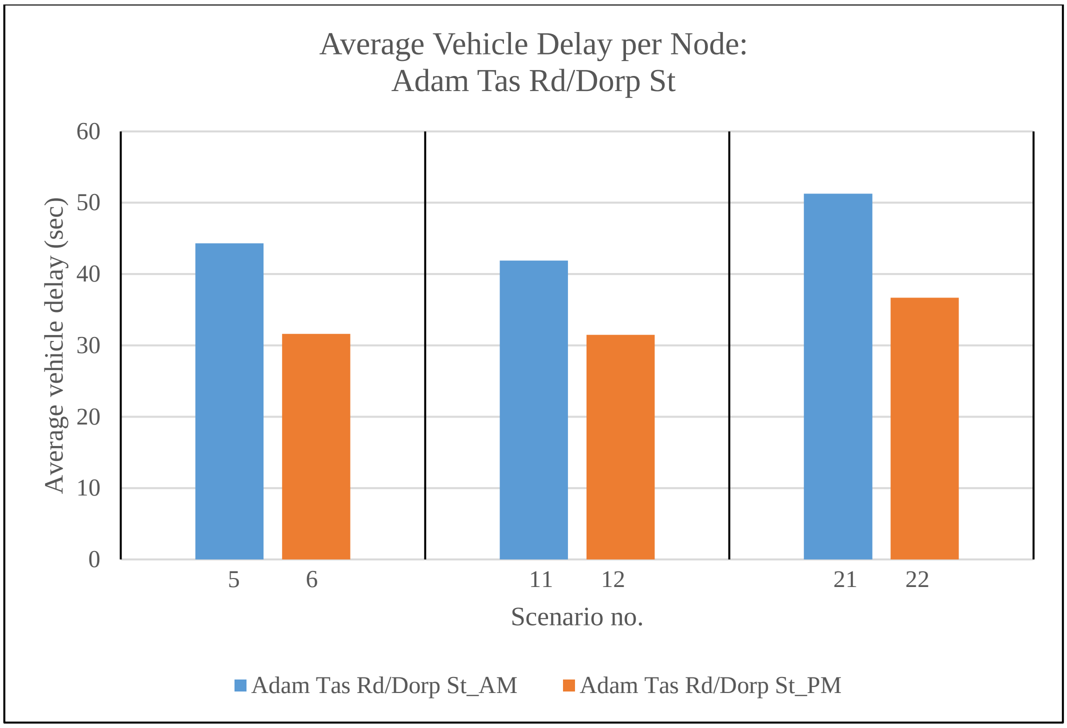

Figure 7-9: Average vehicle delay per node at the Adam Tas Rd/Dorp St intersection

When looking at the next two node results in Figure 7-10 and Figure 7-11 an unexpected change in delay can be seen which does not fit the general expectation. Both of these intersections (nodes 3 & 4 in Table 7-3) include congested *turning movements* in the AM and as can be seen in Figure 7-10 and Figure 7-11, the AM peak hour evaluation is where the “problem” lies, showing an increase in delay after optimisation. It might be the case that these heavily utilised movements are drastically given preference, thus adding to overall network improvement to the detriment of the individual intersections. The turning movement evaluation therefore forms a crucial part of the overall results analysis and is discussed in section 7.4.4.

Looking however firstly at the intersections themselves, in Figure 7-10 an increase in delay of 18 seconds is observed in scenario 11, when utilising not only local but also global control. This again hints at the fact that when the TASC system tries to coordinate, one of the worst turning movements is negatively affected since it links to a minor approach within an exclusive signal stage, and overall node performance decreases. The local control scenario 5 keeps the nodal performance even, yet might also improve the worst turning movement. This is discussed in section 7.4.4. For the PM peak hour both scenario 6&12 bring a decrease in delay of about 50%.

Figure 7-11 shows a similar situation as in Figure 7-10, yet improvement in the PM peak hour (2 second reduction) is not as drastic. This could indicate that the intersection is already operating at such high volumes of traffic that when TASC control is applied it cannot provide any improvements, at least not on nodal level. This might be a different on turning movement level and is discussed hereafter in section 7.4.4. If this is the case and some movements are drastically improved, an increase in overall intersection delay of 7 seconds from scenario 21 to scenario 5 is acceptable as a trade-off.

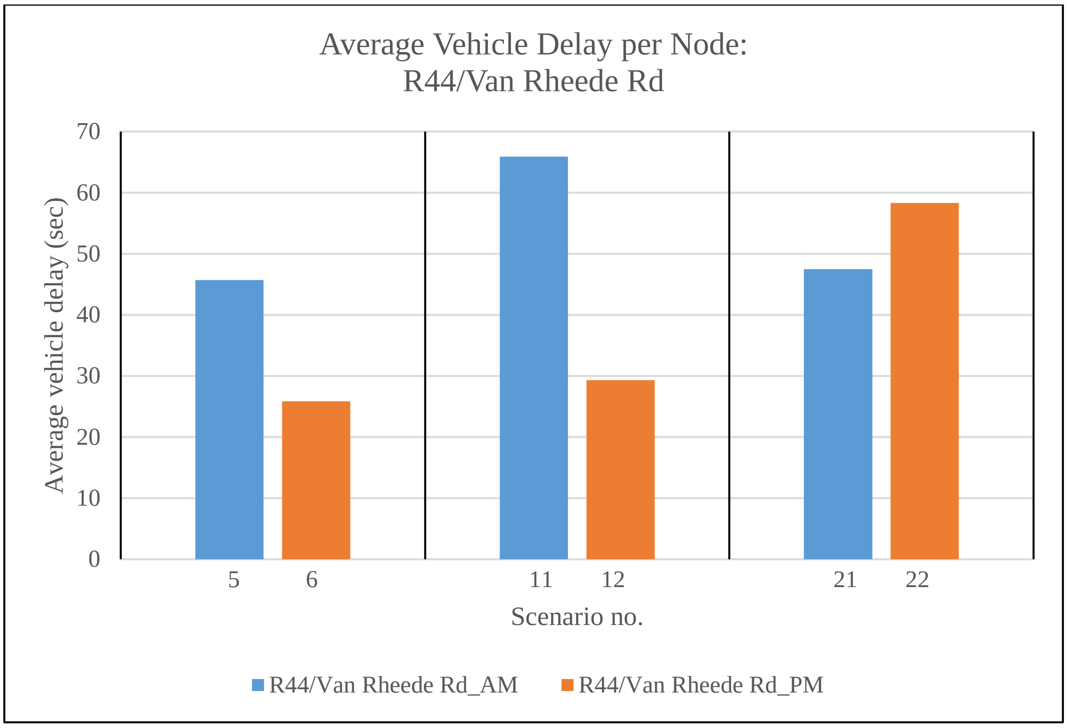

Figure 7-10: Average vehicle delay per node at the R44/Van Rheede Rd intersection

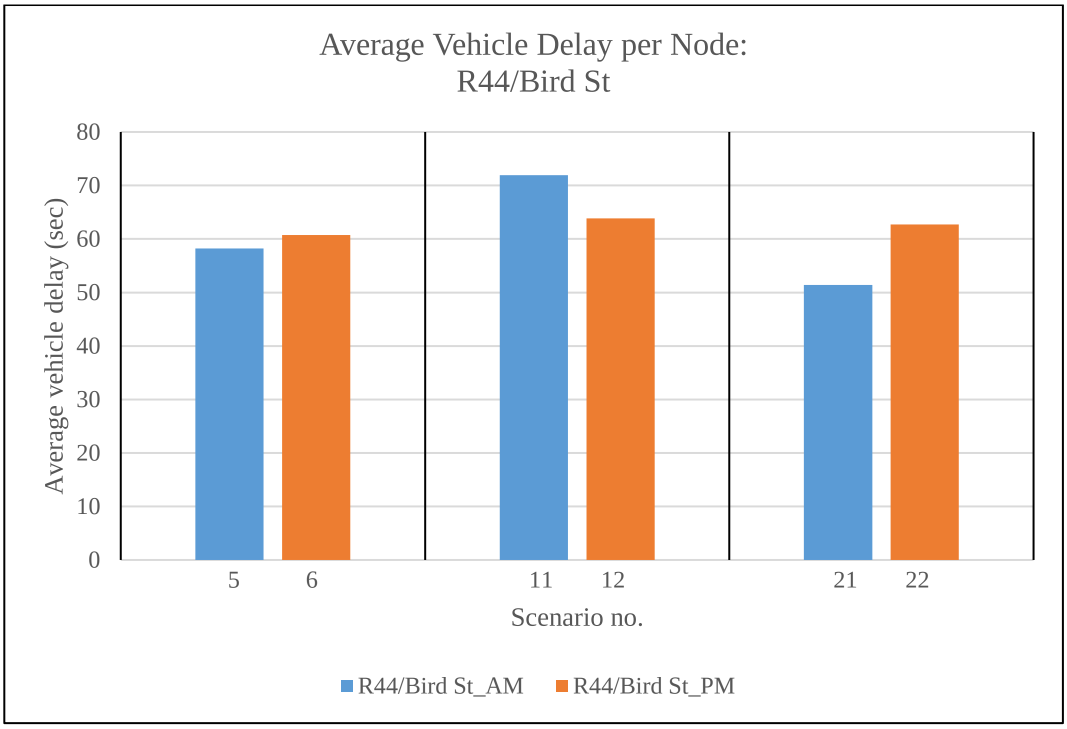

Figure 7-11: Average vehicle delay per node at the R44/Bird St intersection

7.4.4 Opposing turning movement results discussion

After the discussion of nodal level results yielded some expected decrease in delay at some intersections as well as some unexpected increase at others, a further discussion on turning movement level is helpful. The four opposing turning movements described in Table 7-3 are analysed here and link to the aforementioned nodes. They are representative of one of the worst turning movement pairs at each of those intersections. Attention is given especially to the movements at the R44/Van Rheede Rd and R44/Bird St intersections in relation to their potential improvement even if drastic nodal level improvement was not directly realised. This links to the results and discussion in section 7.4.3 as relating to Figure 7-10 and Figure 7-11.

Figure 7-12 highlights the average vehicle delay associated with the turning movement pair at R44/Helshoogte Rd intersection. In the AM peak period a 14% decrease in delay (20 seconds) is observed when using both local and global control. Overall the node had seen best improvement in the AM with scenario 5, yet here the specific movement was extensively optimised with scenario 11. The positive effect of coordination can therefore be seen. In this case the coordination with the R44/Bird St junctions extends the green time of the northern approach through-movement at the Helshoogte Rd junction, inclusive of the left turners under analysis since they are given green in the same stage. In the PM peak, regardless of the level of TASC control, extensive improvement up to 67% can be seen.

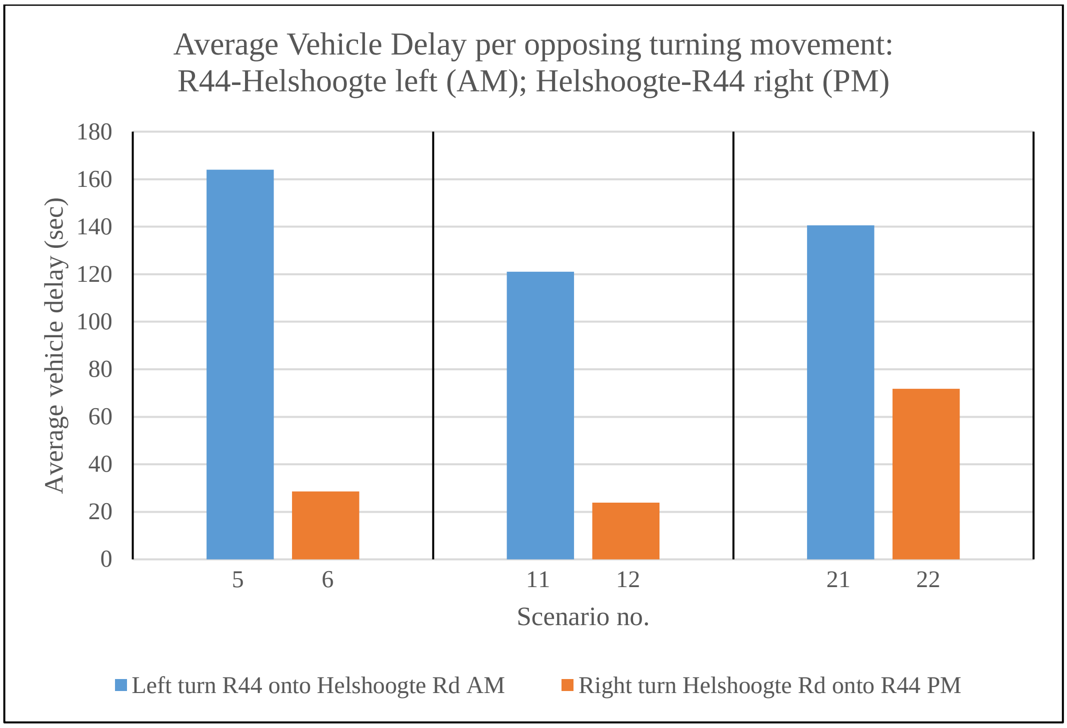

Figure 7-12: Average vehicle delay per opposing turning movement at the R44/Helshoogte Rd intersection

For Figure 7-13, comparing the delay associated with the turning movement at Adam Tas Rd/Dorp St, the AM right-turners clearly fit the same optimisation picture as that of the junction in general. Reduction in delay of up to 22% (26 seconds) can be seen, this being realised in scenario 11. For the PM peak hour, no positive improvement for the turning movement itself was achieved. On first glance this seems sub ideal, yet when looking at the magnitude of increased delay (12 seconds) it is still far less than the opposing movement's improvement. Also, since the entire intersection did see an improvement in the PM, clearly another turning movement was having a greater delay, which consequently then received more TASC attention.

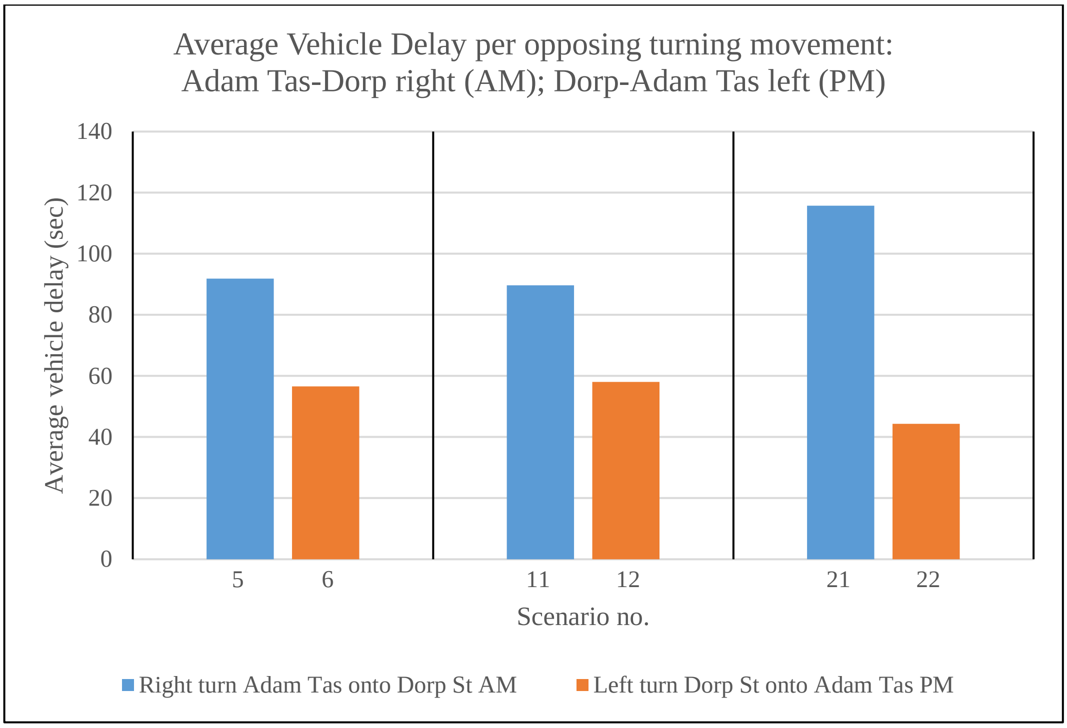

Figure 7-13: Average vehicle delay per opposing turning movement at the Adam Tas Rd/ Dorp St intersection

Interesting results to assess are those shown in Figure 7-14 and Figure 7-15. These are the turning movement delays at the intersections that had shown the unexpected increase in nodal delay. For Figure 7-14 a decrease in delay of 30% can be seen for the observed AM turn. This does not match with the nodal results were barely any improvement was seen. This reveals that although the overall node stayed the same in terms of performance after applying PTV Epics control, this specific movement was drastically improved. For the observed PM movement, conversely, the average delay increased by 6 seconds for scenario 6. The magnitude of delay is however still very low and a similar situation as explained for the PM results relating to Figure 7-13 is most probably applicable here.

Figure 7-15 shows a particularly positive improvement to the observed turns. A decrease in delay of more than 40% (34 seconds) can be seen in the AM peak hour from scenario 21 to scenario 5. As mentioned during the nodal results discussion, such a drastic decrease in delay on turn level would warrant the minor increase in average delay on nodal level. This is clearly one of the worst turning movements at the intersection and local TASC control did a good job of reducing its delay with minimal negative impact to the entire intersection. The evaluated PM turn also yielded a significant decrease in delay of 10 seconds.

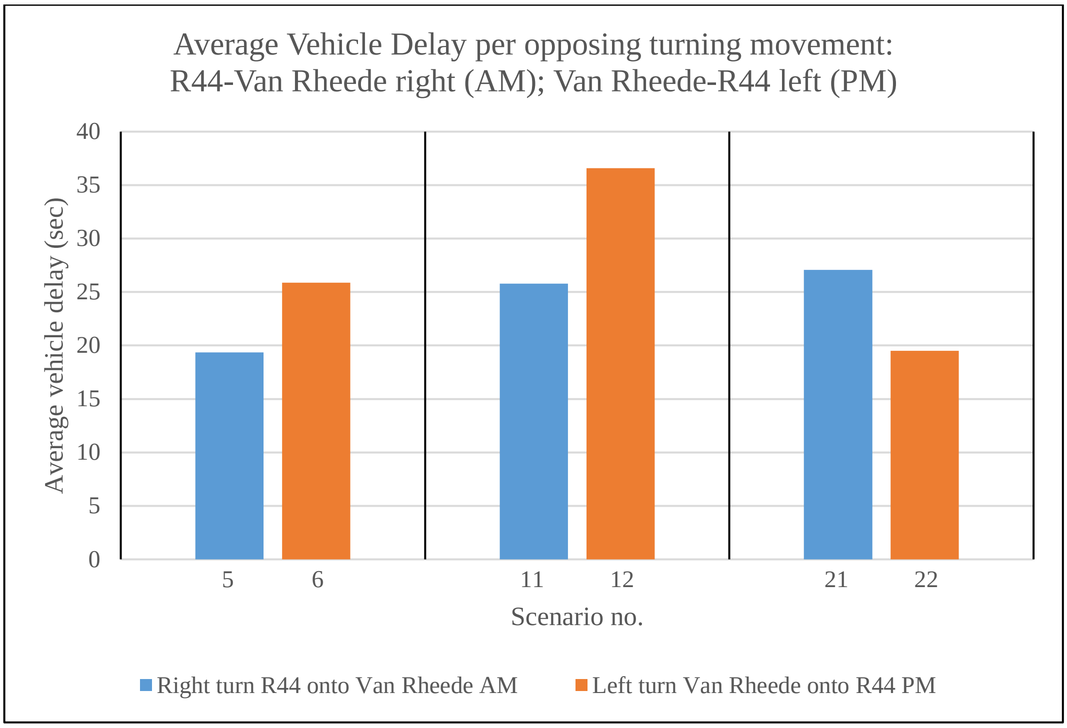

Figure 7-14: Average vehicle delay per opposing turning movement at the R44/Van Rheede Rd intersection

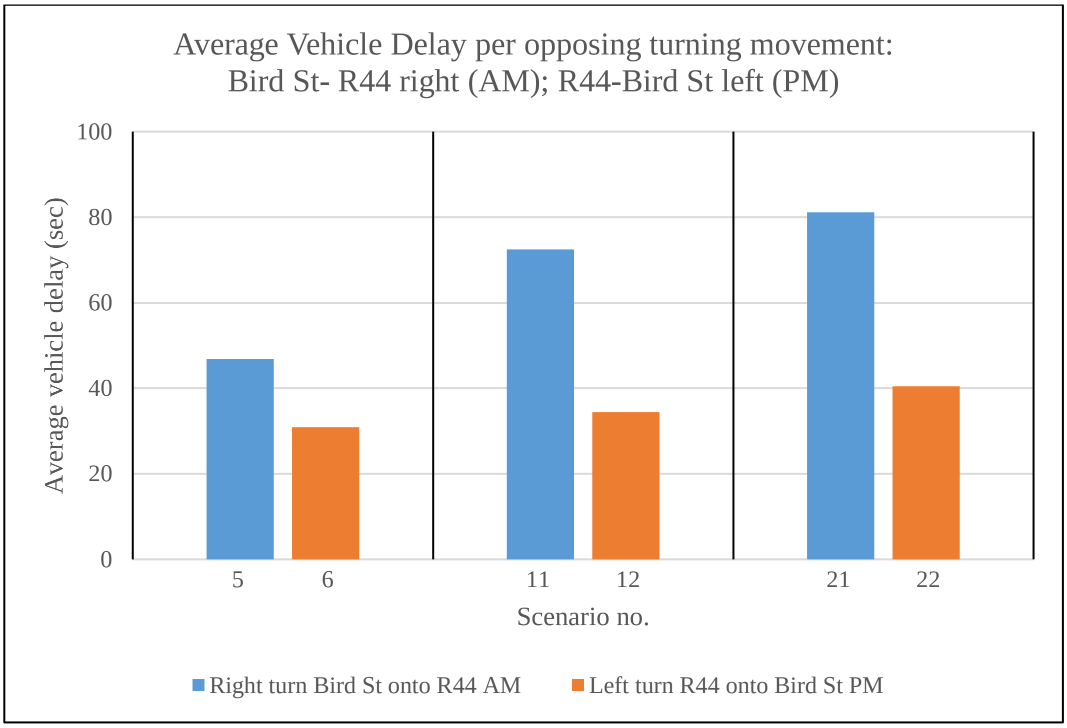

Figure 7-15: Average vehicle delay per opposing turning movement at the R44/Bird St intersection

7.4.5 Nodal and turning movement results summary

The nodal and turning movement evaluation provides an understanding of how the TASC system behaves on an intersection level. This analysis indicated that some junctions yield improvements, while others not quite. The same was true for the opposing turning movement evaluation. Putting these two analysis methods together, however, yielded logical results. The TASC system generally fared better using exclusive local control where the possibility to coordinate was not present. At some junctions where minimal improvement in delay was observed, the turning movement pairs generally showed a big decrease in delay. What this shows is that the TASC system can provide an improved traffic condition on both the nodal and turning movement level. Sometimes, however, the improvement on nodal level will come at the sacrifice of an individual turning movement or vice versa. In general however, the trade-offs between nodal and individual turning movement level were found to be rather insignificant when compared to the benefits.

7.5 Travel time measurements

As an additional and final means of providing insight into the functionality and impact of the TASC system, travel time measurements were compared for some of the scenarios.

7.5.1 Process of results evaluation

These measurements provide the travel time in the network between two specified points of interest. A total of four different travel time measurements were evaluated in the PTV Vissim R44 Micro Model between the following intersections:

1. From **R44/Van Rheede Rd** to **R44/Helshoogte Rd** during the AM peak traffic hour
2. From **R44/Helshoogte Rd** to **R44/Van Rheede Rd** during the PM peak traffic hour
3. From **Adam Tas Rd/Dorp St** to **R44/Helshoogte Rd** during the AM peak traffic hour
4. From **R44/Helshoogte Rd** to **Adam Tas Rd/Dorp St** during the PM peak traffic hour

Important to note is that the actual start and end points are slightly upstream or downstream of these intersections, as shown in Figure 7-16. For ease of reference the closest intersections were chosen to describe the routes. The travel time measurements were selected to provide an indication of the change in travel time when traveling through the network before compared to after the TASC implementation. Generally, the higher peak hour volume of traffic in the network was observed in the northbound direction in the AM morning period and southbound in the PM afternoon period. Figure 7-16 shows the four different routes chosen for the travel time comparison.

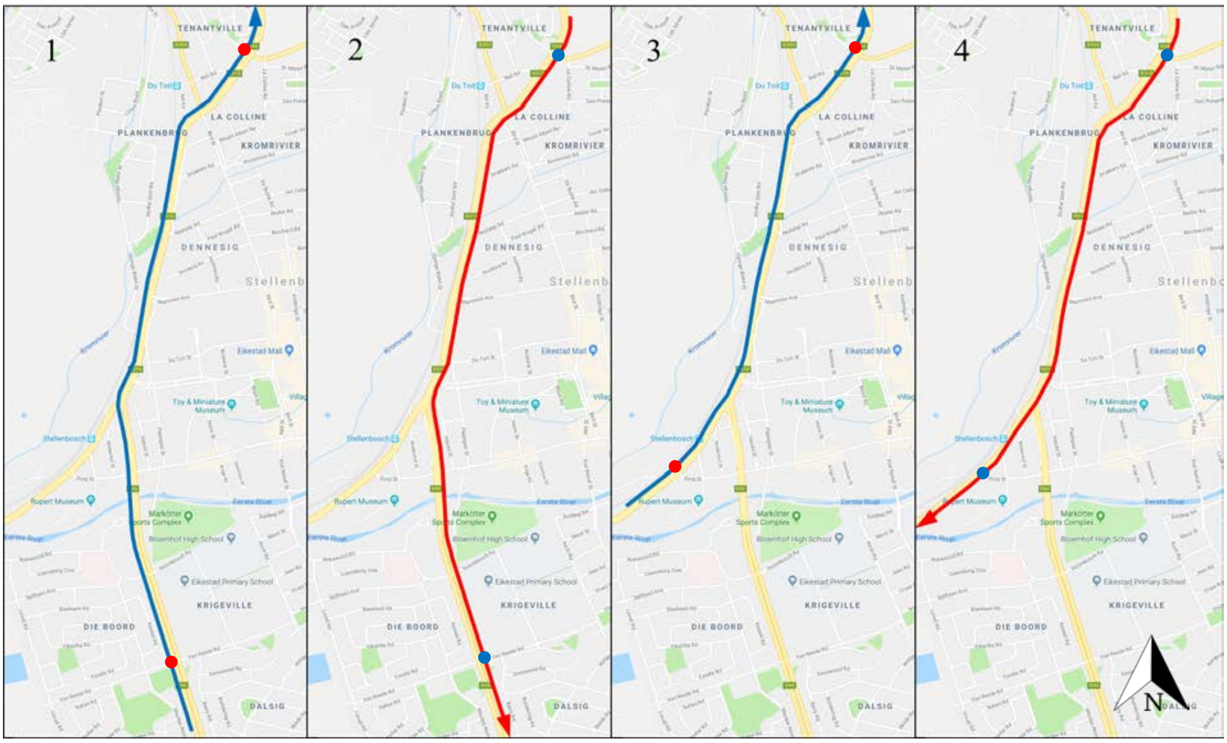

Figure 7-16: Travel time measurement routes 1 – 4, reference junctions marked with a circle (www.google.co.za)

7.5.2 Description of key performance indicator

The travel time measurement used for this comparison was the time in seconds required for a vehicle to make the trip between two specified points. This was recorded for each vehicle having made the trip in a simulation time interval and averaged over the number of vehicles. This was then again averaged over all the simulation time intervals within the entire simulation run and finally also averaged over the 10 consecutive simulation runs which were performed.

7.5.3 Results discussion

When looking at Figure 7-17 and Figure 7-18, it can be seen that a consistent reduction in travel time was observed for all four travel time measurements. Important to note is that this agrees with the total network travel time evaluation relating to Figure 7-7, as discussed in section 7.3.3.

Interestingly, the level of TASC implementation which yielded the best improvement was mostly seen in scenarios 11&12, using both local and global control, except for the AM measurement for the section between the R44/Van Rheede Rd and the R44/Helshoogte Rd intersections. From an overall network perspective scenarios 5&6, local optimisation only, had resulted in the highest total travel time reduction. Important to note is that the *network travel time* evaluation is not based on the major directional route of travel, but over the entire network and all intersection approaches. For these *specific travel time* routes the use of global coordination in addition to local optimisation would therefore make more sense, since it is based on the predominantly major direction of travel thus making coordination easier.

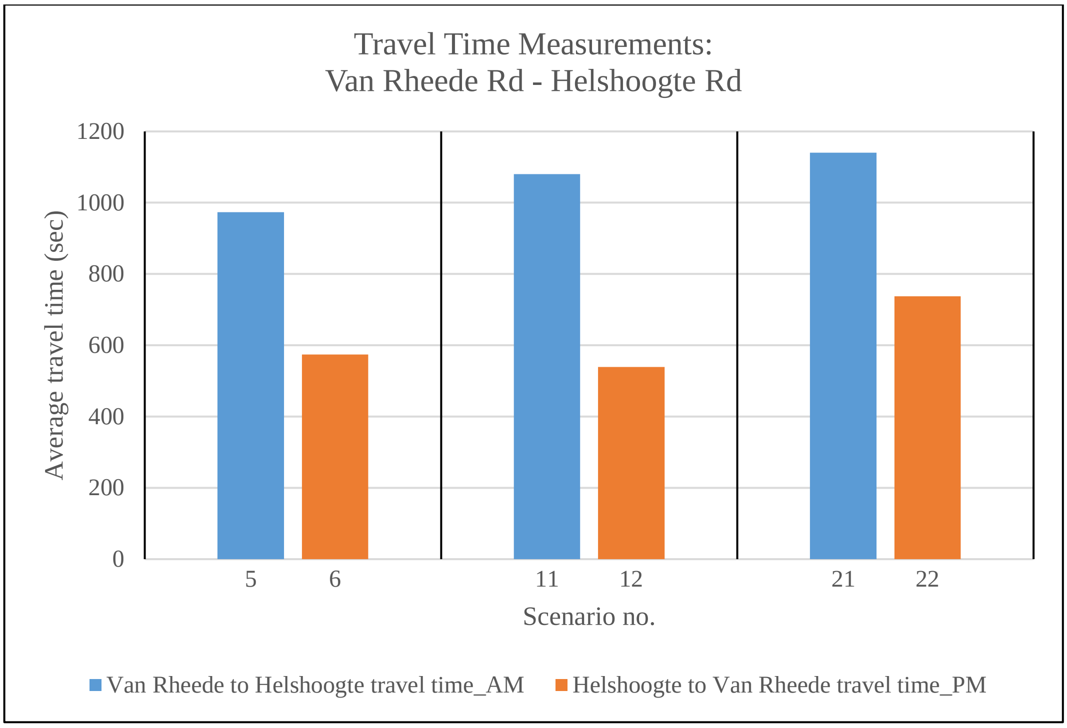

Figure 7-17: Travel time measurement between R44/Van Rheede Rd and R44/Helshoogte Rd intersections

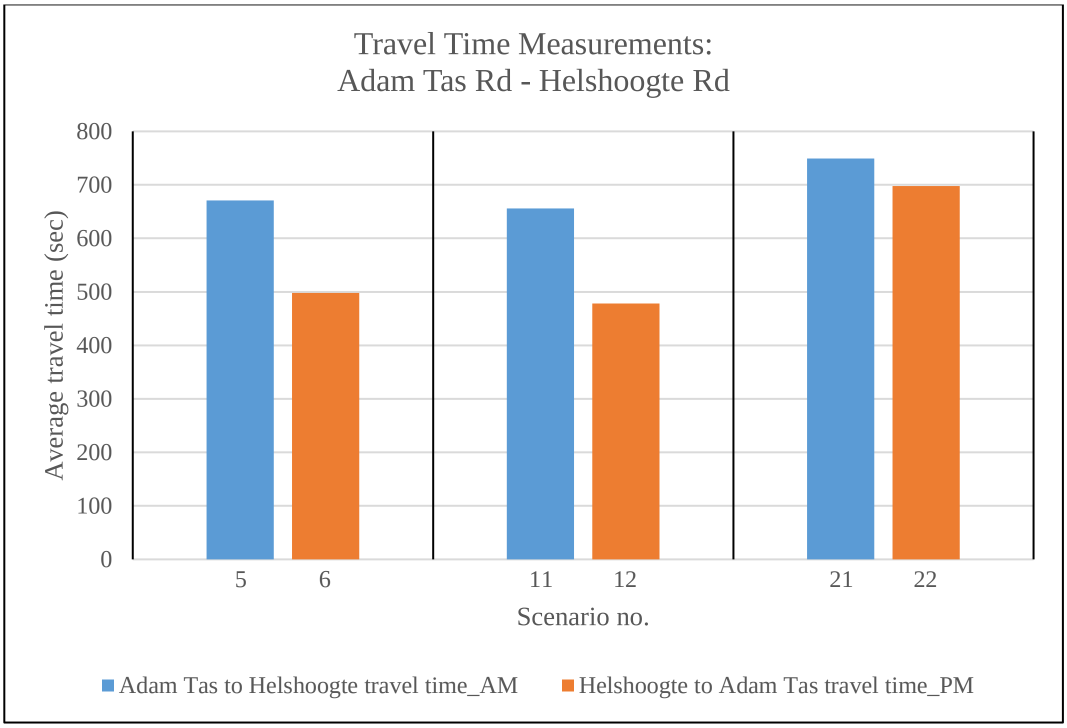

Figure 7-18: Travel time measurement between Adam Tas Rd/Dorp St and R44/Helshoogte Rd intersections

7.5.4 Travel time measurements summary

The travel time measurement analysis was a simple tool to verify the outcomes of the previous result findings. It showed that a TASC system does indeed provide a level of relief to the traffic network. The extent of this travel time reduction over the major-directional travel routes can be seen in Table 7-4 below.

Table 7-4: Percentage change in travel time for the given travel time measurements after implementation of TASC

Travel time measurement no.	Change in travel time
1. Van Rheede to Helshoogte AM	▼ 15%
2. Helshoogte to Van Rheede PM	▼ 27%
3. Adam Tas to Helshoogte AM	▼ 12%
4. Helshoogte to Adam Tas PM	▼ 31%

7.6 Results analysis summary

The results analysis chapter provided an insight into the evaluation of the TASC system under consideration and the aim was to identify the possible success of using this system in the proposed environment, simulated using PTV Vissim.

PTV Epics and Balance were found to definitely bring substantial improvement to the R44 subnetwork. When analysing the network level results, it was observed that the use of PTV Epics (local optimisation only) brought the best improvements for most evaluated KPIs. This was, however, always very closely matched by the scenarios using both PTV Epics and Balance (local optimisation and global coordination). Similar results were analysed during the nodal and turning movement evaluation, as well as the travel time measurement assessment. For reference to the specific outcome summaries, sections 7.3.4, 7.4.5 and 7.5.4 should be consulted. In general it was found that the TASC system realised substantial improvements to the prevailing traffic conditions, ranging from 10 to 30% and sometimes even as high as 40%.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Research summary

This research was aimed at understanding the operation of a Traffic-adaptive Signal Control (TASC) system, specifically considering its potential applicability within a developing country context. The need for insight into novel signal control methods arose from ever increasing traffic demand on traffic networks already experiencing oversaturation in places where conventional methods of signal control cannot fully meet demand. TASC systems could potentially alleviate the difficulty of managing traffic on highly congested, signal controlled corridors due to their ability to regulate the traffic in real-time. This method of traffic regulation has been found to work well in environments were adequate and accurate vehicle detection is available and driving behaviour follows certain standards.

A convenient corridor for evaluating and testing such a TASC system was found to be the R44 arterial through the town of Stellenbosch. Stellenbosch is a rather isolated traffic environment presenting itself as an ideal testbed for such a system. The section of the R44 arterial that was considered contains a number of signal controlled intersections in relatively close proximity to each other, currently individually controlled on a traffic actuated system. AM and PM peak hour demand create a highly oversaturated network and the signal controllers essentially revert back to "fixed-time" plans.

PTV Epics and Balance were identified as the TASC system of choice, considering both local and global model-based control. The system was tested within a traffic modelling environment, set up within PTV Visum and PTV Vissim.

8.2 Summary of work efforts

Since combined model-based centralised and decentralised TASC application has not been proven in the African context, this research was not aimed at creating a new TASC system but rather at applying an established model-based system in the African context and creating documented insight into its functionality and effects. In order to satisfy this objective the following work components, summarised in Table 8-1, had to be undertaken. Detailed discussion can be found in previous chapters of this report.

Table 8-1: Summary of all relevant work components for this research study

Work component		Description
Pre-application	Problem definition	Identifying the initial need for the application of TASC. Specifically, congested signalised traffic corridors were identified that may require a solution approach different to conventional approaches.
	TASC study	Detailed insight into the potential application of TASC, its functionality and various components was developed. The different methods of application, different approaches and resultant outcomes were analysed.
	Literature insight	The combination of model-based centralised and decentralised TASC control was identified as a gap in literature discussion.
Data collection	Needs analysis	Specific needs analysis for TASC application was conducted to ensure the most practical and useful application of TASC on the R44. The process of collecting all relevant data components was extensive.
	Municipality	Collection of most required data components was facilitated through interaction with the Stellenbosch Municipality. Various traffic count data was obtained. Broad ward zones as well as very specific land-use information was acquired and further detailed for the setup of the travel demand model. All necessary signal control data, and current inductive loop information, was also obtained.
	Traffic counts	Additional traffic counts were manually conducted at specific intersections by the student as part of the validation process.
	Site visits	All inductive loop detector positions were determined through physical measurements and testing via the local controller. The driving behaviour in the study area was observed during a range of different time periods to ensure realistic modelling later. Also, the base signal plans were verified with timed observations.
Software related	PTV Visum	Extensive study into the PTV Visum functionality and its practical modelling techniques was undertaken. The required modelling detail for sufficiently accurate comparative results analysis was established.
	PTV Vissim	Extensive study into the PTV Vissim functionality and its practical modelling techniques was undertaken. An understanding into combined macroscopic and microscopic modelling was established in order to ensure an accurate data supply chain.
	Epics & Balance	The real-time modelling components of importance for this study were analysed and studied in detail. Specifically, the integration into the macroscopic and microscopic modelling environment was of importance. This required, for example, that the signal control files were set up to link to both the Visum and Vissim models.

Work component		Description
Modelling	Setup	Extensive effort went into the setup of the various modelling components. These included the initial Visum travel demand model, the Visum R44 model and the Vissim R44 model. The travel demand model required the setup of a 4-Step Model to obtain a representative estimation of the current peak hour trip distribution in Stellenbosch. This, for example, required the calculation of trip generation factors as well as to establish the utility function for trip distribution. Another aspect of extensive effort was the manipulation of all signal control data. The real-time control components were integrated and modified to fit the present traffic environment.
	Calibration	Calibration and validation of all the modelling spheres was essential to ensure that optimisation was based on reliable, representative models. This prevented the system from reaching a false optimum. For example, the turn specific intersection volumes in the travel demand model had to be calibrated to counted volumes and the average speed/section in the Micro Model had to be validated with TomTom data.
	Validation	
	Scenario definition	Identifying various different levels and methods of applying TASC was of importance to ensure insight into how the system could potentially function on the R44 under a range of operational scenarios. This included using only centralised, decentralised or combined control components of TASC.
Evaluation	KPI definition	In order to ensure comparable results analysis, representative key performance indicators had to be identified. This was based on the study of previous TASC applications as well as an understanding into the factors to be minimised during optimisation.
	Methods of analysis	The most accurate and applicable methods of analysis were also identified in order to establish relevant and meaningful results outcomes.
Industry project	Municipality	Involvement in the study-related industry project ensured exposure to the typical processes followed during the establishing of TASC, as well as the challenges associated therewith. Extensive contact with industry professionals aided the structure of the research process.
	PTV Group	
	Syntell	

8.3 Evaluation of the research objectives

A number of individual objectives were identified, based on the main objective and problem statement set out in Chapter 1. Each individual objective is briefly mentioned in Table 8-2 and reference is made thereafter as to how each of these objectives was addressed.

Main objective and problem statement

The main aim of this research was to evaluate the applicability of a TASC system on the R44 arterial through Stellenbosch in order to address the question of how applicable and effective TASC is in a developing world environment as a means to alleviate transport related problems on a traffic corridor.

Table 8-2: Summary of the research objectives

Objective no.	Description	Objective achieved	Relevant Chapter
1.	Evaluate different TASC systems in order to identify the most applicable to the traffic environment under consideration.	Yes	2
2.	Identify the specific challenges, e.g. non-signalised intersection inclusion, and address the effect these have on the TASC system.	Yes	2,5,6,7
3.	Evaluate the differences in the implementation of TASC as compared to the developed world.	Yes	2,4,6
4.	Consider different available data sources in order to identify the most applicable and useful to this environment.	Yes*	2,4
5.	Invest extensive effort into creating an accurate simulation environment reflecting reality as closely as possible.	Yes	6
6.	Provide evaluation results using applicable performance measures to ensure credible, valid and reliable project outcomes.	Yes	7

**Although FCD was initially to be evaluated as a potential addition of real-time data input, it was only used during the PTV Vissim model validation.*

From Table 8-2 above, it can be seen that all individual research objectives were addressed satisfactorily. Each objective is briefly discussed to show *how* this was done.

Objective 1: Three different systems were evaluated as part of the literature review – SCOOT, SCATS and PTV Epics & Balance. Comparison was made based on a number of criteria and PTV Epics & Balance was found to be the most applicable and readily available for use in this research project.

Objective 2: The initially identified challenges associated with the implementation of TASC along the R44 arterial included an unsignalised intersection and a train crossing. The impact of an unsignalised intersection in the TASC network was observed by comparing various signalisation scenarios. The inclusion of the train crossing was handled by PTV Epics local optimisation.

Objective 3: The typical manner of TASC implementation in a developed world context was analysed in the literature study. Differences to developing country application were mostly related to traffic data availability, thus affecting how the model setup was handled.

Objective 4: Different traffic data sources were considered for model setup. Physical intersection counts were used for model calibration and TomTom floating car data (FCD) was used for model validation. Real-time vehicle detection data from inductive loop or camera detectors would be used during real-world application.

Objective 5: The setup of the various simulation components reflected the recommended data supply chain for the PTV Epics & Balance TASC system. Firstly, a macroscopic Stellenbosch Model was created which formed the basis for a subnetwork R44 Macro Model. This in turn fed into a subnetwork R44 Micro Model within which all evaluation and testing was performed.

Objective 6: Evaluation was done on a network level, comparing various key performance indicators such as delay, travel time and speed over different scenarios. Further comparisons were made on an intersection and turning movement level as well as by analysing specific route-based travel time measurements.

8.4 Conclusions

Research propositions

Three different research propositions were defined in Chapter 3. These statements related the understanding gained during the literature review to predict possible outcomes for this project and are discussed hereafter. It was found that not any one of these three statements on its own properly predicted the outcomes of this study.

The **first** proposition envisioned the TASC system to be able to improve current traffic conditions even considering a possible lack of accurate detection options. It also stated that the degree of successful optimisation would thus depend on the extent of accurate vehicle detection. This was found to be partly true seeing that improvement was realised, yet not under all detection setups. This is where the **second** propositions comes in by predicting that only ideal detection would bring improvements and anything else would only lead to equal or worse traffic conditions. This was also not found to be entirely true since the improvements which were realised were neither based on absolutely ideal detection nor on only minimal real-time detection. The “ideal” detection which was used in the best case scenarios was based on the currently possible real-time detection available in the real world environment in order to keep the research relevant. Somewhat of a middle way between the first two propositions was therefore observed during the results analysis. The **third** proposition was found not to be true. It claimed that even the slightest level of real-time data input would exponentially increase the ability to optimise traffic operations. It was, however, found that sub-optimal detection (not per-lane) worsened the traffic conditions rather than improving them.

Network and intersection analysis

It was found that the TASC configuration applied to the R44 corridor improved the traffic flow significantly. Interestingly, the best overall network level improvements were obtained by applying exclusive local optimisation (PTV Epics) to the intersections, followed closely by both local and global control (PTV Epics and PTV Balance). On intersection level, however, this was only seen to be the case when the clear possibility to coordinate was not present. The additional travel time measurements also showed a reduction in route-specific travel time, generally favouring the scenarios where the full combination of both PTV Epics and PTV Balance was used. It can therefore be seen that both PTV Epics and PTV Balance were able to improve on the current traffic conditions. Individually applied, PTV Epics outperformed PTV Balance, yet in combination they complemented each other nicely, as was observed specifically during the turning movement analysis.

Simulation challenges

Considering, specifically, the initially identified challenges within the R44 study area, such as the unsignalised intersection at R44/Alexander St and the train crossing at R44/George Blake St, further conclusions can be identified. The train crossing turned out to be of no issue since the non-cyclical inclusion of a public transport stage was easily done within PTV Vissig, as explained in Chapter 6. The unsignalised intersection (R44/Alexander St), however, was found to present the TASC system with a problem and only when simulating the network with signals at that location were positive and adequate results realised. It can therefore be concluded that such a network, containing a mix of signalised and unsignalised intersections is not suitable for a TASC system.

Developing country application

Another set of conclusions becomes evident when looking beyond the mere results analysis and focusing on the greater picture of setting up the model as well as on the data requirements. The effort and knowledge required to create a reliable and useful optimisation model, both in terms of technical simulation experience as well as local traffic knowledge and data availability, make this specific type of TASC control potentially unattractive to certain application areas in developing countries. This project showed that the effort required for the initial set up of the model was far more extensive than initially expected, especially considering the amount of data required. These problems are easily solved under condition that sufficient resources are available which could potentially, however, increase project costs. The conclusion can therefore be made that the TASC application as demonstrated in this study is by no means a simple plug-and-play type of signal control that can be set up very easily and left to optimise the traffic on its own. It requires technical expertise, sufficient data availability and continued maintenance.

Final conclusion

In final conclusion, it was found that the use of a TASC system can potentially have a very positive effect on traffic conditions and that traffic flow indicators such as vehicle delay and travel time were significantly decreased after this implementation of real-time control. As long as the utilised vehicle detection and model setup adhered to certain minimum requirements it was found that improvements were realised, thus resulting in better overall traffic conditions. The best achieved decrease in network travel time was 13% for the AM peak hour and 27% for the PM peak hour. Network average speed was increased by 40% in the AM peak hour and 49% in the PM peak hour. In the end it can be seen that TASC can be a useful and suitable traffic management tool if applied in the correct situation, under appropriate implementation circumstances and relying on accurate modelling techniques.

8.5 Recommendations

Stellenbosch application

Firstly focusing on Stellenbosch and the R44 corridor as a testbed for this evaluative simulation exercise, it is recommended that the PTV Epics and Balance TASC system is implemented as a measure of relieving traffic related problems, specifically by addressing the signal control. Alongside this it is recommended that continuous attention should be placed on updating the applicable model environment and increasing its accuracy in order to allow changes in the traffic network under consideration to be reflected within the TASC model.

Developing country application

When looking at a broader developing world context and under condition that all required data is available and the expertise and resources are present to make the long term use of such a system viable, it is also recommended that the TASC system as discussed and analysed in this research report should be implemented to alleviate traffic congestion, specifically on signalised traffic corridors. Alongside this recommendation, however, goes a stern acknowledgement of the fact that a TASC system as discussed requires substantial inputs and management and should therefore not be underestimated in this regard nor praised beyond its actual ability and capacity to bring improvements on its own.

Where the resources, expertise and data accessibility are not necessarily as readily available, considering especially now the scenario of a more extensively developing country application, it is recommended that more traditional and affordable signal control management options, such as regular updating of the signal plans, should first be addressed. Upon further optimisation it is recommended that the stand-alone local optimisation PTV Epics technique should be deployed, requiring fewer resources than an entire setup and potentially bringing substantial improvements on its own, as was seen in this study.

8.6 A note on sustainable TASC operation

Having gained insight into the functionality and possible positive application of TASC overall, as well as the realisation that its application can be potentially complex, some mention needs to be made of the prerequisites for the sustainable operation of TASC.

An important first note is that TASC literature has not been found to make specific mention regarding sustainable application practices, particularly in the context of the developing world. The generally visible trend of TASC evaluation and success is based on the changes in performance measures before versus after the implementation of the system. A number of papers hint at possible reasons for failed or ineffective TASC applications, such as a lack of expertise in traffic engineering; using poorly maintained base signal plans or the challenges relating to accurate microscopic modelling (Kergaye *et al.*, 2009; Kergaye, Stevanovic and Martin, 2010; Tian and Zhang, 2017). However, these were generally included only in passing, not focused on as a topic in its own right. The lack of this direct insight into sustainable TASC operation means that it is difficult for municipalities to know in advance what the possible challenges may be to achieve successful implementation.

A helpful concept to consider in ensuring the sustainability of a TASC system would be to focus on a **Systems Engineering** (SE) approach (ASE Consulting LLC *et al*, 2007). This essentially is a process whereby system development considers the entire lifecycle of a system and emphasises up-front planning and system definition. SE is used as a means to ensure the successful realisation of Intelligent Transportation Systems (ITS). An important part of the SE process is the development of a Concept of Operations (ConOps) as well as a clear definition of specific Roles and Responsibilities (R&R) to ensure a successful operations and maintenance phase and ultimately the success of the project.

The ConOps is aimed at describing and documenting the entire system in a non-technical and easy-to-understand manner. This ensures that all involved stakeholder parties understand the process of moving from the problem space to actual system level requirements. Validation of the ConOps is facilitated during initial system deployment, after detailed design was finalised. The following are typical questions which result from this validation step. “Are all stakeholders aware of their roles and responsibilities?” “Are all resources needed for the deployment step available?” The operations and maintenance step within the SE approach ensures that all activities needed to effectively operate and maintain the system in a day-to-day operational environment are described.

The above highlights the need for a clearly defined operational structure, specific roles and responsibilities and how they change before versus after the implementation. From a TASC perspective this would ensure, for example, the presence of trained personnel to handle the operation and day-to-to maintenance requirements. In the case of the Stellenbosch R44 industry project, it was established that two full-time employees of the Stellenbosch Municipality are required to maintain, manage and improve the TASC system. Other aspects would include continuous updating and detailing of the model environment. Together with this the need for continued performance evaluation becomes evident. Application-specific needs might change and the system then has to be adapted accordingly. Another aspect which the SE approach would take into account is the provision of sufficiently capable physical infrastructure and components. This would include, for example, the communications network, the detection mechanisms as well as the actual control room.

A case study in Reston, Virginia has been identified as a real-world TASC implementation indicating some issues that could have been prevented using the SE approach (Gartner, Pooran and Andrews, 2001). A specific challenge was the loss in communication at several intersections due to a mismanaged communications protocol with the local service provider. Additionally, untimely implementation deadlines prevented adequate calibration and fine-tuning before final operation. These challenges could have been identified and addressed within a SE approach before actual damage occurred.

As can be seen from the above example, most of the more specific and detailed components of sustainable TASC operation depend on the particular project and the involved stakeholders. The SE approach, however, can provide the framework and guidelines to establish the required sustainability and should therefore be considered as a helpful tool in establishing TASC in the developing world context.

8.7 Future research

As a final section of this report several future research recommendation are presented. These provide an insight into areas of this study where further work can be done in order to provide a deeper understanding into the application of TASC in Stellenbosch as well as elsewhere in developing countries.

Future research in Stellenbosch:

- Firstly, update the extent of accurate modelling in the PTV Visum Stellenbosch Model by, for example, further stratification. This would also enable the expansion of TASC control to other parts of Stellenbosch.
- Expand the underlying models to accommodate an entire day of TASC control, not just the AM and PM peak hour periods. This would mean additional data input and calibration but is required to successfully run such a system over the entire day.
- Analyse the impact of TASC using signal plans with initially adapted signal cycle lengths and possibly different coordination groups throughout the network to assist with coordination. This could alter the impact PTV Balance has on the traffic conditions.

- Simulate the R44 network with a more suitably derived signal plan at the R44/Alexander St intersection, especially considering the PM peak hour, since the currently used plans were loosely based on the R44/Merriman Ave intersection.
- This research did not focus on pedestrian inclusion at all intersections but only at designated signalised pedestrian crossings. Future research could therefore focus on the way in which the overall network results are affected if pedestrian movements are included at all intersections.

Future research also regarding developing countries in general:

- Use extensive “real-time” vehicle detection data sets to test the TASC system in a simulation environment where outcomes are not purely based on simulated traffic volumes but also on actual detector values representing an even more accurate picture of reality.
- Use more varied ideal detection positions to identify the potential further improvements these could bring, even if they are not necessarily going to be available in the real world.
- Test the extent to which the TASC system would be able to handle untypical, event-based traffic demand, i.e. analyse various demand conditions.
- Possibly test alternate ways in which PTV Balance optimised by altering the PTV Balance-specific parameters.
- Also, an option for future research is to expand testing of the system into different levels of combined local and global control, i.e. the weightings given to PTV Epics and Balance in relation to each other.

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Appendix A – Model Components & Data

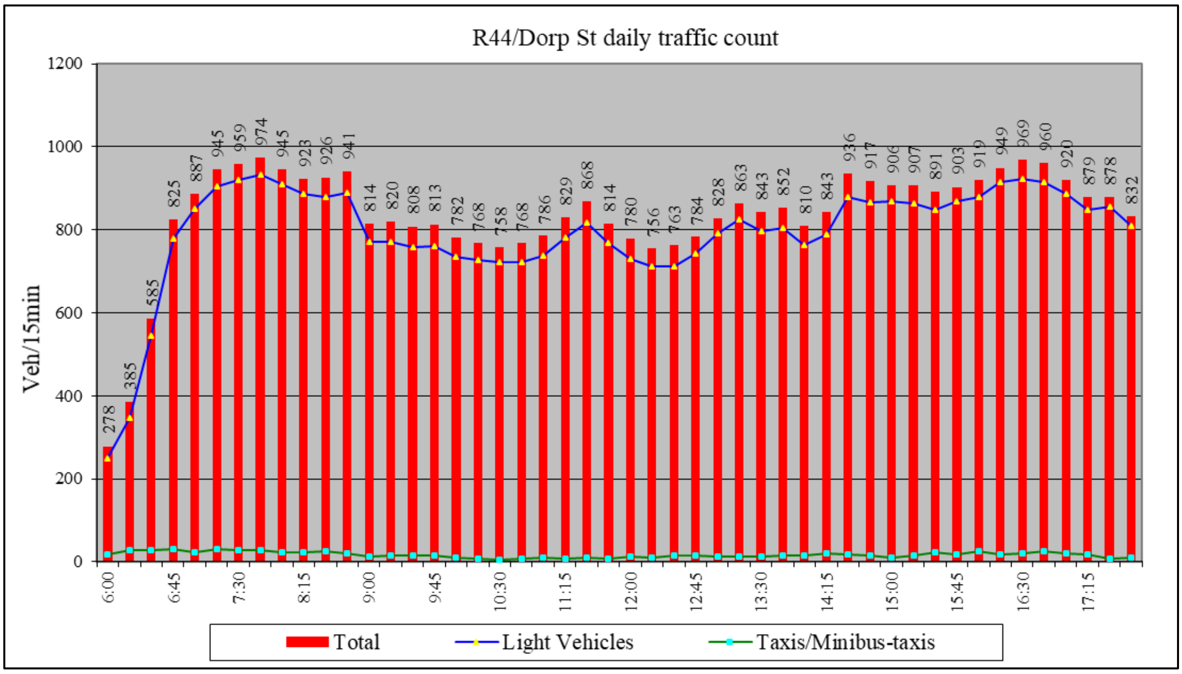


Figure A-1: R44/Dorp St daily full intersection traffic count (NVTS)

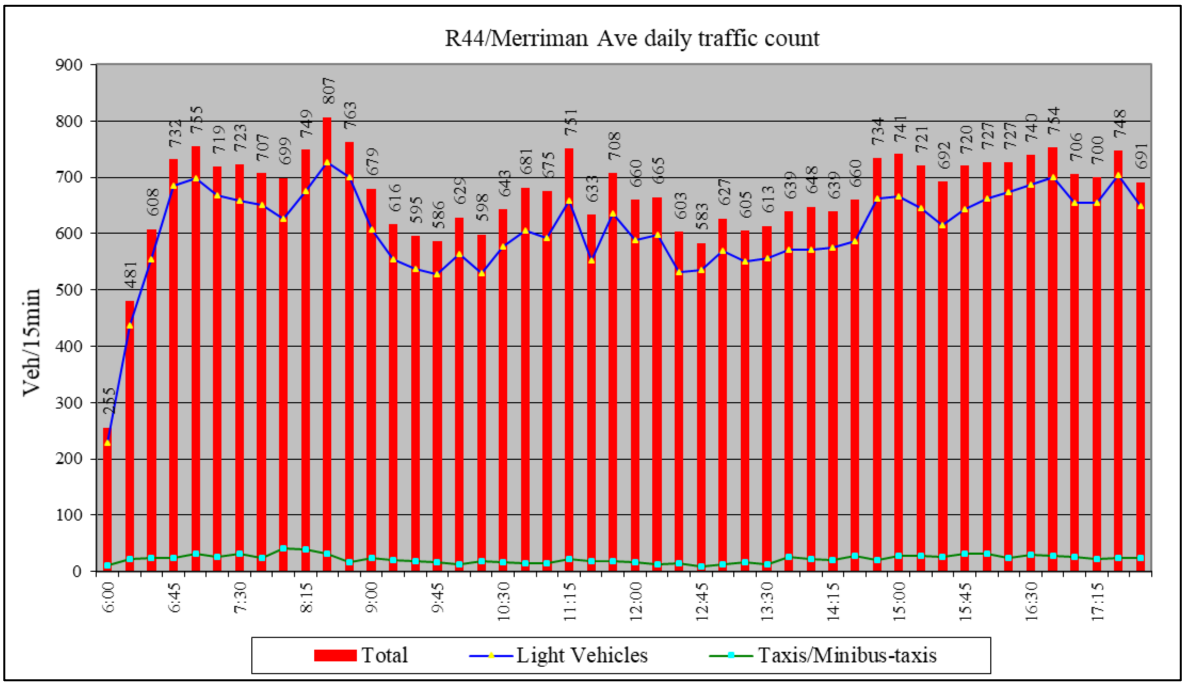


Figure A-2: R44/Merriman Ave daily full intersection traffic count (NVTS)

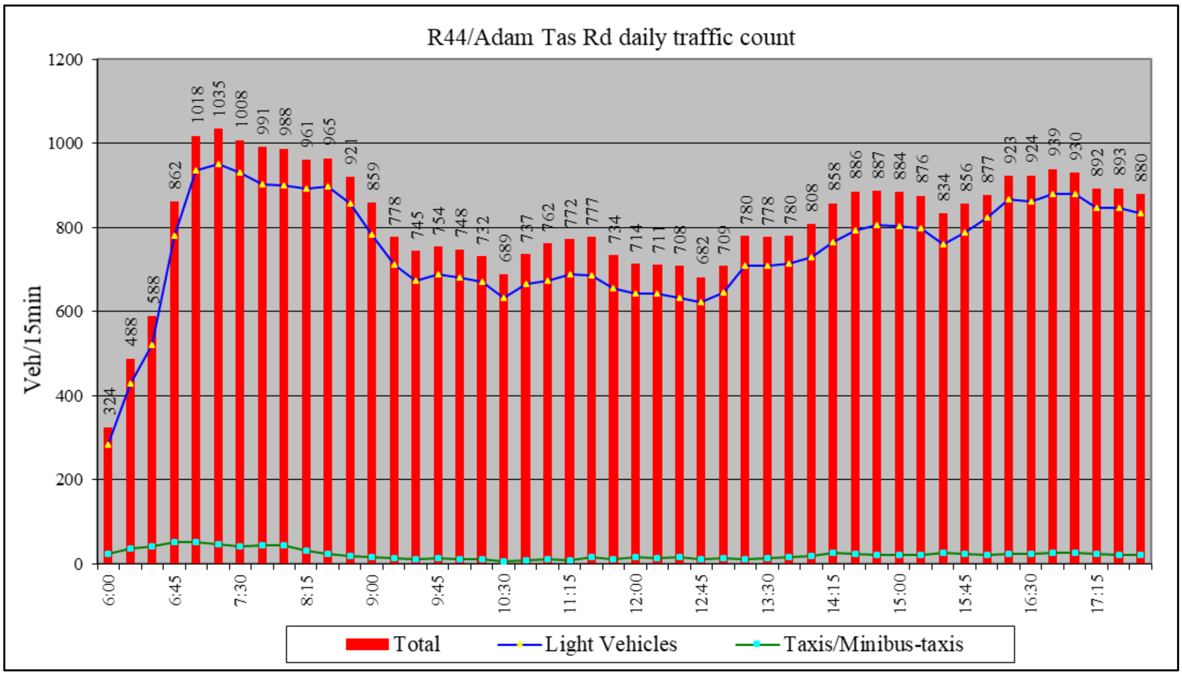


Figure A-3: R44/Adam Tas Rd daily full intersection traffic count (NVTS)

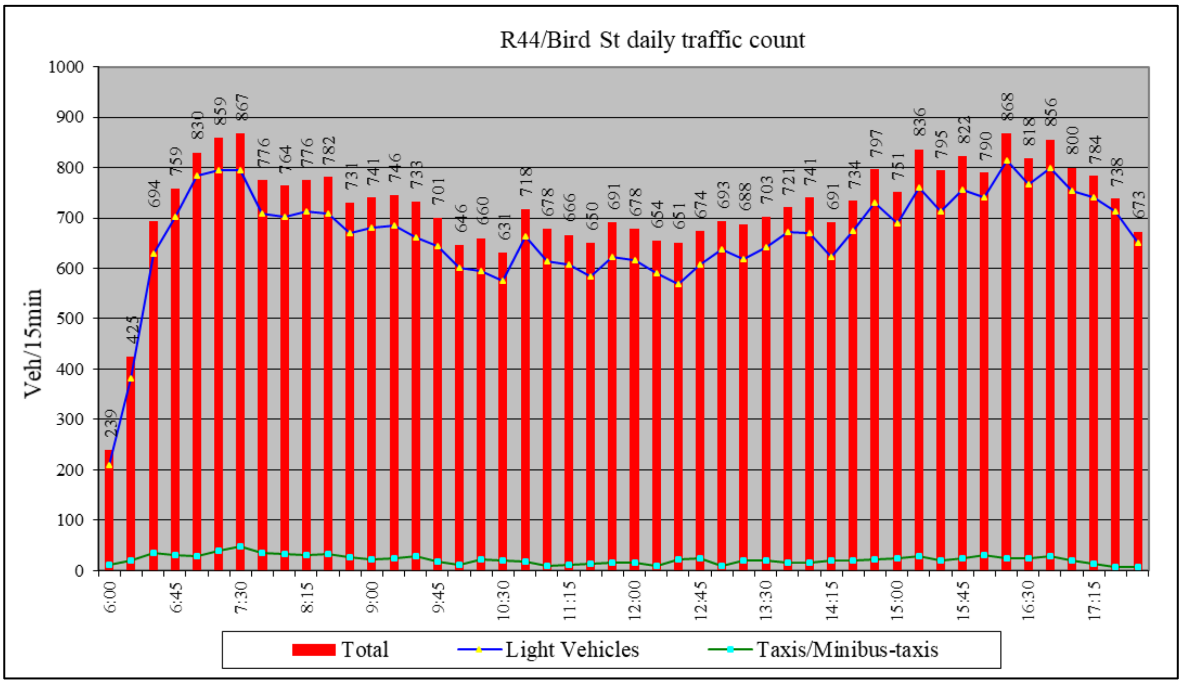


Figure A-4: R44 Bird St daily full intersection traffic count (NVTS)

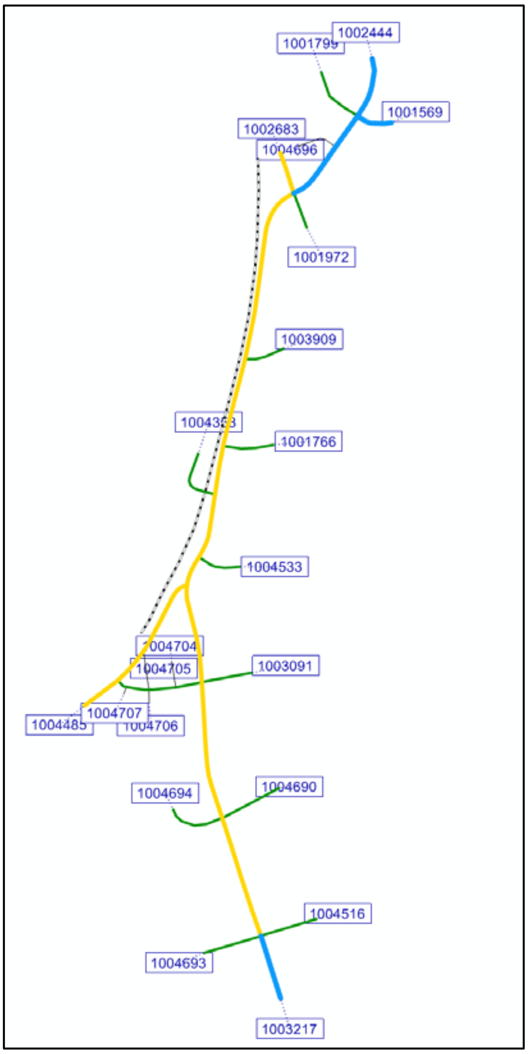


Figure A-5: R44 subnetwork input zone numbering

21 x 21			1001569	1001766	1001799	1001972	1002444	1002683	1003091	1003217	1003909	1004353	1004485	1004516	1004533	1004690	1004693	1004694	1004696	1004704	1004705	1004706	1004707
	Name																						
		Sum	1221.80	662.20	172.50	949.90	825.40	617.70	996.10	1835.40	289.30	689.30	1198.20	1181.50	714.10	279.10	260.30	398.50	182.90	19.80	15.00	205.30	112.40
1001569		560.50	0.00	0.10	87.70	0.00	234.80	112.80	0.00	22.60	0.10	15.50	20.50	1.10	5.80	21.40	0.50	7.40	11.60	0.00	1.80	5.40	11.40
1001766		517.30	4.90	0.00	0.30	0.40	40.70	4.70	0.00	44.20	1.80	176.00	163.90	0.00	0.00	0.40	0.20	21.30	1.90	0.00	0.60	40.20	15.80
1001799		447.10	216.10	0.10	0.00	70.90	6.80	64.70	0.00	83.60	0.10	0.00	2.70	0.10	1.40	0.30	0.00	0.30	0.00	0.00	0.00	0.00	0.00
1001972		498.50	0.20	0.00	0.40	0.00	129.70	360.70	0.00	3.90	0.00	0.00	2.20	0.00	0.30	0.70	0.00	0.20	0.00	0.00	0.10	0.10	0.00
1002444		1566.10	655.90	65.70	10.50	335.00	0.00	21.50	0.00	63.00	11.10	7.40	63.90	6.70	167.70	39.00	0.90	28.50	2.50	0.00	4.00	41.20	41.60
1002683		962.70	12.70	46.10	0.20	537.70	12.40	0.00	0.00	84.00	24.80	16.90	81.30	11.10	17.20	48.60	0.70	37.80	0.00	0.00	7.00	1.80	22.40
1003091		545.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	234.10	0.00	0.00	144.10	0.10	0.00	0.60	0.10	119.40	0.00	2.00	0.00	45.40	0.00
1003217		2800.90	141.70	174.70	37.10	2.90	50.30	13.20	296.00	0.00	101.80	145.90	208.10	1013.00	162.80	38.50	255.30	79.30	10.80	13.00	0.00	56.50	0.00
1003909		174.10	0.00	0.20	0.00	0.00	71.60	0.50	0.00	45.40	0.00	1.70	37.80	0.40	2.00	6.20	0.20	6.80	0.00	0.00	0.20	1.00	0.10
1004353		571.00	18.30	127.50	0.00	0.00	0.00	0.00	0.00	188.70	60.30	0.00	138.70	0.30	13.40	12.00	0.10	11.40	0.00	0.00	0.00	0.30	0.00
1004485		2027.30	117.80	217.10	36.10	1.10	117.90	28.10	438.10	130.30	78.00	231.20	0.00	15.60	330.30	67.40	1.30	51.00	139.30	4.70	1.10	0.00	20.90
1004516		687.70	1.00	0.00	0.00	0.30	29.00	2.40	0.10	628.80	0.40	2.50	21.60	0.00	0.00	0.00	0.90	0.00	0.40	0.10	0.00	0.20	0.00
1004533		418.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	97.20	0.00	72.00	231.70	0.10	0.00	0.00	0.00	4.00	0.00	0.00	0.10	12.90	0.20
1004690		196.40	10.10	0.00	0.00	0.40	69.30	3.70	0.00	22.50	0.50	12.50	47.80	0.00	0.00	0.00	0.00	29.00	0.60	0.00	0.00	0.00	0.00
1004693		240.70	0.90	0.70	0.00	0.20	6.00	1.40	0.20	89.60	2.10	1.20	4.50	132.70	0.90	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00
1004694		468.10	21.80	29.10	0.10	0.90	26.90	2.90	216.10	71.70	6.20	5.80	20.80	0.00	9.00	41.80	0.00	0.00	15.00	0.00	0.00	0.00	0.00
1004696		51.00	13.90	0.20	0.10	0.00	10.20	0.00	0.00	14.30	0.00	0.00	5.40	0.20	2.00	2.10	0.10	2.10	0.00	0.00	0.10	0.30	0.00
1004704		33.80	1.50	0.30	0.00	0.10	2.50	0.50	21.10	5.30	1.00	0.40	0.00	0.10	0.70	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00
1004705		1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1004706		37.30	1.50	0.40	0.00	0.00	1.80	0.60	24.50	6.20	1.10	0.30	0.00	0.00	0.60	0.10	0.00	0.00	0.20	0.00	0.00	0.00	0.00
1004707		20.30	3.50	0.00	0.00	0.00	15.50	0.00	0.00	0.00	0.00	0.00	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure A-6: AM R44 subnetwork matrix

21 x 21			1001569	1001766	1001799	1001972	1002444	1002683	1003091	1003217	1003909	1004353	1004485	1004516	1004533	1004690	1004693	1004694	1004696	1004704	1004705	1004706	1004707
	Name																						
		Sum	421.90	458.90	223.90	511.10	1461.30	1061.20	670.10	1834.10	198.60	458.40	1252.50	722.60	488.70	144.90	270.60	401.70	34.20	179.10	8.30	158.50	57.20
1001569		1109.70	0.00	1.60	77.30	2.30	785.40	119.60	0.00	66.20	0.00	5.30	30.50	2.20	3.10	3.90	0.70	6.50	3.40	0.00	0.60	0.00	1.10
1001766		599.00	0.60	0.00	0.10	0.10	111.40	2.90	0.00	167.00	18.30	110.30	146.80	14.90	0.00	7.40	1.30	17.00	0.10	0.00	0.40	0.00	0.40
1001799		91.30	78.90	0.20	0.00	9.10	0.00	0.50	0.00	0.60	0.10	0.00	0.40	0.20	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1001972		675.00	0.00	0.00	42.50	0.00	238.00	390.20	0.00	1.10	0.00	0.00	0.50	0.90	0.80	0.30	0.10	0.50	0.00	0.00	0.10	0.00	0.00
1002444		487.30	137.90	6.20	15.30	137.30	0.00	38.70	0.00	9.00	41.50	0.00	22.60	18.00	23.10	22.10	2.30	8.80	0.00	0.00	0.80	0.00	3.70
1002683		665.70	36.50	20.50	10.70	348.50	11.10	0.00	0.00	24.70	11.00	0.00	85.80	13.40	76.60	9.70	2.70	12.00	0.00	0.00	1.20	0.00	1.30
1003091		614.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	194.70	0.00	0.00	259.20	0.80	0.00	0.10	0.10	126.00	0.00	16.10	0.00	2.80	14.90
1003217		1973.90	19.10	20.60	69.40	5.30	39.00	88.30	373.10	0.00	36.70	112.40	42.30	541.50	32.00	0.00	112.30	135.60	12.30	155.80	0.00	150.60	27.60
1003909		185.10	0.60	0.20	0.10	0.00	18.10	49.30	0.00	19.30	0.00	35.40	30.60	4.00	19.90	2.00	0.60	3.80	0.00	0.00	0.60	0.00	0.60
1004353		631.50	0.00	176.20	0.00	0.00	0.00	0.00	0.00	122.20	2.80	0.00	201.20	7.20	95.80	16.20	1.60	7.70	0.00	0.00	0.30	0.00	0.30
1004485		1000.90	49.50	68.00	3.30	4.50	74.10	169.20	22.50	117.70	38.70	143.60	0.00	35.20	173.50	51.40	5.50	27.50	11.30	0.00	3.30	0.00	2.10
1004516		804.20	2.50	0.10	0.30	0.20	27.30	47.20	0.20	654.40	3.60	1.10	1.00	0.00	0.10	0.00	54.10	0.00	0.60	5.80	0.00	4.00	1.70
1004533		759.80	52.30	0.00	3.70	2.60	35.80	33.40	0.00	171.30	16.10	34.00	297.30	3.80	0.00	2.60	88.90	10.70	3.90	0.00	0.70	0.00	2.70
1004690		319.80	12.10	77.20	0.20	0.70	27.00	35.40	0.60	92.90	25.40	7.80	0.30	0.00	0.50	0.00	0.00	37.70	1.10	0.40	0.00	0.00	0.50
1004693		150.20	2.10	0.60	0.10	0.20	5.50	4.90	1.40	57.70	0.70	0.30	0.20	75.20	0.10	0.00	0.00	0.00	0.20	0.50	0.00	0.50	0.00
1004694		221.80	5.10	66.90	0.60	0.20	19.10	26.20	11.60	43.20	3.20	7.90	0.10	3.10	6.00	26.30	0.00	0.00	1.20	0.50	0.00	0.60	0.00
1004696		218.50	10.90	0.60	0.10	0.00	17.00	0.00	0.00	58.90	0.10	0.00	106.20	1.90	11.10	2.80	0.40	7.90	0.00	0.00	0.30	0.00	0.30
1004704		29.40	0.50	0.60	0.00	0.00	1.20	3.30	16.50	6.00	0.00	0.10	0.00	0.10	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1004705		6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1004706		307.80	0.20	1.70	0.20	0.10	0.50	16.30	244.20	27.20	0.30	0.10	0.00	0.20	16.60	0.10	0.00	0.00	0.10	0.00	0.00	0.00	0.00
1004707		166.20	13.10	17.70	0.00	0.00	50.80	35.80	0.00	0.00	0.10	0.10	21.50	0.00	27.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure A-7: PM R44 subnetwork matrix

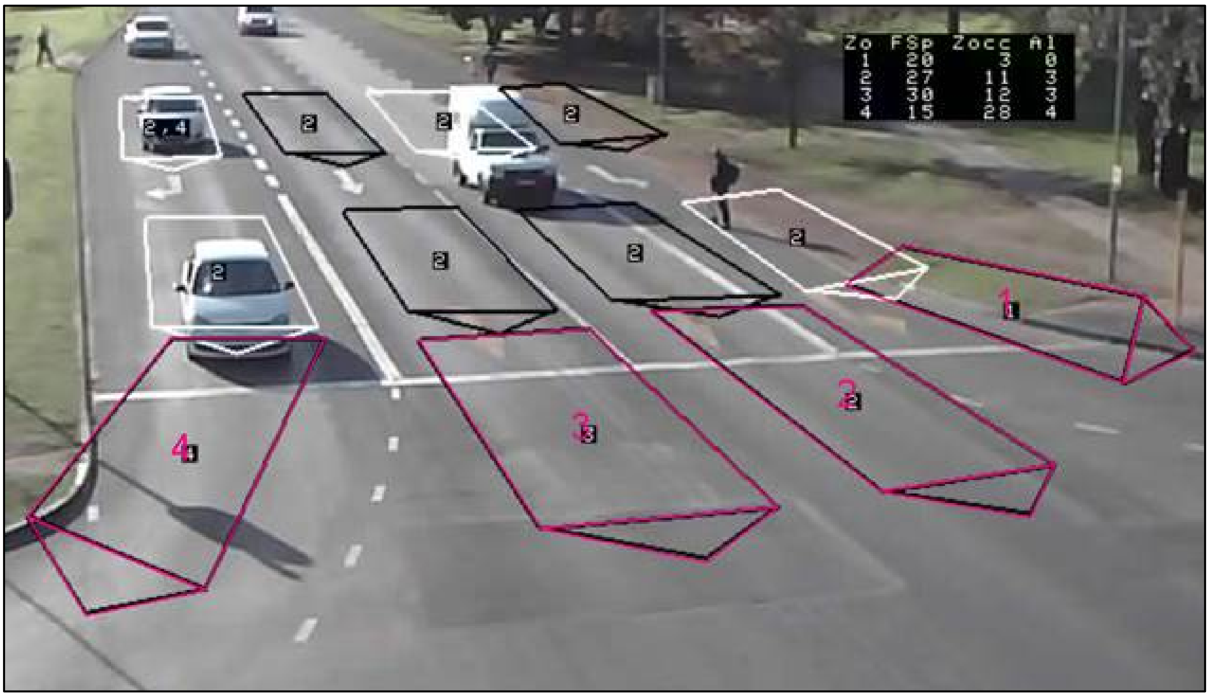


Figure A-8: TrafiCam x-stream vehicle detection configuration (utilising the 5m and 20m loops)

APPENDIX B – MODEL DEVELOPMENT

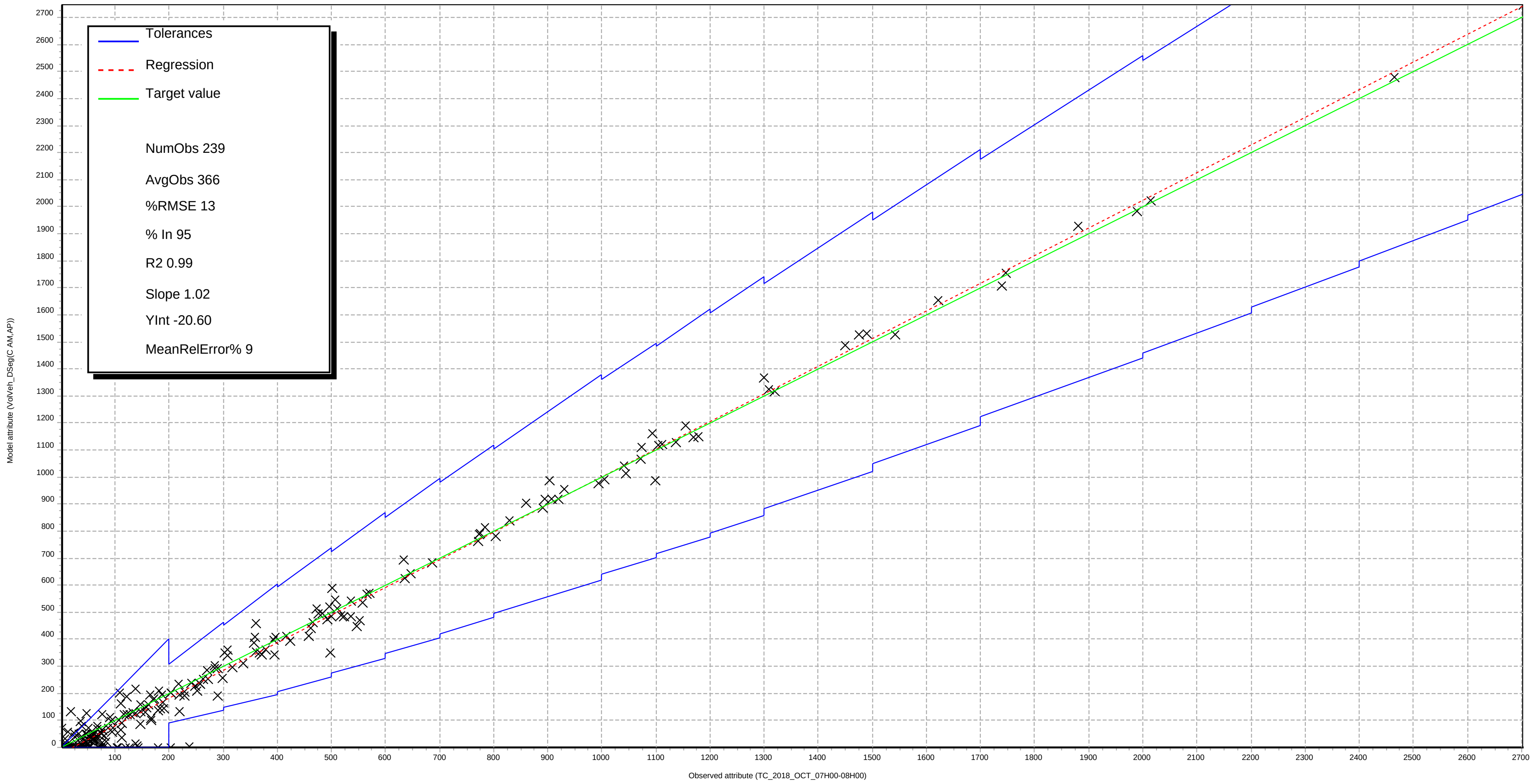


Figure B- 1: AM peak hour goodness-of-fit between the modelled vs the counted traffic volumes after calibration took place

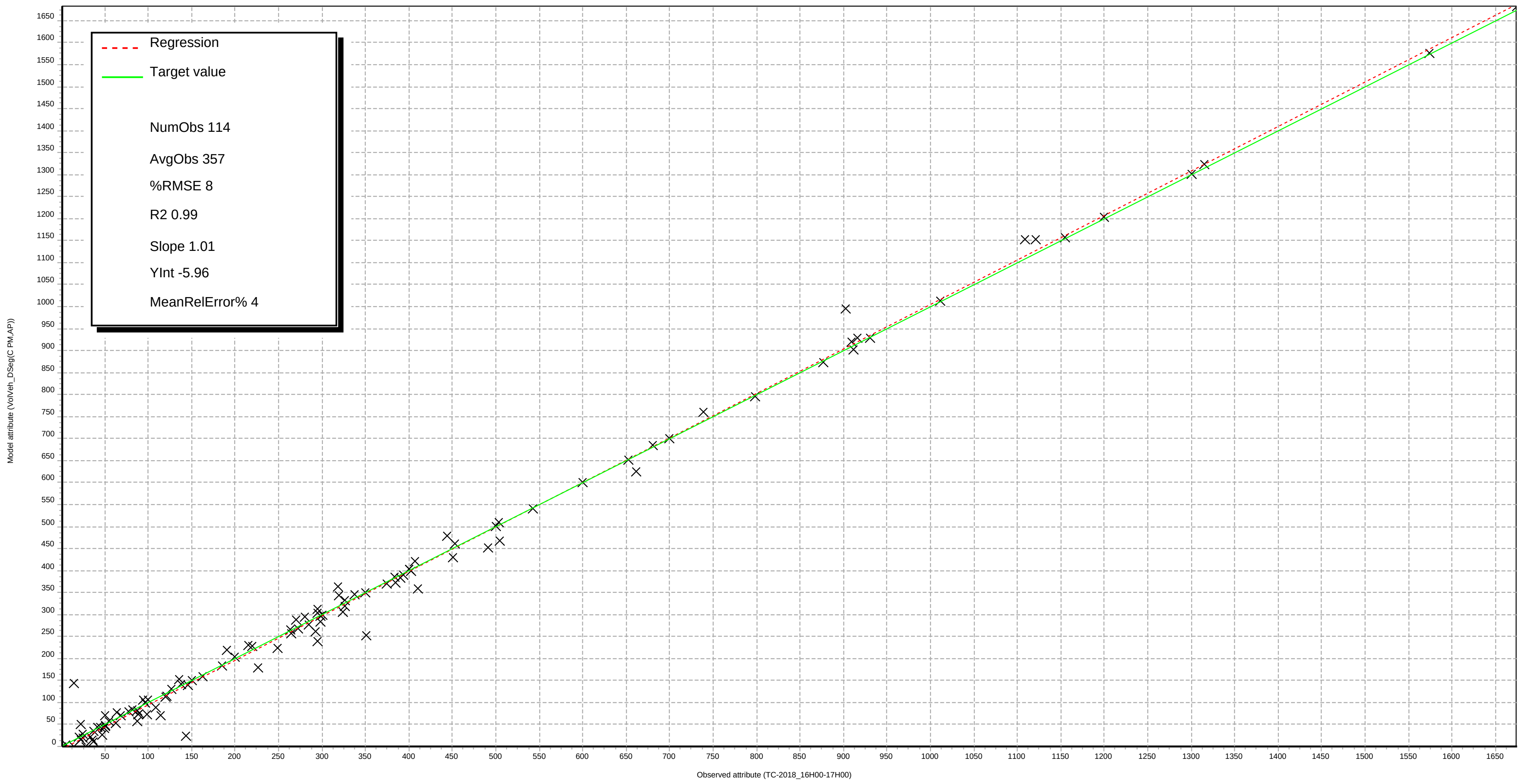


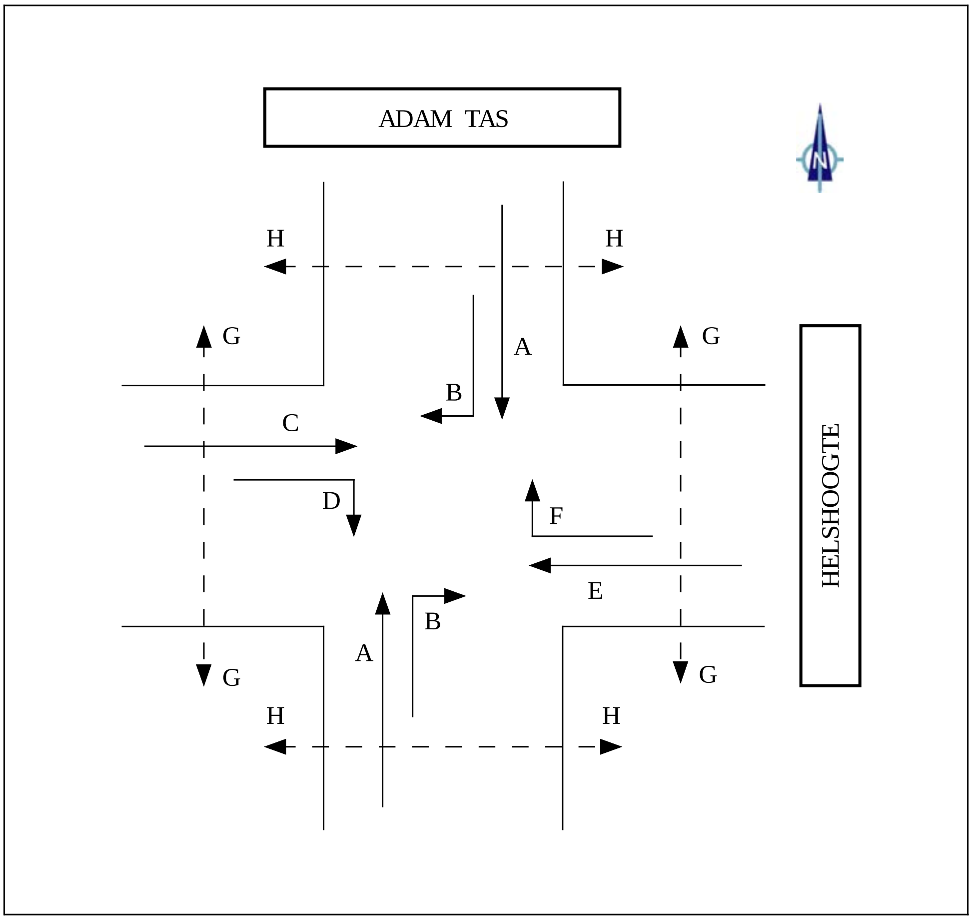
Figure B- 2: PM peak hour goodness-of-fit between the modelled vs the counted traffic volumes after calibration took place

Procedure sequence

Number: 24	Active	Procedure	Reference object(s)	Variant/file	Comment
1	☒	Preprocess Balance Epics			Creates/sets BALANCESATFLOWRATE, loads junction editor layout and activates Balance/Epics attributes visibility
2	☒	Group Initial assignment for first basic s	3 - 10		Initial assignment for first basic signal optimisation_to optimize the base signal programs and to derive suitable turn capacities
3	☒	Run script			Turn of "blocking back"
4	☒	Edit attribute	Turns - CapPrT		Reset Turn-Capacities to default (i.e. BALANCESATFLOWRATE)
5	☒	Edit attribute	Nodes - UseMethodImpAtNode		Set all to false - we do not want this on the initial assignment
6	☒	Init assignment		All	
7	☒	Update impedances at node			Recalculates initial "empty" state
8	☒	PrT assignment	C PM Car PM	Equilibrium assignment LUCE	
9	☒	Signal cycle and split optimization			
10	☒	Signal offset optimization			
11	☒	Group ICA Assignment to calculate turr	12 - 20		ICA Assignment to calculate turn capacities for DUE including the final signal optimisation
12	☒	Edit attribute	Nodes - UseMethodImpAtNode		Set all to true (SC nodes with ICA, others with Turn VDF)
13	☒	Init assignment		All	
14	☒	PrT assignment	C PM Car PM	Assignment with ICA	
15	☒	Signal cycle and split optimization			2nd call but this time based on the ICA assignment
16	☒	Signal offset optimization			2nd call but this time based on the ICA assignment
17	☒	Update impedances at node			update impedances based on the resulting signal plans
18	☒	Read filter		Turn filter for ICA.fil	Turn filter for ICA capacity transfer min threshold>0 and max<BalanceSatFlowRate
19	☒	Edit attribute	Turns - CapPrT		Copy of ICA capacity to turn capacities, force a minimum of 100 (for usage in DUE)
20	☒	Initialize all filter settings			Removes filter settings
21	☒	Group Final DUE assignment for anmro	22 - 24		Final DUE assignment for anmroutes-export
22	☒	Run script			Turn off "blocking back"_ it cannot be used with a dynamic assignment procedure
23	☒	Init assignment		All	
24	☒	PrT assignment	C Dyn PM Car Dyn PM	Dynamic User Equilibrium DUE	

Figure B- 3: Procedure sequence for the PTV Visum R44 subnetwork model indicating the different assignment methods and other processes which were used

INTERSECTION: R44 (ADAM TAS) – HELSHOOGTE



STAGES 1 TO 7

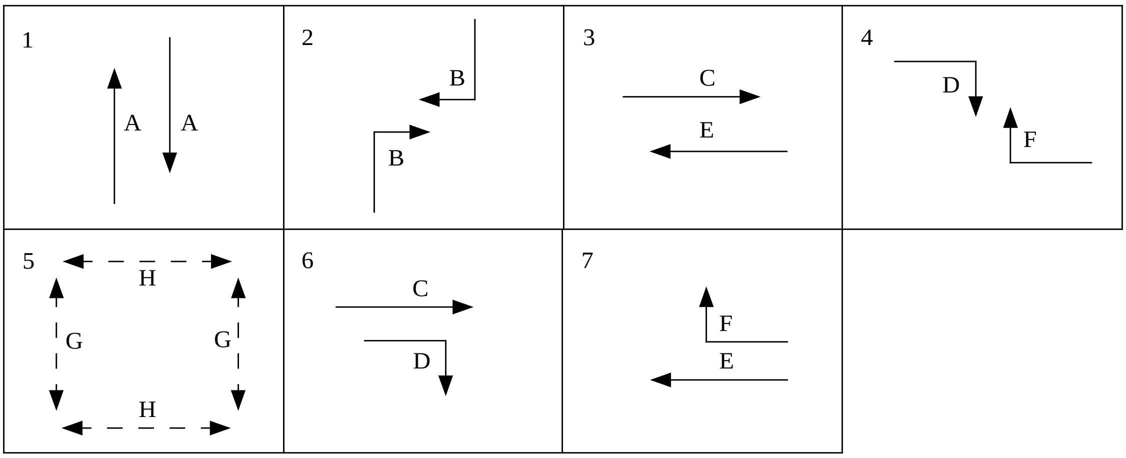


Figure B- 4: R44/Helshoogte Rd signal group and stage sequence example (Stellenbosch Municipality)

APPENDIX C – RESULTS

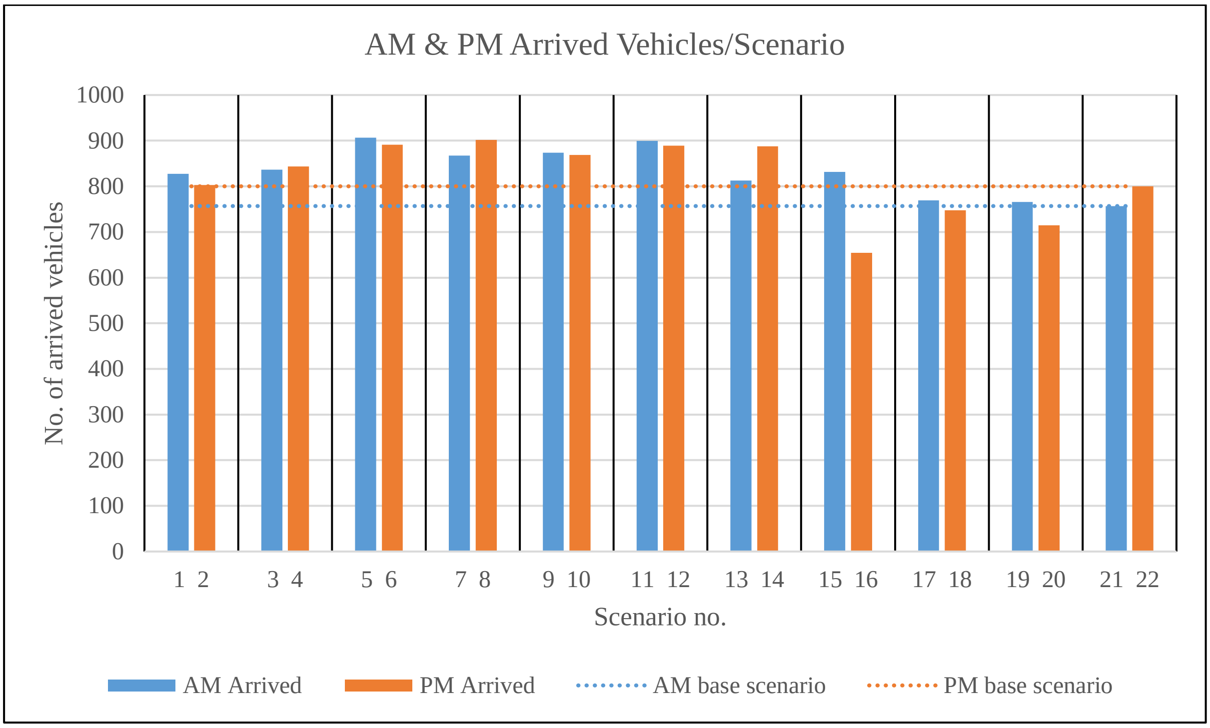


Figure C- 1: AM and PM peak hour arrived vehicles/scenario (all scenarios)

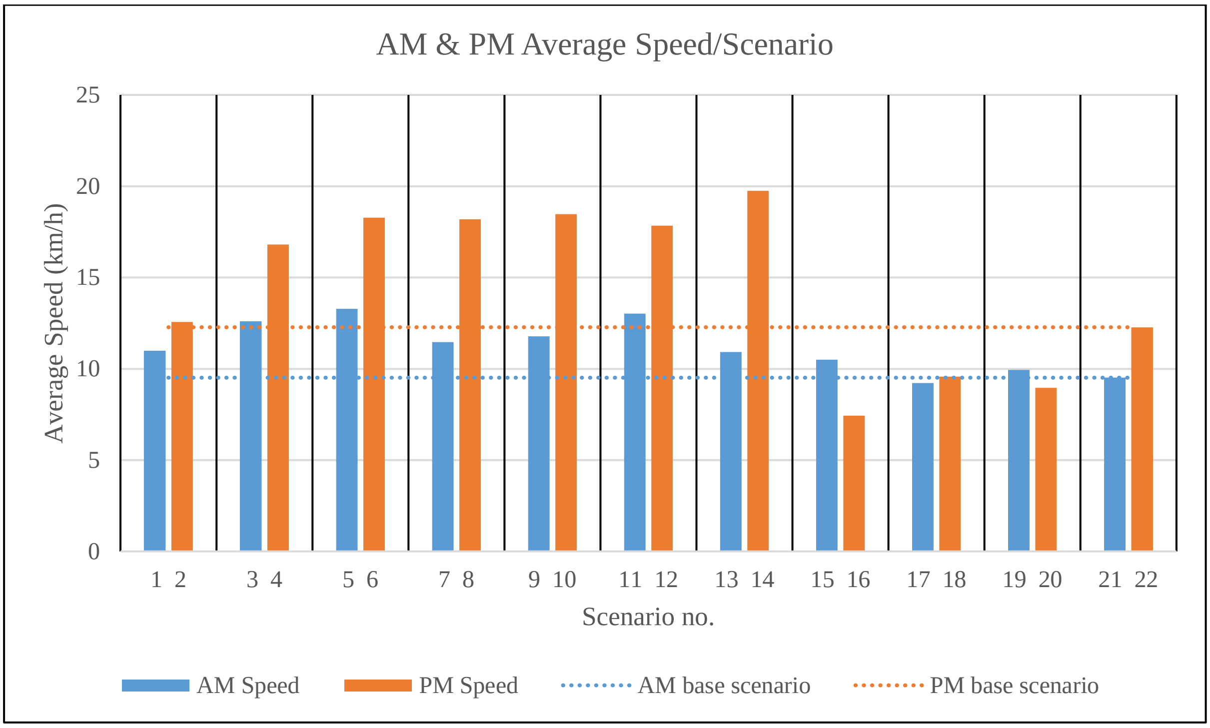


Figure C- 2: AM and PM peak hour average speed/scenario (all scenarios)

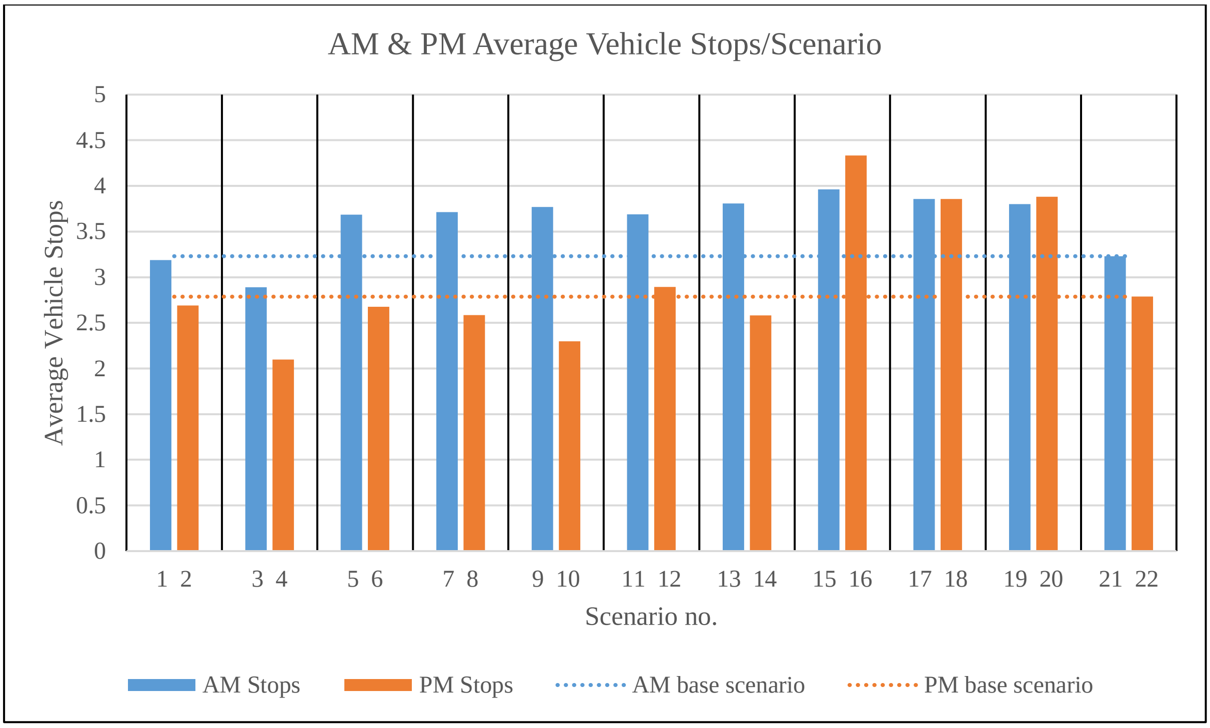


Figure C- 3: AM and PM peak hour average vehicle stops/scenario (all scenarios)

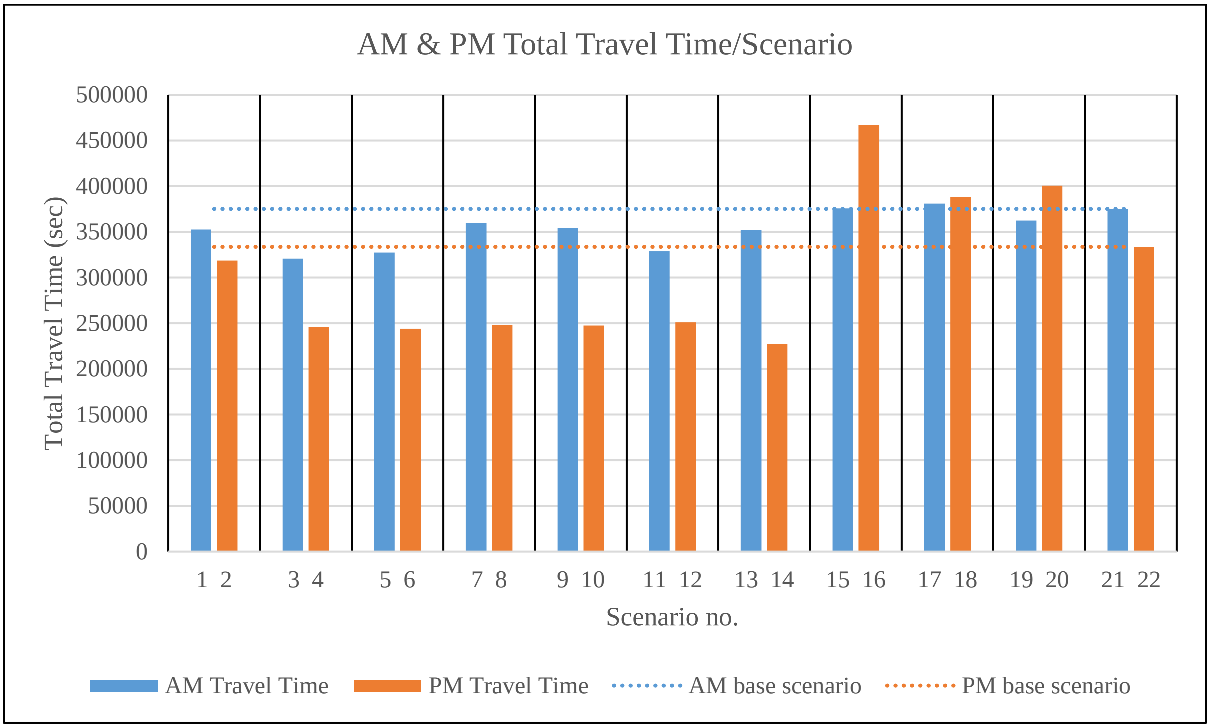


Figure C- 4: AM and PM peak hour total travel time/scenario (all scenarios)