DUBLIN CITY UNIVERSITY

SCHOOL OF ELECTRONIC ENGINEERING

VANET-enabled Eco-friendly Road Characteristics-aware Routing for Vehicular Traffic

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A Dissertation submitted in fulfilment of the requirements for the award of Doctor of Philosophy

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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List of Publications

Journal Papers

- Djahel, S., Doolan, R., Muntean, G. M., & Murphy, J. “A Communications-oriented Perspective on Traffic Management Systems for Smart Cities: Challenges and Innovative Approaches.” IEEE Communications Surveys & Tutorials, pp 1-1, 2014.
- R. Doolan, G. M. Muntean. “EcoTrec – A Novel VANET-based Approach to Vehicle Emission-saving and Congestion Reduction” IEEE Intelligent Transport Systems, 2015.

Conference Papers

- Doolan, Ronan, and Gabriel-Miro Muntean. "VANET-enabled Eco-friendly Road Characteristics-aware Routing for Vehicular Traffic." *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*. IEEE, 2013.
- Doolan, Ronan, and Gabriel-Miro Muntean. "Reducing carbon emissions by introducing electric vehicle enhanced dedicated bus lanes." *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014.
- Harris, C., Doolan, R., Dusparic, I., Marinescu, A., Cahill, V., & Clarke, S. (2014, May). A distributed agent based mechanism for shaping of aggregate demand on the smart grid. In *Energy Conference (ENERGYCON), 2014 IEEE International* (pp. 737-742). IEEE.
- Doolan, Ronan, and Gabriel-Miro Muntean. "Time-Ants: An innovative temporal and spatial ant-based vehicular Routing Mechanism." *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014.

Abstract

There is growing awareness of the dangers of climate change caused by greenhouse gases. In the coming decades this could result in numerous disasters such as heat-waves, flooding and crop failures. A major contributor to the total amount of greenhouse gas emissions is the transport sector, particularly private vehicles. Traffic congestion involving private vehicles also causes a lot of wasted time and stress to commuters.

At the same time new wireless technologies such as Vehicular Ad-Hoc Networks (VANETs) are being developed which could allow vehicles to communicate with each other. These could enable a number of innovative schemes to reduce traffic congestion and greenhouse gas emissions.

1) **EcoTrec** is a VANET-based system which allows vehicles to exchange messages regarding traffic congestion and road conditions, such as roughness and gradient. Each vehicle uses the messages it has received to build a model of nearby roads and the traffic on them. The EcoTrec Algorithm then recommends the most fuel efficient route for the vehicles to follow.
2) **Time-Ants** is a swarm based algorithm that considers not only the amount of cars in the spatial domain but also the amoumt in the time domain. This allows the system to build a model of the traffic congestion throughout the day. As traffic patterns are broadly similar for weekdays this gives us a good idea of what traffic will be like allowing us to route the vehicles more efficiently using the Time-Ants Algorithm.
3) **Electric Vehicle enhanced Dedicated Bus Lanes (E-DBL)** proposes allowing electric vehicles onto the bus lanes. Such an approach could allow a reduction in traffic congestion on the regular lanes without greatly impeding the buses. It would also encourage uptake of electric vehicles.
4) **A comprehensive survey** of issues associated with communication centred traffic management systems was carried out.

Abbreviations and Acronyms

ABS	Anti-lock braking system
ACO	Ant Colony Optimization
APs	Access Points
ASDA	Automatische Staudynamikanalyse: Automatic Tracking of Moving Jams
ARIMA	Auto-Regressive Integrated Moving Average
A-star	Anchor-based Street and Traffic Aware Routing
ATMS	Advanced Traffic Management Systems
BLIP	Bus Lane with Intermittent Priority
BRT	Bus Rapid Transport
BS	Base Station
BSS	Basic Service Set
CAR	Connectivity-Aware Routing
CbCO	Congestion-based Certificate Omission
CCMP Protocol	Counter Mode with Cipher Block Chaining Message Authentication Code
CDMA	Code division multiple access
CMSA/CA	Carrier sense multiple access with collision avoidance
CTS	Cleared to send
DBL	Dedicated Bus Lane
DBS	Direct Broadcast Satellite
DCC	Dublin City Council
DCF	Distributed coordination function
DE	Data Exploitation
DFPA	Data Fusion Processing and Aggregation
DIFS	DCF Interframe Space
DNA	Dynamic Navigation Algorithm
DRCV	Distributed Rate Control Algorithm
DSG	Data Sensing and Gathering
DSSS	direct sequence spread spectrum
ESP	Electronic Stability control Programme
ETPC	Efficient Transmit Power Control
EV	Electric Vehicle
FCD	Floating Car Data
FDMA	Frequency division multiple access
FHSS	Frequency hopping sequence spectrum

FOTO	Forecasting of traffic objects
GEO	Geostationary Earth Orbit
GPCR	Greedy Perimeter Coordinator Routing
GPRS	general packet radio service
GPS	Global Positioning System
GRP	Geographic Routing Protocol
GSM	Group speciale mobile
GWO	Grey Wolf Optimizer
HBEFA	Handbook of Emission Factors
HEV	Hybrid Electric Vehicle
HOT	Heavy Occupancy Tolled
HOV	Heavy Occupancy Vehicle
I2V	Infrastructure-to-Vehicle
IBL	intermittent bus lanes
ICE	Internal Combustion Engine
IR	Infra-Red
IRI	International Roughness Index
ITE	Institute of Transport Engineers
ITS	Intelligent Transportation Systems
IVG	Inter-Vehicles Geocast
LED	Light Emitting Diode
LEO	Low Earth Orbit
LORA_CBF	Location-Based Routing Algorithm with Cluster-Based Flooding
LTE	Long-Term Evolution
MCTP	Mobile Control Transport Protocol
M2M	Machine to Machine
MANET	Mobile Ad-Hoc Network
MMSN	Multi-Media Social Network
MPD	Mean Profile Depth
MS	Mobile Station
MSS	Mobile Satellite Services
OBD	On-board Diagnostics
OD	Origin-Destination
OFDM	orthogonal frequency-division multiplexing
PCF	Point Coordination function
PDC	Personal digital cellular
PDGR	Predictive Directional Greedy Routing protocol

PHEM	Passenger and Heavy duty Emission Model
PM	Particulate Matter
PSO	Particle Swarm Optimization
QoS	Quality of Service
RSN	Robust Security Network
RSU	Road-Side Unit
RTS	Request to send
SCATS	Sydney Coordinated Adaptive Traffic System
SCR	Selective Catalytic Reduction
SCOOT	Split Cycle and Offset Optimization Technique
SD	Service Delivery
SMS	Short Message Service
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TMDD	Traffic Management Data Dictionary
TMS	Traffic Management System
TSP	Traffic Signal Priority
UDP	User Datagram Protocol
UMB	Urban Multi-Hop Broadcast protocol
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS terrestrial radio access network
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VADD	Vehicle-Assisted Data Delivery
VANET	Vehicular Ad-Hoc Network
VMS	Variable Message Sign
VTL	Virtual Traffic Lights
V-TRADE	Vector- based TRAcking Detection
WEP	Wired equivalent privacy
WiMAX	Worldwide interoperability for Microwave Access
WLAN	wireless local area network
WPA	Wi-Fi protected access
WSN	Wireless Sensor Networks

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Chapter 1 – Introduction

This chapter introduces Vehicular Ad-hoc Networks (VANETs) and the main research areas associated with Smart Cities and VANET-enabled transportation solutions for increased efficiency and reduced emissions. In this context the problems associated with vehicle routing are outlined and then three proposed solutions are presented and discussed. Finally the structure of the thesis is detailed.

1.1 Introduction and Research Motivation

A Mobile Ad-Hoc Network (MANET) is a network of wireless nodes with no fixed infrastructure. Each of the nodes is mobile and the network must self-configure. Messages are routed dynamically and are passed by multi-hop communication. The medium is most commonly broadband wireless networks (e.g. Wi-Fi), but could also be satellite, cellular or combination of all of these. MANETs are very useful as they allow for a large amount of data to be gathered from sensors on the individual nodes and examined. Applications include environmental monitoring (e.g. temperature, air pollution etc…), telecommunications (e.g. improving mobile phone coverage) and industrial uses (e.g. mechanical fault detection, electrical failure etc..). They will become more prominent as the sensors and wireless communications drop in price, and as copper for wired infrastructure increases in price. Wired infrastructure also requires more man-hours for deployment than MANETs.

Vehicular Ad-Hoc Networks (VANETs) are a unique kind of MANET. In VANETs individual vehicles function as nodes. This network self-configures and messages are passed by multi-hop communication. VANETs mostly use Wi-Fi for communication, although research has also looked at cellular and satellite for underlying communications. VANETs require a special Wi-Fi protocol IEEE 802.11p [1] as they are highly mobile, for example the differential speed between two nodes could be as high as 240 kmph. VANETs are not true MANETs as they rely on some infrastructure. The infrastructure consists of Road Side Units (RSUs), which connect the network to the internet and databases containing traffic information, and help overcome network partitions. Unlike MANET nodes which move at random, VANET vehicles have relatively predictable mobility. They must stick to roads, obey speed limits, stop at traffic lights etc.

One new area of research which encompasses VANETs is Smart Cities. The idea behind Smart cities is to use digital communications to more effectively distribute resources, making the city more competitive compared with other cities. One key section of Smart Cities is Smart transportation. VANET-based rerouting is one way of improving transportation in Smart Cities [2]. An illustration of VANETs in an urban environment is shown in Figure 1-1.

There is an ever increasing need to reduce emissions and traffic congestion. It was estimated in 2010 that 23% of global CO_2 emissions came from the transport sector and accounted for 30% of CO_2 emissions in Organisation for Economic Cooperation and Development (OECD) countries [3]. It is becoming imperative for governments to fulfil their commitments to reduce their gas emissions, in order to avoid exceeding the 2 degree Celsius threshold, which refers to the temperature rise that the Earth could sustain, without experiencing very dangerous consequences [4].

The number of cars on the road is increasing without a corresponding increase in road capacity. This is particularly the case in urban areas. For instance from 2001 to 2011 the number of cars manufactured has increased linearly from roughly 40,000,000 per year to nearly 60,000,000 [5].

Traffic congestion is worst in cities and the proportion of the human population living in cities is expected to rise. In 1950 30% of the world's population lived in cities, in 2014 it had grown to 54%. By 2050 it is expected that 66% of the world's population will live in cities. This will put enormous strain on road networks [6].

Traffic congestion is a very serious problem both in developed countries and increasingly in developing countries. Sao Paulo, Brazil is known to experience the world's worst traffic jams, with people stuck in traffic for an average of two to three hours according to a report by Jain et al. [7]. This report identified poor traffic management as the leading cause of traffic congestion. Developing countries have seen a surge in vehicle ownership. These countries often have very poor existing infrastructure and very little money to improve on them.

Traffic congestion also contributes significantly to pollution in very built-up areas. A research report [8] shows that children who live in high traffic areas are six times more likely to develop leukaemia and other cancers. The constant low-level noise created by traffic was also shown to negatively affect children's blood pressure.

Traffic congestion also causes a lot of time-related stress for people who waste time in traffic. Studies have shown an increased time behind the wheel correlates with increased blood pressure [9] and likelihood of obesity [10]. The same research report [8] shows that carbon monoxide levels are 10 times higher inside a car, so large amounts of time stuck in traffic will negatively affect a person's health.

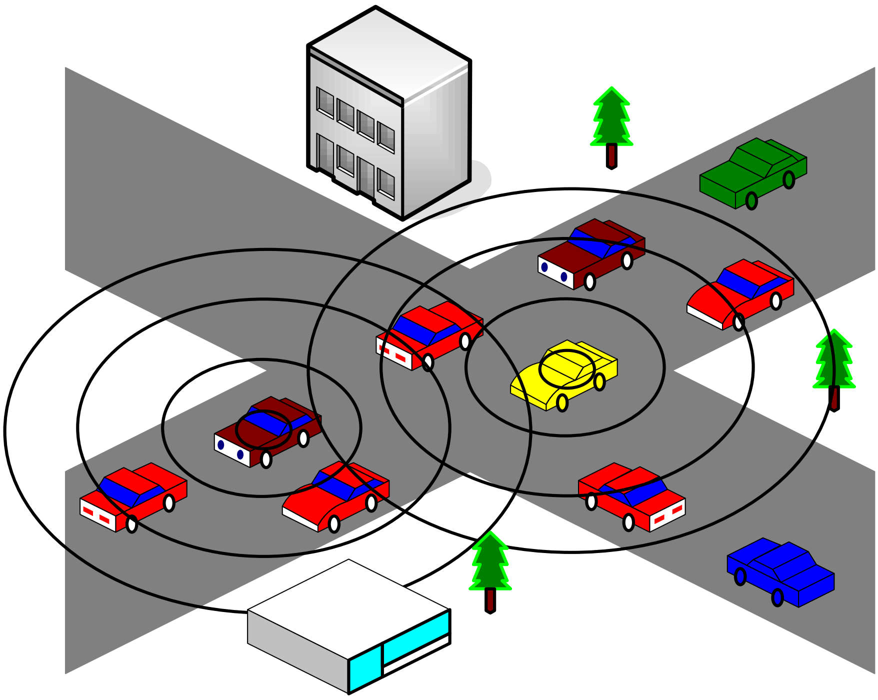

Figure 1-1 Illustration of VANET communications in an urban environment

There many negative economic effects associated with traffic congestion; one example is the downtime for trucks and other commercial vehicles.

By applying VANET-based solutions to traffic management systems traffic congestion could be reduced, thereby reducing pollution and enhancing public health and economic productivity.

1.2 Problems and Goals

1.2.1 Problem 1 Reducing Emissions

CO_2 and other greenhouse gas emissions are steadily rising despite the scientific consensus on the dangers of climate change. As already mentioned the transport sector, particularly private vehicles, is a large source of greenhouse gases. There is an urgent need to find ways of reducing them.

Potential Solutions

One approach is to improve the fuel efficiency of internal combustion engines. However the internal combustion engine has been researched greatly and fuel efficiency has remained static while power has increased. This is another case of induced demand. Jevon's paradox is where an increase in efficiency of a resource leads to greater demand [11].

The second approach is to increase the amount of hybrid and electric vehicles. However electric vehicles still have limited range and very little infrastructure such as charging stations when compared with internal combustion engines.

Another approach is to improve uptake of public transport could dramatically improve carbon emissions, but this would be difficult without using unpopular measures such as the London congestion charge or investing in improving expensive infrastructure.

This Thesis Solution

Several routing mechanisms reroute vehicles in order to reduce travel time. However an approach is needed which would reduce carbon emissions. By taking into account road surface conditions and road gradients it should be possible to reduce fuel consumption without greatly affecting travel time. This thesis focuses on developing an algorithm which takes into account traffic and road conditions in order to reroute vehicles to more fuel efficient routes.

1.2.2 Problem 2 Optimum Use of Road Network

Traffic congestion is a major problem in many urban areas. However simply adding more roads and capacity doesn't reduce the congestion [12]. In Braess's paradox adding extra capacity to a network in which moving entities selfishly choose their route, a decrease in performance is seen. So a more efficient way of using this road network is needed.

Potential Solutions

One possible solution would be to run advanced simulations taking into account each driver's origin and destination to give a route recommendation. This would be very complex and would present privacy issues.

Another possible solution would be to redesign of road network, however this would only be possible for new cities being built from scratch, which does not happen too often.

This Thesis Solution

The solution is to make use of historical data and VANET-based communications in order to reroute vehicles. In this context VANETs could communicate traffic congestion at different sections of the road map to a server, so future vehicles could then receive this information in order to choose an efficient route.

1.2.3 Problem 3 Optimum Use of Lanes

An important aspect of reducing traffic congestion is to ensure optimum use of lanes. Many European cities now have special lanes dedicated to buses, and the United States has heavy occupancy lanes, however these lanes are rarely used at full capacity, so the road network is not as efficient as it could be.

Potential Solutions

One possible solution is to have signs near the bus lanes that alert regular drivers that no buses are in the area and that they can use the bus lane. This approach would require expensive infrastructure.

VANET create a decentralized communication system with little to no requirement for infrastructure, which could be very efficient at addressing this problem, by wirelessly communicating a message to vehicles nearby that they may temporarily access the bus lane.

This Thesis Solution

As many cities have bus lanes which are not used at full capacity, an intelligent approach could be used to enable better use of all the lanes in a city without impacting bus travel times. As a stepping stone towards achieving such an intelligent approach this thesis proposes a policy which allows electric vehicles access to bus lanes and assesses its benefits.

1.3 Solutions and Contributions

The first contribution presented in this thesis is **EcoTrec, a novel eco-friendly routing algorithm for vehicular traffic** which achieves fuel savings for vehicles and reduces gas emissions. EcoTrec balances the travel-time and emissions of the route. The vehicles do not always pick the optimum route as load balancing is needed, in order to not create flash crowds on certain roads. Vehicles periodically send out information on the traffic conditions of the road they are on. EcoTrec considers parameters related to weather, road surface and road gradient. These parameter values are gathered via the individual vehicles and then processed and aggregated. This information is disseminated to all the vehicles via VANET communications. The vehicles use the road and traffic parameters to calculate a quick, fuel efficient route to get to their destinations. The routes taken by the EcoTrec equipped vehicles gave an improvement of over 30% in terms of the number of vehicles which reached their destination and roughly 20% in terms of emissions, when compared with the original real life routes of vehicles collected and made available in [13].

The second contribution presented in this thesis is **Time-Ants, an innovative temporal and spatial ant-based vehicular routing mechanism**. This algorithm is an ant-based swarm solution and involves vehicles leaving a pheromone depending on the efficiency of the route. However, instead of simply leaving the mark in the special domain, the mark will be left in the time domain, giving each road an amount of pheromone depending on the efficiency for the time of day. Vehicles will then be recommended a route based on historical traffic. Time-Ants out-performs another leading algorithm by up to 19% in terms of percentage of vehicles to reach the destination within a given time-frame.

The third contribution presented in this thesis is a new policy to create **Electric Vehicle Enhanced Dedicated Bus Lanes (E-DBL)**. By allowing electric vehicles access to bus lanes, their use will be encouraged without significantly affecting bus travel times while greatly reducing the travel times for the electric vehicles.

Finally an extensive study of the state-of-the-art in this area was done. This included sections on data monitoring and collection mechanisms, data aggregation solutions, vehicle to vehicle routing, inter-vehicle coordination, 802.11p congestion reduction, emission factors, navigation algorithms, infrastructure, swarm algorithms, VANET services and finally user modelling.

1.4 Thesis Outline

The thesis is structured as follows: firstly the thesis is introduced in Chapter 1; this section includes research motivation, problems and goals, solutions and contributions and the thesis outline. In Chapter 2 the background technologies necessary for understanding the work in this thesis are introduced and discussed. The related works which were studied throughout this research are investigated in Chapter 3. The proposed EcoTrec architecture and algorithm are discussed in detail in Chapter 4. In Chapter 5 and Chapter 6 the proposed Time-Ants architecture and algorithm and the proposed lane allocation policy E-DBL are explained in detail. In Chapter 7 the results of the Experimental Evaluation for EcoTrec, Time-Ants and E-DBL are presented. Finally the conclusions as well as the future work of the thesis are presented in Chapter 8.

Chapter 2 Background Technologies

This chapter deals with the background technologies crucial for understanding this research. Firstly IEEE 802.11 (Wi-Fi) is introduced and described and then the amendments to IEEE 802.11 which are used for VANET communications (IEEE 802.11p and IEEE 802.11g) are investigated. Other communication methods for VANET communications such as WiMAX (IEEE 802.16), cellular, satellite and optical communications are also described in detail in this section. Traffic Management Systems are then studied in detail. Packet routing algorithms are also introduced and discussed. As well as navigation algorithms for vehicles in road networks.

2.1 Wireless Communications

This section introduces wireless communications. Wireless communications refer to data communications between two points without a physical wired connection, as opposed to wired communications which have a physical wire between two points. In this regard BSS will be introduced and discussed followed by Wi-Fi, then WiMAX, cellular and others.

2.1.1 Basic Service Set (BSS)

BSS is a station or group of stations controlled via the same coordinating function. These stations cover an area known as the basic service area (BSA). BSS can be used both in cellular and Wi-Fi. An Ad-hoc Network is a deliberate grouping of stations into a single BSS. All stations within a BSA can communicate with each other.

Infrastructure networks in 802.11 use Access points (APs). Access points connect multiple BSSs to each other. They can also allow the station to access the internet.

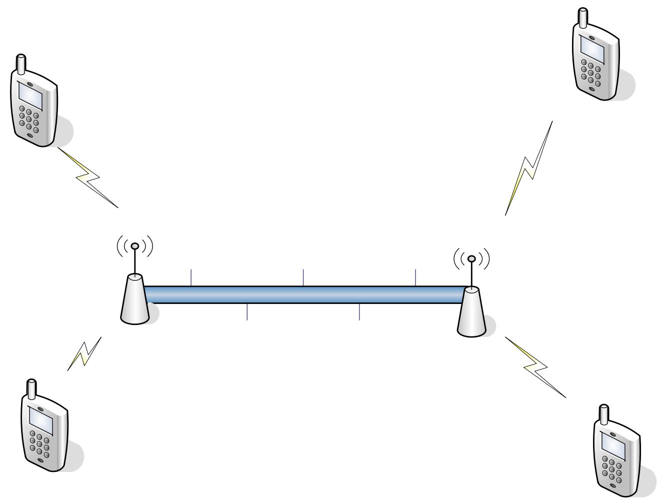

Figure 2-1 Access points

2.1.2 **IEEE 802.11 (Wi-Fi)**

802.11 is a set of Institute for Electrical and Electronic Engineers (IEEE) standards for wireless local area networks (WLAN). IEEE 802.11 is better known as Wi-Fi, which is an acronym of wireless fidelity. IEEE began developing an international WLAN standard in 1990 according to Crow et al. [14]. The first version was released in 1997. The draft standard had rates of roughly 2 Mbps. There are many different amendments to the IEEE 802.11 standard including: 802.11a, 802.11b, 802.11e, 802.11g, 802.11n, 802.11p, 802.11t and many more. Of these only IEEE 802.11p and IEEE 802.11g will be described in detail in this background technologies section, as they are most relevant to this thesis.

Both Hiertz et al. [15] and Davis et al. [16] gave a good summary of the IEEE 802.11 family. Table 2-1 summarises the most important standards in this family.

Table 2-1 List of IEEE 802.11 standards

Name	Description
802.11-1997	This is the basic standard of 802.11. It was first introduced in 1997 and is also known as legacy mode. It only supported a bandwidth of 2 Mbps.
802.11-1999	This is the improved basic standard. It was published in 1999.
802.11a	This included an extension to allow a higher data rate, but it is not backward compatible. It was first published in 1999. 802.11auses OFDM within the physical layer. It has a data rate of 54 Mbps. It uses the 5 GHz band instead of the 2.4 GHz band.
802.11b	802.11b gets its name from task group b within the 802.11 working group. This was first published in 1999. It was designed to have high data rate which was 11 Mbps.
802.11c	802.11c is a bridging standard for 802.11d. It was approved in 1998.
802.11d	This standard was designed in order to comply with other regional requirement (e.g. not Europe, US or Japan). It was published in 2001.
802.11e	This standard was designed in order to improve support for Quality of Service (QoS). Security enhancements were also included.

802.11g	This standard was designed in order to be an amalgamation of 802.11a and 802.11b. 802.11g allowed data rates of 54 Mbps in the 2.4 GHz range. This standard was published in 2003.
802.11h	This standard was designed in order to comply with European regulations in 5 GHz band. It was first published in 2003.
802.11i	This standard was designed in order to improve security and authentication mechanisms. It was first published in 2004.
802.11j	This standard was designed in order to comply with Japanese regulations in 5 GHz band.
802.11k	This standard was made to introduce radio resource management. This was first approved in 2008.
802.11n	This standard was designed in order to improve bandwidth. 802.11n has a bandwidth of 108 Mbps.
802.11p	This amendment was designed specifically for Vehicle Communication. It was accepted in 2003. It has a data rate of up 27 Mbps.
802.11r	This standard was designed for mobile nodes which have to quickly switch between access points. The ‘r’ stands for Rapid hand-off.
802.11s	This standard was designed to enable multi-hop routing. This was approved in 2004.
802.11u	802.11u allows for the creation of large scale networks. This is necessary for specific applications with high demand for success such as VOIP for emergency calls.
802.11v	Radio resource management
802.11w	This is a security amendment which was published into 2009. This extends the original security enhancement 802.11i
802.11y	This standard was designed to provide wide area coverage. It functions in the 3.65-3.9 GHz range.
802.11z	This standard was designed to provide direct link setup.
802.11aa	802.11aa is designed specifically for Audio/Video streaming. It was

	approved in 2008.
802.11ac	802.11ac was designed to have very high throughput. It added new channel bandwidths in the 80 MHz and 160 MHz range. This provided a bandwidth of almost 7 Gbps [17].
802.11ad	802.11ad was also designed to have very high throughput. It uses bandwidth in the 60GHz range. It was published in 2012 [18].

A wireless local area network is an area in which devices can connect wirelessly to an access point to provide an internet connection. Wireless networks can be very useful in a number of scenarios. If the nodes are mobile, they will have to connect wirelessly as in the case of this research. Wireless networks are useful if the network needs to be set up quickly. Wireless networks can also be used as a cost-saving measure. Wireless networks can be cheaper than wired networks as there is no need for expensive copper wires.

If the devices connect via an access point, this is called an infrastructure network. If the devices connect to each other instead, this is called an Ad-hoc Network. These two types of network are illustrated in Figure 2-2 and Figure 2-3.

The users of the wireless network must use the same frequency. IEEE 802.11 uses frequencies in the 2.4, 3.6, 5 and 60 GHz bands [19], [20].

Unlike a wired network, which can physically be secured, a wireless network requires some security as anyone within the range could access it. Data privacy is normally accomplished using encryption. The initial encryption scheme was called Wired Equivalent Privacy (WEP), although this has been shown not to be fully secure [21]. There are however other proposed schemes such as Wi-Fi protected access (WPA) and Robust Security Network (RSN) [21]. WPA addresses the limitations of WEP, by improving the encryption scheme and requiring the user to have a public key. WPA also inspects the packets to make sure there are no errors. RSN [21] is stronger than both WPA and WEP due to its use of dynamic negotiation of authentication and encryption. However RSN is not suitable for old devices, this is due to the fact that older devices do not support Counter Mode with Cipher Block Chaining Message Authentication Code Protocol (CCMP) [22].

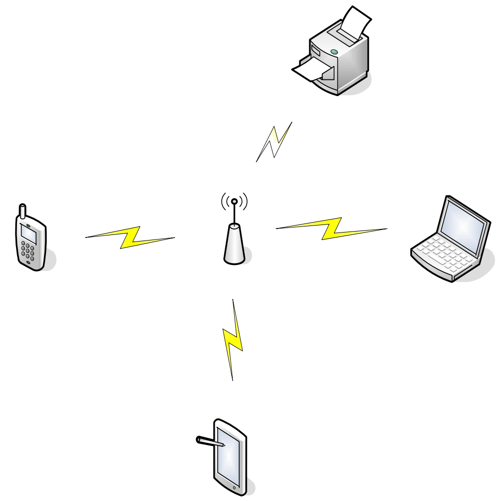

Figure 2-2 Infrastructure Network

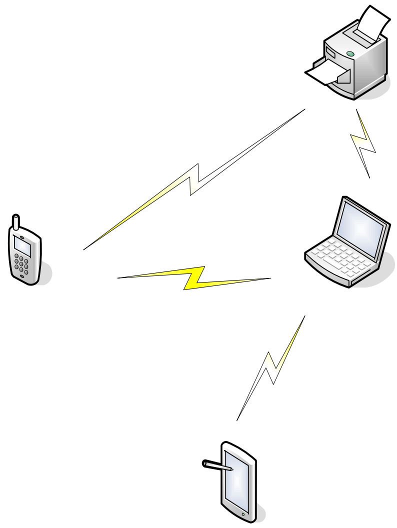

Figure 2-3 Ad-hoc network

Wired nodes are normally connected to the mains, whereas wireless nodes require their own power source such as batteries. This results in power constraints. The wireless communications for vehicles can be powered by the car's electricity supply, so power constraints are not relevant for this thesis and will not be discussed in details.

A number of schemes were implemented in 802.11 at the various layers of the OSI model. The schemes at the physical layer and the MAC layer will now be introduced.

2.1.2.1 Physical Layer

802.11 has three different physical layer interfaces, Frequency Hopping Sequence Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Infra-Red (IR). These were described by Crow et al. [14].

FHSS uses the Industrial, Scientific and Medical band (ISM). The basic data access rate of 1 Mbps uses a two-level Gaussian Frequency Shifting Key (GFSK) and the enhanced data access rate of 2 Mbps uses a four-level GFSK. There are 79 channels in this hopping set. Each channel is placed 1 MHz apart. Three different hopping sequence sets of 26 channels each exist. The use of several hopping sequence sets allow several BSS to operate in the same area.

DSSS uses the ISM band as well. The basic data access rate of 1 Mbps uses the Differential Binary Phase Shifting Key (DBPSK) and the enhanced data access rate of 2 Mbps uses the differential quadrature phase shifting key (DQPSK). The bandwidth is spread into 11 different sub-channels. Each sub-channel is 11 MHz wide. Overlapping BSA have their channels separated by 30 MHz, this is very restrictive and allows only 2 BSAs to overlap.

The IR band is designed for indoor use. It is designed to make use of line-of-sight and reflected transmissions. It has a basic data access rate of 1 Mbps and an enhanced data access rate of 2 Mbps. The IR band uses wavelengths from 850 to 950 Nano-meters.

2.1.2.2 MAC Layer

The problem of having more than one device connected to a WLAN at the same frequency is that this can result in collisions. Collisions can be caused if two nodes attempt to transmit at the same time. One of the main causes of this is the hidden node problem. The hidden node problem is where two nodes are connected to the same access point, but on opposite sides, so they are unaware of each other, and will try and transmit at the same time resulting in a packet collision. This is illustrated in Figure 2-4. In order to prevent packet collisions 802.11 requires collision avoidance. For this 802.11 employs Carrier sense multiple access with collision avoidance (CMSA/CA).

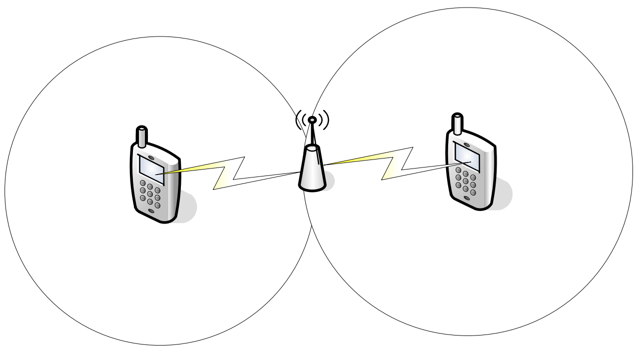

Figure 2-4 Hidden node problem

CMSA/CA is a MAC control scheme. In CMSA/CA the node checks if the channel is free. If it is not free it uses exponential back-off before checking again. If the channel is free the node transmits.

Distributed Coordination Function (DCF) is an access method for asynchronous data transfer for 802.11. It is the main MAC technique for 802.11. It uses CMSA/CA for collision avoidance. DCF gets the station to listen to the channel for a set interval, known DCF Inter-Frame Space (DIFS), before transmitting. If the channel is busy it uses exponential back-off to decide when to retransmit. It also uses ‘Request To Send’ (RTS) and ‘Cleared To Send’ (CTS) messages between the station and node.

Point Coordination Function (PCF) is another MAC technique for 802.11. PCF sits directly on top of DCF. It resides in a point coordinator. The point coordinator waits for PCF Inter-Frame Space (PIFS) time, which is less than DIFS, giving the point coordinator priority of the network.

2.1.2.3 IEEE 802.11p

IEEE 802.11p is an amendment to the IEEE 802.11 standard and is known as Wireless Access in Vehicular Environments (WAVE).

In August 2008 the 5.9 GHz band was allocated for vehicular communications [23]. This band is divided into 7 different 10 MHz channels, among which the central channel is the control channel [24]. Next IEEE 802.11p became an approved standard, this happened in May 2010 [25]. The primary goal of IEEE 802.11p was to improve vehicle safety and secondly to prevent traffic congestion.

The major issue with using the original 802.11 standard in VANETs was dealing with the high mobility of nodes. This means that the connection time between two vehicles is very small, so 802.11p was designed to have special characteristics to deal with this, such as WAVE mode. WAVE mode allows two vehicles which come into contact to communicate instantly. This is accomplished by giving the vehicles a special BSSID basic service set ID, which is known as ‘wildcard BSSID’. All the vehicles have the same wildcard BSSID allowing them to communicate as soon they come into contact with each other.

It is now an approved protocol in both Europe and America. In Europe the ITS_G5 standard is based on it [26]. In America it is used in the Dedicated Short Range Communications (DSRC) standard. The primary goal of IEEE 802.11p was to improve vehicle safety and secondly to prevent traffic congestion.

2.1.2.4 IEEE 802.11g

Another amendment to the IEEE 802.11 standard is 802.11g. This flavour was first introduced in January 2003 and hence is sometimes referred to as 802.11g-2003. 802.11g was designed to combine the benefits of IEEE 802.11a and IEEE 802.11b. IEEE 802.11g provides the high data rates of IEEE 802.11a at the 2.4 GHz band, but it is backwards compatible with IEEE 802.11 and IEEE 802.11b [27]. In fact 802.11g has speeds of up to 54 Mbps. 802.11g uses short preamble to reduce overhead. The IEEE 802.11b group realized the packet header they were using called the physical layer convergence protocol was too long and added considerable overhead. The IEEE 802.11g uses a shorter header called the short preamble which mitigates this problem.

IEEE 802.11g uses both DSSS and OFDM. This allows it to make use of four physical layers which dramatically improves data transfer rates. DSSS was described earlier in physical layer techniques for IEEE 802.11. OFDM stands for orthogonal frequency-division multiplexing. OFDM allows for the encoding of digital data over multiple carrier frequencies.

2.1.3 **IEEE 802.16 (WiMAX)**

IEEE 802.16 is also known as WiMAX, which stands for Worldwide interoperability for microwave access. There are also a number of flavours of 802.16 including 802.16d and 802.16e.

IEEE 802.16 was completed in October 2001 and then published in April 2002. IEEE 802.16 is capable of supplying large geographical areas with broadband without the need of expensive infrastructure. The standard uses frequencies from 10-66 GHz. WiMAX can provide theoretical speeds of 70 Mbps, but the normal rate at a distance of a mile is 6 Mbps [28].

802.16d was designed to replace the previous versions 802.16-2001, 802.16c-2002 and 802.16a-2003. It was first publishing in 2004 and is known as 802.16-2004. This flavour was designed for fixed placements. 802.16e provided mobility enhancements to 802.16d. It is also known as 802.16-2005. It is not backwards compatible [29].

2.1.3.1 Physical Layer

IEEE 802.16 uses OFDM at the physical layer. This gives WiMAX good performance for multipath and non-line of sight communications. OFDM was extended for

WiMAX to allow for multiple access and terminal mobility. The extension is called OFDMA [30].

2.1.3.2 MAC Layer

WiMAX requires a MAC protocol to allow for high data rates and hundreds of end users. WiMAX also contains two MAC protocols Point to MultiPoint (PMP) and mesh-type access.

In PMP the base stations (BS) and mobile stations (MS) communicate via one hop communications. The downlink BS to MSs uses broadcast and the uplink MSs to BS uses unicast. PMP uses sectorized antennas.

Mesh-type access allows for MS to MS station communication. This means that the BS can communicate with MSs using multi-hop communication. Mesh-type access use Omni-directional antennas [31].

2.1.3.3 Discussion

WiMAX offers a communication medium for VANETs. Eklund et al. [32] asserts that WiMAX is only useful for stationary or slow-moving vehicles, but research by Kim et al. [33] shows that WiMAX is competitive with IEEE 802.11p for vehicle-to-vehicle (v2v) communications and WiMAX already has infrastructure to deal with VANETs.

2.1.4 **Cellular Networks**

Cellular communications are another set of technologies which can be used for Vehicle-to-Vehicle (V2V) communications. Each cell has a transmitter which covers that area. Radio communications are used mostly for mobile phones.

There are four different generations of cellular communications which have been developed from the 1970s to today. There are four generations which are described below.

2.1.4.1 The 1st Generation (1G)

According to Fomin et al. [34] the development of 1G cellular phones began in 1969. 1G systems were mainly for analogue voice communications and had speeds of 1.9 kbps, which is extremely slow compared to modern devices [35]. 1G used FDMA (Frequency Division Multiple Access) [36], a multiple access scheme. The different channels or frequencies are divided up among users to allow them to communicate simultaneously [37].

2.1.4.2 The 2nd Generation (2G)

2G systems were designed in the 1980s, but they were only first implemented in 1991. They have speeds of 14.4 kbps and can be used for digital voice communications and short messages. [35]. 2G uses Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). TDMA is another multiple access scheme in which the network resources are divided up in the time domain instead of the frequency domain as in FDMA. CDMA is a third multiple access scheme in which the network resources CDMA is less vulnerable to interference than TDMA or FDMA [37].

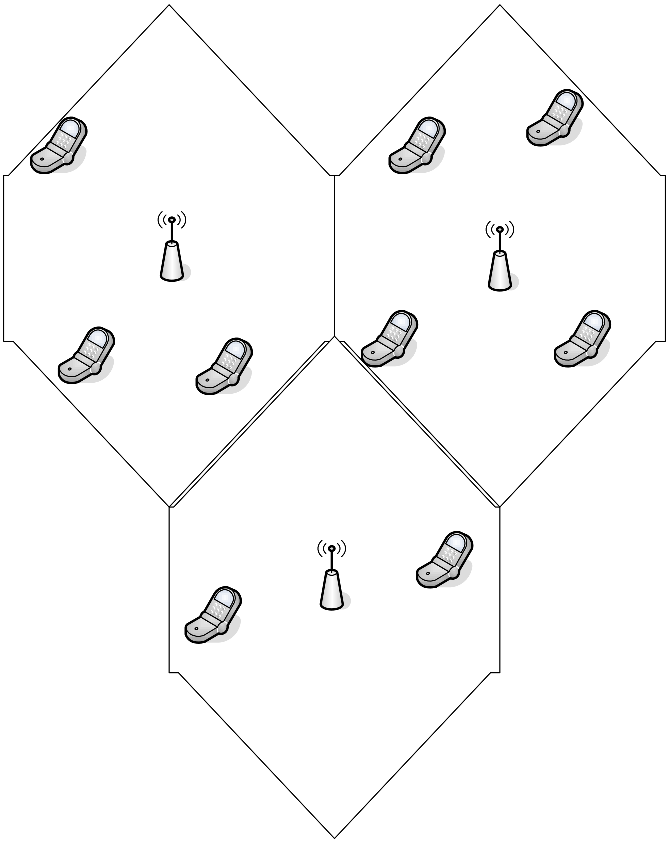

Figure 2-5 Cellular network

Group Speciale Mobile (GSM)

GSM is a 2G standard used in Europe. GSM has a bandwidth of 50 MHz at 890-915 MHz and 935 – 960 MHz [38]. GSM supports SMS (short message services). In 2001 GSM had a 60% market share. GSM uses GMSK Gaussian minimum shift keying. GMSK was designed to:

- reduce power requirements,
- thereby extending battery life,
- reduce required bandwidth, to allow more users,
- Reduce noise, to make voice communications clearer [32].

Personal Digital Cellular (PDC)

PDC is a cellular standard used for Japan. The major difference between PDC and GSM is channel spacing. PDC uses 30 kHz channels whereas GSM uses 25 kHz channels.

2.1.4.3 The 2.5th Generation (2.5 G)

2.5G provides an intermediate rate between 2G and 3G services. General Packet Radio Service (GPRS) is a 2.5G standard and is an extension of GSM. GPRS has a transfer rate of 171 kbps [39]. Use of GPRS first became widespread in 2000 [36].

2.1.4.4 The 3rd Generation (3G)

The design of 3G systems began in 1990 and was first implemented in 2002. It supports speeds of 2 Mbps [35]. UMTS is a 3G standard.

Universal Mobile Telecommunications System (UMTS)

UMTS was defined by standardisation body 3GPP (3rd generation partnership project). There are two parts to the UMTS network: the UMTS core network (CN) and the UMTS terrestrial radio access network (UTRAN) [40].

The core network is responsible for the main functions such as switching of traffic, QoS and mobility. UTRAN runs a number of base stations in parallel but on different bandwidths. This allows UMTS to have a very high bandwidth, of up to 2 Mbps [41], while the core network controls the essential functions [42].

2.1.4.5 The 4th Generation (4G)

The design of 4G began in 2000. 4G has a theoretical bandwidth of 200Mps [35]. Long Term Evolution (LTE) is another standard developed by 3GPP. LTE is based on GSM. LTE uses frequencies between 1.25 and 20 MHz.

LTE

LTE networks have large data transfer capabilities, up to 100 Mbps downlink and 50 Mbps uplink [43]**.** LTE stands for long term evolution. It is a type of 4G network. Several papers showed LTE could be used for vehicle to vehicle communication [1] [44].

Cellular is looking increasingly promising for v2v communications with the advent of 3G and 4G networks. There was a problem of pricing, but with flat rates this is less important.

2.1.5 **Other Access Technologies**

This section discusses less common technologies for inter-vehicle communication such as satellite and optical communications.

2.1.5.1 Satellite Communications

Satellite communications are very slow and unavailable in city areas due to high buildings blocking the signal. A communications satellite sends information in the form of microwave radio to nodes on the ground.

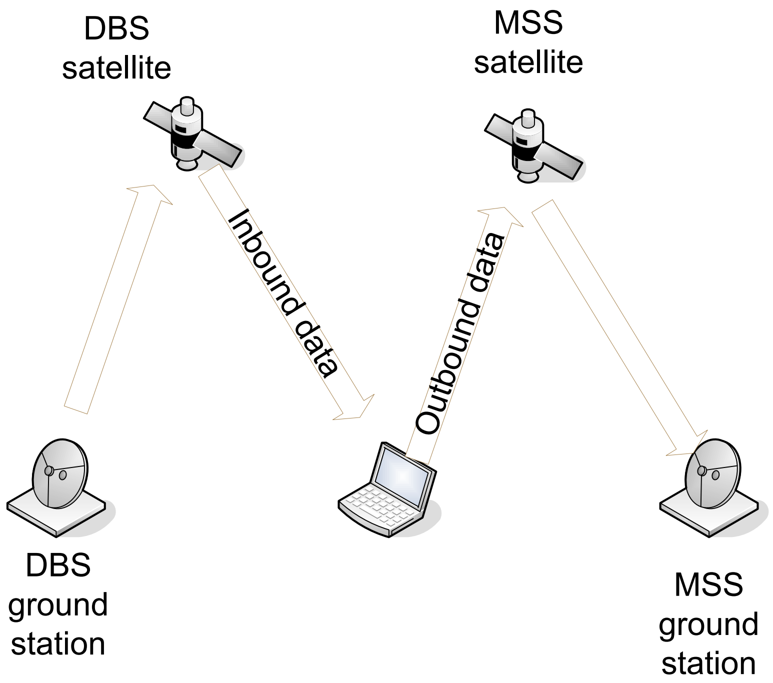

Figure 2-6 Satellite Communications

The advantage of satellite communications is the transmission area. Satellites are capable of very long range communication from any points in the globe e.g. Antarctica. The disadvantage of using satellites is the costly launches and a large propagation delay. There are a number of different orbits the satellites can be placed in. The highest of these orbits is Geosynchronous Earth Orbit (GEO). This is where the orbit of the satellite is synchronous with the rotation of the earth, meaning that the satellite stays in orbit above the same spot. This is roughly 37,000 km above the surface of the earth. Although the Apogee of Molniya Orbit is higher than GEO it is spends most of the time lower because it has a highly elliptical orbit. It is used as geosynchronous orbits are impossible above near-polar regions. Medium Earth Orbit MEO is a circular satellite orbit which is lower than GEO but above Low Earth Orbit (LEO). LEO is an orbit of a satellite which rotates the earth every 90 minutes, it is only able to connect to a point on the ground for 15 to 20 minutes. It is roughly 400 km above the earth's surface. Satellites use FDMA or TDMA.

The paper by Aslam et al. [45] showed that satellites can be used in some circumstances to help increase VANET connectivity. The satellite could be used for downlink only effectively avoiding the propagation delay problem. This paper is discussed further in the related works section.

2.1.5.2 Optical Communications

This section deals with optical communications for vehicles. Yet another method of inter-vehicle communication which can be done is optical communication, be varying the intensity of a light source, LEDs in this context. Information can be coded and sent between vehicles which have a direct line-of-sight. This is a major limitation when compared with the other approaches outlined. However optical communications have been shown to have a high data rate making them worthy of some study.

Wada et al. [46] investigated at infrastructure to vehicular communication. Image analysis is used by the vehicle to decipher information. The approach described in this paper would need high speed cameras, which would present a significant cost. The advantage of this approach is that the high speed flashing would be invisible to humans so traffic lights could be used to transmit information without interfering with their primary function of maintaining traffic flow. The approach outlined in this paper also allows for different lanes to receive different information due to the variation in light being transmitted at different angles. However much more testing is needed to prove these hypotheses, moving cars etc.

Liu et al. [47] created a Vehicular Ad-hoc Network using optical communication. Issues relating to the traffic blocking light signals were also looked at. It also identifies light noise as an issue, from the sun etc. The data transmission rate will drop to zero when the sun is low in the sky, dawn, dusk etc. This would render optical communication useless in countries in the northern latitudes which experience a low sun for months, Ireland, UK, and Scandinavia etc. It also looked at the effect of reflection on packet delivery.

Kumar et al. [48] used intensity modulation of LEDs for information transmission between vehicles and infrastructure. This is suitable for both short and medium range transmission. The authors state this is about 15 m which is very low compared with other vehicle to vehicle communication mechanisms.

Nishimoto et al. [49] prioritized different sets of data with-in an optical stream for infrastructure to vehicle communication. This approach was shown to extend the range in which meaningful data could be sent. This range was up to 70 m a significant improvement on other schemes, but still less than radio schemes and requires line-of-sight. This scheme also requires a high speed camera.

Yamazato et al. [50] compared Vehicle Light Communication with typical radio communication. The authors showed a higher bandwidth for optical communication when line of sight transmissions were possible. These tests showed a transmission rate of 10 Mbps was possible. The author identifies that smog and weather would interfere with the communications. Real tests in driving conditions were carried out. 2 kbps was achieved at 110 m. The author says that the ideal situation would be to have both optical and radio communication. However this would present a significant cost and the author only identified a limited set of cases where optical communication would be superior to radio communication.

2.2 VANETs

VANET is an acronym for Vehicle Ad-hoc Networks. VANETs are a specific kind of MANETs. A MANET is a network of mobile wireless nodes, which self-configure. MANETs require no infrastructure to be set up. These nodes are all moving independently and must constantly form new links between each other to prevent network fragmentation. VANETs use individual vehicles as nodes. VANETs are not true MANETs as there is a need for a limited amount of stationary nodes or road side units (RSUs). The vehicles send messages from one vehicle to another or from one vehicle to an RSU by using multi-hop routing.

The major issue in dealing with VANETs is the high mobility of nodes. Two nodes could have a combined speed of 240 kmph relative to each other. This results in very short connection times. The fact that all the vehicles are heading in different directions makes network fragmentation a continuous problem. One minute the vehicles could be waiting at a traffic lights and have a very high node density. Then after the light goes green they could pull off quickly and head in different directions from the junction resulting in very low node density. However unlike other MANETs, the mobility of VANET nodes is predictable: they have to follow the roads and will generally obey the rules of the road.

VANETs do not suffer from the same power constraints as other wireless sensor networks as the vehicles have their own power source. For most purposes of VANETs power can be considered a non-issue [51].

There can be a lot of obstacles to VANET communications such as tunnels, bridges and tall buildings, resulting in lost communications. Martinez et al. [52] wrote a paper on building a more realistic simulation model to calculate these effects, it was proved that building can have a significant effect on hindering warning message dissemination.

Although there is a huge potential of VANET applications, there are two main areas, safety and traffic congestion. VANET applications will be discussed further in later sections.

There are several methods of VANET communications. VANETs can communicate using Wi-Fi, cellular or satellite. In this research the VANETs communicate using the Wi-Fi standard IEEE 802.11p which is a standard specifically designed to cope with the high mobility of the VANET nodes.

2.3 Traffic Management System (TMS)

A Traffic Management System (TMS) is a technology designed for affecting traffic to improve safety and traffic flow. A TMS has a set of inputs such as traffic cameras and set of outputs to control the traffic, for instance controllable traffic light sequences. The outputs are manipulated in order to have the desired effect, for instance improved traffic flow.

A TMS offers capabilities that can potentially be used to reduce road traffic congestion, improve response time to incidents, and ensure a better travel experience for commuters. A typical TMS includes of a set of complementary phases, as shown in Figure 2-7, each of which plays a specific role in ensuring efficient monitoring and control of the traffic flow in the city.

The cornerstone phase of a TMS is Data Sensing and Gathering (DSG). In this phase heterogeneous road monitoring equipment measure traffic parameters (such as traffic volumes, speed and road segment occupancy, etc.), and periodically report these readings to a central entity. For example, these monitoring tools can detect random incidents and immediately report them through wireless networks, cellular networks or mobile sensing applications.

Subsequently, these data feeds are fused and aggregated during the Data Fusion, Processing and Aggregation (DFPA) phase to extract useful traffic information. The next phase, Data Exploitation (DE), uses this acquired knowledge from the processed data to compute: optimal routes for the vehicles, short term traffic forecasts, and various other road traffic statistics.

Finally in the Service Delivery (SD) phase, the TMS delivers this knowledge to the end users (such as drivers, authorities, private companies, etc.) using a variety of devices such as smart phones, vehicles' on-board units, etc. The capabilities offered by a TMS are not confined to serve drivers and road authorities only, but can also contribute significantly to the economic growth of a country, to the preservation of citizens' safety and to the support of national security. The currently deployed technologies for road traffic surveillance still suffer from a lack of accuracy in traffic parameter measurement and in the real-time reporting of events that occur on the road, especially in developing countries. Also the gathered traffic data usually needs to undergo a filtering process to improve its quality and eliminate the noise. Deploying highly sophisticated equipment to ensure accurate estimation of traffic flows and timely detection of emergency events may not be the ideal solution. This is due to the limitation in financial resources to support dense deployment and the maintenance of such equipment, in addition to their lack of flexibility. Therefore, alternative cost-effective and flexible solutions are needed to guarantee better management of road traffic in both developed and developing countries.

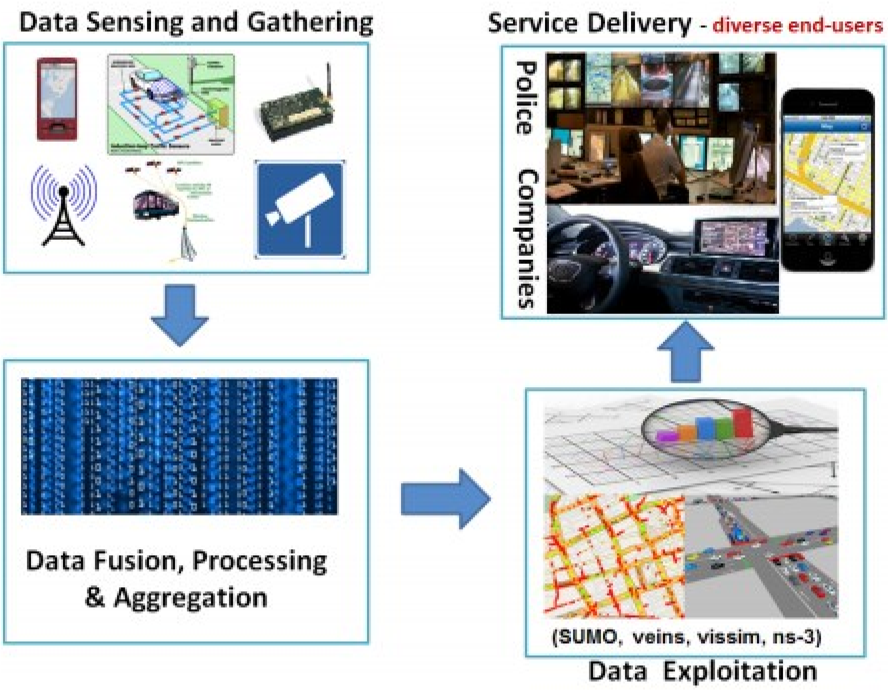

Figure 2-7 Data life cycle in smart transportation

A modern TMS aims to overcome some of the above limitations by designing innovative approaches able to exploit advanced technologies to efficiently monitor the evolving critical road infrastructure. These approaches should be scalable enough in order to enable better control of the traffic flow and enhanced management of large cities' road networks. This will certainly improve the accuracy of the acquired real-time traffic information and the short-term traffic prediction. This will enable the creation and use of short-term predictions based on current traffic volumes to identify bottlenecks and make more informed decisions about how to best reroute traffic, change lane priorities, modify traffic light sequences, etc.

A modern TMS should also provide a visual tool that can display in real-time traffic information related to location of bottlenecks, incidents, and congestion level in each road segment, as well as the estimated travel time from one location to another in the road network. In this way, the transport authorities will have an overall view of the road network in real-time. This will allow them the best possible support for improvements in the traffic flow management and to make more efficient reactions to emergency incidents on the roads.

An adequate TMS for future smart cities should fulfil the following requirements:

- Ensure higher accuracy in estimating traffic conditions and better efficiency in dealing with emergency situations on the roads, compared to the existing TMSs.
- Be able to efficiently manage the traffic in road networks of varying sizes and types.
- Provide real-time road traffic simulation and visualisation, in order to enable authorities to efficiently manage the road infrastructure and allow them to improve route planning for commuters.
- Ensure simplified and smooth integration of existing systems and new technologies, and manage the evolution of these systems.

A high level architectural overview of a modern TMS is depicted in Figure 2-8. This figure shows the main components of the TMS needed to deliver the collected road traffic information to the intended end consumers (e.g. road authorities and commuters). As we can see from this figure, the core system of the TMS collects road traffic information from heterogeneous data sources, according to the consumer's needs and specific requests. These data feeds are then aggregated and stored in a unified format in one or multiple databases.

Later, upon reception of a consumer request, the core system processes the request and extracts the pertinent data from the appropriate database. Then the requested information is sent back to the intended consumer, tailored for their specific purposes: e.g. analysis and statistics, decision-making, etc…

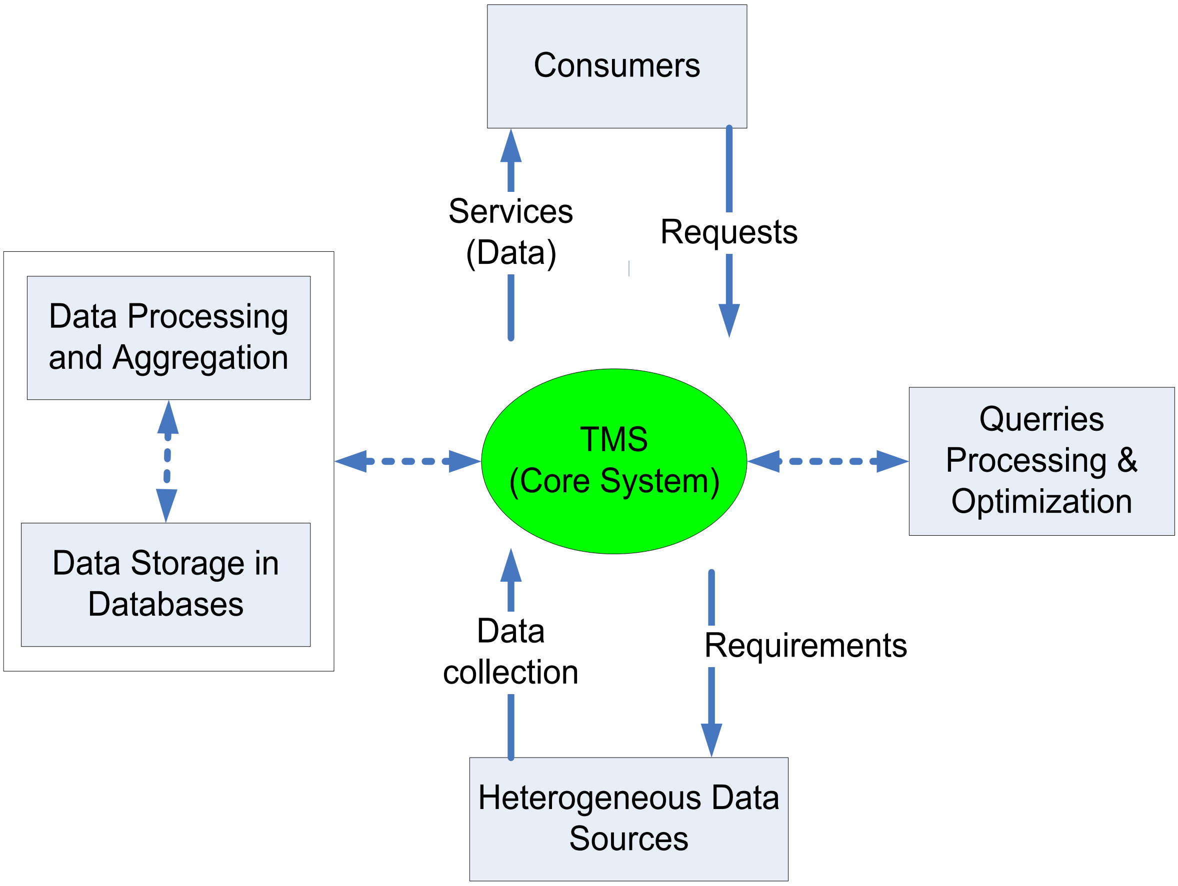

Figure 2-8 A simple architecture of a modern TMS

2.4 Packet Routing

Packet Routing determines to route by which the information packets should be sent in order to enhance throughput, delivery ratio and reduce latency.

This section looked at vehicle to vehicle (V2V) packet routing. The different routing approaches used in vehicular networks to disseminate the gathered data among the vehicles are explored. The information transmitted by the Traffic Management System (TMS) or other service providers, towards all the vehicles or a sub-set of them are discussed along with their advantages and disadvantages, and a comprehensive comparison of their main features is provided. Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communications are expected to play a key role in the development of TMS in smart cities. The efficiency of this type of communication depends on the information dissemination (i.e. routing) protocols. V2V message routing can make use of several data sources to improve message routing.

The most significant protocols proposed to find the best route for the exchanged packets among non-neighbouring vehicles in a road network will be presented, classified and compared. Many of these protocols make use of one or both of the following: the road network map, the vehicles mobility model. Therefore, these protocols are classified, as shown in Figure 2-9, into four categories based on their awareness of these two parameters (i.e. the map and mobility model), as described below.

This section is divided into subsections depending on whether the routing mechanism is aware of map or mobility information.

2.4.1.1 Context-unaware Routing Protocols:

These routing mechanisms do not take into account the road map and nor the predicted mobility of vehicles.

Ad hoc On-demand Distance Vector (AODV) [53] searches for a route using 'route request' and 'route reply' messages whenever a message needs to be sent. If the link becomes broken via moving nodes a 'route error' message is sent, allowing the search to start again.

Greedy Perimeter Stateless Routing (GPSR) [54] uses greedy forwarding decisions based on its nearest neighbour nodes. If the message reaches an area where greedy forwarding is impossible the message is forwarded around the perimeter of the area. This was a very simple approach, but had a higher delivery ratio than DSR and this improved as the number of nodes increased.

Dynamic Source Routing (DSR) is composed of two mechanisms 'route discovery' and route maintenance. When a message needs to be sent each node checks its route cache to see if a route to the destination already exists. If it does not detect the route, route request message are broadcasted. When the correct route is discovered route reply messages containing the route are returned to the original sender. Misra et al. [53] showed that normally AODV outperformed DSR except in resource constrained environments. The scenario was multiple nodes trying to sends messages to the same node. DSR generates less overhead for User Datagram Protocol (UDP) than AODV. However AODV is the better choice for Transmission Control Protocol (TCP).

Greedy Perimeter Coordinator Routing (GPCR) [55] is another position based routing protocol. It used the fact that streets and junctions form a natural planar graph. In this protocol, messages are forwarded along the street with decisions only taken at junctions. GPCR used a repair strategy to get rid of local minimums. This protocol does not require a static street map as it can heuristically detect the junctions on the road. However it is not resilient to network partitioning that may occur due to links loss.

Location-Based Routing Algorithm with Cluster-Based Flooding (LORA_CBF) [56] is a cluster-based flooding mechanism, where a number of gateways are chosen for inter-clusters communication, in addition to the cluster head. When a data packet needs to be sent, the sender first checks its routing table to find the location of the destination node. If this location is missing then a location request message is broadcast to the network. Upon reception of this request, the destination node or any intermediate node, which has fresh location information of the destination node, sends a location reply message to the source. The data packet is then transmitted through this route. The hierarchical architecture of LORA_CBF leads to shorter route discovery time, as well as a better delivery ratio, but the overhead increases considerably [57].

Distributed Vehicular broadCAST protocol for vehicular ad hoc networks (DV-CAST) [58] applies two different approaches according to the network connectivity, it used the broadcast suppression technique in order to reduce the broadcast overhead in case of a dense network, while a 'store-carry and forward' method is used in a sparse network. The network density level is determined based on the size of one-hop neighbours list. This protocol overcomes some of the previous protocols' limitations as it reduces the broadcast storm and adapts its routing approach to deal with the network disconnection problem.

In the **Centroid virtual coordinates** (**3rule)** routing protocol [59], a set of sink nodes aware of their location is deployed and configured to form the network infrastructure. Other nodes then set up a virtual location by judging their distance from those sink nodes. For efficient routing, a greedy geographic approach is used to route the exchanged messages among the nodes, and the evaluation results have shown that this scheme outperforms GPSR (Greedy perimeter Stateless Routing) in terms of energy efficiency, path length and robustness.

Emergency BROADcast Protocol for Inter-Vehicle COMMunications (BROADCOMM) [60] is a fast routing protocol specifically designed for safety applications. It divides the highway into virtual cells which move along at the average highway speed. At the centre of each virtual cell, some nodes are designated as cell reflectors which, in turn, act as virtual base stations. It is worth mentioning that cell reflectors are similar to cluster heads, except that several cell reflectors may co-exist within one cell. BROADCOMM is designed to be fast enough to be used in safety situations. The main weakness of this protocol however, is the high overhead incurred [61].

2.4.1.2 Map-aware Routing Protocols:

In this category of routing protocols, map information is a cornerstone for calculating the end to end path for a data packet.

Urban Multi-Hop Broadcast protocol (UMB) [62] is designed to address broadcast storm, hidden nodes and reliability problems. It makes use of both a directional broadcast and an intersection broadcast. In the directional broadcast the message is forwarded to the furthest node in that direction. In intersectional broadcast the message is forwarded to all the roads in the intersection. UMB used 'Request to broadcast' (RTB) and 'clear to broadcast' (CTB) messaging once in directional broadcast and once for every direction in intersection broadcast. When a RTB message is received by a vehicle, the vehicle creates a black burst. This is a signal which is longer depending on its distance. If the node detects that its black burst went on longer than the others, it sends a CTB message to the sender. If there is a collision due to more than one CTB message, the process starts again. After receiving a CTB message the source sends the broadcast message to all the nodes in the area. The broadcast message contains the ID of the sender of the CTB message, which is the only node which forwards the broadcast message using the above process. In intersection broadcast there is a stationary node at the junction. This node then forwards the message in every direction using the above process. However the use of RTB/CTB may lead to long latency times especially for high node densities [63]. UMB has a high delivery rate but requires infrastructure. It generates approximately 2.5 times less load than flooding mechanisms [64].

Adaptive Road-Based Routing (ARBR) [65] tracks a route-requesting vehicle, as it moves to new location. ARBR forwards the message along road segments with a high traffic density, if possible. Otherwise ARBR used "carry and forward" to overcome network fragmentation. Vehicles send beacons to allow their neighbours to update their position. To prevent a broadcast storm each vehicle only forwards the same message once. It also only forwards one message per set amount of time. ARBR outperforms VADD and GPSR in terms of delivery ratio and end-end delay.

Static-node assisted Adaptive data Dissemination protocol for Vehicular networks SADV [66] is an infrastructure based routing protocol that presumes the existence of a static node (i.e. a Road-side Unit (RSU)) at each junction. Each RSU has a digital street map to determine which road presents the best trajectory. A data packet waits at the RSU till a route to the next intersection is established. This route is selected based on the delay estimation of each road in order to achieve a near optimal choice. SADV improves the packet delivery ratio and presents an enabler for RSUs placement in road networks.

2.4.1.3 Mobility Model Aware Routing Protocols

The following routing mechanisms leverage the knowledge of vehicles' mobility models for messages routing purposes.

Vector-based TRAcking DEtection (V-TRADE) [67] is a mobility model aware routing protocol which uses vehicles positions and directions to ensure more efficient routing. The protocol can be used to send a message to all vehicles in the area, or on a particular road in one direction or in both directions. Node positions are calculated in terms of position (behind, in front or on a different road) and their direction. This determines the route the message will be sent along. V-TRADE [68] shows performance improvements over existing techniques although with slight increase in over-head.

Predictive Directional Greedy Routing protocol (PDGR) [69] routes the vehicles based on both their current and predicted positions. It applies a greedy strategy and forwards the messages in the direction of the destination vehicle without a predetermined route. PDGR considers both the position and movement of a vehicle for forwarding decisions. 'Carry and forward' is also used to make up for limited nodes. It has been shown that PDGR outperforms GPSR in terms of delay, delivery ratio and overhead. Bilal et al. [70] states that PDGR has not been implemented in a city scenario.

MUlti-hop Routing for Urban VANET (MURU) [71] determines the probability that a certain link in the VANETs might be broken at a certain time period. MURU is an on-demand routing protocol i.e. the route is only calculated when required. It used "route request" and then sends on the route with the lowest probability of being broken. MURU improves on existing techniques in terms of packet delivery ratio, data packet delay and overhead. However MURU does not account for network fragmentation [72].

Connectivity-Aware Routing (CAR) [73] used a greedy forwarding approach with anchor points to find the route relaying origin-destination pairs. In CAR, the messages are forwarded to the closest node to the next anchor point instead of the closest node to the destination, and the location of this latter is tracked so that the route can be adjusted to provide connectivity even if the destination has moved a great deal. This allows routes to be adjusted 'on the fly' without a new search being run. Notice that the incorporation of CAR routing approach in GPSR has shown an improvement of the performance by 30%.

However the main shortcoming of this protocol is its inefficiency to handle different sub-paths under frequent topology changes [74].

2.4.1.4 Map and Mobility Model Aware Protocols

There are some routing solutions which consider both the mobility model of the vehicles and map information to determine a robust route for message delivery among vehicles.

Vehicle-Assisted Data Delivery (VADD) [75] is designed specifically to route data packets in sparse VANETs with frequent network fragmentation due to the high mobility of vehicles. These packets will be transmitted over the routes with shortest transmission delay. In case of network fragmentation, the packet is forwarded to a vehicle that crosses the network partitions first and then the vehicle forwards it towards the destination. VADD determines whether there is a direct route to the destination by analysing the map of the area and the traffic conditions around it. This protocol ensures higher delivery ratio compared with GPSR and DSR. However, there is a large delay if there is a varying topology and traffic density [76].

Anchor-based Street and Traffic Aware Routing (A-STAR) [77] is a position based routing protocol. It is similar to Geographic Source Routing (GSR). A-STAR used street map information in order to form anchors, which are placed on each junction the message must pass through. It is also traffic aware so it takes into account how much traffic is on each road, in order to determine the fastest route, one in which the packet will not be dropped. Information from bus routes is used to find paths of high connectivity. The number of bus routes on a road contributes to the edge weight the road is assigned. A-STAR has a lower packet loss ratio than GSR and GPSR due to its consideration of traffic conditions. However A-STAR's use of the right hand rule is inefficiently biased in one direction, as stated in [78].

Inter-Vehicles Geocast (IVG) [79] is a safety based protocol that broadcasts an alarm message to all the vehicles in a given area if there is a danger in front of them. In this case, these vehicles constitute the multicast group that will receive the alarm message, and then forward it in the backward direction. If the vehicles behind are forwarding the message, the vehicle which originally sent the message stops sending it, as this means they have received it. In order to reduce the gratuitous alarm messages IVG takes into account the braking distance before broadcasting this message. However, if the danger is immediate, the alarm message is sent, regardless of this distance, to prevent crashes. The main advantage of IVG is that it reduces the number of gratuitous alarm messages.

Improved Greedy Traffic Aware Routing protocol (GyTAR) [80] is a greedy routing protocol which takes into account real-time traffic conditions and road topology. GyTAR used a greedy strategy to decide which junctions to pass through, which is based on the traffic density and distance to the next junction. GyTAR used a recovery strategy which used “carry and forward” to overcome local optimum. GyTAR was shown to outperform DSR in terms of delivery ratio and overhead.

A QoS routing protocol for vehicular ad hoc networks (GVGrid) [81] is a reactive routing protocol (i.e. the route is created when the message needs to be sent). GVGrid divides the road network map into a set of uniform squares and assume that each vehicle is equipped with a digital map and is aware of its location and direction through GPS. GVGrid constructs a route from a fixed node to a fixed location i.e. one of the grid squares, so when vehicles are sent a message, the message travels to their area. GVGrid used stop signs and highways with constant inter-vehicle distance as prediction indicators for vehicle mobility to enhance messages routing. This protocol ensures route recovery in case of link break due to vehicle mobility. GVGrid is designed for dense vehicle networks, not highway scenarios.

2.4.1.5 Discussion

To summarize, each of these routing protocol categories has advantages and shortcomings and might be suitable for some road traffic scenarios and not applicable in others. The division of the routing protocol categories is shown in Figure 2-9. Moreover, the awareness of vehicle mobility models and road network maps might not be sufficient to meet the requirements of safety applications, especially in emergency scenarios where both fast and reliable dissemination of danger alerts are compulsory.

Therefore, an ideal routing protocol for VANETs in the context of smart cities should be aware of extra parameters, in addition to the mobility model and map, such as the shape of the roads, destination of other vehicles, channel interference level, etc.

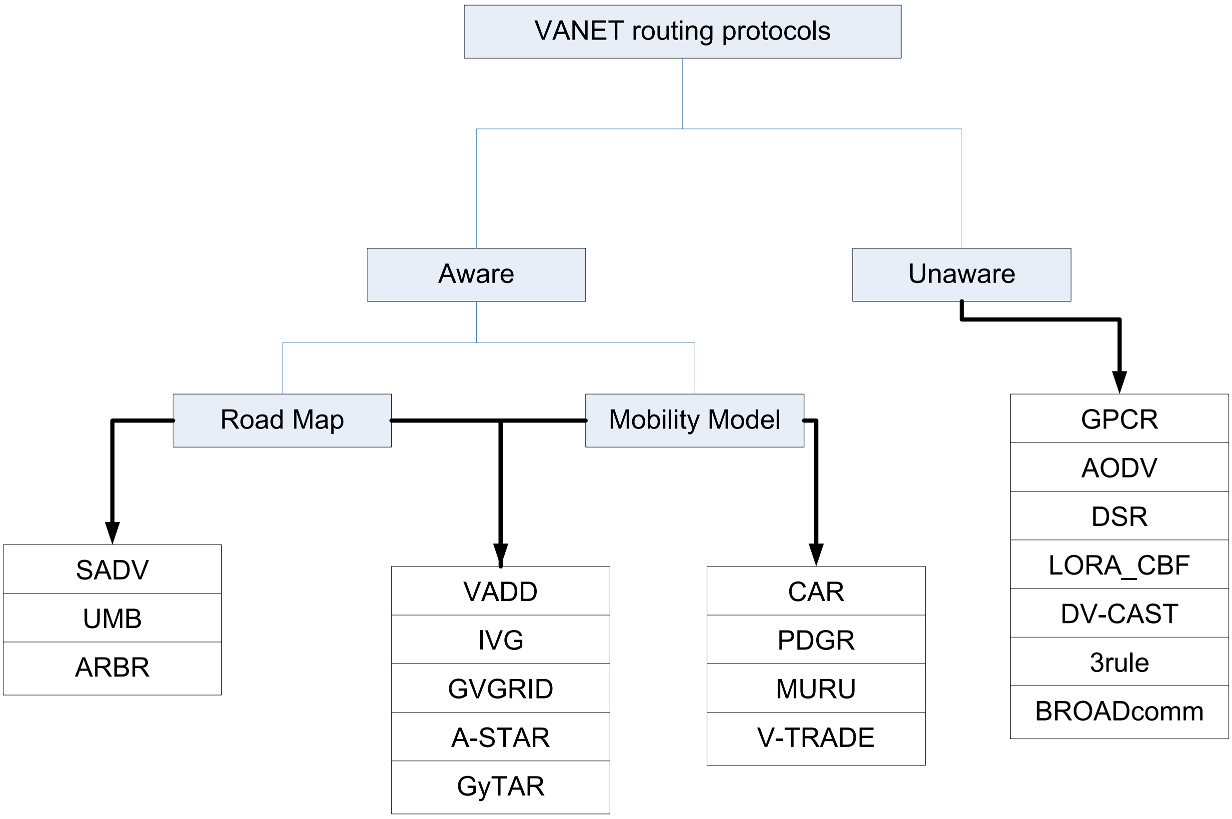

Figure 2-9 A classification of VANETs routing protocols based on their awareness of the mobility model and the road map

Table 2-2 Comparison of vehicle routing protocols

	Communication Overhead	Computation Overhead	Scalability Level	Latency	Delivery Ratio	Network Partition Resiliency	Target Scenario	Infrastructure Dependent
GPCR	Low	Low	Medium	High	Low	No	Urban	No
3rule	Low	Low	Unknown	Unknown	High	No	All	Yes
LORA-CBF	Medium	Low	High	Low	High	Medium	Urban	No
DV-CAST	Low	Low	High	Low	Medium	Very High	All	No
SADV	Low	Low	Medium	Medium	Medium	High	Urban	Yes
VADD	Low	Medium	Medium	Medium	Low	High	Rural	No
UMB	Medium	Medium	Medium	High	Medium	Medium	Urban	Yes
ARBR	Low	Medium	Medium	Medium	High	High	Urban	Yes
CAR	Medium	Medium	Medium	Medium	Medium	Medium	All	Yes
BROADCOMM	High	Low	Medium	Low	Low	Medium	Highway	Yes
V-TRADE	Medium	Low	Medium	Medium	Low	No	Highway	No
PDGR	Medium	Medium	Medium	Medium	Medium	No	Urban	No
MURU	Low	Medium	Medium	Low	Medium	High	Urban	No
A-star	Medium	Low	Medium	Medium	Low	Medium	Urban	No
IVG	Low	Low	High	Low	Medium	High	Highway	No
GyTAR	Low	Low	Medium	Low	Medium	High	Urban	No
GVGRID	Medium	Medium	Medium	Medium	Medium	Medium	Urban	Yes

In the Table 2-2, the different routing approaches presented above are compared, according to the following criteria: incurred communication and computation overhead, extent to which the protocol is scalable, end-to-end delay of the transmitted packets, efficiency in terms of packet delivery ratio, resiliency to VANET fragmentation due to the high mobility of vehicles, applicability in urban and/or highway scenarios, and finally the road-side infrastructure requirement.

2.5 **Vehicle Navigation**

This section focuses on navigation algorithms for vehicles. The navigation algorithms direct the driver to an appropriate route based on some metrics.

The growing complexity of the big cities' road networks has led to an unprecedented expansion of the automotive navigation systems market.

These systems, such as TOMTOM [82] and GARMIN [83], have made the journey of drivers easier and more comfortable due to the valuable information that they provide like the city road map, GPS localization and the guided route towards the destination. Despite the popularity of these systems, fast and accurate route search algorithms under the rapid and sudden variation of traffic conditions are still required to accommodate the needs of future smart and autonomous cars. Typically these would use a Dijkstra search [84].

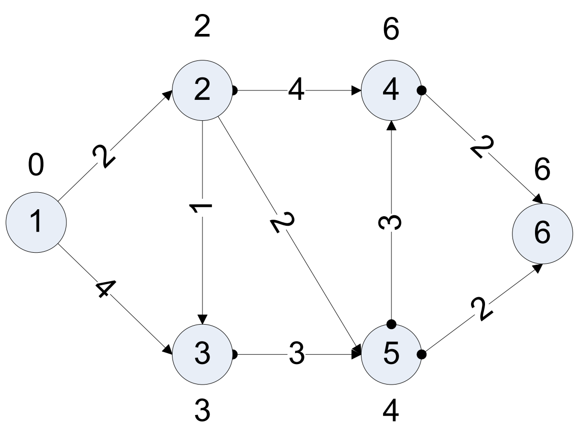

Figure 2-10 Dijkstra graph search

Dijkstra is a graph search, the costs of all the vertices between two nodes are added and then the least cost route is chosen [85]. In Figure 2-10 a small graph search is chosen, adding all the vertices between nodes 1 and 6 it can be seen that the least cost route is 1 > 2 > 5 > 6.

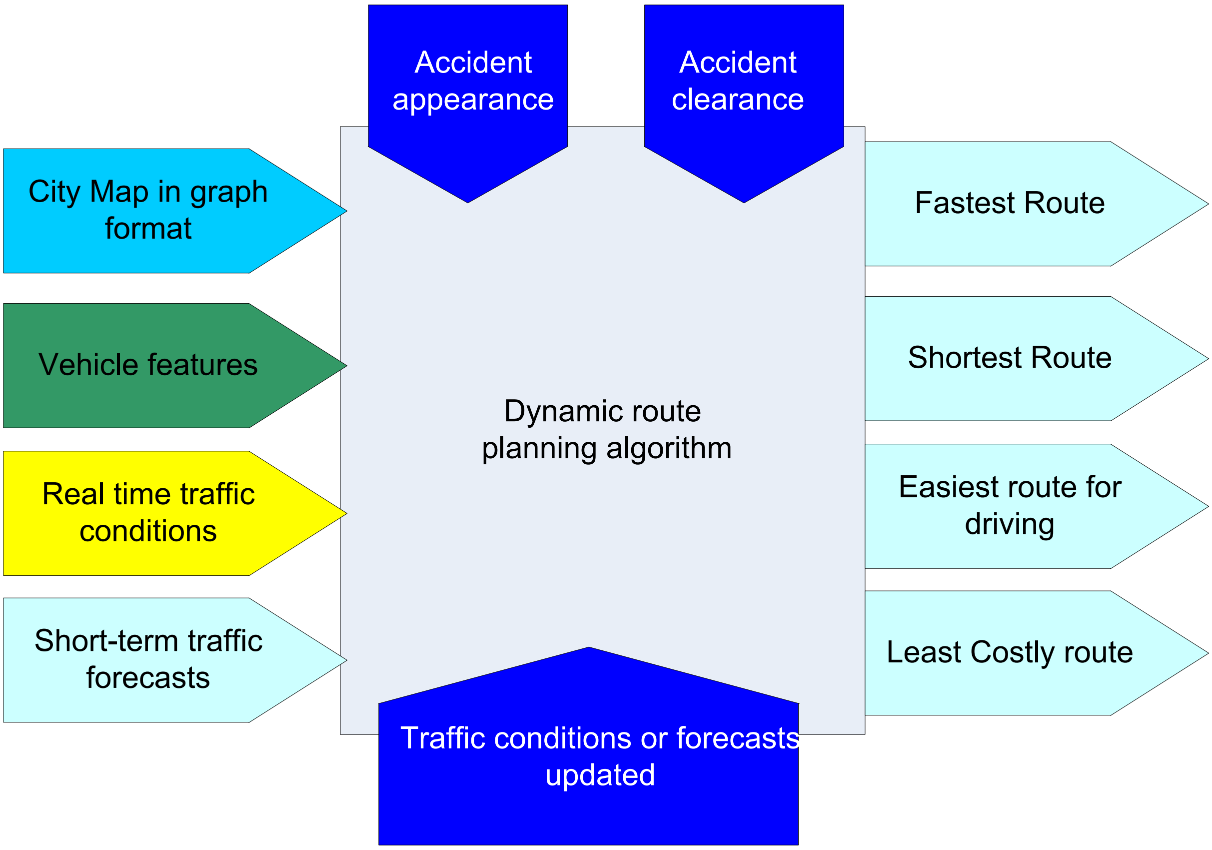

Figure 2-11 Route planning algorithms: main inputs and functionality

As opposed to static routing algorithms used for shortest path finding in graph theory, route planning algorithms must update the best route assigned to each vehicle, as soon as any change in road and traffic conditions that affect at least one road segment that this vehicle should pass through, is detected [86], [87], [88]. A typical dynamic route planning algorithm for smart cars is described in Figure 2-11. This figure emphasizes the main inputs of a dynamic routing algorithm, its output and the road events that may trigger an update of this output. These inputs consist of the city road network modelled as a directed graph in order to reflect one and two way road segments, vehicle features (e.g. its height, weight, type), current traffic conditions and short term traffic forecasts, as well as driver preferences.

By applying the routing algorithm on the directed graph and taking into account all the other inputs, the best route is returned. This latter should be updated dynamically, during the vehicle's journey upon occurrence of any event that may lead to the failure of a road segment included in this route. Notice that the failure of a road segment means its closure due to an incident or road works, or the abnormal increase of travel delay across it. Updating the best route means quickly providing an alternative route that mitigates the detected bottlenecks. One of the challenges here is how to keep the quality of the alternative route very close to that of the failed best route. Usually, the best route depends on driver preferences which may include one criterion or a combination of several criteria. The travel time is the preferred criterion for most of the drivers due to the critical consequences of the delay.

The routing algorithms will be examined under two main headings: VANET-based and non-VANET-based navigation algorithms.

2.5.1.1 VANET-based Navigation Algorithms

This area of research centres on navigation algorithms aided by VANET-based exchange of messages which determine quicker and/or more fuel-efficient routes for the vehicles. Sommer et al. [89] showed that reducing the travel time by VANET-based routing can result in increased emissions. This can happen when the algorithm recommends the vehicle should take a long detour, when, in fact, waiting till the traffic jam eased would have been more fuel efficient. Collins et al. [90] considered the fuel cost per second used on each route; however with no data on the road conditions, the fuel cost is simply a function of speed and acceleration. Several other papers looked at ways in which VANETs could be used to support algorithms which reduce emissions [91]–[93]. Most of the research in these papers concentrated on communication with traffic lights. Optimizing light timing [92], [93] would smooth traffic flow which in turn reduces idle time. Knowledge of when traffic lights will change allows for smoother deceleration/acceleration of vehicles [91], and for turning off the engine of vehicles when waiting for the traffic light to turn green [93], reducing fuel consumption etc.. however there would be a substantial cost to equip traffic lights to enable them to communicate. Other papers concentrated on reducing journey time, which would also reduce emissions by reducing idle time spent [94]. However emissions are influenced by a variety of factors such as acceleration, velocity, road surface, and wind speed and direction, not just idle time as assumed in some of these papers [94].

Wu et al. [95] suggested a traffic-aware VANET-based routing scheme entitled Dynamic Navigation Algorithm (DNA). Several parameters relating to the traffic and road are sent between vehicles and then the best route is computed. The traffic parameters are: average vehicle speed and inter-vehicle distance and the road parameters are: the length of the road and the type of road. This considered the average travel time and distance travelled, however no attention was paid to emissions. Also DNA did not use load balancing and the algorithm added the metrics distance and speed, whereas distance should have been divided by speed in order to get a better estimate of their impact on travel time. DNA out-performed shortest path first (SPF) in terms of travel times by an average of roughly 7%, which was similar to the Dijkstra implementation in this thesis.

2.5.1.2 Non-VANET based vehicle navigation algorithms

A number of navigation algorithms which determined routes from non-VANET sources were looked at.

Dijkstra [85] is used in some on-board GPS navigation systems [96]. This is a shortest path graph search. It can be used to find the shortest path by calculating the sum of all the vertices between two points. It is well-known and has been used for a long-time, it was published in 1959.

Kim et al. [97] used real time traffic information to decide vehicle departure times and routing. Markov decision processes are used to decide these parameters. Trucks have buffer times to ensure that deliveries arrive on time in case of unforeseen circumstances. Buffer time however results in idling time of equipment and labour. Real time data plus historical data can be used to reduce the need for buffer time while ensuring on time delivery. This paper used real data from Michigan, US to show a reduction in cost and equipment use for a trucking company. Markov decision process is used to determine when to reroute. An approach which considers combining real-time and historical data from VANETs could yield better results, due to the higher granularity of VANET systems.

Schaub et al. [98] received information on traffic over FM radio. The paper looked at existing flaws in navigation systems and ways of addressing them. The paper talks about issues such as gullibility errors where the driver follows the automotive navigations directions even when it does not make sense. One important contribution is also the fact that drivers will not always follow the advice of the navigation system. The paper suggests giving the driver choices and giving the advantages of each choice. This is a good idea as machines are not always capable of judging the advantages of some concepts and different users will have different preferences, e.g. some drivers may not like driving a certain road that they consider dangerous.

Horvitz et al. [99] looked at waypoints such as charging stations. It recommends good waypoints even if it is unsure of the ultimate destination. This paper however only considered an empty map for simulations and ignored traffic. This was shown to outperform situations where the driver did not stop for fuel until he needed to by an average of 12 minutes.

Hrazdira et al. [100] investigated 3D routes to destination, hence predicting the energy used by battery to wheels and predicted most energy efficient routes for Hybrid Electric Vehicles (HEVs). For testing a map was retrieved from open street map and then the height was obtained from another source, a similar approach was used in this thesis. The paper showed the potential journey time and expected charge of two different routes.

Valle et al. [101] looked at routing using semantic techniques. The user can ask a question on nearby amenities and the search engine will interpret it and route the vehicle accordingly. This is a novel idea which could greatly enhance the intuitiveness on vehicle navigation systems. However this paper did not include testing however.

Zhang et al. [102] looked at improving the overall traffic system without causing user dissatisfaction. Also if all users are lead to the path with least traffic, flash crowding can occur. The paper identifies a local optimization problem in this approach. This paper showed an improvement in travel time when compared with the shortest path. However an important metric to consider for this scheme would have been compliance rate, what would be the effect if a subset of the users decided to ignore the instructions as they are sent along a longer route.

Silva et al. [103] described the WAZE application. The authors state that the participation of users should allow for much greater data sources. It states that users can provide greater granularity of information on a road by flagging a section as heavily congested and not just congested. However, human estimation can be inaccurate in terms of quantification of parameters when compared with machines. The paper analyses the effect of WAZE on traffic from both cities of New York and Rio de Janeiro.

2.6 **Summary**

This chapter presents a number of background technologies crucial for understanding this work. Firstly Wireless Communications are introduced. This includes the Basic Service Set (BSS) and different types of communication available in VANETs, Wi-Fi, WiMAX and cellular. A number of less used communication methods are also discussed along with the limitations of these technologies. Packet routing and a number of the most important protocols are introduced and discussed. Finally vehicle navigation algorithms in road networks are discussed in detail.

Chapter 3 Related Works

This thesis investigates fuel-efficient rerouting using information from VANET communications. In order to identify the state of the art in research and development in the areas related to the topic of this thesis, a detailed literature review was performed. A number of areas were looked at in the course of this literature review. These were broken up into eight different sections, which will be presented next: data monitoring and collection mechanisms, data aggregation solutions, inter-vehicle coordination, IEEE 802.11p congestion reduction, factors influencing emissions and fuel consumption, infrastructure, swarm algorithms, and VANET services and applications.

3.1 Data Monitoring and Collection Mechanisms

This section examined various methods for gathering information on traffic, from either VANETs or non-VANET sources. Data monitoring mechanisms are very important for VANET-based vehicle management as this is the information on which applications can be based. Data can be gathered from the on-board diagnostics system (OBD) as described in Dashtinezhad et al. [104]. Sensors on the vehicle gather electrical and mechanical data on the vehicle and then send them to the OBD. For instance, if a vehicle has a faulty light, warning information could be sent to nearby vehicles.

Hull et al. [105] gave a good summary of potential data monitoring mechanisms such as environmental monitoring and civil infrastructure monitoring. In environmental monitoring each vehicle could monitor its own emissions and then send this information to a central server. This would allow cities to monitor the effects of their policies to reduce emissions. In civil infrastructure monitoring an accelerometer could be placed on each vehicle to monitor road roughness and potholes. CarTel also makes use of the OBD to identify efficient and inefficient driving patterns and behaviours. This information could be aggregated to show which cars are most reliable and what their specific flaws are. CarTel also could make use of media-rich sources such as cameras on vehicles.

Burke et al. [106] looked at information gathering by Wireless Sensor Networks (WSN), not exclusive to VANETs, but shows how sensor networks with many nodes can be very useful for gathering and analysing data.

The data monitoring mechanisms are divided into VANET-based and non-VANET-based data monitoring mechanisms which are explained below.

The data sensing and gathering phase focuses on the scalable collection of traffic flow information from a large number of heterogeneous sources. Many of the current deployed systems used by traffic management agencies collect data in a variety of formats, time scales, and granularity. This is due to the fact that those systems have been deployed at different time periods with little or no integration between them. This creates a management problem for operators who must manage, analyse and interpret all of this dissimilar data. A modern TMS will analyse a number of the existing traffic information collection mechanisms employed by city authorities and identify where new technologies and systems can be used to improve the accuracy, timeliness and cost efficiency of data collection. In addition, these new data collection technologies must provide a more detailed explanation of the root causes behind the increasing congestion levels on the roads.

More specifically, the current trends in TMS development consist in leveraging advanced communication and sensing technologies like WSNs, cellular networks, mobile sensing and social media feeds, as potential solutions to circumvent the limitation of the existing systems. The main wireless technology used for events sensing and gathering on the roads are small sensor devices. These sensors could be mounted on vehicles, at the roadside or under the road pavement to sense and report different events. In the former case, the in-vehicles embedded sensors monitor and measure several parameters related to the vehicle operations, and communicate them to the nearby vehicles or roadside units. In the latter case, the sensors are mainly used to measure the passing vehicles' speed, the traffic volumes as well other environmental parameters. WSNs can be used to interconnect these sensors and greatly reduce the cost of monitoring systems deployment. In an urban scenario, we can imagine a plethora of sensors being deployed to collect data about traffic conditions, air pollution, environmental noise and many other applications. Information can also be obtained from vehicles that have proper sensors and communication antennas on board; these would primarily be public transportation vehicles, taxis, police cars, and freight vehicles. A modern TMS will, therefore, focus on designing innovative solutions able to collect data from a specific region of interest under specific time constraints, while minimising cost and spectrum usage and maximising system utilisation.

3.1.1 **VANET-based Data Monitoring Mechanisms**

Information gathered from individual vehicles in VANETs consists mostly of traffic information and safety messages, but could potentially include information such as weather or structural condition of the roads which are travelled on. The data monitoring mechanisms described in detail next are related to traffic congestion, safety, weather, road conditions, parking places, different vehicle types, traffic lights, emissions and other sources.

3.1.1.1 Traffic Congestion

This section discusses methods of monitoring data on traffic congestion. There are two main methods of monitoring traffic using VANETs. The first is for each node to send its speed to the other nodes. All these messages can then be aggregated to determine the average speed of each road segment. The second method is to monitor the amount of nodes on a road segment compared with the capacity of the road segment. This however requires a high penetration rate to yield accurate results. A number of different research proposed methods are described below.

In Dornbush et al. [107] considered each vehicle continuously recording its speed on each road to determine the amount of traffic. This information is then used to build a traffic map. When the vehicles come within range to exchange messages, they send each other information on their traffic maps. The authors successfully showed via simulation that gathering and distributing traffic information is possible using ad hoc wireless communication.

Little et al. [108] proposed each vehicle sending information warning messages to other vehicles if it detects traffic congestion on the road. Additional information such as the wait time at a toll booth can be calculated and sent to other vehicles. This could help determine traffic congestion. This approach uses average speed. This was successfully accomplished in simulations of VANETs.

In a paper by Wischoff et al. [109] each vehicle monitors traffic information by receiving information packets from the other vehicles in its area and then forwards this information to other vehicles in other areas. The traffic information is based on the speed of the transmitting node compared with the speed limit of the road; the messages from all the vehicles on the road are averaged to give the traffic rating of the road segment. The authors proved via simulations that it is possible to distribute this data wirelessly between vehicles, even with a very low penetration rate of 2%.

Advantages and Disadvantages of Approaches

The limitations of these approaches are that they only consider either average speed or node density. There are no algorithms which take into account, the average speed, node density, penetration rate as well as road parameters such as bottlenecks and traffic lights. Such algorithms would yield more accurate traffic congestion estimates.

3.1.1.2 Accidents and Safety

The second scenario for data monitoring studied in this research is accident detection. A vehicle sends danger messages to the other vehicles if the vehicle crashes or brakes suddenly. Warning messages can also be sent to following vehicles to indicate a risk to safety when encountering issues such as, pot-holes, slippery surfaces or livestock on the road. A number of different research papers on accident detection using VANETs are described in this section.

Taha et al. [110] considered sending emergency messages between cars if any dramatic change of speed or direction is detected. This was shown to be a reliable mechanism for alerting drivers. Additionally this paper provides a list of public safety applications: work zone warning, lane change warning, approaching emergency vehicle and co-operative collision warning.

Eigner et al. [111] introduced a mechanism for quickly calculating whether there is a danger of accident from the information gathered by the sensors. This was shown to reduce the number of false positives. The paper also provides a useful summary of the sensors used in safety applications.

Sukuvaara et al. [112] used several sensors which could be used to detect accidents including sensors for the Anti-lock Braking System (ABS), brake status, traction control, stability control and airbag burst detection. When one of these sensors is triggered a warning message is sent to all nearby vehicles. These applications are expected to increase safety, saving lives and reducing injuries.

Hiller et al. [113] presented WILLWARN, which is a decentralized hazard detection system, in which vehicles have methods of detecting hazards and sharing this information. This could be very useful with possible applications including: fog bank detection, ABS, ESP and rain. It also presents research into the different reliability rates of applications.

3.1.1.3 Weather

Weather is one area where data monitoring by vehicles could be useful. Yang et al. [48] showed how weather influences the average velocity of vehicles upon a road and that considering weather factors yields more accurate traffic data for VANET-based systems.

Vehicles normally have sensors to detect air and road temperature. If this information is aggregated over the VANET, high granularity maps of temperature could be made as described in Sukuvaara et al. [112]. These could be for vehicle use or other consumer use, if they access it over the regular Internet. Information on wind speed and direction, rain and road grip could also be gathered in a similar way. The settings of the wind screen wiper and whether it is on or not, could determine whether it is raining and the intensity of the rain. The ABS can also indicate how slippery the road is. Gathering information on wind could be more difficult but possible, if the resistance to acceleration was measured.

Advantages and Disadvantages of Approaches

These weather-aware applications are useful for traffic prediction as described in Yang et al. [114]. However besides specialized weather experiments, the high granularity maps described in [112] are not very useful. Sending this amount of information from all the cars could present significant overhead.

3.1.1.4 Road Conditions

Information on road conditions is one area where VANET-based systems could be very useful. Information on how smooth the road is, whether it has ice on it and the gradient of the road could all be recorded and disseminated. No papers were found which gave detailed discussion on this. However several papers gave information on how potholes could be detected by vehicles. Erikson et al. [115] gathered information on potholes by installing accelerometers in cars. Koch et al. [116] looked at gathering information on potholes from images. Mednis et al. [117] looks at detecting pot-holes by using microphones. This information could be used to warn drivers of approaching potholes and tell them to take precautions, reroute them to a smoother route, or alert the road authorities to fix the potholes.

Advantages and Disadvantages of Approaches

Gathering large amounts of data on road conditions would be very useful for navigation systems. All three systems mentioned could be integrated. A VANET-based system which gathers not just pothole information, but road roughness information (IRI and MPD values) as well is needed.

3.1.1.5 Specialization of Data

Different vehicles have specific characteristics which could be useful for VANET-based systems. By analysing different vehicle types for data some interesting patterns can be spotted. Some researchers looked at specific vehicle types and their interaction with the rest of the system. Specific data related aspects which were studied were different vehicle types including taxis, buses and trains.

Taxis

Several papers looked specifically at taxi traces for Zhu et al. [118] and Mathur et al. [119]. Taxi traces are easier to obtain as they are a commercial operation and are more interested in having their movements tracked for business information than private vehicles. Privacy aspects are not as relevant as well.

Yuan et al. [120] examined the routes taxis took. The rationale behind this was that taxi drivers have very good knowledge of the local roads and how busy they are throughout the day. This frequently enables the taxi drivers to pick the shortest route. The routes that taxis took were recorded and used to calculate the best route to send to other VANET-based system users. Improvements were shown in most cases in comparison with the original routes.

Zhu et al. [118] also investigated the routes of taxis. This is because the taxis were the first to have GPRS communication devices installed. Taxis will probably be the first drivers to install VANET technology because of their interest in reducing travel time and emissions. The authors use this data to estimate the inter-contact time vehicles will have with-in an ad-hoc network.

Mathur et al. [119] used traces from taxi cabs for its simulations. This paper chose taxis as they regularly comb the city, particularly densely populated areas. The authors used the taxi trace data to test their hypothesis of a parking place sensor system, which is described in a later section.

Buses

Information on bus traces are of considerable interest as they follow regular predefined routes. Xu et al. [121] used the fact that buses normally have reliable travel times to determine sections of traffic congested roads. These values are averaged to eliminate the individual bus delay which could be due to a driver mistake or a bus breaking down.

Karnadi et al. [122] used data from public bus timetables to estimate traffic traces for use in simulations in SUMO. This is an interesting approach which would be very useful if they could add this data to OpenStreetMap to allow SUMO and iTETRIS users to rapidly generate realistic traffic scenarios.

Trains

Hartong et al. [123] looked at getting vehicles to communicate with trains in order to prevent accidents. This information could also be used in order to gather more accurate train timetables and to inform the user whether he would be quicker getting to work by train or by driving.

Lehner et al. [124] developed a VANET specifically for trains. Trains can have higher speeds than cars, up to 200 kmph for high speed trains. Railway networks have large curve radii. Trains have significantly larger braking distances, despite this VANETs were able to deliver safety messages in time for braking manoeuvres.

Traffic lights

Data can be gathered by sensors at traffic lights and their light timing could be sent to vehicles in order for them to choose a quicker route. Ferreira et al. [125] presented an interesting proposal where if all vehicles were VANET-equipped, virtual traffic lights would be possible. As vehicles approach a junction from several directions VANET communications allow them to elect which road has right of way, similar to how a traffic light junction operates.

Gradinescu et al. [126] showed that by communicating with vehicles a traffic light could make its light timing more efficient. This scheme was only tested on one junction at a time so it is difficult to predict how multiple junctions in a row would be affected. Wegener et al. [127] again described traffic lights sending their phase schedule to vehicles and shows how this can be used to reduce energy consumption, by vehicles braking smoothly for lights about to change and by turning off the engine if the light will remain red for greater than 5 seconds. This showed a reduction of up to 75% of fuel consumption. There is no vehicle to infrastructure communication in this scheme though.

3.1.1.6 Emissions

VANET communications offer another interesting application. Emissions could be monitored by each vehicle. This information could then be sent to a central server. This would be very useful in quantifying greenhouse gas emissions and for looking at ways to reduce them. Emissions have a number of very hazardous effects, the most important being climate change, but also health effects such as cancers from Particulate Matter (PM). A VANET-based application which monitors the emissions would show which populated areas suffer from too much PM emissions, whether certain vehicles need maintenance to improve emissions and gathering greenhouse gas statistics from the transport sector.

Hull et al. [105] recorded the speed and acceleration to calculate emissions, but more advanced sensors could be placed on the exhaust pipe to more accurately calculate emissions and then this information could be sent over the VANET and then aggregated by a central server. However this was not implemented in the testing in this paper.

Santos et al. [128] proposed equipping public transport vehicles with environmental sensors in order to monitor emission levels throughout the road network. SUMO simulations were run and concluded it was possible to use VANETs and public transport vehicles to monitor emissions. No results in terms of emissions were shown however.

3.1.1.7 Miscellaneous

There were a number of other data monitoring mechanisms of considerable interest which did not fit into any of the above categories.

Lee et al. [129] proactively gathered information exploiting the fact that the vehicles are moving. In this paper agents (e.g. police cars) act as the information processing sinks and travel around the city using Levy flights path in order to collect large amounts of data from the vehicular sensor network. This does not represent any energy savings as requiring agents to drive around using Levy flights would represent far more energy and cost, than adding a new communication mechanism such as cellular to make sure the data reaches the server.

Delot et al. [130] proposed that when a user wants information on a certain area, they send a query to the cars in that area. The cars then return the required information and in 80% of cases the user retrieved the correct information. More work is needed to make an innovative application, instead of just a generic approach, as different applications will have different requirements. For instance, for an infotainment application a delivery ratio of 80% would be sufficient, but a higher rate would be required for safety application.

Hull et al. [105] collected images as people often give verbal images as directions. This creates a novel way in which GPS guidance systems could give instructions to the driver. A database for storing images for directions was developed in this paper.

3.1.2 **Information from non-VANET Sources**

There are also other methods of gathering information on traffic apart from VANET-based solutions. Existing systems such as the TomTom Navigator [82] give real-time traffic information to drivers. These gather their information using induction loops, aerial photography, toll bridges and mobile phones.

3.1.2.1 Induction Loops

Induction loops are the most common way of gathering traffic data [131]. They are placed at junctions in order to collect traffic counts and inform real-time traffic signal control systems algorithms and analysis making use of induction loops to predict traffic flow. Induction loops can also measure the type of vehicle like in the paper Tropartz et al. [132], instead of classic induction loops laser sensors were used., which counted the number and height of passing vehicles. This approach was able to identify correctly the type of vehicle with 98.5% accuracy for 2.3 million vehicles.

3.1.2.2 Aerial Photography

A traditional way in which information on traffic is gathered is via aerial photography or aerial-based radar. This can be done by one of the following: mast, zeppelin, helicopter or plane. The following paper describes different methods for determining information from these images. According to [131] planes are not ideal due to their high speed. Of course this has disadvantages like vehicles going under bridges or behind trees and the difficulty associated with identifying the same vehicle in multiple pictures. Several papers dealt with extracting traffic data from these images.

Angel et al. [133] detailed a method for collecting and analysing traffic from aerial photography. This includes methods for calculating the speed of vehicles.

Ernst et al. [134] described a system for real-time traffic monitoring from aerial photography. This proposal uses thermal sensors which can be used at night or during fog. It can also estimate the speed and the type of vehicle.

Reinartz et al. [34] presented a method, not only to monitor traffic but also the speed of traffic from either airborne cameras or cameras placed in high places such as towers. This paper states that satellites are unsuitable due to their inability to take quick photographs.

Rosenbaum et al. [131] also described monitoring traffic from airborne cameras to produce near real-time traffic data. They also show that images taken at night can produce vehicle data by looking at the lights which change position.

Palubinskas et al. [136] used cameras on planes to detect traffic congestion. The paper states that vehicle detection has far too low accuracy to generate meaningful information.

3.1.2.3 Wireless Sensor Networks (WSN)

Due to their high efficiency and accuracy in sensing the different events, wireless sensors have been widely deployed in various environments for data collection and monitoring purposes [137], [138]. Indeed, it is foreseen that WSNs can enable several applications that may significantly improve the control of road traffic flow and ease its management.

Examples of these applications include real-time control of traffic lights [139] and their adaptation according to the congestion level [140], as well as parking space management [141]. However, the deployment of wireless sensors in the road environment to realize these applications faces several challenges, in addition to the well-known issues in WSN [142], that require careful consideration and design of appropriate protocols. Among these challenges, we highlight the need of a fast and reliable MAC access protocol [143] and data forwarding mechanisms to guarantee timely transmission of critical messages carrying information about the occurred emergency events on the road.

An example of WSNs deployment for road traffic monitoring is shown in Figure 3-1. It is also worth mentioning that the expected wide and dense deployment of wireless sensors on the roads necessitates the design of robust data aggregation techniques. These are needed to deal with the high redundancy and correlation of the transmitted information, especially from neighbouring sensors, as the redundant transmission of this information may lead to quick depletion of sensors battery, increased delay of emergency messages, as well as increased collision rate. The optimal placement of wireless sensors on road networks is needed to reduce traffic data redundancy and a trade-off solution between the number of sensors deployed in a specific area, and road events detection and accuracy, should be designed.

The spatial and temporal correlation of traffic data are intrinsic characteristics of road networks, which can be leveraged to solve both sensor data aggregation and optimal sensor placement problems in future smart cities.

3.1.2.4 Machine to Machine (M2M) Communications

A key technology that is a promising solution for reliable and fast traffic data monitoring and collection is Machine to Machine (M2M) communication. The M2M communication technology has recently attracted increasing attention from both academic and industrial researchers aiming to foster its application for data collection in various environments. Recent forecasts [144], [145] indicate an outstanding market growth over the next few years for M2M devices usage and connectivity. According to these forecasts, billions of devices will be potentially able to benefit from the M2M technology. The report published by the Organisation for Economic Co-operation and Development (OECD) in [146] reveals that around 5 billion mobile wireless devices are currently connected to mobile wireless sensor networks, and foresees that this number will grow to reach 50 billion connected devices by 2020.

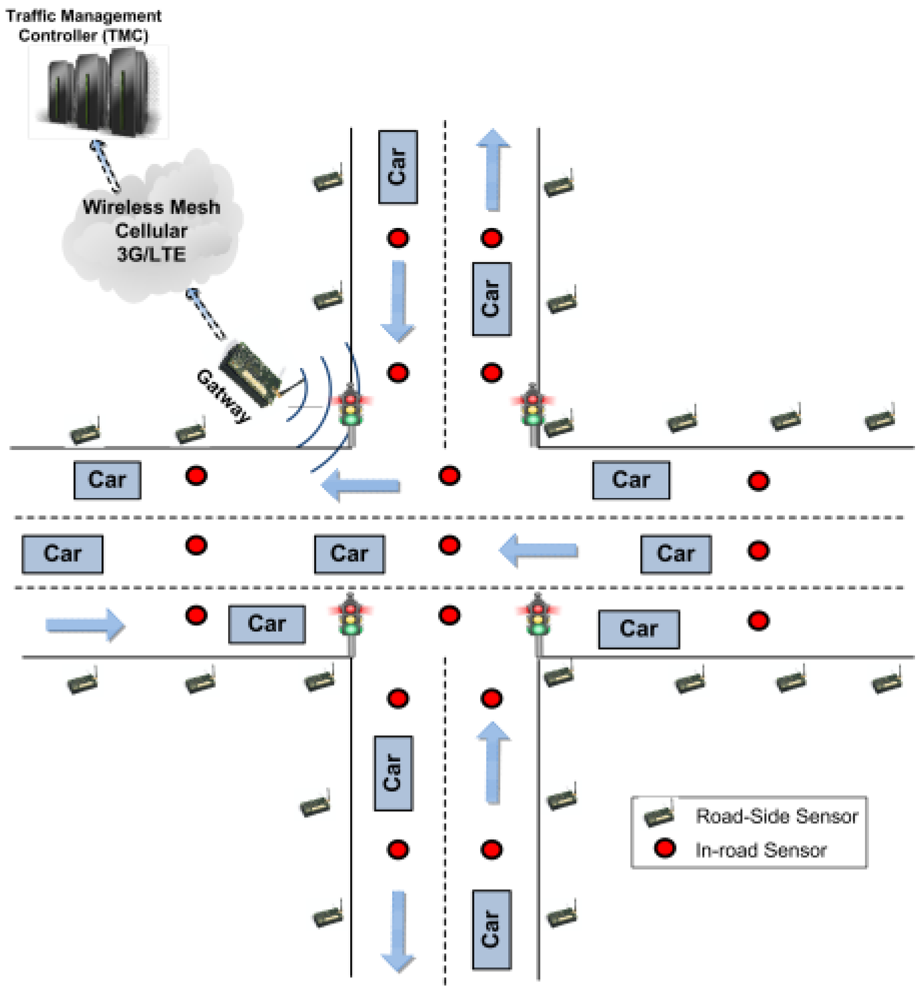

Figure 3-1 Scenario Illustrating wireless technology deployment in a road environment for data sensing and gathering

In M2M communication, sensors gather traffic data and send it via wireless communication networks (e.g. Wi-Fi/cellular/3G/LTE) towards one or multiple central servers for processing purposes. The ability of M2M devices to avoid multi-hop transmissions, as opposed to WSNs, makes the data transmission faster and more reliable, which represents a significant benefit for the sensors reporting delay-critical events. Moreover, it is foreseeable that this technology will significantly enhance the accuracy of data collection and lead to more flexible deployment of sensors, including on the roads, in particular M2M over LTE networks is expected to be a key aspect of future TMS.

These M2M devices are equipped with access technology capable of communicating in a reliable, fast and extremely efficient way with the central entity that processes and aggregates the collected data. Moreover, M2M solutions support different classes of QoS and thus they can efficiently collect prioritized data from multiple sources and ensure that appropriate QoS is applied to each stream. The M2M technology provides an extremely attractive solution for data collection in urban areas due to its management benefits in terms of reduced data reporting delay, high efficiency, and low complexity. However, deploying M2M devices as an alternative to WSNs technology will incur an additional cost related to the use of cellular networks. Therefore, this may hinder the wide deployment of M2M technology by city traffic managers, especially for cities with limited financial resources, which is the case of the majority of cities in developing countries.

3.1.2.5 Social Media

In the context of smart cities, social media feeds, such as Twitter and Facebook, for instance, can play an important role in improving the accuracy and richness of the traffic information provided by the traditional monitoring equipment such as road sensors and induction loops. Despite the fact that these pieces of equipment can measure vehicle speed and road segment occupancy to enable estimation of traffic congestion level, they are unable to identify the root event that has led to this situation.

Daly et al. [147] have shown that relying on social media feeds, in addition to the traditional data sources, can significantly enrich the real-time perception of traffic conditions in the cities, and help to explain the reasons behind the variation of the congestion level. Indeed, revealing the real causes of the sudden increase of the congestion level (e.g. accident, road works, political or social protest etc…) will enable more appropriate reaction from the road authorities to alleviate the impact of this situation. Therefore, there is a need to deeply investigate [148] this traffic data source to enhance citizens' quality of life and aid the traffic authorities for efficient management of the increasing number of cars. In order to maximize the benefits of using this novel traffic data source, we need to raise the citizens' awareness of its utility. Applying a reward system, for example, to encourage the citizens to use social networks to report accidents and unusual events that occur in the roads is highly recommended. In this case, any citizen who reports an authentic emergency/non-emergency event will get a reward which will increase their rank among road users. Higher ranked users could get higher quality of service from the TMS.

For example, when road users sign up to the TMS to plan a trip they will get the route that satisfies all their requirements, while other drivers may just get a route that satisfies a subset of their preferences. Using social media feeds may also assist the road authorities in the planning of road networks expansion, as well as determining optimal road signs placement and speed limits. This is feasible by analysing the citizens' feedback, including that of drivers and pedestrians, which may significantly improve traffic flow control and improve road safety. However, at the same time, there is a need to verify the accuracy of the data acquired from such poorly reliable sources of information. Mechanisms are needed to be proposed and deployed which best balance the need for fast information propagation with validation and verification of both the source of data and the content accuracy. At least an indication of the level of trust in the data is required to be present in order for any further processing to make use of it in an informed manner.

To this end, some recent efforts have been devoted to design robust security and privacy preservation solutions. Kumar et al. [149] have investigated the various hacking techniques that may threaten the reliability of such data sources, and presented potential mitigation methods. This paper highlights the dangers incurred by poor security, such as identity theft and corporate espionage etc…, and proposes a novel architecture mainly to improve the security of personal data.

On the other hand, Zhang et al. [150] have shown the potential security and privacy challenges that may arise as a consequence of the emergence of Multimedia-oriented Mobile Social Network (MMSN) concept. MMSN is a new social media application in which users in the vicinity share useful multimedia content of interest, such as road traffic information etc. However, this application may create new security threats such as privacy disclosure. The authors presented three MMSN applications emphasising their corresponding security and privacy problems, and discussed a set of solutions to face those threats. The studied applications were mainly content query, service evaluation, and content filtering. In addition to the above works, other researchers have also thoroughly investigated privacy concerns and trust management issues in social networks such as [151], [152] and [153].

3.1.2.6 Mobile Phones

A recent development in determining traffic information is using mobile phones, particularly with the recent market uptake of smart phones. A very simple solution is described in Caceres et al. [154] where the signal strength of mobile phones on the road helps determine how many mobile phones are in the area and hence one can make an assumption relating to the traffic density. Mohan et al. [155] and Mednis et al. [117] used sensors on smart phones to gather information on the road. Mohan et al. [155] used sensors to detect potholes, traffic noise and congestion. This approach was shown to be useful for cities with limited funds for infrastructure for ITS systems, such as the test case of Bangalore. Mednis et al. [117] used microphones available on a phone to sense for potholes, in order for road maintenance crews to quickly determine which areas are in greatest need of repair. This approach detected potholes accurately despite background noise.

In addition to the above data sources, mobile sensing using mobile devices is expected to enable fast detection of events on the roads and enhance the accuracy of traffic condition monitoring. According to recent studies in [156] and [157], mobile crowd-sensing systems have been recently used to provide more accurate real-time traffic information on a large scale, using smart phones that enable services such as: accurate localization of vehicles, faster and more precise reporting of incidents and accurate travel time estimation for improving commuters travel experience. The key enabler of the widespread of mobile sensing applications, mainly for traffic monitoring purposes, is the voluntary participation of the users. These users demand high level of privacy, anonymity and security guarantees in order to participate to such a system. Indeed, these requirements constitute major concerns that need to be carefully addressed to instigate larger participation of mobile devices users to mobile sensing applications. These issues can be dealt with as discussed in the following, in order to mitigate their impact on the TMS efficiency and accuracy of its decisions.

- **Trust management of mobile sensing data sources** refers to how to build a trust relationship with the mobile sensing data source. In this case, reputation systems, such as [158], need to be used continually to assess the level of trustworthiness of each mobile sensing data source. A mobile data source is deemed trustworthy if the information it has reported has been validated by either other mobile sources or a trusted data source such as road-side sensors, induction loops or CCTV cameras.
- **Privacy preservation of mobile devices users**: several levels of privacy could be defined in the context of smart cities, and users can adjust the setting of their devices to increase/decrease the privacy level for example, according to traffic conditions (e.g. normal driving conditions, traffic jam, incident) and according to the service they need to request from the TMS (e.g. optimal/fastest route to their destination). Therefore, adaptive privacy protection techniques that manage the user's privacy preferences and adapt the privacy level to the contextual factors in smart cities are required.

- **Robust authentication techniques** need to be designed to prevent any misuse of the system such as identity spoofing and fake alerts, etc.

3.1.2.7 Historical Traffic Information

A simple way to judge traffic on the road would be to look at historical data as in which roads were busy or empty on this day last year. However with internet connectivity this could become more advanced by using cookies, Marca et al. [159], or combining historical data with real-time information, Horvitz et al. [160].

Advantages and Disadvantages of Approaches

There could be privacy concerns with collecting traffic information from mobile phones, but the advantage is it is a novel way and mobile phones are ubiquitous. The disadvantage of induction loops and aerial photography is that they are very expensive. Each of these methods is useful, but they each have their drawbacks, so an integrated approach is needed.

3.2 **Data Aggregation Solutions**

This section discusses methods for aggregating data in order to reduce overhead or to make sense of the information gathered by sensors at each individual node. These must be scalable as described in Scheuermann et al. [161]. The aggregation solution must reduce data coming from distance *d* by a rate of *1* over *d* squared in order to be considered scalable. Ibrahim et al. [162] described the difference between semantic versus synthetic data aggregation. Synthetic data aggregation combines data from several cars whereas semantic data aggregation combines the data from the different sensors on the individual vehicles. Most of the schemes looked at in this study relate to synthetic data aggregation. The solutions described in this section involve: node clustering, combining identical messages, location-based aggregation, probability-based aggregation and use of fuzzy logic. These are introduced and described below.

Although there are a large number of systems currently employed for road traffic monitoring, there is very little integration between these systems and in most cases the data from each system has different types, formats and metadata. Much of the data is also of different time-scales and levels of granularity. During the Data Fusion, Processing and Aggregation (DFPA) phase of TMS numerous techniques are applied to combine these heterogeneous data sources to produce unified metrics that can be processed and delivered to various consumers based on their requirements. A modern TMS should enable the real-time aggregation of these high volume data sets from a plethora of heterogeneous sources. It will also store this data over long periods of time to perform statistical analysis, which can be further used to better plan and deploy changes/upgrades to the transportation network. This will enable the system to combine the various traffic measurements produced by existing traffic systems - such as induction loop counters, CCTV cameras and cellular handover information - to monitor and manage traffic flow within the city. The main steps involved in DFPA phase are summarized in Figure 3-2 which describes the processing flow of the data and what are the different issues that this phase deals with. After receiving the gathered data from various data feeds, the DFPA engine applies cleansing and verification techniques to identify incorrect, inaccurate and incomplete data and either correct or remove it.

Afterwards, this data will be prepared for the fusion phase by resolving time synchronization issues and exploiting the geographical correlation of this data to further reduce the amount or extract new knowledge. Subsequently, the chosen fusion algorithm is applied to integrate the different set of data into a consistent, accurate and valuable representation of the road network traffic. The output of this phase will be then transmitted to the core TMS system and samples of the forwarded data will be stored for future aggregation and redundancy removal purposes. In order to enable the TMS to scale to larger cities, the deployed techniques must be capable of aggregating traffic data feeds from various levels and at various levels of granularity.

For example, a modern TMS will investigate how traffic feeds can be aggregated and filtered for specific geographic regions, before they are passed to the core system. This reduces the amount of information processing and filtering that is required at the core. It will allow the system to scale and evolve over time and will allow it to be deployed to cover increasingly large geographic regions.

Due to the heterogeneity of the collected traffic data formats, a common data format is required to enable high level management and processing of the aggregated data. The IBM intelligent transportation product [163], for example, uses the Traffic Management Data Dictionary (TMDD) standard developed by the Institute of Transportation Engineers (ITE) [164]. This standard describes the data concepts for traffic data, metadata, network devices and events. Moreover, the IBM Intelligent transportation product uses the TMDD standard to ease interfacing with Traffic Management Centres and Advanced Traffic Management Systems (ATMS). The aim of the TMDD standard is to provide a standards-based, high-level definition in a protocol-independent manner, from which a system specification interface can be prepared. Besides its main purpose, which is supporting traffic management applications, all ITS practical areas can benefit from TMDD format such as for emergency situation management, products shipment and travel information for communication needs.

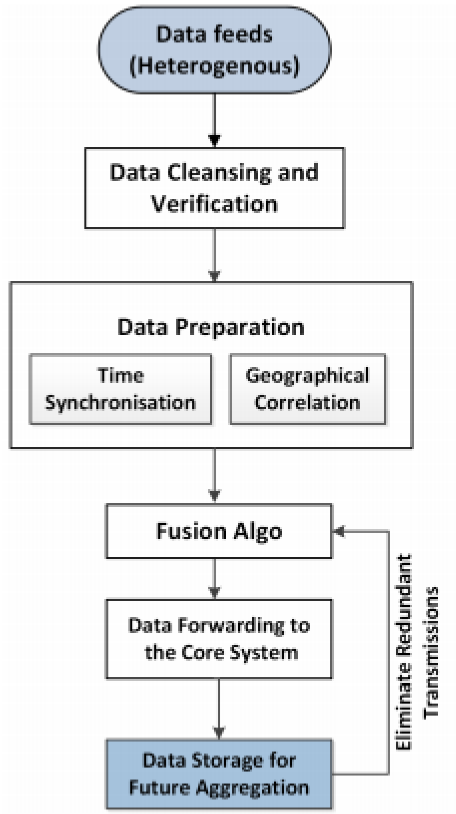

Figure 3-2 The major steps in TMS DFPA phase [165]

The ultimate objective of the introduction of TMDD standard and the development of data fusion and integration techniques is to improve the overall system efficiency. This can be accomplished by simplifying and automating data collection from existing and future systems, as well as by reducing data aggregation, conversion delay and complexity. To this end, recent research studies have designed innovative techniques to ensure efficient fusion and integration of the traffic data gathered from heterogeneous road monitoring equipment. A snapshot of these recent works is given below.

Treiber et al. [166] have developed a technique to improve the quality of detector data which is combined with FCD. It is acknowledged that discovering the dynamic properties of the traffic is a difficult task due to the sparseness of induction loops and low penetration rates of vehicles transmitting FCD. To overcome this issue, the authors have used conventional spatio-temporal interpolation to determine fine structures, such as stop and go waves from the collected data. Moreover, interpolation can also be used to compensate for detector failure. The efficiency of this approach has been evaluated using real traffic dataset collected from the roads of Birmingham, which has a high penetration rate of induction loops.

A more recent technique has been proposed in [167], where Automatische Staudynamikanalyse: Automatic Tracking of Moving Jams (ASDA)/ Forecasting of traffic objects (FOTO) model has been applied to process induction loops data, and then fuse the resulting data with Floating Car Data (FCD). Both of these datasets are processed to determine traffic state changes (e.g. from free flow to congested flow, stopped to congested flow etc…). Subsequently, they are fused to construct a spatiotemporal map of the traffic state changes. This work has shown that a vehicle penetration rate of 1.5 % has yielded a very similar model to detectors deployed at every 1-2 km. Hence the assertion that now they can be easily combined, resulting in a more efficient traffic model than the original ASDA /FOTO model.

3.2.1 **Node Clustering**

A major method for reducing overhead is node clustering. This involves groups of nodes (e.g. vehicles) organizing themselves into groups with one of them acting as a cluster head. Each of the nodes in the cluster communicates with the cluster head and then the cluster heads communicate with each other. A number of schemes related to node clustering were studied.

Fan et al. [168] used gateway nodes as well as cluster heads to re-broadcast. The gateway nodes are nodes at the edge of each cluster which forward messages from the cluster head to other clusters. This was shown to be more reliable and to reduce the overhead in comparison to other schemes, probability-based clustering, counter-based clustering and simple flooding. The authors approach outperformed the next best approach, counter-based clustering by roughly 50%.

Bononi et al. [169] introduced a distributed dynamic clustering algorithm which uses dynamically determined relay nodes. These form the virtual backbone of the system. This approach showed an advantage in performance reliability and overhead reduction when compared with DCF.

Ibrahim et al. [170] proposed an algorithm to cluster vehicles, while balancing the trade-off between local view length (the distance ahead that vehicles are aware of) and expected frame size (the size of the beacon message). The paper determined a cluster size of 16m wide and 126m long provided the best information to the drivers and the best use of bandwidth. The paper doesn’t compare against other approaches, the authors simply ran the tests with a number of different local view lengths and used this information to determine the ideal size.

Kuklinski et al. [171] presented a clustering algorithm which considers density of connection graph, link quality and traffic conditions. A different routing mechanism is used in the dense part of the network as connectivity is assumed and multi-path routing is used in the sparse parts of the network. This was shown to balance the trade-off between packet drops and overhead.

Shea et al. [172] stated that mobility must play a central role in cluster formation. They proposed making some nodes more likely to be assigned as cluster heads e.g. trucks. However why this would be a good idea is never explained. An algorithm is devised which is compared against another mobility-based clustering algorithms, namely MOBIC by Prithwish et al. [173]. The author's algorithm outperforms MOBIC in terms of life-time of clusters in some cases by over 200%.

3.2.2 **Combining Identical Messages**

Another way of reducing the amount of data exchanged is to combine identical or similar messages. This method was used in several papers. For instance, Eichler et al. [174] looked at combining messages related to the same event. Messages contain the information on the event, location, and nodeId. If a message contains the same event and location, it is merged. This was shown to reduce the overhead up to 48% without affecting the number of vehicles which received information related to a static event. However the scheme was only compared against the overhead from the original non-aggregated messages.

Dieztel et al. [175] also looked at combining information related to the same event, but they go further to expand on the data of the event by getting different vehicles' view of the event. For instance, instead of just giving the average value on a road, the standard deviation could be displayed as well, allowing the user to determine the certainty of information. However no results were contained in this paper.

Yu et al. [176] stated that "catch-up" is important so that vehicles can receive data related to the same event in order to aggregate it. By using "catch-up" certain messages are delayed in order for a node to receive all the information from an event before aggregation. This allows the slower messages to "catch-up". This was shown to reduce the number of redundant messages. The authors used a machine learning approach when deciding how long to delay a message.

3.2.3 **Location-based Aggregation**

Data can also be aggregated if it is coming from the same location. A traffic related message could send the average speed on the road instead of the individual speeds of the vehicles. Raya et al. [177] stated that message aggregation improves not only efficiency but security and information dependability as well. This is accomplished by use of combined signatures, the vehicles in a cluster vouch for each other allowing a reduction in overhead and improved security as other vehicles have vouched for a node. Another possibility is onion signatures, the message contains the signature of the last sender and the first sender allowing malicious messages to be traced. The higher the vehicle density the more accurate the information becomes as the aggregation method has more nodes from relating to an event in area.

Ibrahim et al. [162] stated that data aggregation is needed to allow a single frame to store information on a large amount of vehicles. The authors introduced a scheme Cluster-based Accurate Syntactic Compression of Aggregated Data (CASCADE) which uses compression in order to prevent collisions and to make the best use of bandwidth. CASCADE maintains very high accuracy in compression, unlike other schemes. CASCADE is designed to gather information on traffic conditions but also safety messages. Each vehicle has primary records, which store the data sensed by its own sensors and aggregated records are formed which aggregate the data from primary and other aggregated records from other vehicles. Differential coding is used to compress the aggregated records. CASCADE not only clusters vehicles based on area but also based on similar speeds. How regularly messages are sent depends on the density of the vehicles. This scheme uses a cost function to aggregate data and aims to support collision warning applications. It achieves a compression ratio of 86%.

Nadeem et al. [178] presented a method of information aggregation where data on multiple vehicles will be stored as a table which is then sent to other vehicles. This was shown to improve the area of which the vehicles had traffic information about. However this was not compared against other approaches.

Wischoff et al. [179] aggregated all the data from nodes on a road segment and then produces a message for said road segment. This allows for greater scalability, if the network is dense with nodes a large amount of traffic information regarding the same road will be sent overloading the system. This was validated via testing using ns2. Traffic information was successfully sent over a varying amount of network densities.

3.2.4 **Probability**

Another method of reducing overhead is to take probability into account so the number of messages sent can be reduced. A solution like this was put forward in Lochert et al. [180]. Information is merged from several messages instead of forwarding each one of them. The further away the messages relate to, the greater an area they are merged with other messages to cover. Soft state sketches, an extension of Flajolet-Martin sketches, are used for probabilistic approximation. Soft-state sketches are used as probabilistic approximation. This work proposed an algorithm for storing distinct elements in a data structure. Soft state sketches apply this to VANET communications so only new information is forwarded.

3.2.5 **Fuzzy Logic**

Another approach for data aggregation is to use Fuzzy logic. In some situations you may be able to merge data, but in other very similar cases this may not be so.

Dietzel et al. [181] used fuzzy logic for data aggregation, but they argued that you cannot decide the granularity of aggregation just by distance. The fuzzy-logic based decision algorithm decides the qualitative needs of the application when deciding the degree by which the data needs to be merged. If for instance, two roads have very similar speeds, but different standard deviations, the algorithm might not decide to merge them.

Fuzzy rough set theory has been also used in [182] to fuse heterogeneous traffic data feeds, each of which can often yield contradictory evidence. By using this theory, a significant reduction of the redundant data can be achieved. In addition, a novel fusion technique based on Yager's formula [183] has been developed to rank the different data sources. Furthermore, the maximum fuzzy probability function is applied for the different datasets to avoid the subjective factor effect. It is worthwhile to note that this work is different from the two previous techniques as it considers induction loops, video detectors and Origin-Destination (OD) analysers instead of induction loops and floating car data. The efficiency of the developed fusion technique is tested against traffic data from Hangzhou city in China, and the obtained results have proven its effectiveness.

Advantages and Disadvantages of Approaches

The probability and fuzzy logic approach represent novel ways of reducing the overhead without interfering with routing. A lot of these methods could be used simultaneously. What is lacking is a study which simulates all the methods presented here.

3.3 **Inter-Vehicle Coordination**

An Inter-vehicle coordination protocol coordinates the position and velocity that the vehicles should have relative to each other. This is used in vehicle platooning for instance. It does not choose which road segments the vehicles should travel on, as in the case of vehicular routing protocols. This section presents a variety of vehicle coordination mechanisms.

Chuah et al. [184] described a variable speed limit based mechanism in order to smooth traffic flow. For instance, if there is an accident and one lane is blocked on a highway, lowering the speed limit improves the throughput, by 50% in some cases. It also provides a smooth flow pattern.

Ferreira et al. [185] proposed a solution which used virtual traffic lights based on vehicle to vehicle communication, in order to improve congestion. This approach was shown to reduce CO_2 emission by nearly 20%, when compared against the original traffic lights. However this requires a high level of accuracy to prevent crashes.

Yamashita et al. [186] used route information sharing to minimize traffic congestion. This allows a central server to calculate the expected delay on each road and use load balancing to determine better routes for vehicles to take. This paper suggests that traffic lanes could also be changed depending on demand. Overall this approach was shown to reduce travel times by up to 50% when compared with a shortest distance algorithm, similar to Dijkstra used in this thesis.

Olaverri-Monreal et al. [187] developed a mechanism which gives instructions to the driver to help him overtake. Video streaming is used to give the driver, who is about to overtake, a view of what is in front of the vehicle he is overtaking. This was implemented on a real car and truck, video latency of 1 μs and a packet delivery ratio of 99.88%, meaning that video transmission is very accurate for overtaking. This application could dramatically improve safety for cars overtaking long vehicles. In a driving simulator which was built the average overtaking time was reduced by 10% to 50 seconds.

Reichardt et al. [188] described a highway merging solution. Vehicular communication in this scenario would be very useful as misunderstandings between drivers cause a lot of crashes in this scenario. Typical information which could be exchanged could be vehicle trajectories for example. However no testing was shown in this paper.

Knorr et al. [189] proposed a VANET based scheme which sends messages to other vehicles to maintain a greater distance between vehicles when the node density crosses a threshold. Maintaining a greater distance between vehicles makes the traffic less susceptible to traffic waves. The author ran simulations based on real data from induction loops on the German Autobahn. This approach was shown to improve traffic flow with a VANET penetration rate of just 10%. This research only considers a highway section with realistic traffic data, how this would affect traffic congestion over a whole city is not tested.

Advantages and Disadvantages of Approaches

Apart from Olaverri-Monreal et al. [187], all of these approaches require very high penetration rates to be useful, for example, the virtual traffic lights in Ferreira et al. [185] would be dangerous without a 100% penetration rate.

3.4 IEEE 802.11p Congestion Reduction

This section describes solutions for reducing bandwidth congestion over IEEE 802.11p. Different methods include data aggregation or power and transmission rate adjustment.

3.4.1 Distributed Rate Control Algorithm for VANETs (DRCV)

DRCV [190] is a congestion control algorithm specifically designed for VANETs. Messages are given different priority levels in order to make sure the channel is free for safety critical messages. The frequency of the less important messages, such as position update, decreases as the used bandwidth increases. This approach was shown to increase the packet delivery ratio by 15%, however the author only compared DRCV against no method of congestion control.

3.4.2 Efficient Transmit Power Control (ETPC)

ETPC [191] is a mechanism which adjusts the transmission power to reduce channel contention while making sure safety messages reach their destination. An algorithm was used to deal with this trade-off. Information on the power settings is added to the position beacon messages. If the number of messages the vehicle receives is above a certain threshold, the algorithm looks at the vehicles it is communicating with from closest to furthest. The vehicles which are beyond this threshold point are sent messages to reduce their transmission power. ETPC outperforms existing power control algorithms, by extending the range that over 90% of packets arrive successfully, in some cases nearly doubling it, from 17m to 30m.

3.4.3 **Congestion-based Certificate Omission CbCO**

CbCO [192] is a mechanism which leaves out authentication certificates if the channel is busy. The algorithm decides whether or not to include identification certificates, in order to minimize overall packet loss. CbCO reduces the amount of overhead, however some messages can become unverifiable.

3.4.4 **Enhanced Distributed Channel Access (EDCA) for VANETs**

Rawat et al. [193] suggested that power and Contention Window (CW) size of individual vehicles be adjusted by an algorithm, which takes into account vehicle density and collision rate. The algorithm must be dynamic, as VANETs have rapidly changing topologies. The vehicle density is estimated from beacon messages. EDCA from 802.11e is added and messages are grouped into different priorities with the emergency messages getting greatest priority. The author's scheme outperforms another existing dynamic transmission range scheme by Artimy et al. [194] in terms of normalized transmission range by roughly 100% in some cases. The author's scheme improves on another existing scheme by Chen et al. [195] in terms throughput by roughly 30%. The author's scheme also reduces the delay by roughly 30% when compared with a default EDCA scheme, which did not vary power and CW size.

3.4.5 **A Robust Congestion Control Scheme for Fast and Reliable Dissemination of Safety Messages in VANETs**

Djahel et al. [196] proposed a control scheme in which different priority levels are assigned to messages, and the level of congestion is measured and the power and transmission rate adjusted accordingly. The level of congestion is calculated from the average waiting time for a message, the collision rate, and the beacon reception rate. If this is above a certain threshold a certain amount of bandwidth is preserved for emergency messages. The new bandwidth is determined by the bandwidth for each vehicle in the vicinity and the bandwidth required for emergency message propagation divided by the bandwidth size. The transmission power is based on the minimum power used by the nearby vehicles to transmit to the vehicle and the distance to the next forwarder of emergency messages. This scheme is not compared against other schemes, but was shown to improve the delivery ratio, by ~200%, and the delay, by ~30%, when compared against no congestion control method.

3.5 **Factors influencing Vehicle Emissions and Fuel Consumption**

This section discusses the various factors which influence the fuel consumption and the exhaust emissions of vehicles. Rexeis et al. [197] gave a detailed study which analysed the different metrics. The authors gave the following formula which details what factors determine fuel consumption.

$$P = P_{rolling\ resistance} + P_{air\ resistance} + P_{acceleration} + P_{road\ gradient} + P_{transmission\ losses} + P_{auxiliaries} \qquad (3\text{-}1)$$

$P_{rolling\ resistance}$ is the power to overcome the rolling resistance due the road acting on the wheels. This is determined by the road conditions and the tyre conditions.

$P_{air\ resistance}$ is the power to overcome the air resistance. This is determined by the frontal area and the shape of the car, the speed of the vehicle and the wind, and the air density.

$P_{acceleration}$ is power losses due to the vehicle accelerating.

$P_{road\ gradient}$ is the power to overcome the road gradient.

$P_{transmission\ losses}$ is the power to overcome losses in the transmission from the engine to the wheels.

$P_{auxiliaries}$ is the power going to the battery, lights and other things.

The authors asserted that the higher results for real world simulation in Passenger and Heavy duty vehicle Emission Model (PHEM) are probably due to higher driving resistance (non ideal tyres and tyre pressure, rain, snow, loose chippings, wind, etc). Petrol, diesel, hybrid and electric vehicles have similar formulae as the research does not focus on the internal parameters of vehicles, such as battery, engine and transmission losses.

3.5.1 **Road Roughness**

The main road characteristic which was looked at in this study was road roughness, although other parameters such as the materials can make a difference for heavier vehicles, as noted in Zaniewski et al. [198]. Road roughness is the smoothness of a road, both in terms of its variation in elevation and the rolling resistance it generates. Road roughness is generally measured as International Roughness Index (IRI) values or Mean Profile Depth (MPD). Road roughness varies from road to road. The major roads tend to have better ratings due to frequency of repair. This can be seen from a 2004 study [199] in Ireland which noted the average values for regional, local primary, secondary and tertiary, these are shown in the table below.

Table 3-1 IRI values for road types in Ireland

Road type	Average IRI value
Regional	5.5
Local Primary	7.9
Local Secondary	9.4
Local Tertiary	12.0

There was some discrepancy in the research in terms of quantifying the effect of road roughness on fuel consumption. According to [200] tire temperature affects rolling resistance, as the tire pressure increases with temperature, making it difficult to define. Gyenes et al. [201] estimates that road roughness accounts for 5% of fuel consumption for cars and 10% for goods vehicles, but this is higher on unpaved roads. Rolling resistance accounts for 33% of energy for motion. A 20% change in rolling resistance results in a 3% change in fuel consumption.

Descornet et al. [200] discussed road-surface influence on tire rolling resistance and showed fuel consumption was affected by the road by 9%. It was also noted that heavier vehicles are more affected by the road. [200] stated that the fuel consumption is affected by road surface conditions by 7% for cars and 20% for trucks. Road roughness can also have a greater effect than expected as the Handbook of Emission Factors (HBEFA) [202] noted. This study stated that actual experience shows the driving resistance data used for approval of the car represents the optimum situation, not real tires on real roads.

A number of formulae for relating fuel consumption to the road were looked at during this study. The following formula was given by Rexeis et al. [197] for determining power to overcome road resistance. This formula determined the power by multiplying the mass of the vehicle, gravity and the velocity of the vehicle by 5 rolling resistance coefficients which were each multiplied by different orders of the velocity of the vehicle.

$$P_R = m \times g \times (fr_0 + fr_1 \times v + fr_2 \times v^2 + fr_3 \times v^3 + fr_4 \times v^4) \times v \quad (3\text{-}2)$$

Where: P_R= power in [W]

m = mass of vehicle + loading [kg]

g = gravitational acceleration [m/s^2]

fr_0, fr_4 = rolling resistance coefficients

v = vehicle speed in [m/s], the vehicle is speed is computed as average speed of second i and second (i+1) from the given driving cycle. The corresponding acceleration is $(v_{i+1} - v_i)$.

The author asserts that the higher orders, v squared and greater, are insignificant in the testing so this formula was used.

$$fr_0 = C_0 - C_1 \times F_{z,tyres} \quad (3\text{-}3)$$

With: fr_0= rolling resistance coefficient (speed independent term)[-]

$C_0 = 0.00825$ = Constant factor[-]

$C_0 = 0.000075$ = Constant factor $[kN^{-1}]$

$F_{z,tyres}$ = average single wheel load [kN]

Lu et al. [203] gave a formula for road roughness.

$$s_z(\gamma) = \frac{G_0}{\gamma^2} \quad (3\text{-}4)$$

Where

$s_z(\gamma)$ =power spectral density of road elevation,

γ =wave number (wave number = 1/wavelength), and

G_0 =road roughness coefficient (indicates the level of road roughness)

This paper also gave several more advanced formulae for road resistance, however due to the difficulty of obtaining realistic data on road roughness values this was considered unnecessary.

Fuel consumption of vehicles as affected by road surface characteristics [200] gave the following formula:

$$a = (A + gG) + (B + \frac{0.5\rho C_D A_F}{M})V^2 \quad (3\text{-}5)$$

Where:

A = rolling resistance related to external factors,

B = rolling resistance related to internal factors

ρ = air density, kg/m^3

C_D= aerodynamic drag coefficient of the vehicle,

A_F = projected frontal area of the vehicle, m^2

g = gravitational acceleration, 9.81 m/s^2

G = gradient, m/m

v = vehicle speed in [m/s],

Greenwood et al. [204] gave a formula for relating IRI values to road resistance:

CR = 0.0218 + 0.00061 IRI for cars and LCVs (3-6)

CR = 0.0139 + 0.00026 IRI for buses and HCVs (3-7)

In this instance the rolling resistance CR was a constant plus a constant multiplied by the IRI of the road. These constants were different for different types of vehicles.

The formula from Hammarstrom et al. [205] was chosen as the formula to be used in simulations, the Cr factors are constants relating road roughness to rolling resistance. Hammarstrom gave an easy to use formula which related road roughness to rolling resistance:

Cr01	Cr02	C_2	C_3	C_4	C_5
0.00926	0.0000695	0.000380	3.47E-05	0.00221	0.000111

$$* Cr = Cr_{01} + Cr_{02} \times V + \text{dCr(IRI,v)} + \text{dCr(MPD)} \quad (3\text{-}8)$$

$$dCr(IRI, v) = C_2 \times IRI + C_3 \times IRI \times (V - 20)$$

$$\text{dCr(MPD)} = C_4 \times MPD + C_5 \times MPD \times (V - 20)$$

Zaniewski et al. [198] stated that the road surface material does not matter for cars, but affects the fuel economy of trucks. Trucks, being heavier, deflect the road more. This has the effect of the truck constantly having to drive "uphill" due to the deflected road underneath its wheels. Four different materials were studied in this paper: asphaltic concrete, Portland cement concrete, asphalt surface treatment and gravel. The main two considered were asphaltic concrete and Portland cement concrete, with roughness indexes of between 3.2 and 4.4, the typical values for most US highways. The trucks were affected by up to 2 gallons per mile by the road material, whereas the cars showed no statistical significance. Additional analysis of pavement structure on truck fuel consumption [206] showed that the effect of road roughness was higher as a percentage of fuel consumption at lower speeds.

Advantages and Disadvantages of approaches

Most of this research shows contradictory evidence as to how much road roughness impacts fuel consumption. For instance, Gyenes et al. [201] estimates that road roughness accounts for 5% for cars and 10% for goods vehicles of fuel consumption and [200] which has estimates of 7% and 20%. This might be accounted for by tire temperature as stated in [200] or the fact that [203] did not consider unpaved roads. The equations presented are also very different. Due to the importance of road roughness on fuel consumption a more comprehensive study is needed, but current research does include such a study.

3.5.2 **Road Gradient**

Road gradient refers to the rate of change of elevation of a road. Rexeis et al. [197] asserts that both the fuel consumption and emissions are heavily influenced by road gradient. The following formula was provided to account for fuel consumption caused by road gradient:

$$P_g = m \times g \times Gradient \times 0.01 \times v \quad (3\text{-}9)$$

With: P_g = power in [W]

$Gradient$ = road gradient in %

m = mass of the vehicle + loading in [kg]

g = acceleration due to gravity in $[m/s^2]$

v = vehicle speed in [m/s]

Only two road gradients were tested for 6% and 0%. Hence the study is not very conclusive. 6% is one of the highest gradients that would be seen on a normal road. HBEFA [202] stated that its results for road gradients include a high level of uncertainty and were measured on a very limited number of cars. This testing included 7 road gradients -6%. -4%, -2%, 0%, 2%, 4%, 6%. The testing showed that the fuel consumption and the CO_2can be modelled accurately using the Passenger car and Heavy duty Emission Model (PHEM), however the results for NO_x, HC and even CO were quite inaccurate. The model makes a basic assumption to overcome the lack of data, that the vehicle is driving at regular engine power plus the power required to overcome the acceleration of gravity due to the gradient. This was shown to be accurate.

Only the CO_2 emissions have been considered for in this thesis as this is the most widely considered metric and due to the difficulties with accurately calculating some of the others such as NO_x. The Selective Catalytic Reduction (SCR) for reducing NO_x emissions is very sensitive to temperatures, making it difficult to predict NO_x with varying road gradients.

Advantages and Disadvantages of approaches

The disadvantage of HBEFA [202] is the that it was measured on a limited number of cars. A more extensive study is needed in order to account for road resistances and emissions such as NO_x and Particulate Matter (PM). The advantage is that the formula can accurately predict the fuel consumption and CO_2 emissions.

3.5.3 **Air Resistance**

Air resistance is the force due to the front of vehicle displacing an amount of air as it drives along the road. Air resistance makes up the majority of fuel consumption at higher speeds. Air resistance will heavily depend on the weather, as a strong head or tail wind will dramatically change air resistance. Rexeis et al. [197] also provided a formula for air resistance:

$$P_{air} = C_D \times A_F \times \frac{\rho}{2} \times v^3 \qquad (3\text{-}10)$$

With: P_{air}= power in [W]

C_D= drag coefficient [-]

A_F= frontal area of the HDV in [m^2]

ρ = density of the air [on average 1.2 kg/m^3]

v = vehicle speed in [m/s],

Drag coefficient depends on the shape of the front of the vehicle. The numbers for different vehicles can be viewed online. This paper gives an accurate way of determining power due to air resistance and was sufficient for the purposes of this study.

3.5.4 **Others**

There are several other factors which have some influence on fuel consumption, but are not greatly considered in this work. Rakha et al. [207] gave a list of factors which can influence fuel consumption. These included vehicle age, driver behaviour, road topography, fuel properties, temperature and humidity level. The author also mentions the difficulty of building a complete mathematical model of the factors which effect fuel consumption. Rahman et al. [208] looks at the amount of fuel used by trucks during idling and methods of reducing this figure. If the duration of idling is longer than ten seconds, the truck is using more fuel than it would take to restart it. The author provides a good motivation for reducing idling fuel use, namely engine wear and tear, as well as inefficiency. This also contained a very extensive study of engine idling. The author recommends having electrification for truck stops to help reduce idling, as the drivers would no longer need to idle the engine in order to run appliances such as air-conditioning.

3.6 **Infrastructure**

In this section the infrastructure components related to this work will be discussed. This is composed of bus lanes and traffic lights. Several different types of bus lane schemes and traffic light timings will be discussed in this section.

3.6.1 **Bus Lanes**

The first area of the related works in terms of infrastructure deals with solutions related to using bus lanes. Bus lanes are a section of lane or lanes on a road restricted to buses during the day or at certain times. These are used to allow public transport to bypass sections of traffic congestion. These help address the issue of road capacity underuse by employing various kinds of policies, as follows.

Dedicated bus lanes (DBL) are lanes which are exclusively dedicated to buses and remains so throughout the day. These are mainly useful in roads with low traffic flow rates as they reduce capacity [209]. The problem of capacity misuse can be solved somewhat by *intermittent bus lanes (IBL)* and *bus lanes with intermittent priority (BLIP)*.

The easiest method to improve road capacity use with DBLs is to close them to regular traffic during certain times of the day only, such as rush hour period, for instance. This approach has advantages and disadvantages. When there are no buses or very few buses, during the night or Sunday, regular traffic can drive on DBLs. However during rush hours, the number of buses is highest and regular traffic also peaks in this situation; when a road reaches full capacity, bus lanes are not that useful.

Using IBLs which employ methods, such as asking Internal Combustion Engine (ICE) vehicles to leave the bus lane when a bus appears, are difficult to enforce. Placing traffic light signals on all the roads as proposed in Viegas et al. [210] is very expensive. This approach allows ICE vehicles ahead of the bus to continue to use the bus lane, but no new vehicles may enter until the bus has passed.

BLIPs are a specific type of IBL. They use variable message signs (VMS) to request that cars leave the area if there is a bus [209]. This would be more effective than the IBLs in Viegas et al. [210] as vehicles ahead of the bus would move out of the way. However implementing VMS would require wireless communication between buses and signs, as loop detectors are not sufficient, increasing the deployment costs.

3.6.2 Heavy Occupancy Vehicle (HOV) Lanes

Another type of lanes is Heavy Occupancy Vehicle lanes. These allow access of vehicles carrying a certain amount of passengers to encourage carpooling.

Menendez et al. [211] looked at how HOV lanes affected road capacity. The authors state that although HOV lanes increase the delay per vehicle they should reduce the delay per person on average by giving HOV priority. The authors examine the speeds on both regular lanes and HOV lanes. The HOV lane does not greatly reduce flow through an area where the number of lanes has been reduced.

Kwon et al. [212] examined how HOV lanes affected travel times for their users. The authors found a mean saving of 1.7 minutes over a 10 mile (~16 km) journey and that four regular lanes carry the same amount of people per hour as a road with three regular lanes and a HOV lane, however the main benefit of HOV lanes would be to encourage carpooling and public transport, and this paper did not consider public transport.

Turnbull et al. [213] studied of the effect of HOV lanes over traffic over a number of years. This looks at 1970s to the early 2000s. They were first set up in Houston, Texas in response to the oil embargo. These were found to be very popular. Heavy Occupancy Tolled (HOT) lanes were also introduced. These charge solo drivers a few to access them.

Safirova et al. [214] investigated at the effect of placing tolls on HOV lanes to create HOT lanes. These have been shown to be used more than HOV lanes, however they reduce carpooling.

3.6.3 **Traffic Lights**

Traffic lights are a group of light signals which indicate which direction of traffic may pass at a junction. Traffic signal priority (TSP) allows the traffic lights to give priority to certain types of vehicles. This is already deployed for emergency vehicles. When an emergency vehicle approaches a traffic light, the lights will change in its direction. This is safer than simply breaking the light, as other vehicles will have to stop [215]. The method used in this case is based on the emergency vehicle driver sending a message to the traffic light and the light changing immediately. For other types of vehicles there is not any justification for this type of reaction, so two alternative solutions are used. They are:

- *Extended green* - in order to allow the favoured vehicle to benefit from the green phase. This phase is extended.
- *Early green* in which the green light appears slightly earlier for the favoured vehicle in case it waits during a red phase.

These two methods do not dramatically impede the traffic in other directions and are described in Niu et al. [216]. Niu also showed that TSP negatively affects non-priority vehicles. However this is intuitive and might be acceptable in some cases. TSP can be used in conjunction with DBL to improve the flow for buses. Similar to DBLs, TSP loses effectiveness as the traffic gets heavier [209].

The first area of research on traffic lights deals with basic traffic light control systems.

The two most common types of traffic control systems are Split, Cycle and Offset Optimization Technique (SCOOT) [217] and Sydney Coordinated Adaptive Traffic System (SCATS) [218]. These use induction loops at junctions to detect traffic levels. However induction loops are expensive and Abuelela et al. [219] stated that over 50% of induction loops are defective. Our proposed solution uses VANET communication instead, which is more reliable and does not require expensive infrastructure.

Sattari et al. [220] combined a routing algorithm with a traffic signal control algorithm. This paper does not compare against other dynamic traffic signal control algorithms however.

Wiering et al. [221] proposed the usage of a reinforcement learning algorithm to coordinate traffic lights. This scheme was shown to reduce waiting times when compared with three other schemes, by up to 30%. This scheme is not tested on a realistic map, it simply uses a grid with artificially generated traffic.

The second area of research on traffic lights deals with existing research in the area of specialised dynamic traffic light assignment. These traffic light assignment schemes focused on prioritising different vehicle types over one another.

Niu et al. [216] also suggested prioritising buses in a paper which compares early green and extended green methods and uses a delay parallelogram instead of a delay triangle to describe the traffic light phases. This was shown to reduce the average delay by 7% when compared with the delay triangle.

Jeng et al. [222] developed a traffic signal control with bus priority. This approach showed improvements in bus times without greatly affecting other vehicles. However this study did not use any real data or a real map.

Viriyasitavat et al. [223] set up priority for emergency vehicles at Virtual Traffic Lights (VTL). The author states that VTL can reduce the dead period of traffic lights. This paper aims to make sure that emergency vehicles are always in the green wave. This proposed scheme showed gains for emergency vehicles without affecting non-emergency vehicles.

Nyambo et al. [224] considered weighting vehicles, but how different vehicles will be weighted is not described in this scheme, instead it is left to the relevant authorities. This scheme is only for virtual traffic lights which have the disadvantage of requiring a 100% penetration rate. The simulations did not consider either a real map or real traffic data.

3.7 Swarm Algorithms (SA)

A swarm is a decentralized system with quasi-homogeneous units [225], called agents. These simple agents can solve complex tasks by interacting with each other. Swarm algorithms are algorithms based on swarms found in nature such as ant colonies or fish schools. Diverse swarm algorithms model this interactive behaviour differently and various results are obtained [226]. Several different types of swarm algorithms were looked at in the course of this study including: ant-based, bee-based, firefly-based, particle swarm, differential evolution, river formation dynamics, grey wolf optimizer and others.

3.7.1 **Ant-based Swarm Algorithms**

Ant-based algorithms are the obvious swarm theory that might be relatable to vehicles. Ant colony swarm theory is described in Teodorovic et al. [226]. Each ant leaves a pheromone trail, hence the most effective trails have the most pheromones. The ants naturally chose a path with high pheromones, so this results in a learning algorithm which in turn results in an optimal path. Ant colony optimization is a form of stigmergy, a mechanism of indirect coordination between agents. It is a stochastic procedure.

Ramesh et al. [227] used ant-based routing to route messages over a mobile ad hoc network. This scheme is designed for a MANET with frequent disconnections, such as interplanetary communication. The nodes have a pheromone value which is increased after a message travels by it, and decreased when no messages travel by it after a set amount of time. This protocol is compared against a number of others in terms of delay, overhead, and delivery ratio. It was shown to be competitive with several recent schemes, Endemic routing and 'Spray and Wait' [228]. Outperforming these schemes in terms of delivery ratio, overhead and latency in every scenario tested.

Wu et al. [229] proposed using ant-based clustering for mobile ad hoc networks. Clustering is a Non-deterministic Polynomial-time (NP)-hard problem and has multiple metrics to balance. The paper proposes using a Pareto-based solution, which aims to reduce the number of cluster heads, balance the number of nodes in each cluster and reduce power consumption. This was shown to outperform another scheme WSACO in all scenarios in terms of load balancing.

Parvatkar et al. [230] designed a solution to maximize the lifetime of nodes within a wireless sensor network. It lists the main causes of energy inefficiency at the MAC layer. The paper proposes keeping a highly used set of nodes simply in a low power state instead of sleep state as turning on after sleep state uses a lot of energy. No testing was done in this work however.

Cong et al. [231] proposed a centralized dynamic ant-based routing algorithm. The ants are given different colours for different destinations and other ants only pay attention to pheromones left by ants of the same colour. A network pruning step is used to reduce the complexities of the different destinations, so a colour can be applied to a particular area. Load balancing is applied to avoid flash crowding. This approach is compared against Dijkstra. The ant-based approach maintained a constant flow rate for two hours whereas the Dijkstra approach caused heavy congestion after a half an hour.

3.7.2 **Bee-based SA**

Unlike other community-based insects bees communicate via dancing. When a bee returns from a food source it communicates the distance, direction and quality to the other bees via dancing. Bees use this information to choose the optimum food source to visit. The bee colony swarm is described in Teodorovic et al. [226]. Initially the bees use a random walk model to determine a partial solution. A local optimal is determined which is communicated to the other bees this partial solution is then built on to determine a full solution.

Kiran et al. [232] improved the fault tolerance using bee-hive routing with-in Mobile ad hoc networks. The faults refer to errors in message data, such as environmental interference. This looks mainly at hardware failure and routing messages to working nodes. The proposed solution was tested using OPNET for both Wi-Fi and WiMAX. This approach allows for fault recovery without degrading the bandwidth significantly. However it was not compared against any other schemes.

3.7.3 **Firefly-based SA**

Fireflies light up to communicate to other fireflies. With real fireflies this lighting communication is used for mating purposes, but in the firefly algorithm described in Yang et al. [233], this is not the case. All the fireflies are drawn to each other in this algorithm regardless of sex. The dimmer fireflies will be drawn to the brighter fireflies. The brightness decreases over distance and if a particular firefly cannot see any others it moves randomly. For using this algorithm to solve problems the brightness can be proportional to a certain parameter or fitness function in order to attract the nodes to a better location. The authors compared this approach with the particle swarm algorithm and a generic algorithm. The Firefly-based algorithm found a global optimum in 99.8% on average for the different scenarios compared with 90% and 94% for the other approaches.

3.7.4 **Particle Swarm Optimization (PSO)**

Particle swarms are based on the behaviour of bird flocks and fish schools. This set of algorithms is described in Teodorovic et al. [226]. A particle remembers its best solution and that of the best solution obtained by any particle. In the next time step the particle moves in the direction of its best solution and the global best solution.

Belmecheri et al. [234] used particle swarm optimization for routing of courier vehicles. The problem consists of a single depot with multiple courier vehicles of different capacity as well as some customers who need a pick up. PSO had previously been applied to similar but less complex problems such as all the courier vehicles having the same capacity and no pick up requirements. This approach showed improvement in most of the scenarios by roughly 5% in terms of the time taken to deliver all the packages, when compared against ant colony optimization.

Garcia-Nieto et al. [235] applied particle swarm optimization to optimize traffic light timing. This approach showed improvement in terms of the number of vehicles to reach destination and the overall travel time. A differential evolution algorithm is compared against the authors approach. The authors showed a 31.4% improvement in terms of the number of vehicles to reach destination with in the time frame and 74% of vehicles had a decrease in travel time.

Chan et al. [236] predicted traffic flow using a swarm-based neural network. This was based on adapted particle swarm. This problem requires swarm intelligence due to non-linear characteristics of traffic flow. It was tested against real traffic data from a road in Western Australia and the results were shown to be effective. This algorithm successfully predicted the traffic flow from a 60 second sample time within 2-3 seconds.

3.7.5 **Other Solutions**

Sur et al. [237] proposed a river formation dynamic solution which used a water droplet algorithm when dealing with routing vehicles on a congested road network. The algorithm here can determine and route vehicles to all the under-utilized roads with-in a network. It is called the intelligent water drop algorithm. The author states the confliction between the fastest route and the number of vehicles going on this route as a key problem that is addressed by this algorithm.

Another solution proposed is the Grey Wolf Optimizer (GWO) Algorithm which divides the nodes hierarchically, similar to the behaviour of wolf packs. There are four main groups: alpha, beta, delta and omega. Each of these performs different tasks as part of the pack: searching for prey, encircling prey and attacking prey. Mirjalili et al. [238] applied this to a number of real world problems and performed better than a number of other swarm algorithms, such as PSO. This paper mentions the no free lunch theorem that no meta-heuristic algorithm provides the best solution to all problems, as this approach only gave the best result in 3 out of 30 of the test cases.

Stolfi et al. [239] used a swarm-based algorithm to reroute vehicles using V2I communication from traffic lights. This showed a 19% reduction in travel times and was compared against a number of competing algorithms. However these algorithms were designed by the author making the results less impressive.

3.7.6 **Conclusion**

A number of different types of swarm algorithms were discussed in thesis. Some such as the water droplet algorithm [237] and ant-based swarm algorithm [231] proposed innovative ways to address the problem of vehicular traffic congestion. However more studies are needed which consider realistic traffic traces. Other works proposed solutions to wireless networking or generic problems and shown substantial improvements in this regard.

3.8 **VANET Services and Applications**

An important related work includes potential VANET based services and applications. These are introduced in this section. The research performed in the area of VANET-based services and applications are divided into several areas: short term traffic prediction, route planning, parking management, life-critical applications, safety warning applications and others. Significant works in these areas are introduced and described next.

Figure 2-7 shows the processes involved in a TMS. Firstly the data is collected by various sensors such as phones and cameras. Secondly the data is aggregated. This data is then made sense of using software so that applications can be delivered to the end user, such as:

- routing vehicles to shorten commuter journeys
- traffic prediction that enables early detection of bottlenecks
- parking management systems that ensure optimal usage of the available spots and interact with routing and prediction services for improved control of traffic flow
- Infotainment services that provide useful information (e.g. tourism information, multimedia contents delivery over VANETs, shopping centre offers, cinema, etc ...) for both drivers and passengers.

In the following, we will discuss the importance of these services and how their efficiency can be improved to optimize the traffic in the transportation system.

3.8.1 Short-term Traffic Prediction

The traffic forecasting research topic has been widely investigated in several academic studies outlining the key factors that influence its design and modelling decisions.

In general, the following three factors characterize a short-term traffic forecasting system [240]: scope, data resolution and technique.

The **scope** refers to whether the forecasting model will be implemented as part of a TMS, and the area where it will be used (e.g. highway, urban arterials etc.).

Data resolution is highly dependent on the chosen forecasting horizon and step. The horizon refers to the limit in time for which the traffic conditions will be predicted, while the step defines the time interval upon which the prediction is made, as stated in [240]. The forecasting accuracy is strongly related to the choice of the horizon and step values, hence defining appropriate time interval for both of them is compulsory to achieve accurate prediction. According to the experiments conducted in [241] the prediction accuracy is inversely proportional to the forecast horizon duration. The Highway Capacity manual (2000) [242], as well as some studies in the literature, have suggested 15 minutes as the most appropriate horizon value. For the step value, the most used value is a 5 minute interval due to the high variability of the traffic flow. However, we argue that the horizon and step values should be also adapted to the requirements of the application for which the forecasting algorithm will be used.

Finally, the third factor that affects the forecasting accuracy is the **technique** used to model the traffic data, such as statistical and time series analysis models [243], [244], the well-known Auto-Regressive Integrated Moving Average (ARIMA) model [245], [246], Neural Networks [247], pattern recognition techniques, etc. In addition, some recent works have used spatio-temporal correlation of traffic flow across the road network [248], as well as the collected GPS data [249], to provide more precise prediction. Accurate real-time road traffic forecasting is a required capability to avail of advanced smart transportation technologies. From the point of view of transport authorities, the ability to predict traffic pattern evolution is a key requirement in enabling efficient management of the traffic flow in urban, sub-urban and highway scenarios. Traffic prediction can enable early identification of traffic jams, which allows the traffic authorities to take preventive measures to alleviate the congestion on the roads. On the other hand, traffic prediction is a substantial step towards providing accurate journey duration estimation for the commuters, as it is one of the major inputs of route planning algorithms, as highlighted in section 2.5

In the past decade, numerous traffic prediction techniques have been proposed in the literature; however, most of them have been devoted to highways rather than to highly congested urban arterials, which are far more likely to be monitored by the traffic authorities. Therefore, the design of accurate and scalable traffic prediction tools for urban road networks is required. To achieve this goal, the efforts should be focused on defining real-time forward-looking analysis techniques that use the large stores of historical traffic data, the social media feeds as well as real-time traffic feeds (i.e. traffic flow, road segments occupancy and speed) to predict how traffic conditions will evolve in time-frames ranging from a few minutes to a couple of hours, as illustrated in Figure 3-3.

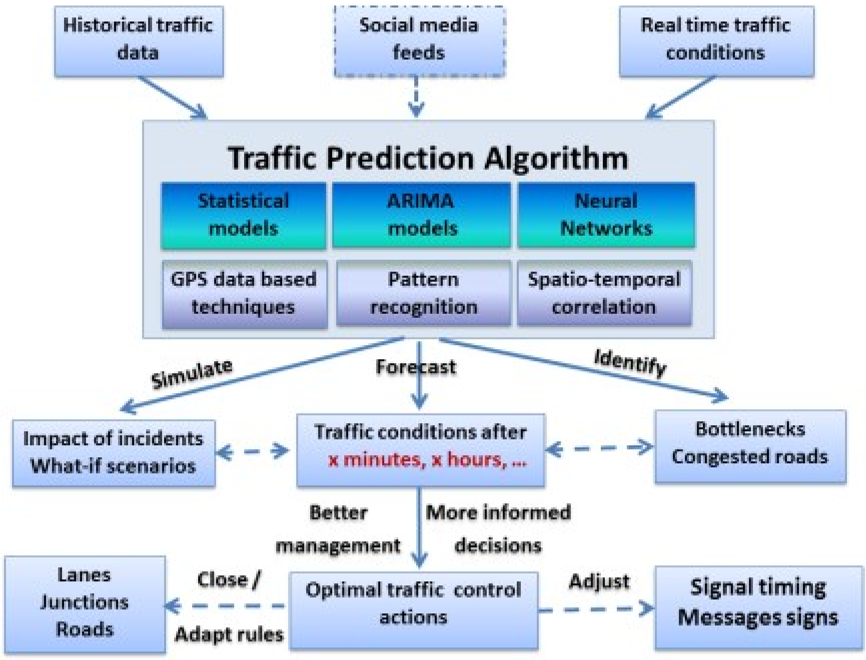

Figure 3-3: Overview of traffic prediction system and its impact on TMS efficiency

It is worth noting that social media feeds are substantial input as they provide a comprehensive explanation of the traffic conditions, which significantly helps the traffic managers to take the adequate actions. The key principle of a prediction algorithm is to use a combination of simulation, traffic modelling, real-time feeds and historical data to predict how the traffic situation will evolve in the near future. These techniques may also leverage some properties of the road network such as the spatio-temporal correlation for faster inference of traffic jam, as well as other techniques as discussed above. The typical outputs of a prediction algorithm are the traffic forecast and the identification of the bottlenecks.

Moreover, it can also explore a set of what-if scenarios through simulation to infer the impact of random incidents on the expected traffic conditions, and therefore more informed decisions can be taken in case of real incident. These decisions may involve adjusting the traffic signal timing, the message signs, as well as closing some road lanes or changing the driving rules. A comprehensive comparison of the major traffic prediction approaches in the literature is provided in Table 3-2. Those approaches are compared based on their achieved prediction accuracy, their scalability level when applied to large scale road networks, the modelling technique used (i.e. parametric or non-parametric), the road environment in which the forecasting approach is applied (i.e. highway or urban area).

Moreover, we also considered the type of traffic data source, meaning whether the prediction is based on data collected from fixed monitoring equipment, such as sensors and CCTV cameras, or by using mobile data sources such as floating GPS data and SMS, social data feeds etc. This metric is very important as the heterogeneity of data sources and the variety of their format and level of granularity may add extra constraints on the designed prediction algorithm, and may also affect its efficiency and accuracy. Since some prediction techniques impose constraints on the quality, type and format of the used data feeds in order to ensure high level of accuracy, we have also addressed this metric. Finally, the privacy and security concerns that may arise as consequence of the sensitivity of some used data feeds such as social media and GPS data are also covered. Designing effective tools for fast, scalable and accurate road traffic prediction is a key solution in overcoming the weaknesses of the existing TMSs.

The fast prediction allows the traffic managers to take early actions to control the traffic load and prevent the congestion state. Fast and accurate road traffic prediction is a paramount technique to enable better efficiency of TMSs and mitigate the awful impact of road traffic congestion. However, most of the prediction algorithms are likely to combine historical data with real-time traffic feeds, and apply some advanced and complex modelling approaches to predict the future traffic state, as discussed earlier in this section. Therefore, the legacy simulation approaches are not suitable in this case and distributed simulation is required to allow fast and accurate reaction to the change in traffic congestion in order to mitigate its consequences. The main advantages of fast road traffic simulation are summarized below:

- To enable more accurate recommendations from the TMS to the police regulating traffic at a junction, especially after an incident or during special events. After an accident it is a hard task for a human to take the optimal action that mitigates other problems (i.e. accidents, increase the congestion, block other roads etc…). Hence, adequate recommendations to traffic authorities are needed, for example in the case of an accident, the recommendation of optimal lanes to close to ease traffic congestion. This would be based upon exploring the entire solution space (i.e. what-if scenarios) to achieve a reasonably optimal solution. Therefore, this requires extremely fast simulation tools in order to provide the optimal recommendation within a very short time-frame.

- To enable faster and more efficient emergency service delivery (i.e. ambulance, police and fire fighters) which significantly reduces the incurred financial loss and saves human lives. Here, fast simulation allows the traffic authorities to detect the traffic bottlenecks in advance and take effective actions to prevent them.
- To enable better load balancing of the traffic over the road networks infrastructure, which decreases the traffic congestion and its economic and environmental impact as well as improves road safety.

Table 3-2 A summary of the main features and limitations of road traffic microscopic simulation tools and applications

	VANETMobiSim	STRAW	SUMO	PTV Vissim	SIDRA TRIP
Transport Modes	Trucks and cars	Cars	Multi-modal	Multi-modal	Cars
Accuracy	Time-step of 1ms		Time-step of 1s	Time-step of 0.1s	Time-step of 1s
Scalability	Medium	Medium	High - Up to 100,000 vehicles	Very High - No built-in limits	Very low - single car
GUI	Limited	Limited	2D - view	2D and 3D view	2D view
Realistic Simulation of pedestrian and passenger behaviours	No	No	No	Yes	No
Parking Management	No	No	No	Yes	No
C2X support	No	No	No	Yes	No
Accurate analysis of single car trip	No	No	No	No	Yes
Popularity	Medium	Low	Very High	Medium	Low
Licence Needed	No	No	No	Yes	Yes

3.8.2 **Route Planning**

The growing complexity of the big cities' road networks has led to an unprecedented expansion in the automotive navigation systems market. These systems, such as TOMTOM [82] and GARMIN [83], have made the journey of drivers easier and more comfortable due to the valuable information that they provide like the city roads map, GPS localisation and the guided route towards the destination. Despite the popularity of these systems, fast and accurate route search algorithms under the rapid and sudden variation of traffic conditions are still required to accommodate the needs of future smart and autonomous cars.

A typical dynamic route planning algorithm for smart cars is described in Figure 3-4. This figure emphasizes the main inputs of a dynamic routing algorithm, its output and the road events that may trigger an update of this output. These inputs consist of the city road network modelled as a directed graph in order to reflect one and two way road segments, the vehicle features (e.g. its height, weight, type), current traffic conditions and the short term traffic forecasts, as well as the driver preferences. By applying the routing algorithm on the directed graph and taking into account all the other inputs, the best route is returned. This latter should be updated dynamically, during the vehicle's journey upon occurrence of any event that may lead to the failure of a road segment included in this route. Notice that the failure of a road segment means its closure due to an incident or road works, or the abnormal increase of travel delay across it. Updating the best route means quickly providing an alternative route that mitigates the detected bottlenecks.

One of the challenges here is how to keep the quality of the alternative route very close to that of the failed best route. Usually, the best route depends on driver preferences which may include one criterion or a combination of several criteria. The travel time is the preferred criterion for most of the drivers due to the critical consequences of the delay. For example, people may lose their job for recurrent late arrival at work, companies may lose money for late delivery of goods to their customers and injured people may lose their lives due to the delay of emergency services. An algorithm that finds the fastest and most reliable route with less computation complexity is, therefore, required. The reliability of the route in this context refers to the probability that no abnormal delay occurs on any link constructing the fastest route during the vehicle journey, as stated in [250].

In addition to the travel time, other criteria such as, the length of the best route, its cost and its associated level of driving easiness and risk are considered by some drivers due to their specific needs. The cost of the route is computed in terms of the fuel consumption level and the number of toll tags included in this route. The fuel consumption is highly dependent on the traffic conditions as well as the road conditions measured in terms of the roughness and the gradient of the road segments of the chosen route [251]. The easiness of driving varies according to the number of turns, number of traffic lights, lanes width and number of hills in the best route, and it could be an interesting criterion for elderly, new drivers and people with poor driving skills.

Finally, the level of risk of a route is calculated based on historical statistics about the number and severity of accidents on a given route, and some drivers may prefer to avoid this route for safety purposes. Although several dynamic routing algorithms have been proposed such as [252], [253], and [254], many problems are still unresolved. A noteworthy problem in this context is how to ensure better usage of the road infrastructure while maintaining a reasonable satisfaction for the drivers. Load balancing mechanisms based on centralized system architecture are more appropriate in this case, but guaranteeing their efficiency is another challenge, especially during the peak hours. We foresee, then, that managing efficiently the growing number of vehicles in smart cities necessitates a mix of centralized and distributed system architectures through leveraging vehicular communication and mobile sensing information during the decision-making process.

For example, the vehicle can combine the alternative route received from the system with the acquired information from the vehicles ahead to take a more informed decision about the alternative route that it will follow. Moreover, the system can adapt the quality of the best route assigned to each vehicle, according to the level of participation of the driver with the mobile sensing process as well as allowing a level of information disclosure.

Consequently, this can help to achieve a balance of the traffic load and maintain adaptive satisfaction of the drivers. To get more insight into the proposed approaches in the literature to improve route planning in smart cities, the reader may refer to the following recent papers [255], [256], [257], [258], [259] and [260].

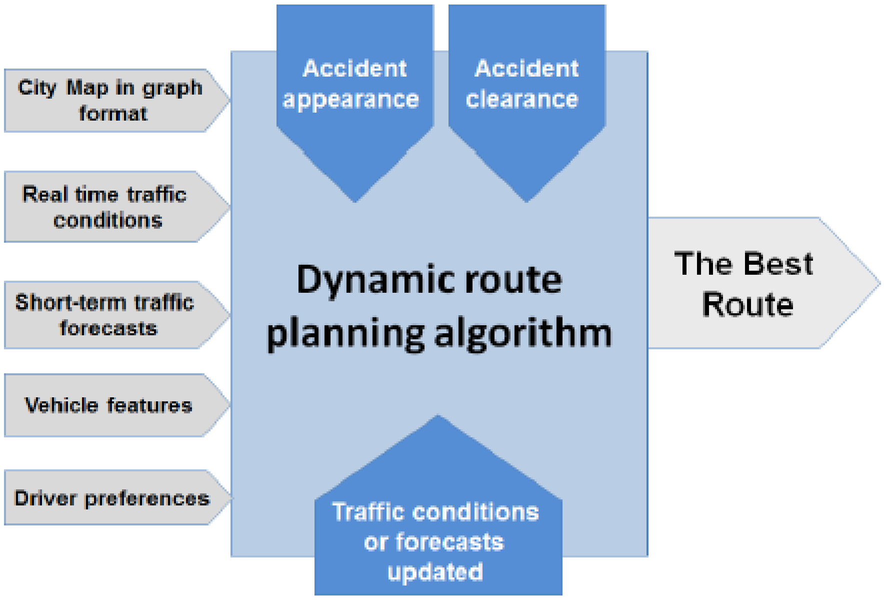

Figure 3-4 Route planning algorithms: main inputs and functioning

3.8.3 Parking Management Systems

Another area of interest for data gathering by VANETs is finding parking places. A large amount of time and fuel is wasted in urban areas searching for places to park. A VANET-based application could address this issue reducing traffic congestion.

To be more specific, an advanced parking management system should be operating in tight cooperation with the prediction and routing components of a TMS due to the fact that knowing the volume of traffic heading towards a destination will give more insights about the expected demands on parking spots in the near future.

Therefore, the routing component may adapt the individual vehicle's route based on its awareness of the available parking spots in an urban area, such that the traffic jam is mitigated and the usage of parking spots is optimized. Figure 3-5 illustrates a scenario in which the parking management system regularly reports the available parking spots to the routing component in order to increase its awareness of parking availability.

Then, the routing component combines this information with the traffic forecasts reported by the prediction component, and adapts the routing decisions accordingly, in order to achieve a global traffic load balance and maximize the usage of available parking spaces. To this end, the routing component may request the parking management system to adjust the number of free spots to be advertised through its mobile applications in accordance with the routing objectives. This is done in order to direct the drivers towards a specific area of parking such that the occurrence of traffic jam is mitigated.

Nowadays, finding an available parking spot is becoming a difficult problem for car drivers. Usually a long time is spent looking for available parking places, especially in big cities. Often taking public transportation rather than driving private cars is the preferred option for many people. This problem is mainly due to the lack of efficient parking management systems that would ensure early notification to the drivers about the available spots as well as the limited number of available parking spots.

The major consequences of this problem are time wasted, increased cost for the journeys and especially, the increase in the congestion level, as the drivers will occupy the limited road infrastructure for longer time than was expected. Therefore, developing efficient solutions for parking management and smart phone based applications (e.g. ParkYa [261] application developed in Ireland and ParkingLook [262] in Australia) that signpost parking locations and provide real-time information about spot availability to drivers are needed. These will certainly alleviate the traffic load on the roads and enhance the TMS effectiveness.

In order to contribute to the ongoing efforts aiming at making smart cities happen, WorldSensing [263] has developed a green and self-sustainable smart parking solution named *Fastprk* which makes use of M2M technology to ensure real-time monitoring of available parking spaces. *Fastprk* has proven its efficiency through the success achieved in the city of Moscow, known for its heavy traffic congestion, where WorldSensing has deployed a huge number of parking monitoring sensors (approximately 15,000) to provide both end users and city council authority with real-time information regarding parking space occupancy. This solution allows the users to find their parking places via electronic street signs or smart phone applications. *Fastprk* was shown to reduce travel time and fuel consumption, by reducing the time and distance driven to find a parking space. In addition to these applications, other solutions are being investigated by the research community such as sophisticated carpooling [264], [265] and public transportation systems that may stimulate the citizens to use these alternative transportation modes, instead of driving their own cars.

Most recently, many researchers have designed solutions to detect available parking spaces and share this information with other cars, via V2V communication, within a specific area. Mathur et al. [119] have focused on urban on-street parking availability and have designed a mobile system named ParkNet that uses vehicles equipped with GPS receiver along with ultrasonic sensors to determine the parking spots occupancy while passing by. Based on real data collected in San Francisco, ParkNet has proven an accuracy of more than 90% in determining the free parking spots. It would also achieve a cost saving of an estimated factor of 10 compared to static sensors deployed at each street-parking place.

Klappenecker et al. [266] have proposed a system to predict the number of parking spaces available which will be available when a vehicle reaches the parking area. In this system, the parking ticket machine regularly communicates the number of available spaces to the vehicles upon arrival using Markov chain based estimation. This system, however, does not exploit the free spaces efficiently as more than one vehicle may drive to the same parking spot as described in [267]. To overcome this drawback, [267] proposes a reservation protocol that allows a vehicle to claim a spot when it becomes free, thus an optimal use of the available spots is guaranteed in this case.

Panayappan et al. [268] have proposed to deploy sensors on the sides of each vehicle to detect the presence of any vehicle in the place next to it. This is a useful mechanism to prevent abuse as the multiple cars and car park sensors will check whether the space is free. In the paper by Kokolaki et al. [269], each vehicle gathers the location of each empty parking space and then forwards this over the ad-hoc network. This approach was compared with a non-assisted search and centralized server approach. The VANETs based scheme did not always outperform the centralized server but the paper highlights the fact that the VANETs based scheme requires no additional infrastructure to be built, so it is a much more cost effective solution.

A decentralized and scalable parking spots information system has been developed in [270] to inform the drivers about parking availability in an urban area. This system makes use of VANETs to disseminate micro and macro parking information either locally or on a large scale, respectively. Micro information refers to free parking spots coordinated by one automat, while macro (i.e. aggregated) information covers several parking within one urban area. This system has shown high efficiency under realistic model of German city in which 5% of the vehicles, out of 10,000, are equipped with wireless communication capabilities.

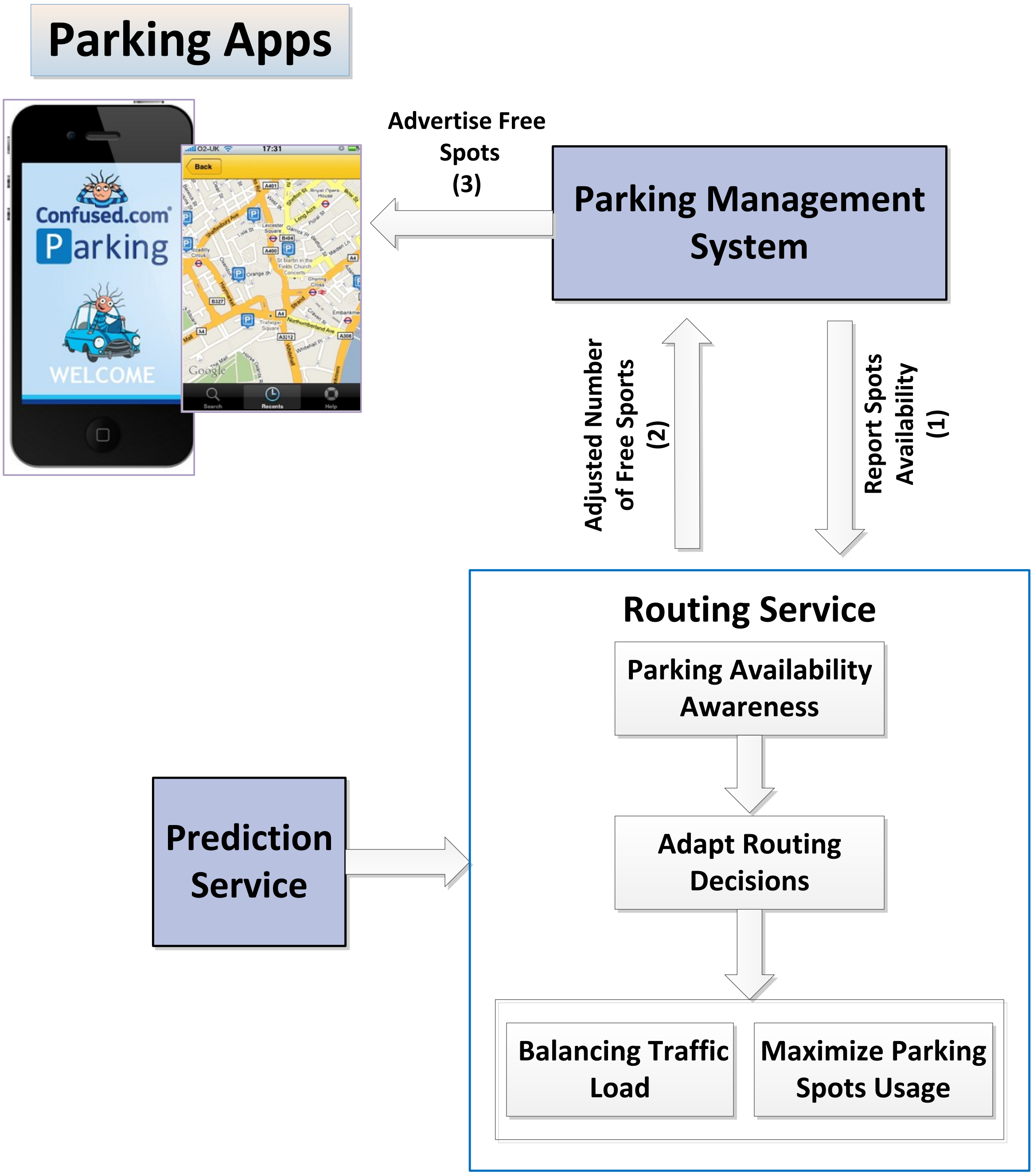

Figure 3-5 Illustration of Prediction, Routing and Parking service Cooperation

To complement the previous work, Caliskan et al. [271] have developed a model using homogenous Markov chains and queueing theory that estimates the future occupancy of parking spots located within the vehicle's destination area at its arrival time. Based on the parking information received through VANETs, the vehicles apply this model to decide on one of the available parking spaces.

Szczurek et al. [272] have proposed a machine learning algorithm for determining whether a given car park will have a space to park. In this system, when a vehicle leaves a parking space, it sends a message over VANETs announcing that a parking space has become available and specifies its corresponding coordinates. This work has shown a reduction in the time spent searching for a car park space of over 25% compared to a blind search. It is well known that on-street parking offers most car parking spaces in cities, which means that an efficient management of these spaces may lead to a substantial benefit for both city and citizens. Unlike off-street parking lots where the car park gate can be used as a sensor to assess the occupancy level, a sensor per parking space is required to monitor and detect the availability of on street parking, which represents a significant cost for their deployment. However, to reduce this cost, Evenepoel et al. [273] have proposed to deploy the sensors on a fraction of on-street car park spaces only and then use extrapolation to infer the amount of cars parked in the entire city. A probabilistic model was devised to quantify the reliability and efficiency of the proposed approach and the obtained results were promising, as they show that ensuring slightly less than 2% of parking space coverage by sensors would be optimal. Therefore, a significant reduction of the sensor deployment cost would be achieved. However, the main shortcoming of using so few sensors is that some drivers might be tempted to ”cheat” in order to guarantee easy and fast parking for themselves or their colleagues at work. For example, an employee may intentionally park on the parking spot equipped with a sensor so that the road would appear full to other users, whereas this is not the case.

3.8.4 **Life-critical Applications**

The most important applications enabled by VANETs are applications which can quickly save lives. A number of these applications have been the subject of research.

Park et al. [274] used video streaming between vehicles for safety purposes. Video clips of an accident or dangerous situation allow the drivers heading towards the event to gauge how severe it is. Rescue vehicles would also greatly benefit from knowing the circumstances and severity of an accident.

Chen et al. [102] gave a good list of safety applications:

- Traffic signal violation warning.
- Curve speed warning.
- Emergency electronic brake.
- Lights pre-crash warning.

- Cooperative forward collision warning.
- Left turn assistant.
- Lane change warning.
- Stop sign movement assistance.

These applications could all allow the driver greater time to respond to dangerous situations. Zang et al. [275] describes the emergency electronic brake light. This application sends a warning message to following drivers when a vehicle in front brakes harshly, similar to the brake on normal vehicles. The paper describes the disadvantages of current optical brake lights, which are visibility problems and the cumulative stopping distance. This emergency electronic brake could enhance the distance of the warning message, remove the cumulative stopping distance problem and give greater details on the level of braking in front. This application would be very useful in preventing pile-ups.

Martinez et al. [276] investigated the potential of using VANET information to trigger airbags, emergency brakes or other emergency mechanisms. Also sending the location of an accident to emergency vehicles can significantly reduce the response time.

Szczurek et al. [277] used an emergency electronic brake light, which used machine learning to decide if the safety message is relevant. It is important to have reliable messages, as if the system sends too many false messages the driver will start to ignore them and then they will become pointless.

Haas et al. [278] proposed a collision avoidance application. The vehicles constantly send each other updates on their acceleration rates, speeds and position to detect if a crash is likely. If the speed is below a certain level, or if the vehicle in front has been decelerating already, it is assumed the driver will have sufficient time to react, but if the driver has to react quickly a warning message is sent. This was implemented in simulations and showed a decrease in crashes.

3.8.5 **Safety Warning Applications**

Safety warning applications are applications which improve the safety but are not as critical for saving lives as Life-Critical applications.

ElBatt et al. [279] considered a lane change warning application. If the path the lane changing vehicle is on is unsafe, a warning is issued to the driver changing lanes and the driver already in the lane.

Kargl et al. [280] gave a list of e-safety applications, some of which are quite novel.

- Traffic signal violation warning
- Stop sign violation warning
- General in-vehicle signage
- Left turn assistant
- Intersection collision warning
- Pedestrian crossing information
- Emergency vehicle approaching warning
- Emergency vehicle signal pre-emption
- Emergency vehicle at scene warning
- Vehicle safety inspection
- Electronic license plate
- Electronic driver's license
- In-vehicle Amber alert (crime haunt)
- Stolen vehicles tracking
- Post-crash/breakdown warning
- SOS services
- Pre-crash sensing
- Event data recording
- Work zone warning
- Curve-speed warning (rollover warning)
- Vehicle-based road condition warning
- Infrastructure-based road condition warning
- Cooperative (forward) collision warning
- Emergency electronic brake lights
- Blind spot warning / lane change warning
- Wrong way driver warning
- Rail collision warning

Advantages and Disadvantages

Kargl et al. [280] presents a good exhaustive list but no testing or implementations. The authors show that there was a reduction in causalities from car accidents after the introduction of seat belt, airbags, ABS and Electronic Stability control Programme (ESP), and argues that these new applications would have a noticeable effect on injuries from car accidents.

3.8.6 **Other Applications**

3.8.6.1 Electronic Toll Collection

Another potential for VANETs is toll collection. The vehicles could send a message with payment details to a RSU at the toll station allowing payment without the vehicle being required to slow down. Choi et al. [281] describes a VANET-based toll collection. The vehicle sends a message when passing a RSU for billing purposes.

3.8.6.2 Internet Access

Internet access would be a very useful application, both for the drivers and passengers. It would enable a much greater range of applications. Bechler et al. [282] looks at internet access for vehicles. A modified version of TCP, Mobile Control Transport Protocol (MCTP), is developed in order to allow novel applications, such as email checking for business cars and trucks accessing their fleet management software. RSUs function as proxies to allow synchronisation of the VANET with the internet. Internet access of the VANET was emulated using NISTnet. MCTP allowed double to the information to be transmitted between vehicles.

Gerla et al. [283] mentioned internet advertising as something which could be enabled by VANETs. This could create a much needed revenue stream to motivate companies to get people to take up VANETs and pay for Road-side units. Four main areas are looked at: content downloading, advertising, driver to driver communication and environmental sensing.

3.8.6.3 Road Service Finder

Wolfson et al. [284] Systems looked at searching for nearby services such as gas stations. Each vehicle in the VANET disseminated information regarding the service. The further the vehicles are from the service the less relevant the messages will be so the priority of gas station beacon will be a function of distance. No testing was shown in this paper.

Dikaiakos et al. [285] proposed location based services. The suggestions made are for: traffic congestion information, traffic alerts (i.e. a crash on a certain road), and services such as the cheapest fuel in an area or the menus of nearby restaurants. These services illustrate the potential of VANET-based services. Road-side units would be placed at local businesses, such as petrol stations and restaurants, improving VANET connectivity in exchange for gathering more customers through these services.

3.8.6.4 Infotainment

Guo et al. [286] looked at live video streaming utilizing vehicle to vehicle communication. This would allow the driver to more accurately gauge the traffic of a certain area, or the seriousness of an accident. Simulations are performed which shows that video streaming over a VANET is possible.

Lee et al. [287] allowed users to buy/sell items such as sports tickets to other users in a nearby area. The paper proposes ad-stations which would send advertisements to nearby vehicles. The proposal is called FLEANET a virtual market for VANETs. VANETs provide the ideal platform for location-based searching for buyers and sellers of goods and services.

Nandan et al. [288] discussed location aware advertising to vehicles. In the paper Access Points deliver ads to nearby vehicles. This has the potential of improving targeted advertising due to more information can be assumed about the consumer. He/she is driving on an inter-city route there is a good chance they are on holiday and want to be aware of a cities attractions etc… Beyond simulation of a mobility model no testing was done regarding the feasibility of this contribution.

Smaldone el al. [289] looked at creating a vehicle social network (RoadSpeak) and sending voice messages to nearby vehicles. Many people spend a large amount of time commuting by road vehicle, if these vehicles could communicate with each other social networks could be formed. RoadSpeak was successfully implemented on two laptops with exchanged voice communications via 3G.

3.8.6.5 Fuel stations

Woerndl et al. [290] described a gas station recommender. The recommender displays the prices and locations of gas stations within the vehicle's range when the fuel tank is nearly empty. This would also be useful for company cars to keep track of travel expenses, as the driver would have picked the optimum fuel station when it was needed and the price would be recorded. The recommender also determines whether there is a good fuel station along the route or whether a detour is required.

3.8.6.6 Driver Behaviour

In Chaurasia et al. [291] the driver is sent messages to reduce dangerous behaviour such as short safety gaps or frequent lane changes. This should reduce dangerous driving and result in fewer crashes. The disadvantage is that is difficult to simulate real drivers, for example drivers might ignore the messages. It is difficult enough to simulate average drivers never mind dangerous ones.

Reichardt et al. [188] described a highway merging application. The vehicles exchange trajectory information in order to improve safety, as a large amount of lane-changing crashes happen due to misunderstandings regarding other drivers' intentions. This research lacked testing however.

Advantages and Disadvantages

Choi et al. [281] did not state the advantage of this system as compared the current systems, which take photographs of registration plates, although the VANET approach could reduce the amount of false readings from toll bridges. A number of useful applications are presented in Bechler et al. [282] and Gerla et al. [283]. There is a need for testing in the road service finder area, for example take traces of drivers searching for gas stations, and then compare actual routes, levy flights and current system. There is no testing in Woerndl et al. [290], which compares fuel and time savings with other approaches.

3.9 SUMMARY OF RELATED WORKS

This chapter presented the related works of this thesis. The chapter starts by introducing data monitoring mechanisms, both VANET-based and non-VANET-based. The next section of the chapter deals with data aggregation solutions. Inter-vehicle coordination mechanisms are then introduced, followed by IEEE 802.11p congestion reduction solutions. Factors influencing fuel consumption and emissions are discussed afterwards. Swarm algorithms are then introduced and explained in detail. Finally VANET services and applications are discussed in detail.

Chapter 4 - EcoTrec Architecture

EcoTrec is a novel VANET-based environmentally friendly routing mechanism for vehicular traffic proposed in this thesis. As already mentioned, there is an urgent need to reduce greenhouse emissions from the transport sector, and EcoTrec helps reduce the amount of emissions from private passenger cars. EcoTrec takes road and traffic conditions into account to reroute vehicles to a more fuel efficient route without significantly affecting journey times. EcoTrec was shown to reduce fuel consumption (and therefore greenhouse gas emissions) when compared against other routing schemes.

EcoTrec has a distributed architecture. This is shown in Figure 4-1.

The EcoTrec architecture is built upon a ***Server*** and many communicating vehicles. The ***Server*** communicates via the RSUs and is used for storing information when no vehicles are in the area. Communication between the vehicles uses IEEE 802.11p V2I and I2V communication. This server may take the form of a physical server or a “cloud”-type of server may be used.

Figure 4-1 illustrates the EcoTrec architecture which is composed of a ***Vehicle Model***, a ***Road Model*** and a ***Traffic Model.*** The ***Vehicle Model*** is built by each individual vehicle, using information from GPS sensors, speedometer and accelerometers. This model contains vehicle type, mass, air and rolling resistances, position, velocity and direction. The vehicle’s local traffic conditions, such as the average speeds along the road segments, are used to create and maintain the ***Traffic Model***. The ***Road Model*** can be determined by the gathering information from vehicles, if no information is available on the ***Server*** regarding nearby roads. This model contains the road roughness values, IRI and MPD, road gradient, the roadID and the speed limit and length of the road segment. If information has been stored previously, the vehicle retrieves this data by communicating with a ***Server*** which has a ***Road Model*** instance on it. The data is communicated using IEEE 802.11p [292]. The EcoTrec engine takes the data from the various models and runs the EcoTrec algorithm. The EcoTrec Algorithm determines the most fuel efficient ***route*** from the road and traffic information and is described greater detail in section 4.2 This ***route*** is a list of road segments the vehicle is recommended to follow. Once ***the route*** is determined it is returned to the driver. The ***Server*** is needed to store data on the road models as these values should be constant over a small timescale and will need to be kept when the VANET is not operating due to no vehicles on the road, e.g. Christmas day or late at night.

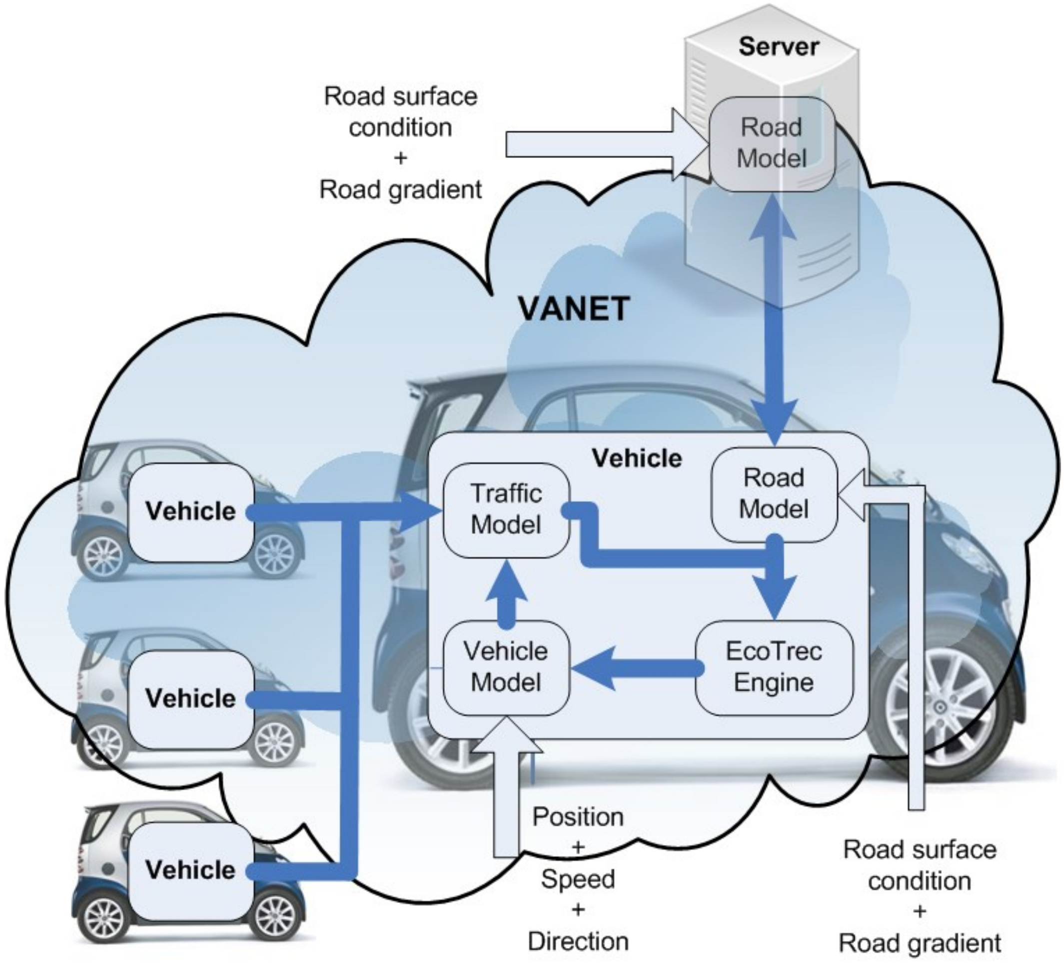

Figure 4-1 EcoTrec system architecture

4.1 **Architecture Components**

The Vehicle model, the Road model and then the Traffic model will now be introduced and discussed in detail.

4.1.1 **The Vehicle Model**

The Vehicle model models the characteristics of the each individual vehicle. The purpose of the vehicle model is to accurately represent the important characteristics of each vehicle in order to simulate emissions and traffic dynamics.

The position of the vehicle can be determined from the on board computer from GPS sensors, the direction from an electronic compass, and the velocity from the speedometer.

The vehicle parameters such as type of vehicle, mass, air resistance and rolling resistances are placed in the vehicle model when it is initialized. The other inputs are position, direction and velocity. This is illustrated in Figure 4-3. These inputs are determined by the on board computer from the GPS sensors and accelerometers on the vehicle. These inputs are updated regularly. The outputs of the model are: the vehicle's emissions (which are determined regularly) and the position information.

The vehicle sends the position and speed from the Vehicle Model to the vehicle Traffic Model, as well as to other vehicles traffic models in VANET messages. The vehicle then receives similar messages from the other vehicles again via VANET communications. The sequence of these events can be seen in Figure 4-2.

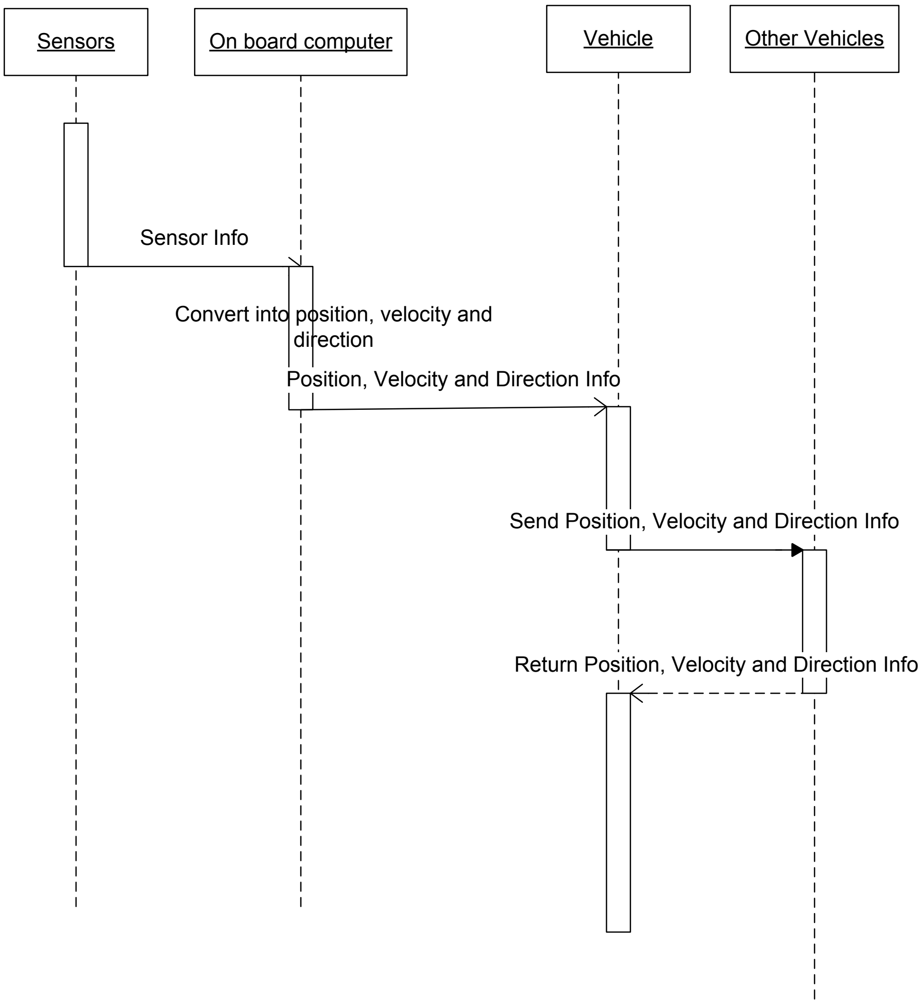

Figure 4-2 Vehicle Model sequence diagram

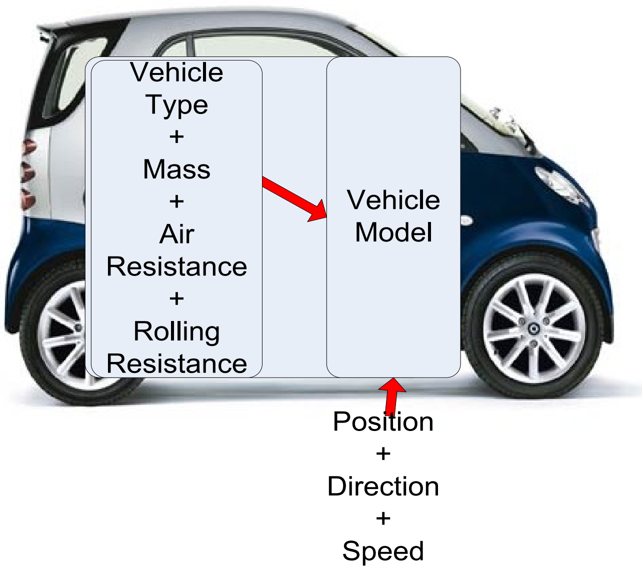

Figure 4-3 Vehicle Model

4.1.2 **The Road Model**

The Road Model includes a representation for each individual road section in terms of its characteristics. Both the server and the vehicles contain a complete set of road models of the road network.

The function of the road model is to allow the vehicles to query or update the road characteristics of each individual road segment.

The road's roughness values IRI and MPD, the roads ID, the maximum speed, the length, as well as the road gradient are the inputs to the road model. The road model is stored on a central server. This road model is initialized at start up, but may be updated with information from the vehicles if the information stored on the server is wrong, due to errors or to the data being out of date. The vehicles are equipped with accelerometers and tilt sensors to detect the road surface conditions and the road gradient. The information from these sensors is retrieved by the on-board computer and converted to digital information as input for the road model.

When a vehicle first enters the map it communicates with the server to retrieve the road models for the area. This is the initialisation step.

The vehicles send the server a message regarding road conditions if they are different from the model allowing the server to update. The update message contains a number of fields: SenderID (the id of the vehicle), message type (broadcast or unicast), message id (road or traffic condition), road id (the road referred to), message (containing the road or traffic rating), timestamp and sequence number of message. It will be discussed in greater detail in section 4.3

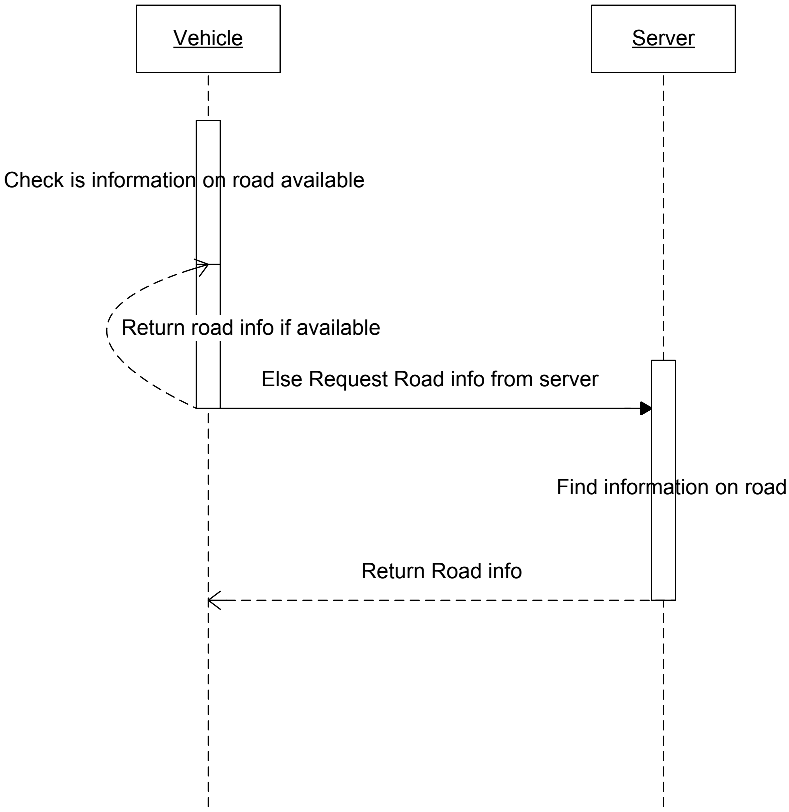

Figure 4-4 Road model sequence diagram

The outputs are the road's roughness and gradient. The vehicle sends a request message with the roadID to retrieve the road roughness and gradient. The server-vehicle communications are also done using 802.11p via the use of RSUs. The ***Server*** is important as the road gradient should be constant, provided there are no errors and the road surface conditions change gradually over time.

Figure 4-4 illustrates the sequence of these events. First the vehicle checks is any information on the nearby road stored on the on board computer. If there is the road conditions, gradient and roughness, are forwarded to the EcoTrec engine. If this information is not stored on the vehicle, it is requested and returned from the ***Server.***

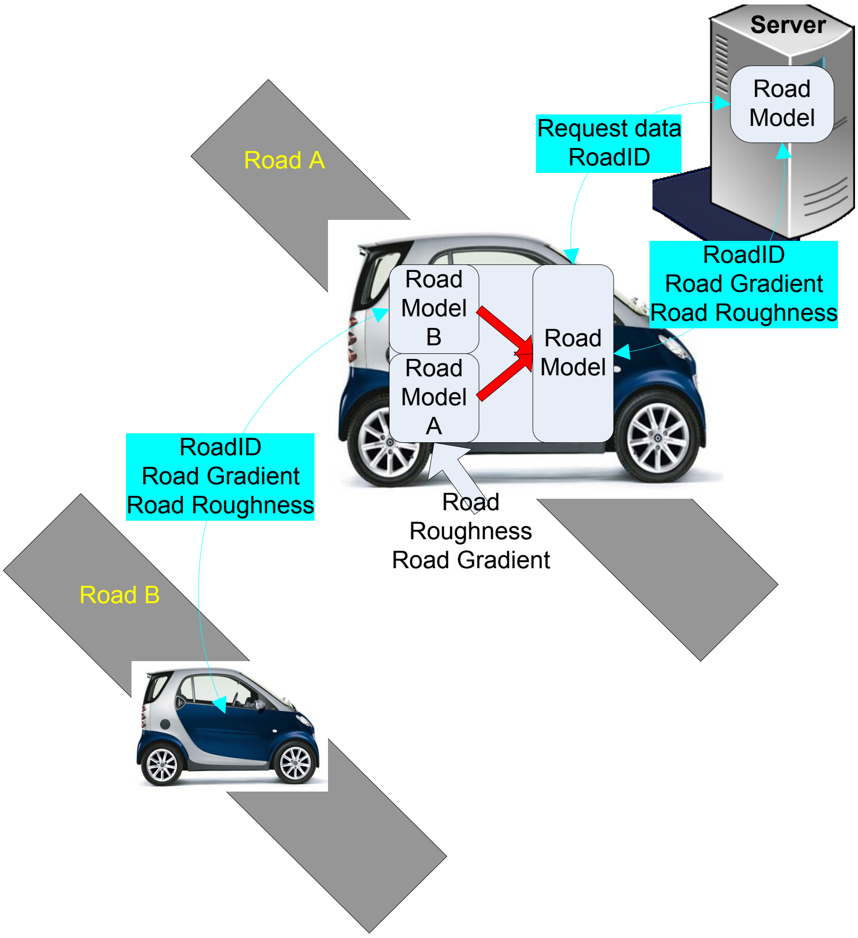

Figure 4-5 Road Model

When a vehicle sends a VANET message set up as in Figure 4-12 requesting information on a road from the server, the server responds with a message containing the road roughness and gradient of the requested road.

The vehicle takes the road roughness and road gradient values from the vehicle model and inputs them into the EcoTrec Algorithm to allow the vehicle to calculate the optimum route.

Figure 4-5 illustrates the Road model architecture. How the models are distributed between the Server and the vehicles is shown. Also the communications and their contents between the Server and the vehicles are shown.

4.1.1 The Traffic Model

The traffic model models the full traffic conditions of an area.

The inputs to the traffic model are the roadIDs, as well as the traffic congestion rating (*T*) for the corresponding road section. The traffic congestion rating is calculated from the average speed of cars along that road, compared with the speed limit. This will be defined later as part of the EcoTrec Algorithm (see equation 4-3).

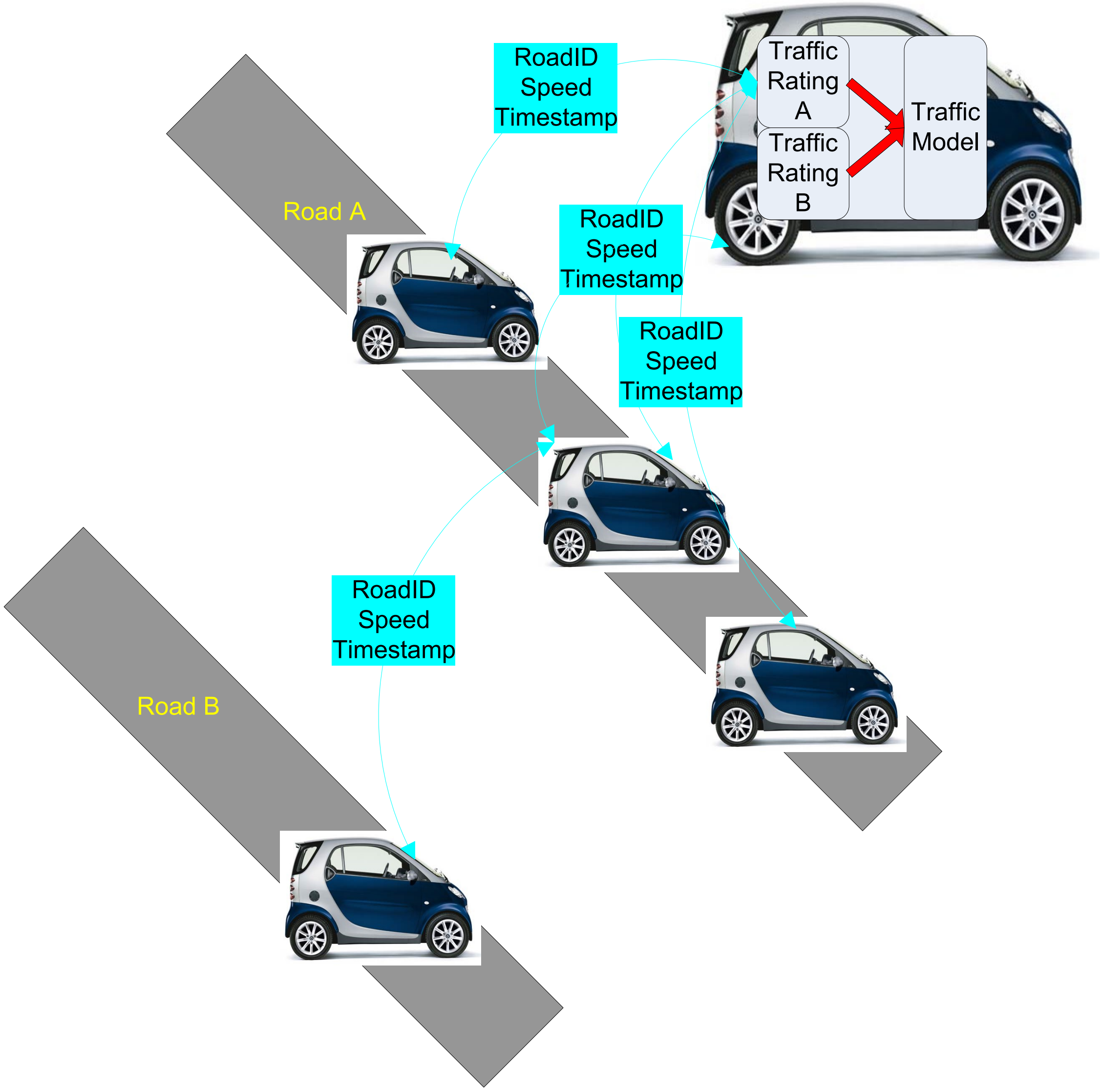

Figure 4-6 Traffic Model

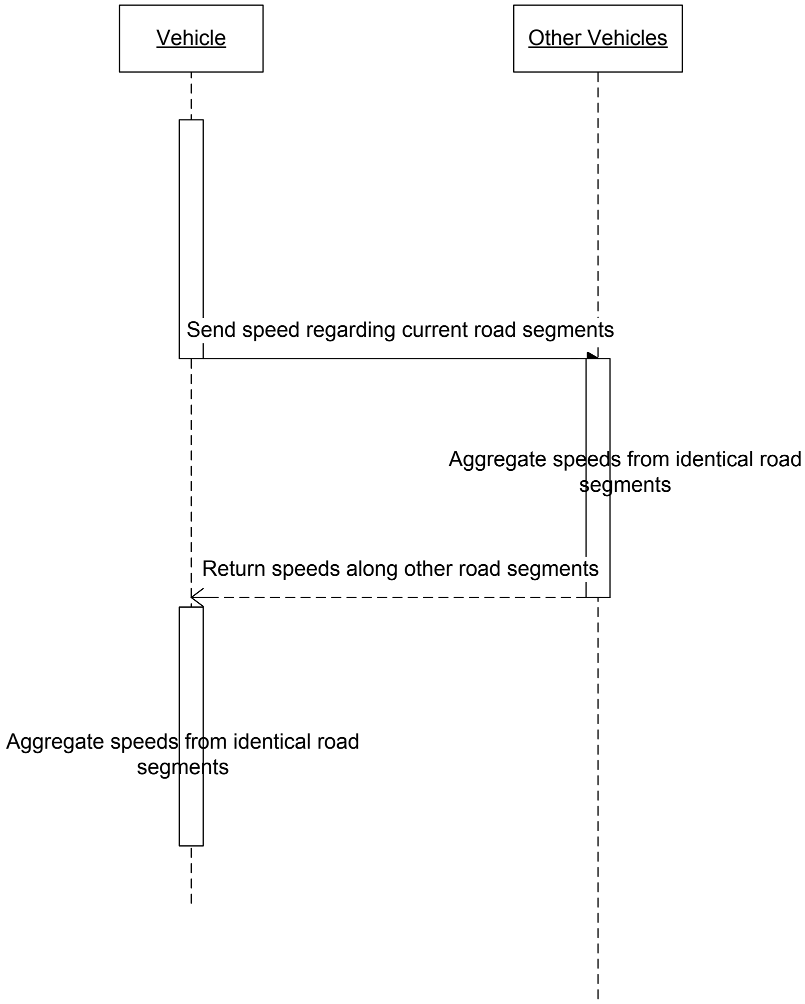

Figure 4-7 Traffic Model sequence diagram

The traffic conditions on the road are determined by the average speed of the vehicles on the road segment. The road conditions will be determined in the same way. When a vehicle receives a message concerning traffic conditions it first checks if the message is out-of-date. A message is out of date if its timestamp is greater than the time plus message lifetime L. If the message is out-of-date it is disregarded. If the message is not out of date the road segment the message concerns is looked at. The vehicle checks if it has any information regarding that road segment. If the vehicle does not, the message's traffic rating is stored as the vehicles traffic rating for that road segment, the time stamp of the message is stored as the time stamp of that rating. If the vehicle does have information on that road segment the time stamp of the message and stored information are compared. If the time stamps are not equal, the newer information is stored. If the time stamps are equal the traffic ratings are averaged.

The vehicles exchange messages detailing information relating to traffic conditions. Figure 4-7 illustrates this exchange. The messages contain the roadID of the road they are on, their current speed and the time the message is sent, this is displayed in Figure 4-12. The speed of the different vehicles on a particular road at a certain time is averaged. The average speed is used as the congestion rating for that road. A complete list of average speeds along with the road ids is stored forming the traffic model. The traffic model describes the congestion of the roads in the area or on the map. Again the messages are exchanged between vehicles using 802.11p. The purpose of the traffic model is to allow the vehicles to query real-time traffic conditions on each individual road segment.

The vehicle takes the traffic condition values from the traffic model and inputs them into the EcoTrec Algorithm, in order to allow the vehicle to calculate the optimum route.

Figure 4-6 shows the distribution of the traffic models across the vehicles and the information the vehicles exchange.

```
MaxHopCount = (traffic_density)/distThresh;


if(pktCollisions < colThresh)
        comChannel = waveSCH
else
        comChannel = waveCCH
```

Figure 4-8 Pseudo code of broadcast parameters

MaxHopCount is the number of times a message will be rebroadcasted by nodes

Traffic_density is the number of vehicles per square km

distThresh is the range of IEEE 802.11p

pktCollisions is the number of packet collisions

colThresh is the maximum number of collisions before a degradation in performance of the algorithm

comChannel is the WAVE channel used to send EcoTrec messages

waveSCH is one of the 6 data channels

waveCCH is the control channel for IEEE 802.11p.

The algorithm for determining the broadcast parameters is shown in Figure 4-8. The traffic density is compared with distance messages are required to travel. This calculates the MaxHopCount. Then the number of packet collisions is examined if it is over a certain threshold the EcoTrec messages will be sent over the control instead to give them a higher priority

4.2 EcoTrec Algorithm

EcoTrec is the proposed algorithm whose goal of this algorithm is to reduce the fuel consumption of the vehicles without greatly affecting their travel times. This is the first main contribution of the thesis. In this section firstly the ***utility function balancing fuel consumption and travel time*** is described then the ***load balancing scheme*** is introduced. The ***fuel consumption algorithm*** is discussed next followed by the ***expected travel time algorithm***. Then there is a discussion of ***timeline of model calculation and messages*** and finally the ***message routing scheme*** is discussed.

4.2.1 EcoTrec Utility Function

The EcoTrec algorithm takes into account two main factors: the road conditions, reflected in the road condition rating (R) and the traffic conditions, reflected in the traffic condition rating (T). The multiplicative utility function presented in equation (4-1) relates the two parameters to determine the value associated with a road segment. It uses a weight W_T which helps tune the contribution of the traffic conditions on the overall utility function. The rationale behind using a multiplicative utility function was that a very good road would be useless to the driver if there was a serious traffic jam on it, due to an accident or road works.

$$U = R/(T^{W_T}) \qquad (4\text{-}1)$$

Making use of this novel utility function, the vehicles are then routed according to the Dijkstra lowest edge weight algorithm [293], this is described in section 2.5 Each time a vehicle receives new information from VANET messages, the vehicle updates the models, and then re-computes the utility function updating the optimum route.

4.2.2 **Load Balancing Scheme**

Load balancing is used when recommending routes for vehicles in order not to create flash crowds on certain roads.

```
random_int = rand() % N;
if(random_int == N)
        next_edge = Select_2nd_best(edge);
else
        next_edge = Select_best(edge);
```

The Dijkstra algorithm was augmented to include load balancing. A random number generator was introduced so that every N road segments would be replaced by the second best road segment within the recommended route. For the testing-based simulations N was set to 9, in order to be close to the optimum solution, but introducing a small degree of randomness to prevent flash crowding.

4.2.3 **Fuel Consumption Algorithm**

The road condition rating R is calculated according to equation (4-2) and is derived from the Handbook Emission Factors for Road Transport (HBEFA) formula [202], which is described in detail in section 3.5. R is normalized by making use of a value for the most emission intensive route (R_{max}).

$$R_N = \frac{R}{R_{max}}$$

$$R = A \cdot RR \cdot v + B \cdot RR \cdot v^2 + C \cdot v^3 + m \cdot g \cdot RG + m \cdot a \cdot v \qquad (4\text{-}2)$$

In equation (4-2), RR is road roughness-dependent coefficient which accounts for the increase in emissions due to the surface conditions; RG- road gradient, g- gravitational acceleration, v –velocity, m- vehicle mass, a- acceleration, A, B – rolling resistances for the vehicle and C- air resistance for the vehicle. C is dependent on the frontal area, which is measured in meters squared. A and B are friction coefficients and RG is a ratio of height over distance and they do not have units. Acceleration and gravitational acceleration are recorded in meters per second squared, velocity is measured in meters per second, and mass - in kilograms.

4.2.4 **Expected Travel time Algorithm**

The traffic condition rating defined in equation (4-3) is obtained by gathering information on the different speeds of the vehicles on a stretch of road and then by normalizing the average speed of the vehicles by considering the maximum speed on that road. This information is then distributed to other vehicles via the VANET.

$$T = \frac{AS}{MS} \qquad (4\text{-}3)$$

In equation (4-3), AS=Average Speed and MS=Maximum Speed of vehicles on a road segment, both are measured in meters per second.

```
if(message.roadID == stored.roadID)
        if(message.timestamp < stored.timestamp)
                message.averageSpeed = stored.averageSpeed;
                message.timestamp = stored.timestamp;
        elseif(message.timestamp == stored.timestamp)
                (message.averageSpeed + stored.averageSpeed)/2 =
                        stored.averageSpeed;
stored.trafficRating = stored.averageSpeed/roadID.maxSpeed;


Forward stored;
```

Figure 4-9 Pseudo code of how traffic rating is calculated

Figure 4-9 shows the process of how the new traffic rating is calculated. When a vehicle receives a message from another vehicle, it checks the time-stamp and the *roadID* of the message. If the message is newer than the data stored for that road, the traffic congestion rating of the message is stored. If they relate to the same time interval, the values of the message and the value stored on the vehicle are averaged. If the message is older, it is discarded. The vehicle now forwards this value as the traffic congestion rating on that road. This accomplishes the calculation of the average speed on a road in an entirely decentralized manner. The maximum speed is stored in the *Road Model.*

Each time step the vehicle has received new information, it runs the EcoTrec algorithm to check that it is on a fuel efficient route.

4.2.5 **Timeline of Models and Messages**

The timeline of the model calculations is presented in Figure 4-10. First the vehicle checks its sensors. The vehicle receives the information on its position, speed, direction and the road roughness and road gradient from the sensors. The vehicle then calculates the road that it is on from the position information. Next it sends its speed and the ID of the road that it is on to the other vehicles and then waits to see if any other vehicles send messages regarding their speed and location. The length of time the vehicle spends waiting is τ seconds. A period of τ = 0.5 seconds was used for the tests in this thesis. This value is used to allow equal time for sending and receiving. After the vehicle has waited this period, it then updates the Traffic Model from the information it has received. Then it requests road data from the server. When it has received the road data from the server, it calculates the optimal route using the EcoTrec algorithm and the models.

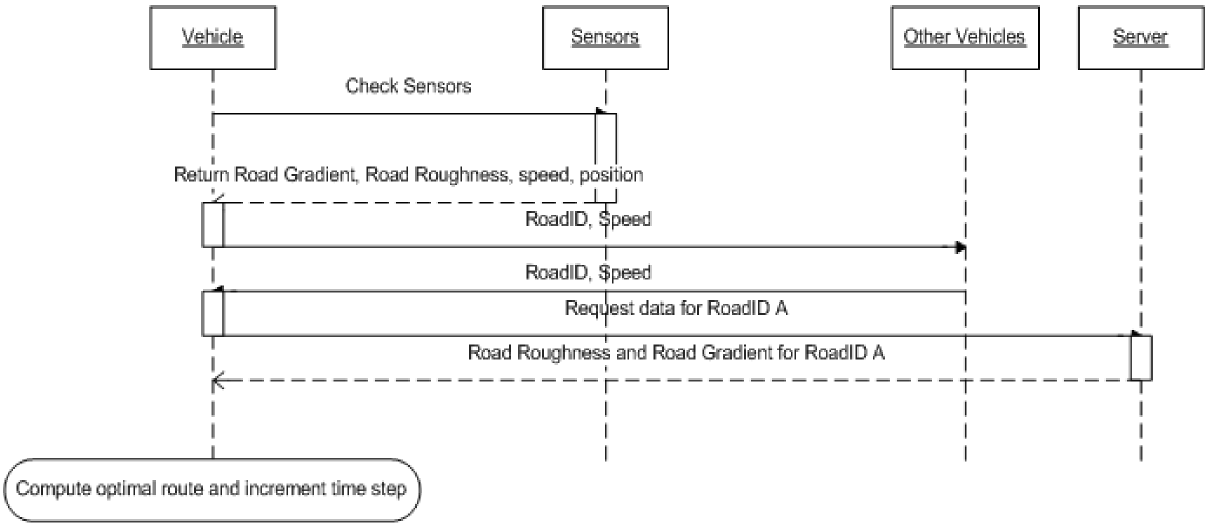

Figure 4-10 Timeline of model calculations

4.2.6 **Message Routing Scheme**

The GeoRouting protocol (GRP) [294] was used to route the VANET messages. GRP uses the fact that all nodes are aware of their location to route messages. By using beaconing and listening to the channel the node is able to create a table of nearby nodes. The messages are sent using topology-based broadcast (TopoBroadcast) GeoRouting scheme. TopoBroadcast sends messages to all vehicles within a certain distance in terms of hops. The number of hops is up-bounded by MaxHopCount. This was done for a number of reasons, in order to: localize message exchange, not to load the VANET too much and to avail from high throughput (which decreases with the number of hops). The 802.11p data channel is used to exchange the messages, but the control channel may be used if the VANET network is congested with less important messages.

4.3 **Complexity Analysis**

The complexity the EcoTrec system will now be discussed in detail within this section.

Messages are exchanged between vehicles with a frequency of $\boldsymbol{\phi}$ = 1 Hz. The number of cars $\boldsymbol{V}$ should be roughly 1,000 is most simulations. The size of the message is roughly $\boldsymbol{S}$ = 57 bytes or approximately 450 bits. The calculation of 57 bytes is shown in equation (4-6). The number of hops is $\boldsymbol{z}$ = 10. According to Han et al. [292] 802.11p has a data rate of between 3 -27 Mbps, the commonly assumed default is $\boldsymbol{D}$ = 6 Mbps. The amount of data exchanged is:

$$\text{Total amount of data} = \frac{S\ x\ V\ x\ z}{D} \qquad (4\text{-}4)$$

$$\text{Total amount of data} = \frac{450\ bits\ x\ 1{,}000\ vehicles\ x\ 10\ hops}{6{,}000{,}000\ bps}$$

$$\text{Total amount of data} = 0.75$$

However the cars only send a new message when they are on a new road segment or the velocity of the road has changed and the number of consecutive hops may vary due to network disconnections. This will reduce the total number of sent messages in the actual simulations.

Each individual vehicle has a traffic model stored in its database. This database stores the most up-to-date information on the local traffic conditions. This is being constantly updated from the messages received from other vehicles.

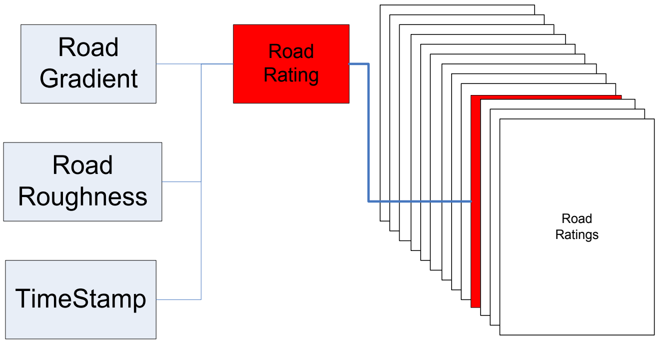

Figure 4-11 The contents of the road rating link list

This information is stored in a link list, in order for the data to be quickly searched for information. This information is stored in structures along with the road ID, traffic rating or road rating. This list will be n x m structures large, assuming for n vehicles, each storing information regarding m nearby roads. This totals S x n x m bytes as each structure is S = 57 bytes in size. The calculation of 57 bytes is shown in equation (4-6).

As already mentioned, the historical traffic conditions as well as the road conditions are stored by a central Server. The traffic conditions are sent to the Server so that the traffic conditions for that certain time are recorded for future use. The vehicles send the Server road conditions, if they detect a change. This way the road conditions are kept accurate and up to date. The Server also stores the location and severity of potholes encountered by the vehicles.

Each message contains a number of fields: SenderID (the id of the vehicle), message type (broadcast or unicast), message id (road or traffic condition), road id (the road referred to), message (containing the road or traffic rating), timestamp and sequence number of message. These can be seen in Figure 4-12.

According to Han et al. [292] 802.11p has a data rate of between 3 -27 Mbps, the commonly assumed default is $\boldsymbol{D}$ = 6 Mbps. The frequency is F = 5.9 GHz. This would mean that each of the EcoTrec messages would take up approximately 0.0075% of the bandwidth.

$$\frac{450\ bits}{6{,}000{,}000\ bps} \qquad (4\text{-}5)$$

$$= 0.0075\%$$

The messages sent between the vehicles contain the senderID, which is stored as a string, and is 20 bytes long. Next the message type is stored. This can be a broadcast message or a unicast message and is stored as a Boolean, which is 1 byte in size. The messageID is stored as an integer, which is 4 bytes in size. This determines whether the message is to do with the average speed of vehicles on the road, the spacing between vehicles, the road gradient or the road surface conditions. The road the sender is on, roadID, is stored as a string, and is 20 bytes long. This field is obviously quite important for determining either the traffic conditions or road conditions on that road. The message itself is stored as a float, which is 4 bytes in size.

The time-stamp is stored as an integer, which is 4 bytes in size. Lastly there is the sequence number, which is an integer detailing the number of messages the sender has sent, this is 4 bytes in size.

$$S = 20 + 1 + 4 + 20 + 4 + 4 + 4 = 57\ bytes \qquad (4\text{-}6)$$

SenderID	messageType	messageID	RoadID	message	timestamp	Sequence Number

Figure 4-12 Message data fields

For example a message frequency of ϕ and z hops would lead to a maximum of z*ϕ number of messages per second being exchanged which totals (z*ϕ)*0.0075 % of the bandwidth.

The frequency for the simulations in this thesis was set to one Hz. The number of hops used with-in the multi-hop communication was set to 10, which would give a maximum of 0.75% use of the bandwidth.

4.4 Summary

This chapter introduces the EcoTrec**,** a novel eco-friendly routing algorithm for vehicular traffic. The architecture and algorithm are introduced and discussed. The various models and sequence diagrams are presented, along with detailed analysis of messages and overhead.

Chapter 5 TimeAnts - Architecture and Algorithms

5.1 Introduction

This chapter introduces the Time-Ants architecture and algorithm. *Time-Ants* is an *ant-colony optimization-based algorithm,* which considers that an amount of "pheromone" or a traffic rating is assigned to each road at any given time in the day. Using an innovative algorithm the vehicle's routes are chosen based on these traffic ratings, aggregated in time. After several iterations this results in a global optimum for the traffic system. Bottlenecks are identified and avoided by machine learning.

Existing traffic information systems such as TomTom [82] or Google maps traffic [295], take information from induction loops. However these are expensive and not placed at every junction. Collecting information from vehicles via VANETs could provide traffic maps with far higher granularity. VANET-based solutions could improve the efficiency of use of the road network. Traffic congestion could easily be detected and predicted without having to install many induction loops or traffic cameras. The vehicles could be instructed to avoid busy roads at certain times without having to set up large expensive electronic signs. This would benefit all cities, but especially those which are experiencing a great increase in population and number of vehicles on the road, and have limited finances to invest in urban planning and/or infrastructure upgrades.

Often nature presents the best solutions to problems, by virtue of millions of years of evolution. Among these solutions, swarm algorithms address the problem of decentralized routing of units and Ant colony optimization (ACO) presents a brilliant method for choosing the best route. Each ant leaves some pheromone down when it walks along. Other ants then follow and leave down more pheromone, reinforcing the route. Although ACO is not directly applicable to vehicle routing, because when too many cars go on the same road traffic congestion occurs, an innovative ACO extension is beneficial.

This chapter introduces *Time-Ants, a novel ACO-based algorithm which determines optimum routes for vehicular traffic in both space and time dimensions.* Rakha et al. [296] showed that US vehicle traffic is very similar for weekdays , but varies considerably on weekends or if there are incidents. The paper by Immers et al. [297] described how the traffic flow affects congestion, namely that as the number of vehicles in a road system increases, a tipping point is reached at some stage. When the number of vehicles goes above this point, the average speed of vehicles rapidly drops. Time-Ants takes into account both these studies and optimizes the road use.

Firstly the information collection and aggregation is discussed. Secondly the architecture and its various components are introduced and discussed. The algorithm is then described in detail, followed by an examination of the communication protocol description. Finally the load balancing for Time-Ants is explained followed by a summary of the chapter.

5.2 **Architecture**

Figure 5-1 illustrates the Time-Ants architecture, which is composed of: ***vehicle models***, ***road models***, a ***time-dependent traffic model*** and a ***current traffic model***. This architecture is distributed across a number of vehicles and a Server. The ***vehicle model*** contains the vehicle's speed and position. The ***road model*** contains the id, position, length and speed limit information for a road segment that the vehicle is on. The ***current traffic model*** contains the instantaneous traffic information in the area, whereas the ***time-dependent traffic model*** contains the traffic information collected throughout a whole day.

Each vehicle is equipped with a digital map and GPS receiver to determine which road it is on. Information from these sensors is fed into the ***Vehicle Model***.

A Server has a database with all the roads and their traffic scores, for all the time-steps throughout the previous day. The time-step t is the discrete period for which traffic data is stored. This information is used to form the ***time-dependent Traffic Model***.

The vehicle communicates with the server to retrieve the traffic information on the roads at specific times, relevant to the vehicle. The vehicle sends messages containing the road ID and the time the vehicle will be on that road. The Server then responds with the traffic rating for that road at the indicated time. This information on the traffic ratings at the required times will allow the vehicle to construct a model of the current traffic conditions, called the current Traffic Model. The estimated traffic on each road is then entered into the Time-Ants algorithm to compute the optimum route for the vehicle. This route is then sent to the vehicle model in order to help reroute the vehicle.

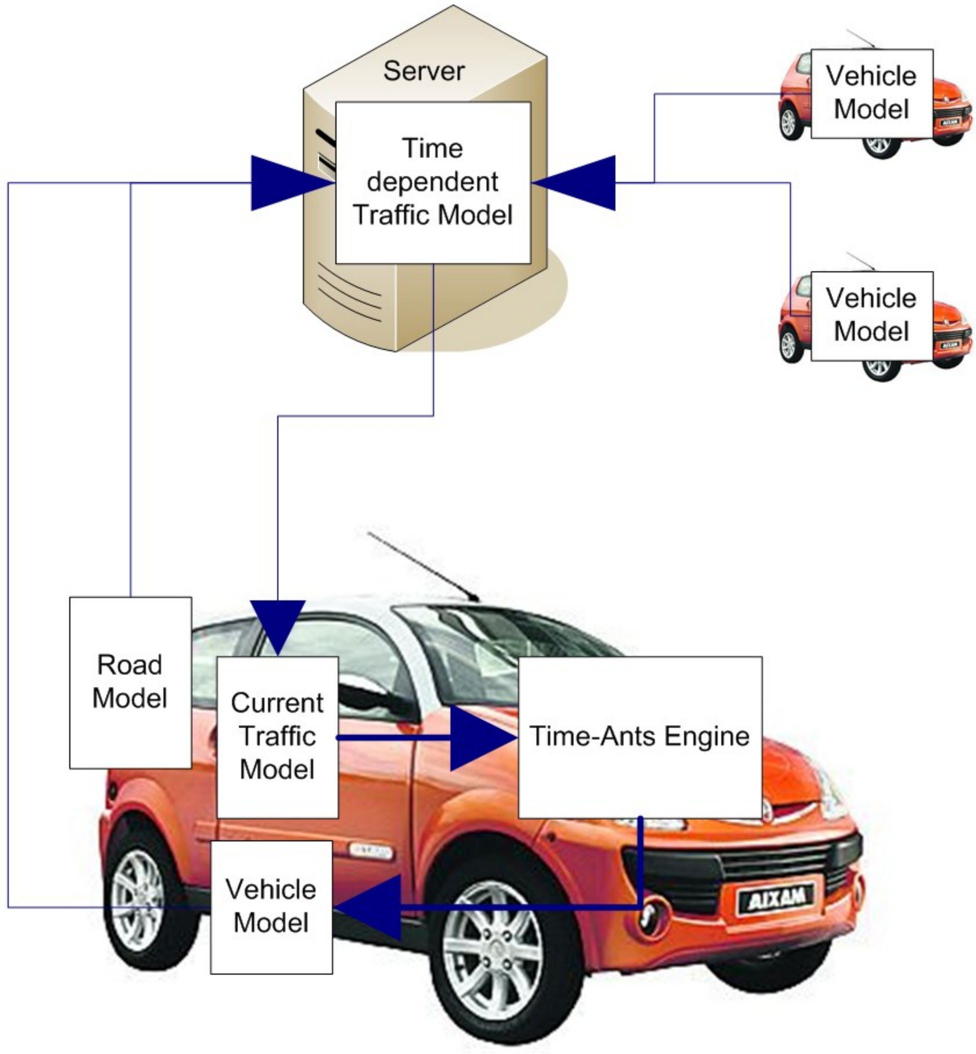

Figure 5-1Time-Ants Architecture

A Vehicle Model contains information on vehicle position and speed. The current position, speed and time from all the vehicle models are sent to the server regularly. This allows the server to build a new time-dependent traffic model.

The vehicle-server communications are achieved using 802.11p and the use of RSUs. If the vehicle is not in the immediate range of an RSU, multi-hop communication, via other vehicles, is used to reach the nearest RSU.

5.2.1 Vehicle model

The vehicle model is illustrated in Figure 5-2. The position of the vehicle can be determined from the on board computer from GPS sensors, the direction from an electronic compass, and the velocity from the speedometer. This is needed to calculate the average velocities along road segments at each time-step t. This information is then passed on to the time-dependent traffic model on the server.

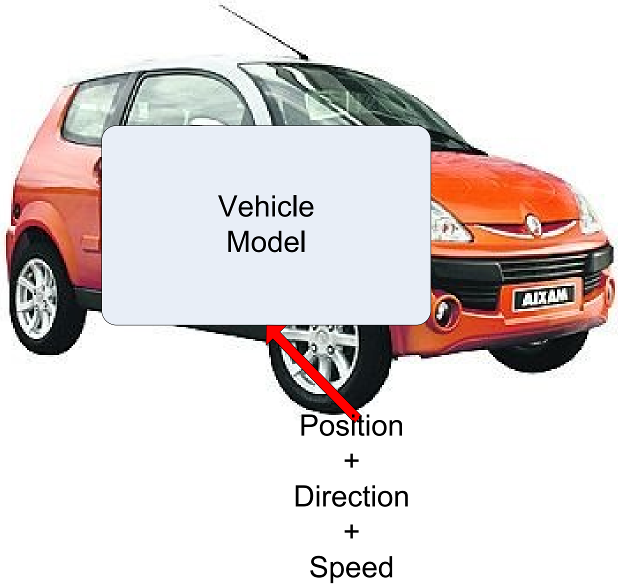

Figure 5-2 Vehicle Model

5.2.2 **Road Model**

The Road Model stores the id, position, length and speed limit of the various road segments. This is needed in order to keep the information in order, so when a vehicle sends its speed and position, an algorithm is able to deduce that this vehicle is traveling at that speed on road segment ***r***. The information on the length and speed limit is also important for the load balancing algorithm. The load balancing algorithm is needed to prevent traffic congestion forming on road segments. It is discussed in detail in section 5.4 All of these values are constants and a complete set of road models of the area are stored on each vehicle.

5.2.3 **Time-dependent Traffic Model**

The Time-dependent Traffic Model is illustrated in Figure 5-3. This stores the entire traffic information for one 'day', in other words the average speed along each road segment at every time-step. This is created for vehicles in the next day to be better informed regarding nearby traffic conditions.

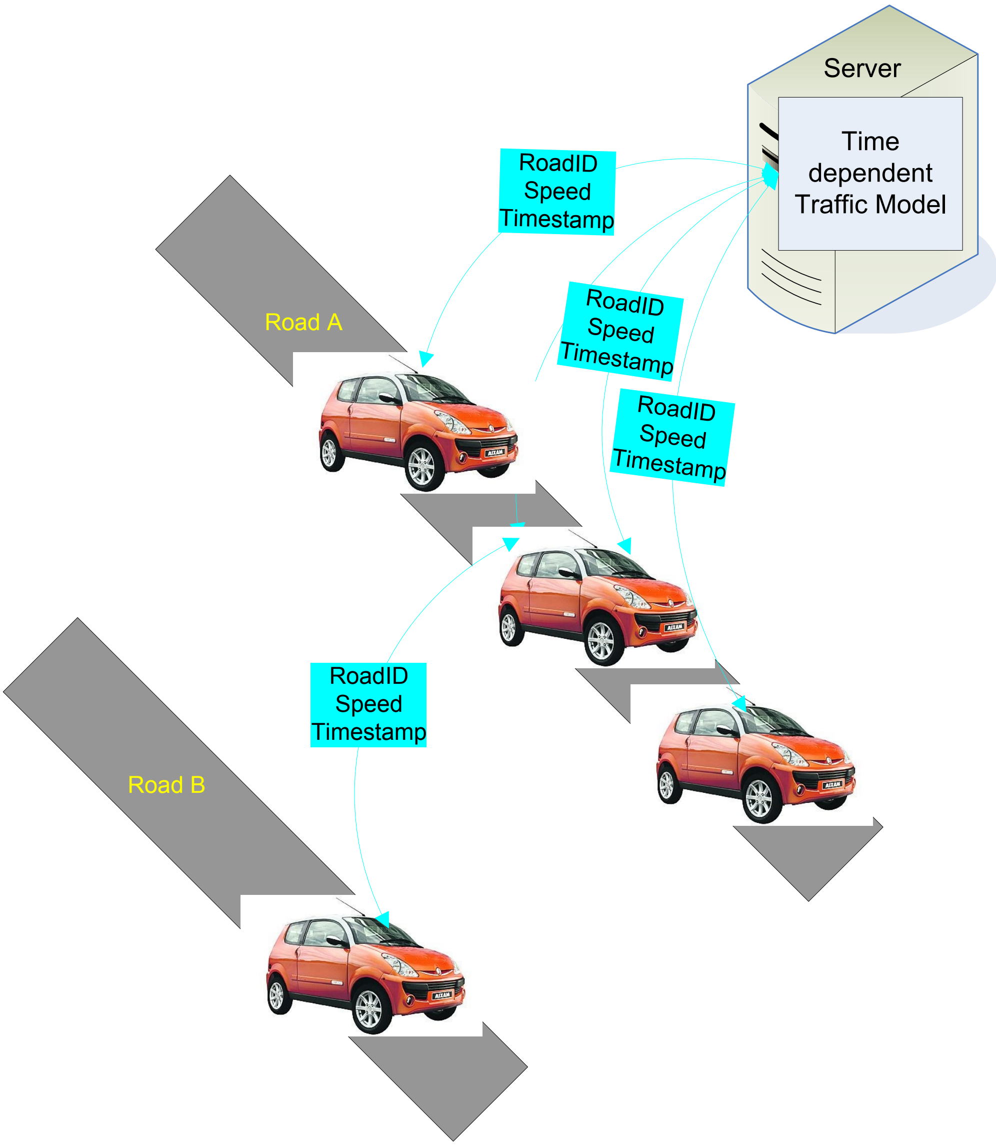

Figure 5-3 Time-dependent traffic model

These are stored in a list of arrays each containing an int for the time-step, a string for the road ID and a float for the average speed along that road ID at that time-step.

This is updated via messages received from the vehicles regarding their position and speed. This is used in the next day to send messages regarding the expected to vehicles to allow them to create a current traffic model.

Figure 5-4 shows the sequence diagram for the time-dependent traffic model. The vehicle's sensor information is sent to the on board computer where the position, velocity and direction are calculated. Next the vehicle sends this to the server using VANET communications.

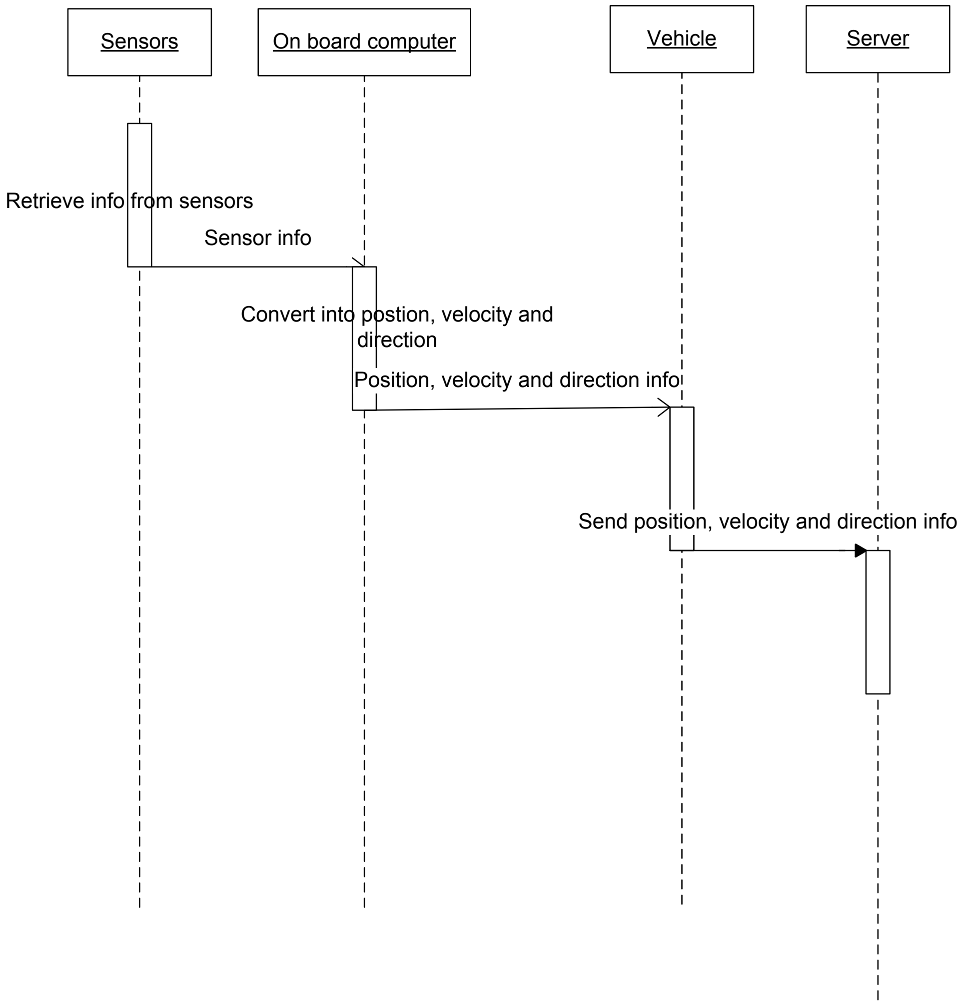

Figure 5-4 Vehicle calculating information to send to server to build time-dependent traffic model

5.2.4 **Current Traffic Model**

The Current Traffic Model is illustrated in Figure 5-6. This stores the expected congestion at nearby roads for the times that the vehicle will be near the roads. This is done by calculating the distance divided by the expected speed. This allows the vehicle to determine the best route during the time it will travel there. It is created from traffic data sent from the server to the vehicles, and is updated in the same way. It is used by the vehicle to determine its route based on expected traffic congestion.

Again these are stored in a list of arrays each containing an int for the time-step, a string for the road ID and a float for the average speed along that road ID at that time-step.

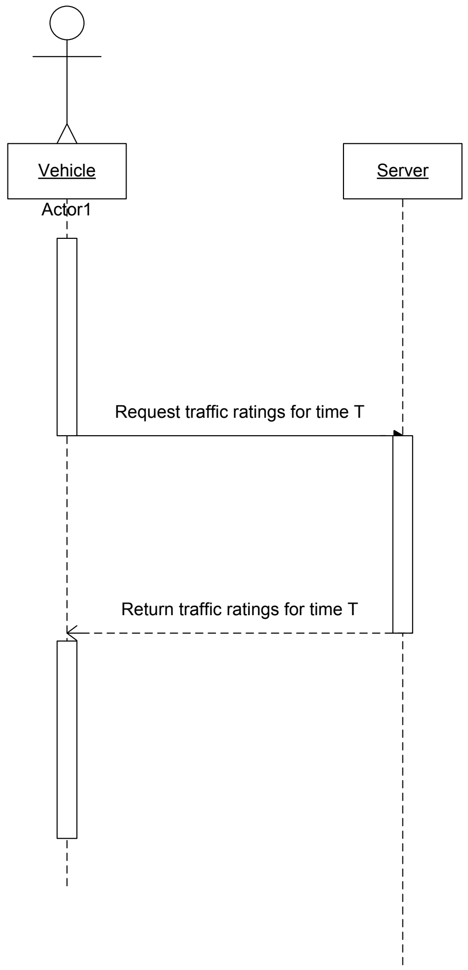

Figure 5-5 Requesting information from server to build current traffic model

Figure 5-5 shows the sequence diagram for the current traffic model. The vehicle requests information on the nearby roads and then the server returns the requested information.

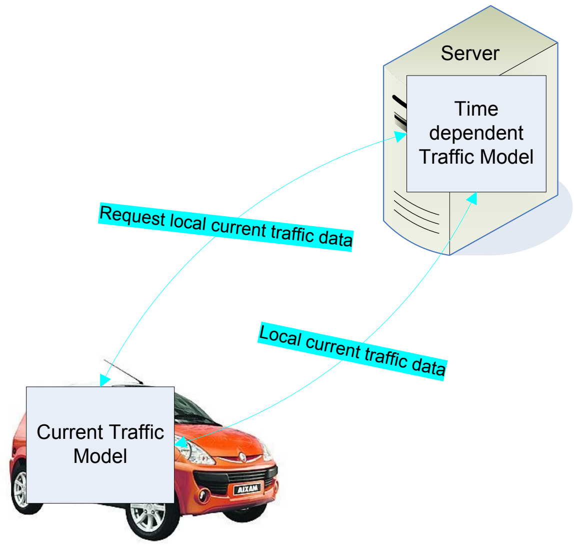

Figure 5-6 Current traffic model

5.3 Time-Ants Algorithm

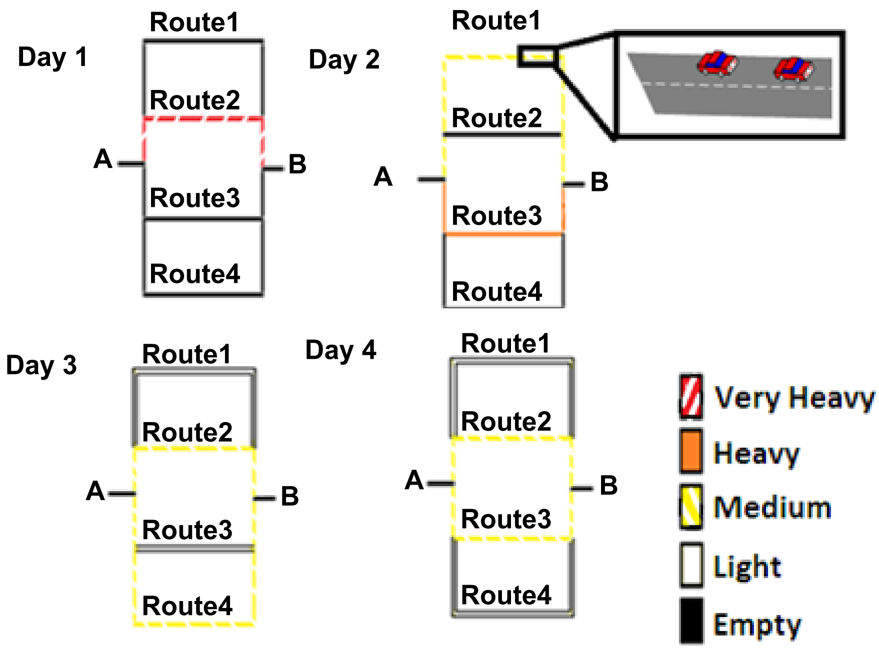

Figure 5-7 Illustration of iterative improvement in Time-Ants

As traffic conditions are roughly similar from day to day during weekdays, historical data can be used to make decisions for routing and eventually the road network can be more efficiently used.

Iterative use of the Time-Ants algorithm over several days enables important benefits, as illustrated for instance in Figure 5-7. During Day 1 Route 2 is overused, so the next day more vehicles are sent on other routes using Time-Ants. This process continues from day to day. By Day 4 the traffic is a lot smoother. Periodically, each vehicle determines the traffic rating on the road it is travelling. The road rating is determined by comparing the speed of the vehicle divided by the speed limit of the road. The vehicles then send this information over the VANET to a server. This is recorded on the central server for that location and time of day.

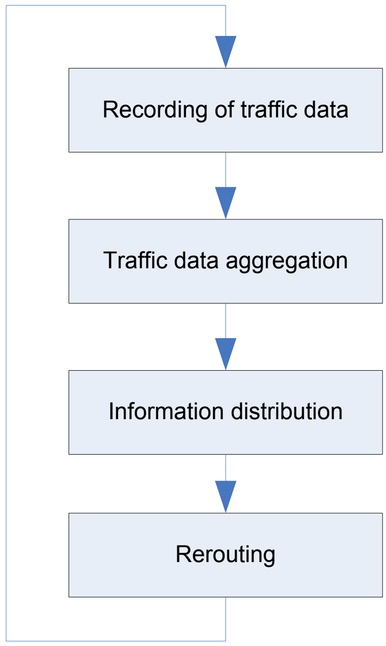

Figure 5-8 Time-Ants Stages

This algorithm is divided into a number of stages. Firstly the traffic data is recorded by the vehicles during a 'day' (one instance of the simulation). Secondly this data is aggregated by the Server to create a model of traffic conditions during this 'day'. In the third stage this information is distributed to vehicles in the next 'day'. In the final stage the vehicles choose load balanced routes based on this information and this process repeats itself. This process is shown in Figure 5-8.

5.3.1 **Recording of traffic data**

Each vehicle consistently records its speed every time step t. For the simulations in this thesis t was set to one second. The vehicles send this information to the server via multi-hop communication using 802.11p. The messages containing the speed of the vehicles are shown in Figure 5-9.

5.3.2 **Traffic Data Aggregation**

The server then computes the average speed on each road segment for that time. This is done by adding all the speeds for each segment and dividing by the number added to get the average speed. By the end of the simulation a complete time-dependent traffic model is built. Each road segment then has a score or "pheromone" amount for a given time in the day.

5.3.3 **Information Distribution**

This section introduces the message contents, number of messages exchanged, the size of some models and the sequence diagrams of the various models.

SenderID	messageType	messageID	RoadID	message	timestamp	Sequence Number

Figure 5-9 Message contents

Figure 5-9 is used for both the messages building a new time-dependent traffic model and returning the traffic information to the vehicles.

The messages sent, between the vehicles and server, contain the senderID, which is stored as a string, and is 20 bytes long. Next the message type is stored. This can be a broadcast message or a unicast message and is stored as a Boolean, which is 1 byte in size. The messageID is stored as an integer, which is 4 bytes in size. This determines whether the message is to do with the speed of a vehicle on the road or a previous average speed on a road from the time-dependent traffic model. The road the sender is on, roadID, is stored as a string, and is 20 bytes long. This field is obviously quite important for determining either the current traffic conditions or previous traffic conditions on that road. The message itself is stored as a float, which is 4 bytes in size.

The time-stamp is stored as an integer, this relates to the time the message refers to for consideration of the Time-Ants algorithm. This is 4 bytes in size. Lastly there is the sequence number, which is an integer detailing the number of messages the sender has sent, this is 4 bytes in size.

$$20 + 1 + 4 + 20 + 4 + 4 + 4 = 57\ bytes \qquad (5\text{-}1)$$

Once again the GeoRouting protocol (GRP) [294] was used to route the VANET messages. GRP uses the fact that all nodes are aware of their location to route messages. By using beaconing and listening to the channel the node is able to create a table of nearby nodes. The messages are sent using topology-based broadcast (TopoBroadcast) GeoRouting scheme. TopoBroadcast sends messages to all vehicles within a certain distance in terms of hops. The 802.11p data channel is used to exchange the messages, but the control channel may be used if the VANET network is congested with less important messages.

5.3.4 Rerouting

As suggested in the traffic flow theory by Immer et al. [297], vehicle speeds are only effected by traffic congestion when vehicle numbers increase above a certain point. Consequently, Time-Ants load-balancing is performed, when the speed of vehicles on a road drops beneath the congestion threshold. The congestion threshold is when the actual speed drops beneath a certain percentage of the speed limit of the road. This is discussed in greater detail in section 5.4

If load-balancing is not needed, the vehicles simply drive on the fastest route. The fastest route is determined by dividing the route length by the speed limit.

When choosing a route, each vehicle estimates how long it will take to get to each junction. It then sends a request to the server for any ratings associated with the adjoining roads near the time it will arrive there. After the vehicle receives the information, one of these roads is chosen according to the Time-Ants load-balancing mechanism and according to the road's score. If there are no recorded ratings stored on the server around the requested time, then it is assumed that the road is empty at that time and then the rating is defined as the speed limit of that road.

5.4 Load-Balancing

Time-Ants load-balancing is performed based on a metric determined from the ratio between the speed limit and the actual speed on that road as discussed in the speed/flow diagram by Immer et al. [297]. Time-Ants applies load-balancing when the actual speed drops beneath 80% of the speed limit.

The load-balancing algorithm should prevent flash-crowding on the roads with high scores. The number of vehicles which choose to travel on a road at a junction is proportional to its score. More vehicles will travel on the roads with higher scores. The probability that a car will drive on route R_{xy} from junction j is set to the average travel time on that route to the power of 3 divided by the sum of all travel times of the routes leaving that junction to the power 3. This value was chosen in order to balance the fastest (when empty), with the slower but currently roads. This gives us the following equation.

$$Prob(R_{xy}) = \frac{(TIME\_R_{xy})^3}{\sum_i (TIME\_R_{ij})^3} \qquad (5\text{-}2)$$

TimeAnts extends Dijkstra lowest edge weight algorithm, with load-balancing along congested edges, to determine the route. In other words the route with the lowest overall score will be chosen, as long as none of the edges chosen have a lower congestion score than the threshold. The congestion score is determined from the speed of vehicles on an edge divided by the speed limit of an edge. If there is a congested edge, vehicles will be distributed to other edges at this point leading to multiple good but sub-optimal routes for vehicles to follow.

A full graph search, from the origin to the destination, is performed. The fastest edges are chosen in this fashion, unless an edge is congested; in this case load-balancing is performed near this edge. This graph search is described in Algorithm 1. The algorithm makes use of the following functions: *no_following()* – returns the number of edges following an edge; *traffic_congestion()* returns the traffic congestion expected on an edge; *traveltime()* returns the expected travel time on an edge; *assign_random()* returns an edge determined by equation 5-2 from the random number generated R, the travel times and the following edges.

Algorithm 1 TimeAnts Algorithm Pseudo Code

```
//from Origin (O) to Destination (D)
route_list.clear()
//loop: through edges on map
for all edge[i] in Map
//if destination reached exit
if (edge[i] == D)
{
    exit
}
//return number of edges leading from this edge
int n = no_following(edge[i])
total_travel_time = 0
float edge_traveltime = max_traveltime
//loop through following edges
for all edges[j] following edge[i]
{
total_travel_time = total_travel_time +     (traveltime(edge[j])^3)
//if this edge is faster than previous ones consider it as fast edge
if (edge_traveltime > traveltime(edge[j]))
{
   fast_edge = edge[j]
   edge_traveltime = traveltime(edge[j])
}
```

```
}
//return traffic congestion on edge
TC = traffic_congestion(fast_edge)
//check if edge is congested with traffic
if (TC < threshold)
    route_list.add(fast_edge)
else
{
Load balance here according to equation 5-2
R = rand() % (total_travel_time)
Rand_edge = assign_random(R, total_traveltime, edge[i])
route_list.add(rand_edge)
}
```

5.5 Overhead

Table 5-1 Overhead parameters

η	number of roads to request
U	update frequency
ΔV	number of vehicles entering map
V	Vehicle
ΣV	total number of vehicles
S	size of message
z	number of hops
T	time step

Each vehicle must receive the relevant information on the roads ahead of it. The number required initially is $\boldsymbol{\eta}$. This is requested as the vehicle first enters the map, so the initial requests would be $\boldsymbol{\eta}$ by the number of vehicles entering the map each second $\Delta\boldsymbol{V}$. The update for each vehicle happen every $\boldsymbol{U}$ seconds. Each message is of size $\boldsymbol{S}$ and travels a maximum of z hops. Each vehicle $\boldsymbol{V}$ also sends a message to the server regarding their road segment each time step $\boldsymbol{t}$.

$$initial\ traffic\ model\ request = \boldsymbol{\eta} \times \Delta\boldsymbol{V} \times \boldsymbol{S} \quad (5\text{-}3)$$

The number of roads to the destination of the vehicle in these simulations roughly $\boldsymbol{\eta}$ = 10. It would be less than this per vehicle during the update as it is closer to its destination. All the vehicles do not enter the map at the same time, in most of these simulations it is less than 1 vehicle per second $\Delta\boldsymbol{V} = \boldsymbol{1}$. The size of the messages is $\boldsymbol{S}$ = 57 bytes = ~450 bits as shown in equation (5-1).

$$initial\ traffic\ model\ request = \boldsymbol{\eta} \times \Delta\boldsymbol{V} \times \boldsymbol{S} \quad (5\text{-}4)$$

$$initial\ traffic\ model\ request = 10 \times 1 \times 450$$

$$initial\ traffic\ model\ request = \sim 4.5 \text{ kbps}$$

This works out at approximately 4.5 kbps.

The Server is at the centre of the map and the number of hops z is set to 10. The most vehicles $\boldsymbol{\Sigma}\ \boldsymbol{V}$ contained in these simulations were 500 vehicles. If we assume the update occurs roughly every 5 seconds $\boldsymbol{U}$ = 5.

$$size\ of\ messages\ from\ update = \frac{\boldsymbol{\Sigma V} \times \boldsymbol{z} \times \boldsymbol{S}}{U} \quad (5\text{-}5)$$

$$size\ of\ messages\ from\ update = \frac{500 \times 10 \times 450}{5}$$

$$size\ of\ messages\ from\ update = \sim 450 \text{ kbps}$$

Each vehicle also must inform the server of its speed on each road segment in order to create the time-dependent traffic model. This would add an extra 450 bits per second per vehicle.

$$time - dependent\ traffic\ model\ creation = number\ of\ vehicles \times size\ of\ message \times numberof\ hops \quad (5\text{-}6)$$

$$time - dependent\ traffic\ model\ creation = \boldsymbol{\Sigma V} \times \mathbf{s} \times \boldsymbol{z}$$

$$time - dependent\ traffic\ model\ creation = 500 \times 450 \times 10$$

$$time - dependent\ traffic\ model\ creation = 2.25 \text{ Mbps}$$

$$total\ number\ of\ messages \qquad (5\text{-}7)$$

$$= size\ of\ messages\ from\ update + initial\ traffic\ model\ request + time\ dependent\ traffic\ model$$

$$total\ number\ of\ messages = 450 + 4.5 + 2250$$

$$total\ number\ of\ messages = \sim 2700 \text{ kbps}$$

$$\text{Bandwidth used} = \frac{2700\ kbps}{6{,}000\ kbps} \qquad (5\text{-}8)$$

$$\text{Bandwidth used} = 45\%$$

This should take up roughly 45% of the available bandwidth.

5.6 Size of Models

The size of the Time-dependent Traffic Model will be a product of the total number of time steps in the simulation$\Sigma \boldsymbol{t}$, the total number of road segments on the map $\Sigma \boldsymbol{r}$, and the size of information for that road ς.

$$\Sigma \boldsymbol{t} \times \Sigma \boldsymbol{r} \times \varsigma \qquad (5\text{-}9)$$

There is roughly 1750 time-steps in the largest simulation, along with about 100 road segments. These must store a float for the average speed on the road segment, an integer for the time-step and a string for the road segment name.

$$1750 \times 100 \times (4 + 4 + 20) \times 8 = \sim 40\ Mb$$

The size of the Current Traffic Model will be a product of the total number of road segments on the map $\Sigma \boldsymbol{r}$, and the size of information for that road ς.

$$\Sigma \boldsymbol{r} \times \varsigma \qquad (5\text{-}10)$$

$$100 \times (4 + 4 + 20) \times 8 = \sim 24\ kb$$

The size of the Road Model will be a product of the total number of road segments on the map $\Sigma \boldsymbol{r}$, and the size of information for that road **c**.

$$\Sigma \boldsymbol{r} \times \mathbf{c} \qquad (5\text{-}11)$$

The information stored will be the road id plus four floats specifying its start and end positions.

$$\Sigma \boldsymbol{r} \times \mathbf{c} = 100 \times (20 + 4 + 4 + 4 + 4) \times 8 = \sim 30\ kb$$

The size of the Vehicle Model will be the vehicle id plus two floats specifying its position, one float for direction and one float for its velocity.

$$(20 + 4 + 4 + 4 + 4) = \sim 300\ b$$

5.7 Summary

This chapter introduced Time-Ants a VANET-based ant-colony optimization algorithm which uses historical traffic data to improve traffic flows; this is a unique approach to dealing with traffic congestion.

Chapter 6 - Electric Vehicle Enhanced Dedicated Bus Lanes

6.1 Introduction

Most cities now have special lanes dedicated to buses, however these lanes are rarely used at full capacity. At the same time governments around the world are encouraging people to buy electric vehicles. This chapter proposes a policy change, namely the creation of electric vehicle enhanced dedicated bus lanes (E-DBL), by allowing electric vehicles access to bus lanes, in order to improve the use of road capacity. By opening bus lanes to electric vehicles, traffic congestion could be eased, the range of electric vehicles could be extended, and the travel times for electric vehicle owners could be reduced significantly. The chapter shows how by introducing E-DBLs, the bus journey times are not significantly affected given the current uptake of electric vehicles in most developed countries.

Every year sees an increase in the amount of CO_2 released into the Earth's atmosphere. This is despite growing awareness of the dangers of climate change. Governments around the world are constantly looking for ways to reduce their carbon footprint without reducing economic growth. The transport sector, particularly private vehicles, is a major source of CO_2. The transport sector in the USA accounted for 27% of CO_2 emissions in 2010, and of this 62% was emitted by passenger vehicles [298]. These figures were roughly similar in 2012, with a slight drop due to fewer miles travelled [299]. Much research has focused on improving vehicle efficiency in order to reduce net emissions. However producing higher efficiency vehicles has simply led to increased consumer demand for higher performance vehicles [300]. One possible solution to this problem is the increase in the uptake of electric vehicles (EV).

However, apart from many advantages, EVs have a number of disadvantages. EVs suffer from very short range in comparison with internal combustion engine cars (ICE). Currently, there is also very limited infrastructure for electric vehicles compared with that of ICE cars. This lack of infrastructure compounds the problem of limited range, making EVs suitable for short journeys only. EV batteries take a relatively long time to charge, when compared with the length of time for ICEs to refuel [301]. However new battery technologies [302], and introduction of schemes such as car-swapping and battery leasing

[303] are attempting to address this issue. There are also cultural barriers to EVs as described by Sovacool et al. [304] whose research showed that many people viewed EVs as cheap and small.

The savings promised by EVs are not sufficient at the moment either. Diamond et al. [305] showed that fuel prices were the biggest influence, but upfront payments had strong effects. Lave et al. [306] estimate that fuel prices would have to be three times higher than today's in order to make EVs competitive.

Another possible solution to limit the amount of CO_2 produced is to increase the use of public transportation. Bus lanes have become common in most developed cities as a way of making public transport more desirable. Bus-based rapid transport (BRT) is a transport system in which the buses have their own dedicated bus lanes (DBL). BRTs were first deployed in South American cities such as Bogota and they have now been planned worldwide, including in North America, Asia (China), South East Asia and Western Europe [307]. However DBLs have been criticised for making bottlenecks even worse and not using road capacity efficiently [209].

Opening bus lanes to electric vehicles is one way of solving both of these problems simultaneously. This would allow for more efficient use of road capacity, and make buses and EVs more desirable because of real or perceived reduction in journey times.

6.2 **Proposal**

This section proposes the introduction of *electric vehicle enhanced dedicated bus lanes (E-DBL)*, improving the current bus lane-based policy by allowing EVs to use DBLs. This contribution is a policy document. This has the effect both of encouraging the use of EVs by reducing the amount of charge they require and their journey time, and of making better use of road capacity, which otherwise is not efficiently used when employing DBLs, as mentioned earlier.

Figure 6-1 illustrates how by employing E-DBLs and moving the EVs to the bus lane, reduces congestion on the regular lanes and makes better use of the bus lanes, in comparison with DBLs. In the DBL picture, the top two lanes are congested but the bus lane is in free flow. By moving some of the vehicles into the bus lane as shown in the E-DBL picture, congestion can be reduced and EVs are now in free flow.

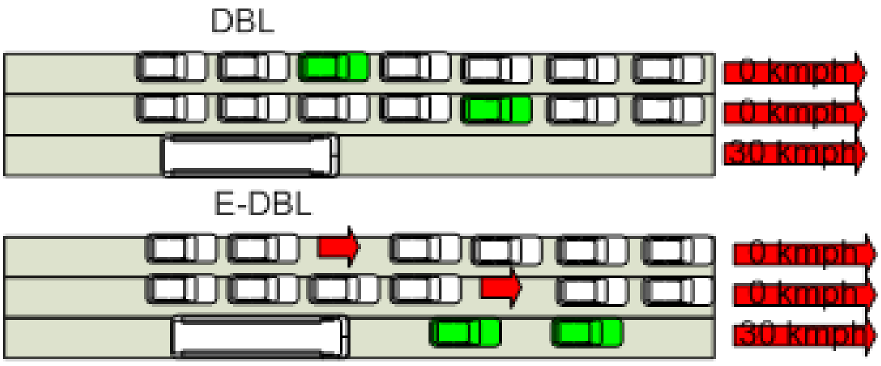

Figure 6-1 Diagram showing traffic with DBL and E-DBL

λ_b, λ_c and λ_e refer to the rate at which buses, electric vehicles and internal combustion engine vehicles enter the road segment respectively. δ_b, δ_e and δ_c refer to the rate at which buses, electric vehicles and internal combustion engine vehicles leave the road segment respectively. μ_b, μ_e and μ_c refer to the buses, electric vehicles and internal combustion engine vehicles on the road segment respectively

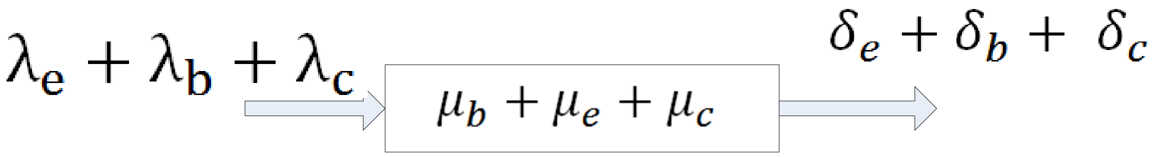

Figure 6-2 All lanes open

Figure 6-2 displays the all lanes open solution all the vehicles as $\mu_b + \mu_e + \mu_c$ enter the all the lanes.

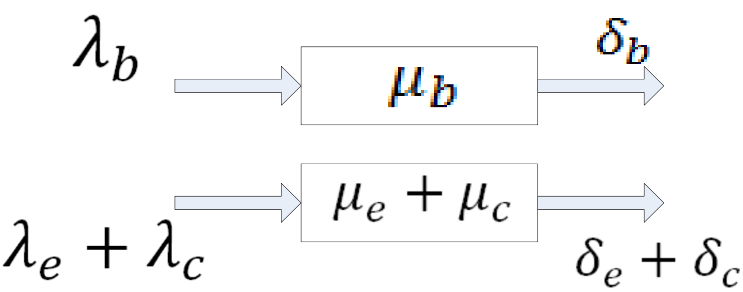

Figure 6-3 DBL

Figure 6-3 shows the DBL solution. The left lane is restricted to μ_b and the rest vehicles travel on the other lanes.

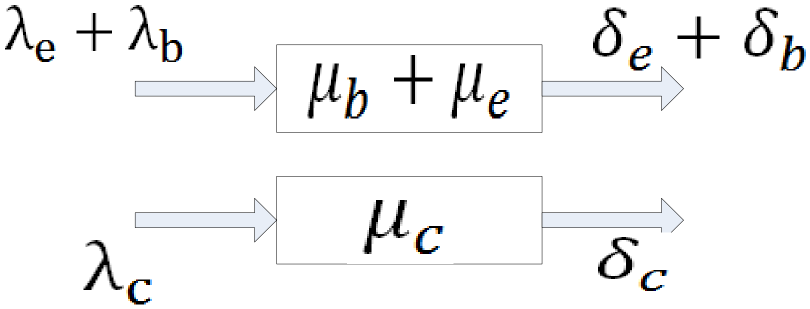

Figure 6-4 E-DBL

Figure 6-4 displays the E-DBL solution. The left lane is restricted to electric vehicles and buses and the internal engine vehicles must travel in the other lanes.

6.3 **Initial Testing**

A SUMO scenario was set up to test the effects of the three different lane schemes on the throughput of vehicles. This scenario consisted of a 1750 m road with three lanes. The vehicle trace consisted of 80 vehicles in total (50 regular cars, 20 EVs and 10 buses). The simulations with the different lanes schemes are shown below in Fig. The simulations were run for 1500 seconds and the amount of vehicles to reach the destination was recorded throughout.

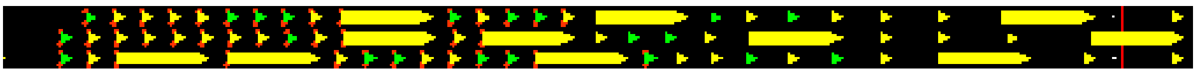

Figure 6-5 All lanes open in simulation

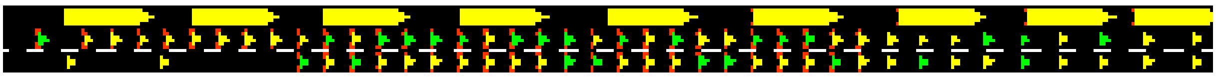

Figure 6-6 D-BL in simulation

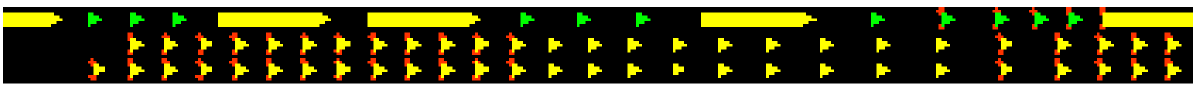

Figure 6-7 E-DBL in simulation

The effect of the different lane schemes with regard to throughput is shown next. In Figure 6-8 the effect of ‘All lanes open’ is shown all the vehicles have equal priority and reach 100% throughput at approximately the same point at 900 seconds. T-Tests confirmed that there was not any statistical difference between the results for the different vehicle types.

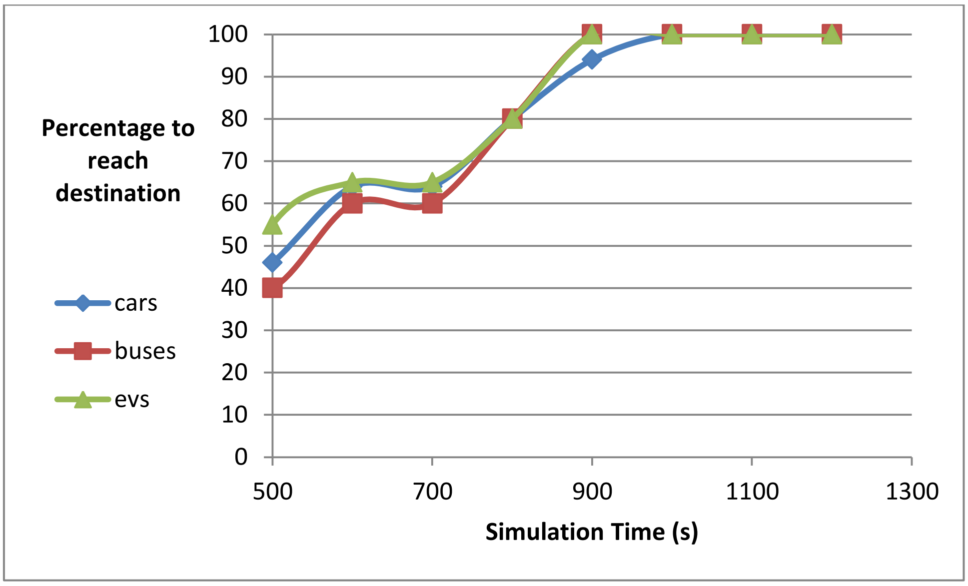

Figure 6-8 Percentage of different vehicle types to reach destination under ‘All lanes open’ scheme

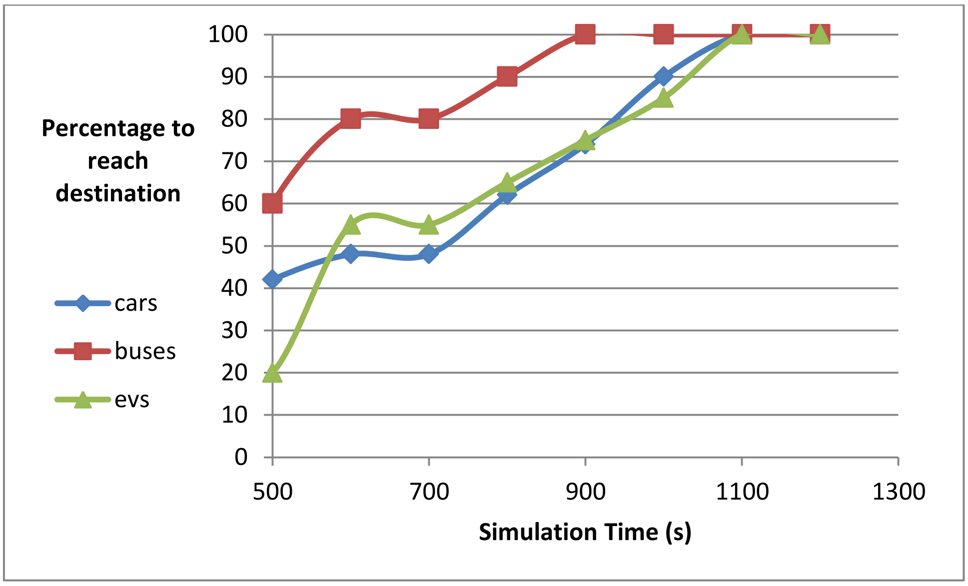

Figure 6-9 Percentage of different vehicle types to reach destination under DBL scheme

Figure 6-9 shows the effect of DBL on the throughput of the different vehicles. In this scheme the buses reach 100% throughput sooner, by 200 seconds, than the EVs and

ICEs. T-tests confirmed with a 95% confidence interval that there was a statistical difference between the buses and cars under this lane scheme. The buses outperformed the cars by 15% on average under this lane scheme.

Figure 6-10 shows the effect of E-DBL on the throughput of the different vehicle types. Again the vehicles with priority achieve higher throughput. The EVs have consistently a higher throughput than the ICES, by 5% on average from 500 to 1000 seconds. This difference was confirmed by T-Tests with a 95% confidence interval.

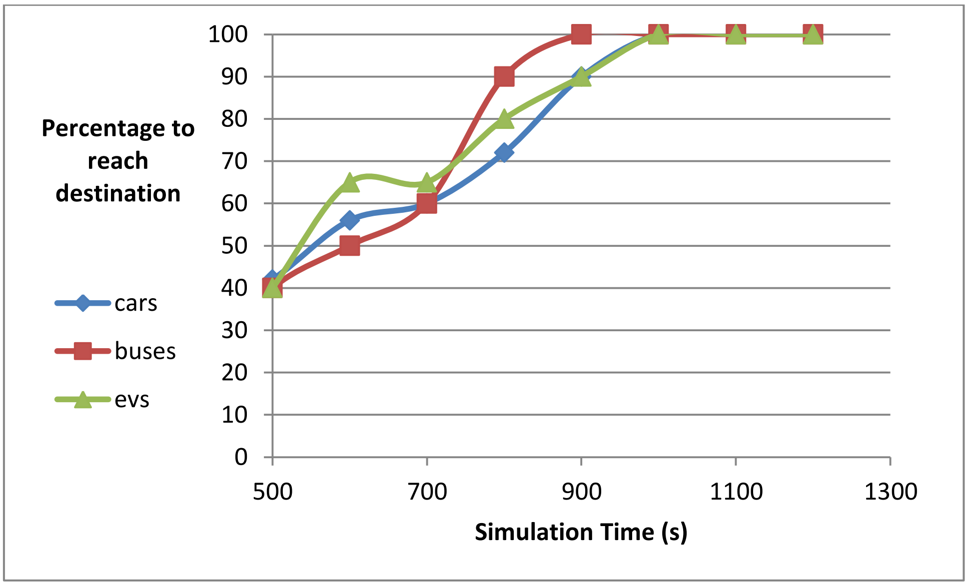

Figure 6-10 Percentage of different vehicle types to reach destination under E-DBL scheme

6.4 Summary

This chapter introduced Electric Vehicle Enhanced Dedicated bus lanes (E-DBL). By allowing electric vehicles access to bus lanes their use can be encouraged by reducing their journey times. This can be done without greatly affecting the journey of buses. This also improves the use of road capacity reducing congestion.

Chapter 7 – Testing and Results Analysis

7.1 Introduction

This chapter introduces and discusses in detail the testing and results for the algorithms and schemes presented in Chapter 4, Chapter 5 and Chapter 6. These were EcoTrec, Time-Ants and E-DBL.

7.2 EcoTrec Simulation-Based Testing Setup

This section presents the simulation-based testing setup for the assessment of EcoTrec, a traffic and road characteristic aware VANET-based routing solution for reducing carbon emissions.

7.2.1 Simulation Environment

The EcoTrec algorithm was modelled and tested on the iTETRIS simulator [308]. iTETRIS is an open source simulator designed to test inter-vehicle communication solutions and its development was funded by the European 7th Framework program. iTETRIS creates a bridge between the network simulator NS-3 [309] and the vehicular traffic simulator SUMO [310]. It was designed to be flexible, scalable and accurate and was coded in C++. SUMO is an open source vehicular traffic simulator. It is a microscopic traffic simulator, which simulates each individual vehicle as opposed to just traffic flows. NS-3 is an open-source discrete event network simulator and allows for the packet-level simulation of both wired and wireless networks.

For this research SUMO was extended to include data about road conditions, such as International Roughness Index (IRI), Mean Profile Depth (MPD) and gradient. For vehicle emission calculation the additional acceleration required to overcome gravity on slopes was added to the vehicles' acceleration to determine the fuel used on that route.

7.2.2 Simulation-based Modelling

EcoTrec was modelled as described in Chapter 4. Each vehicle deploys the vehicle model, the road model and the traffic model. To implement the EcoTrec algorithm the edge weight was calculated according to equation (4-1) Chapter 4, using the information on that route. If no traffic data was available for the route or the most recent traffic data was too old (over 20 seconds), the route was assumed to be free of traffic leaving a Traffic value (T) of 1. For these simulations Traffic Weighting (W_T) from equation (4-1) was set to 2 in order to give traffic a relatively high importance and MaxHopCount was set to 10 in order to make sure the overhead did not run too high

The proposed EcoTrec routing algorithm was compared against three alternative approaches: the routing algorithm described in Sommer et al. [89], Dijkstra shortest path algorithm, commonly used by GPS road guidance systems [84], and against real-life routes taken by the vehicles, as recorded in the TAPASCologne dataset [13]. The TAPASCologne project aims to reproduce "*with the highest level of realism possible, car traffic in the greater urban area of the city of Cologne*". This was chosen as it includes the routes the cars took if they had no rerouting information. This trace was generated from a survey from 2001-2002 of the journey of 12,600 people in Cologne [311]. The TAPASCologne dataset includes information such as a 400 km squared map as well as 700,000 individual car trips over a 24 hour period. Only the trace for 6:00 am to 8:00 am are available without special request [13].

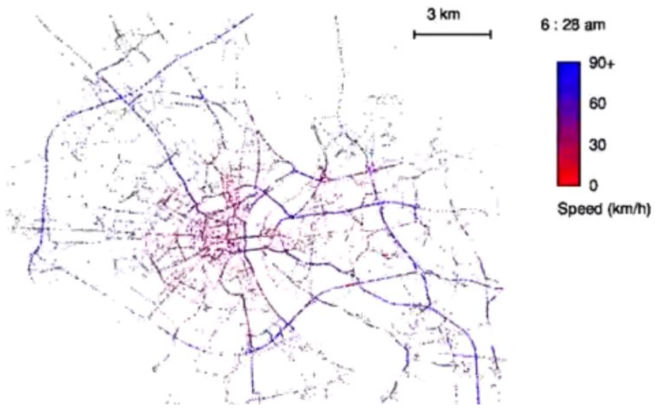

Figure 7-1 Screenshot available from TAPASCologne website [13]

The Dijkstra's shortest path algorithm uses a graph search to find the shortest path based on certain metrics. To simulate the Dijkstra routing algorithm, a travel time function available in SUMO was used. The Sommer algorithm implementation involved assigning roads with heavy traffic a high edge weight so the vehicles avoid these routes.

7.2.3 **EcoTrec Testing Scenarios**

7.2.3.1 Scenario 1-Influence of Compliance and Penetration Rates

The time of day, 6:00 am to 6:15 am and 6:15 am to 6:30 am, is varied in Scenario 1 to see the effect of this metric on the system. The penetration rate and compliance rate are also varied to note their effects. Penetration rate refers to the percentage of vehicles which are VANET communications-enabled. When dealing with compliance rate in this testing all the vehicles have network connectivity, can forward VANET vehicular routing algorithm messages, and can receive algorithm recommendations. Yet some vehicles choose not to follow the advices. The compliance rate is the percentage of vehicles which follow the recommendations and is an important factor in any algorithm's performance.

The map used for the testing Scenario 1 is taken from the TAPASCologne project. The map was cut in order to reduce the simulation time and the area considered in the simulations is represented in Figure 7-7. The new map is 2,000 m x 3,000 m in size and is at the location 50.924043, 6.93643 to 50.950456, 6.96611, latitude and longitude. The gradients for the roads in the map were obtained using Google-Earth [312], the heights of all road segment ends on the map were retrieved using the Google Map APIs [295] and stored in a .cvs file. A purposely built Python script was then run which took the length of the individual road segments and the heights of the start and end points of the road segment, and used these to calculate the gradients. These were then stored in the maps xml file. Appendix 1 includes the detailed procedure for computing these and the python script.

Two vehicle traces, one of 900 vehicles and the other of 1,100 vehicles, were obtained from the TAPASCologne website. All the vehicles were considered to be light passenger vehicles with engines between 1.4 and 2 litres in the SUMO simulations. The two vehicle traces consider the situation in the German city of Koln from 6:00am to 6:15am and 6:15am to 6:30am, respectively.

In order to test the effects of compliance and penetration rates a number of extra simulations were run for the first vehicle trace. These consisted of running the simulations at compliance rates of 0%, 25%, 50%, 75% and 100%. Another set of simulations varied the penetration rates to 0%, 25%, 50%, 75% and 100%.

7.2.3.2 Scenario 2- Influence of Different Traffic Sets

The purpose of scenario 2 is to test the system with different data sets, as well as to note the effect similar, but different days have on the algorithms' outputs.

For Scenario 2 a map of Dublin was obtained from the OpenStreetMap website [313] was used. The map size is 1,500 m by 2,000 m and the GPS coordinates are 53.333274, -6.291900 to 53.356862, -6.202507, latitude and longitude.

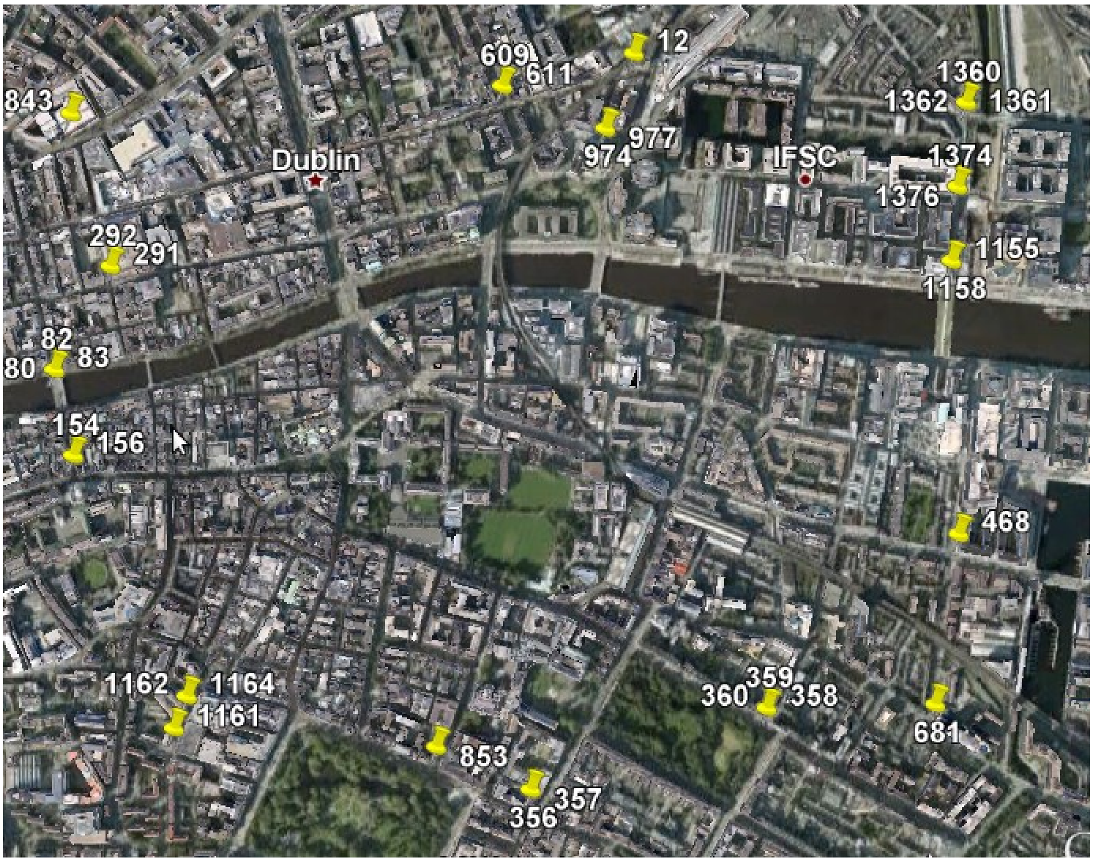

Figure 7-2 Location of induction loops which generated the vehicle counts used for simulation of Dublin city centre (Screenshot from Google-Earth [312])

Figure 7-3 Map of Dublin used for simulations (taken from OpenStreetMap [313])

The vehicle traces used in Scenario 2 were constructed from vehicle counts available from the Dublin City Council website [314]. The data collected from the website includes traffic counts at major junctions which are shown in yellow in Figure 7-2. Four traces of different Monday mornings in the month of January 2012 were generated with vehicles travelling between 6:00 am and 6:15 am. These traces contained approximately 450 vehicles each. The vehicles were considered to be light passenger vehicles with engines between 1.4 and 2 litres in the SUMO simulations.

The road gradients were obtained from Google-Earth [312], using the same method described in Scenario 1 and Appendix 1. The road roughness values were obtained from Dublin City Council (DCC). These were in the form of IRI and MPD, and were used to generate the road roughness values of the major roads. The smaller roads' roughness were estimated from a statistics document obtained from the National Roads Authority [199]. Figure 7-4 and Figure 7-5 show the IRI and MPD values for the major roads in the Dublin area respectively. These were obtained from DCC [314].

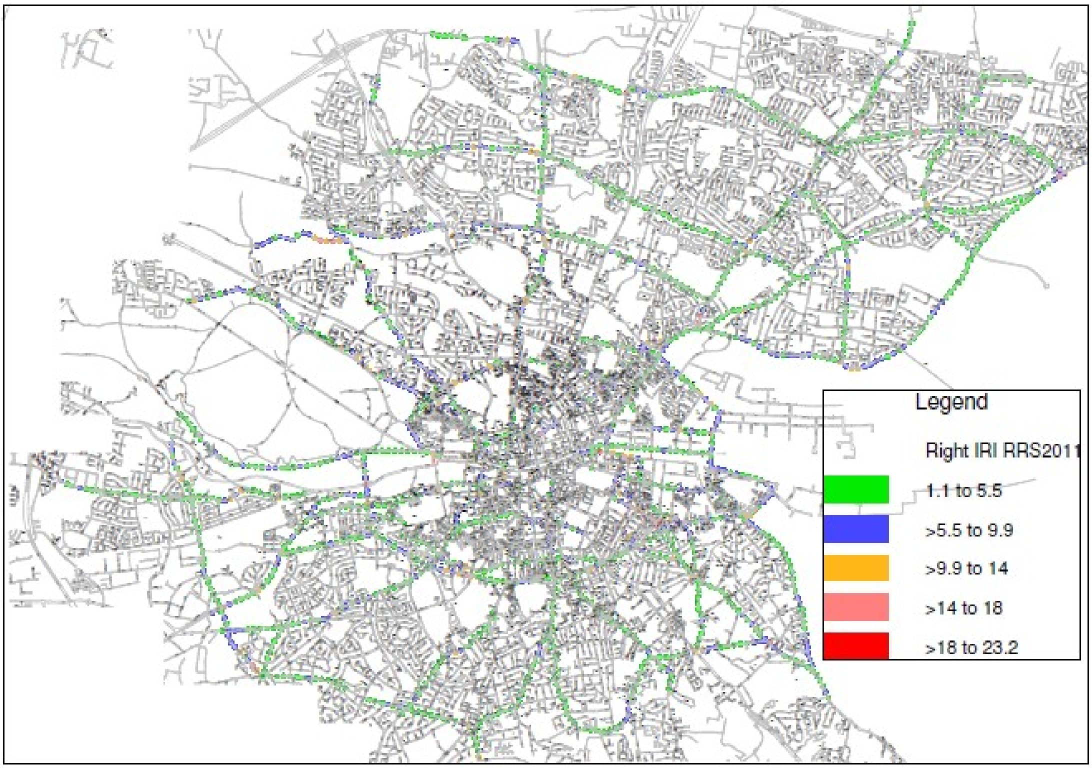

Figure 7-4 Map showing IRI values of roads in Dublin Data from DCC [314]

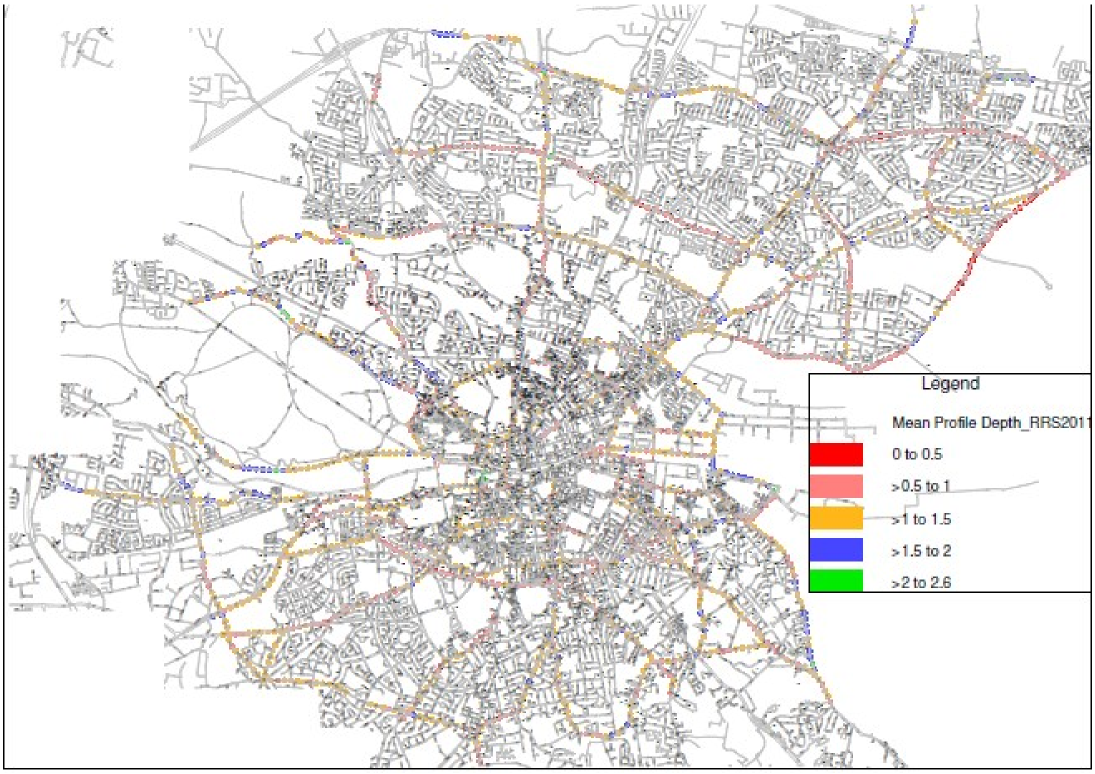

Figure 7-5 Map showing MPD values of roads in Dublin Data from DCC [314]

In Figure 7-6 LP is local Primary, LS is local Secondary and LT is local Tertiary and refer to the road types in Ireland.

7.2.3.3 Scenario 3- Influence of Map Size

Testing of Scenario 3 focuses on studying the effect of map size on the vehicular routing algorithms. Testing for Scenario 3 considered a 3,000 m x 3,000 m and a 3,000 m x 4,000 m map of the centre of Koln. The coordinates are 50.923896, 6.9221 to 50.950888, 6.96349 and 50.924249, 6.93623 to 50.951759, 6.99172. The purpose of this scenario is to note the effects of larger simulations on the algorithms.

The trace for the first map contained 1,400 vehicles and the trace for the second map contained 1,200 vehicles. These traces were obtained from the TAPASCologne website. The vehicles were considered light passenger vehicles with engines between 1.4 and 2 litres in the SUMO simulations. The two vehicle traces consider the situation in the German city of Koln from 6:00 am to 6:15 am.

Unfortunately no data on road roughness was available for the city of Koln and therefore the road roughness values were generated using similar statistics from the roads in Ireland for larger and smaller roads respectively. The roads were separated into the German equivalents of regional, local primary, local secondary and local tertiary. Using a python script the road roughness values were randomly assigned according to the cumulative frequency graph in Figure 7-6. Appendix 2 includes the detailed procedure for computing these and the python script.

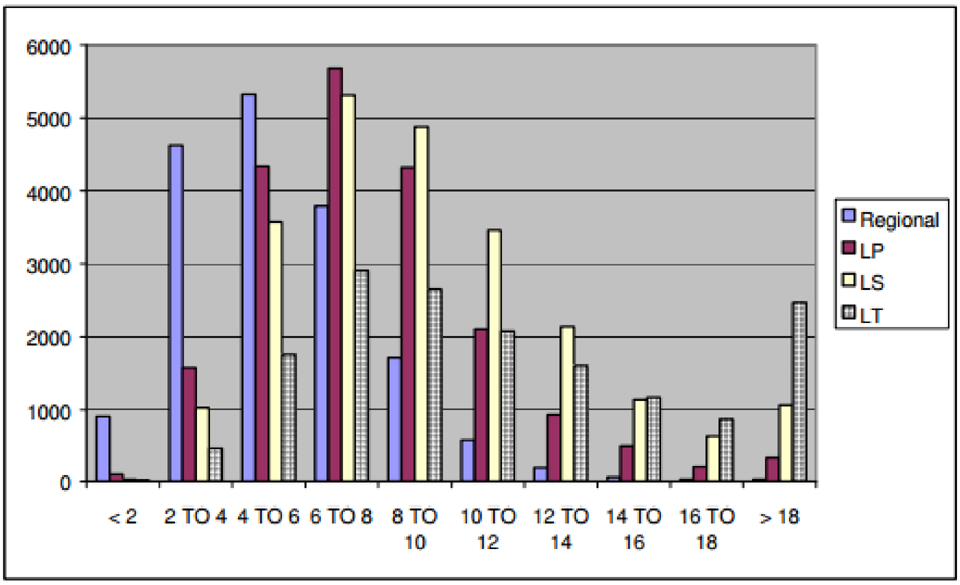

Figure 7-6 Cumulative frequency graph of IRI values on Irish roads (data from Irish National Road Authority)[199]

7.2.3.4 Scenario 4 – Influence of Map Type

The purpose of Scenario 4 is to compare the effect of different map types and therefore rural with urban maps were considered. A section of road outside Koln city was simulated for the urban vs. rural comparison. The rural map was 10,000 m x 10,000 m and its coordinates are 50.97029, 7.04784 to 51.080232, 7.20403. The trace for the rural map contained 370 vehicles. These traces were obtained from the TAPASCologne website. The vehicles were considered to be light passenger vehicles with engines between 1.4 and 2 litres in the SUMO simulations. The vehicle traces consider the situation in the area surrounding Koln from 6:00 am to 6:15 am. The urban scenario uses the 6:00-6:15 am trace and the 2,000 m x 3,000 m Koln map from Scenario 1.

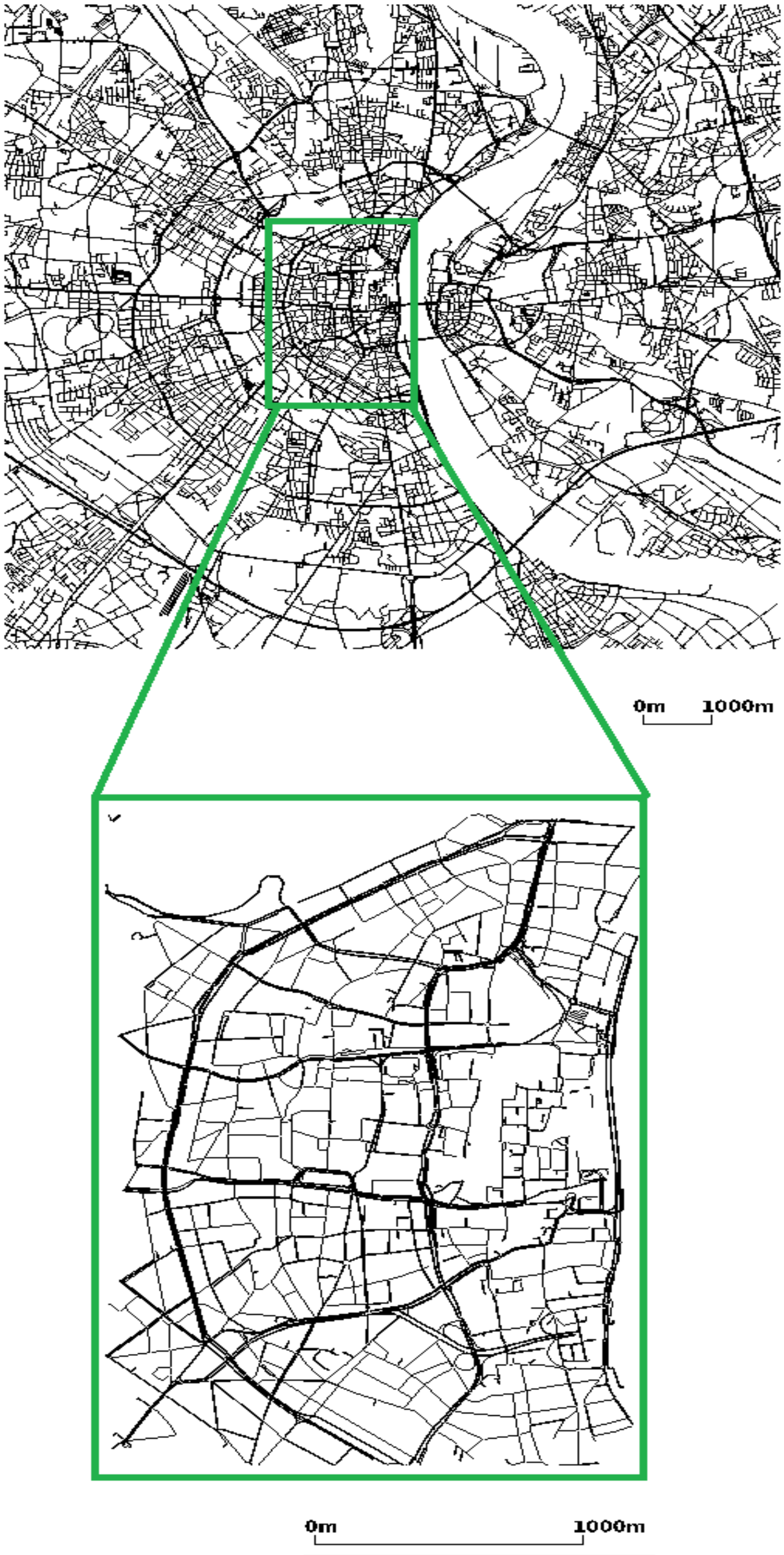

Figure 7-7 Inset map of the area of Köln used for Scenario 1 simulations (data for the maps was obtained from TAPASCologne [13])

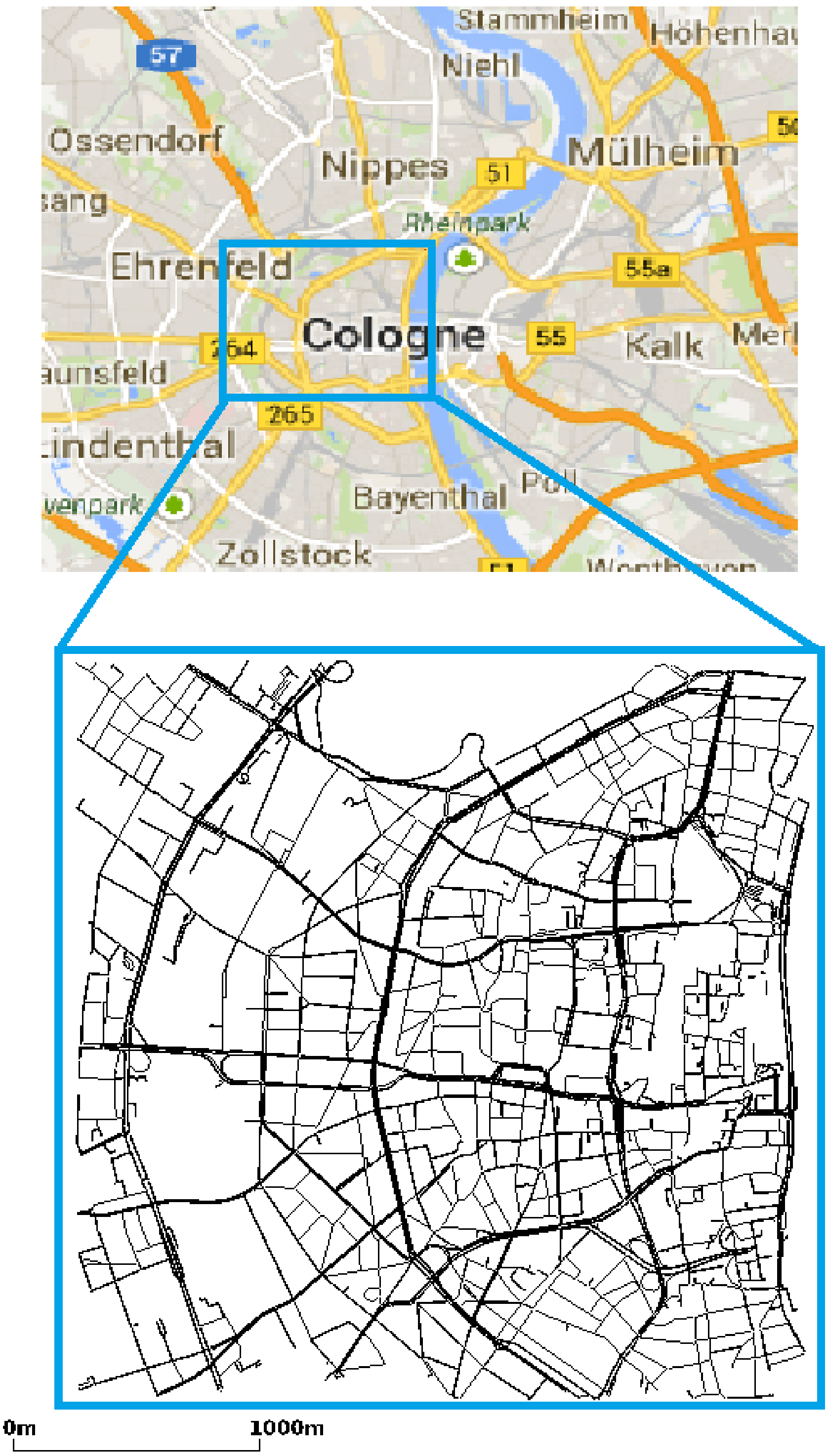

Figure 7-8 Scenario 3 Map Koln1.5 3,000 x3,000m map of Koln centre (taken from TAPASCologne [13])

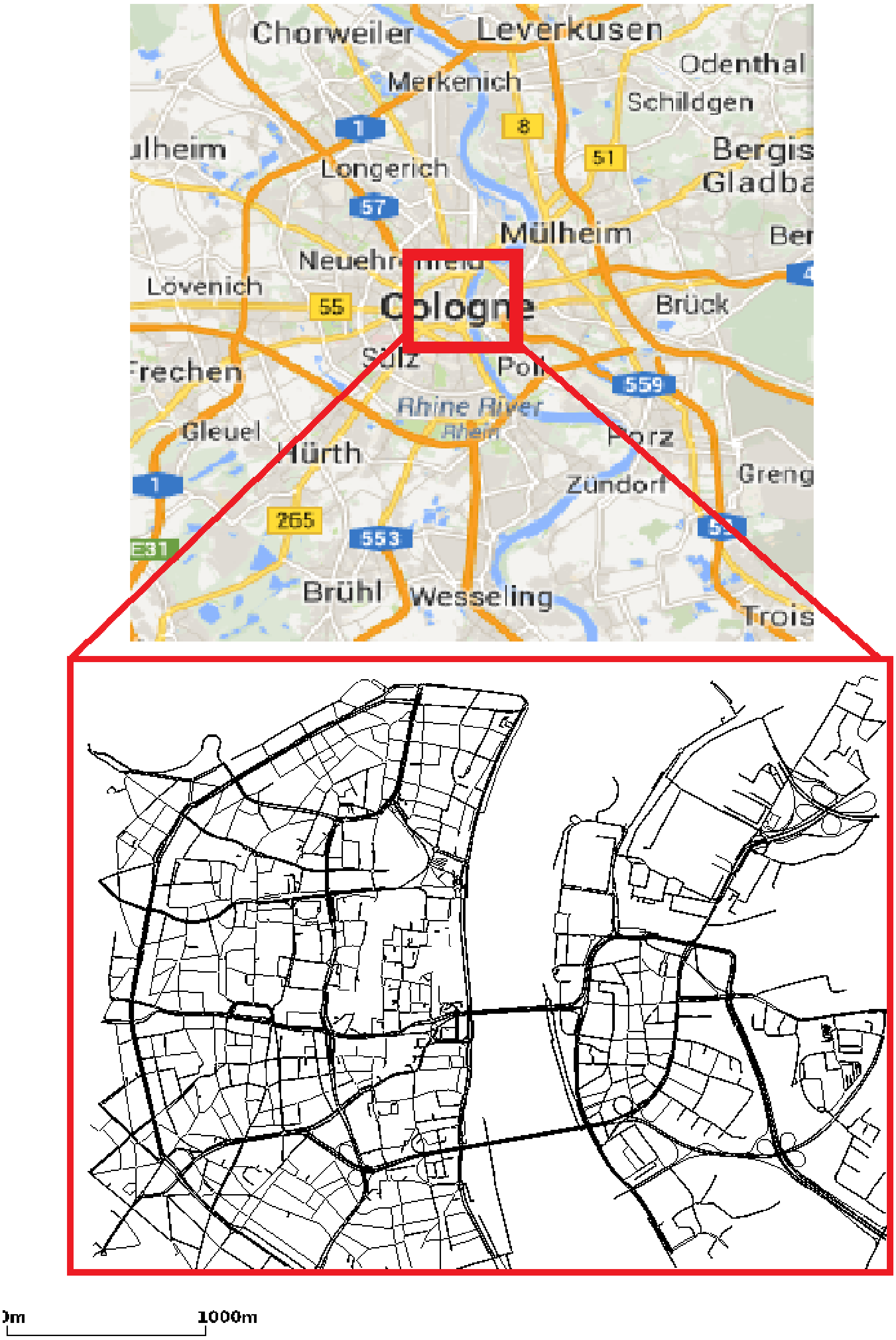

Figure 7-9 Scenario 3 Map Koln2 3,000 m x4,000 m map of Koln centre (taken from TAPASCologne [13])

Figure 7-10 Scenario 4 10,000m x10,000 m map of rural area near Koln

7.3 EcoTrec Testing Results

7.3.1 Scenario 1- Influence of Times of Day, as well as Compliance and Penetration Rates

The first set of results is for the 2,000 m by 3,000 m map of Koln. Two traces of 900 and 1,100 vehicles were simulated using the four different rerouting mechanisms indicated in section 7.2.2

Table 7-1 Percentage of vehicles which have reached their destination in Scenario 1

	900 vehicles 6:00-6:15 (%)	Gain from baseline (%)	1,100 vehicles 6:15-6:30(%)	Gain from baseline (%)
EcoTrec	65	36	60	30
Sommer	52	10	53	14
Dijkstra	54	16	52	12
TAPASCologne	47	0	46	0

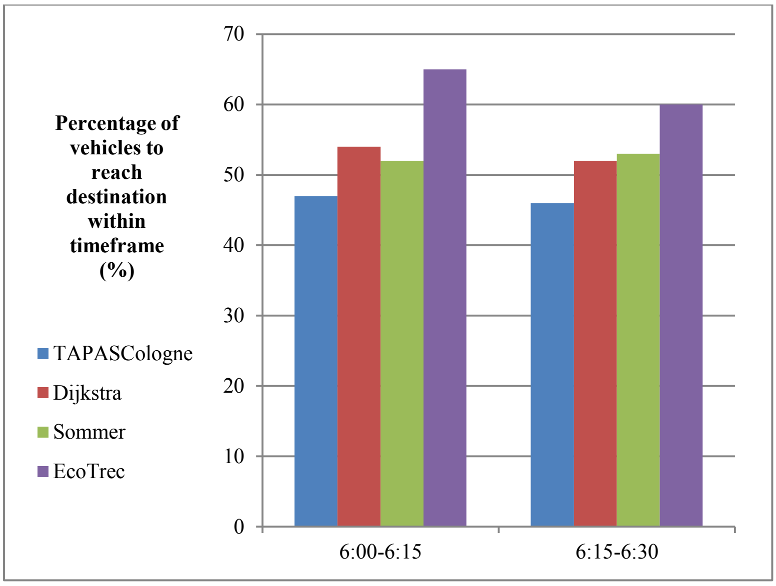

Figure 7-11 Percentage of vehicles which reached their destination between 6:00-6:15 and 6:15-6:30 for different routing mechanisms

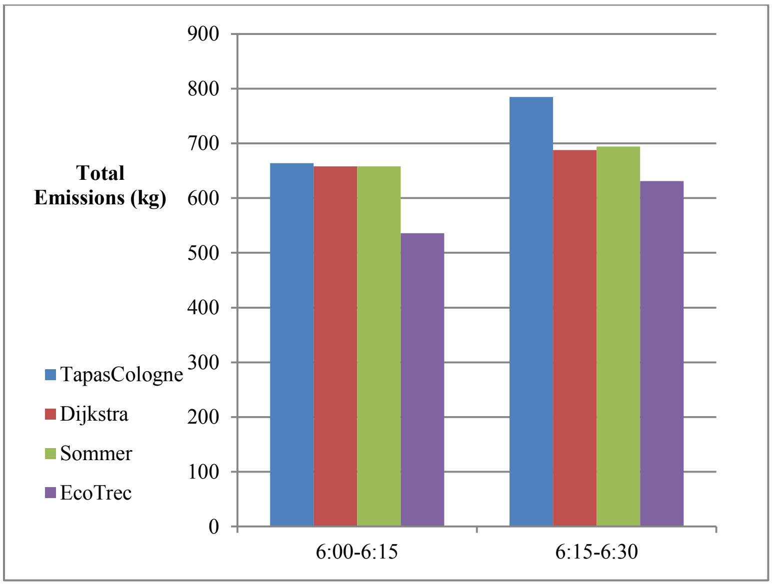

Figure 7-12 CO_2 emissions generated by the vehicles between 6:00-6:15 and 6:15-6:30 for different routing solutions

Table 7-2 Total Emissions in kg

	900 vehicles 6:00-6:15 CO_2 emissions (kg)	Gain from baseline (%)	1,100 vehicles 6:15-6:30 CO_2 emissions (kg)	Gain from baseline (%)
EcoTrec	536	19	631	20
Sommer	658	1	694	12
Dijkstra	658	1	688	12
TAPASCologne	664	0	785	0

Figure 7-11 shows the percentage of vehicles which have reached their destination within the allotted time. For both vehicle traces the EcoTrec algorithm resulted in the highest number of vehicles reaching their destination. EcoTrec improved on the baseline, TAPASCologne, by 36% and 30% in the 900 and the 1,100 vehicle traces, respectively. It also outperformed the next most energy efficient solution, Sommer by roughly 24% and 13% in the 900 and 1,100 vehicle traces, respectively. EcoTrec performed better than the other schemes because it considers the speed of the vehicles on each road in order to judge how long it will take to traverse the road infrastructure.

Figure 7-12 shows the total amount of CO_2 produced during the simulation time by all vehicles. For both vehicle traces the EcoTrec algorithm resulted in the least amount of emissions produced by the vehicles. EcoTrec improved on the baseline, TAPASCologne, by 19% and 20% in the 900 and 1,100 vehicle traces, respectively. It also outperformed Sommer solution by roughly 18% and 9% in the two scenarios considered. T-tests were performed and confirmed that there is a significant statistical difference between EcoTrec's results and each of the other schemes results with 99% confidence interval. EcoTrec results are better than those of the other schemes, because it considers the amount of emissions which will be released into the atmosphere on each road in order to judge which route will determine the least emissions. At the same time it also reduces the idle time by avoiding very slow roads.

Scenario 1 was also simulated with varying penetration rates and compliance rates in order to see how the system is influenced by these parameters.

7.3.1.1 PENETRATION RATE

The penetration rate was varied from 0%, 25%, 50% and 75% and 100%. This indicates how many vehicles were VANET equipped and so only these vehicles could send and receive messages.

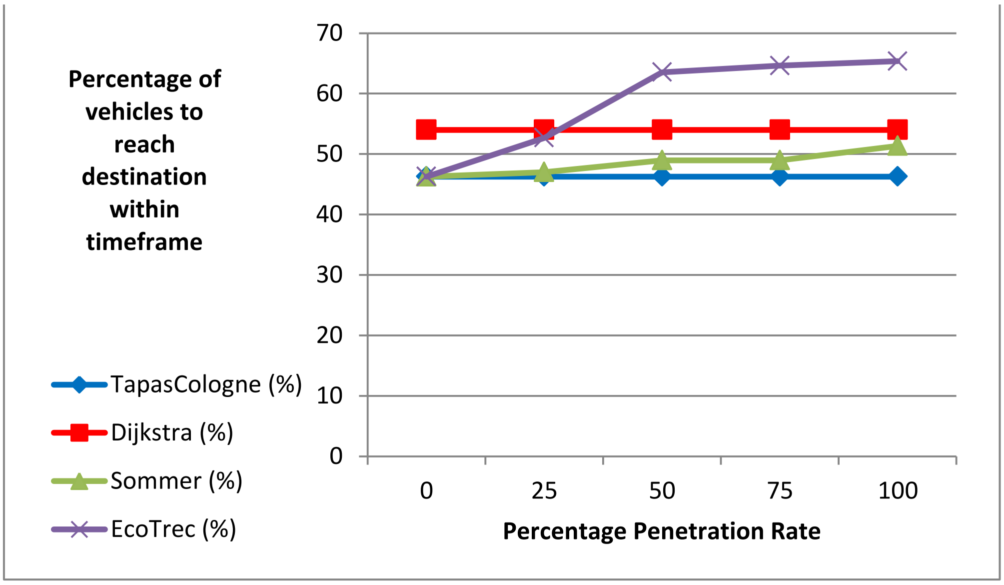

Figure 7-13 Scenario 1: Percentage of vehicles which reached their destination between 6:00-6:15 under different penetration rates

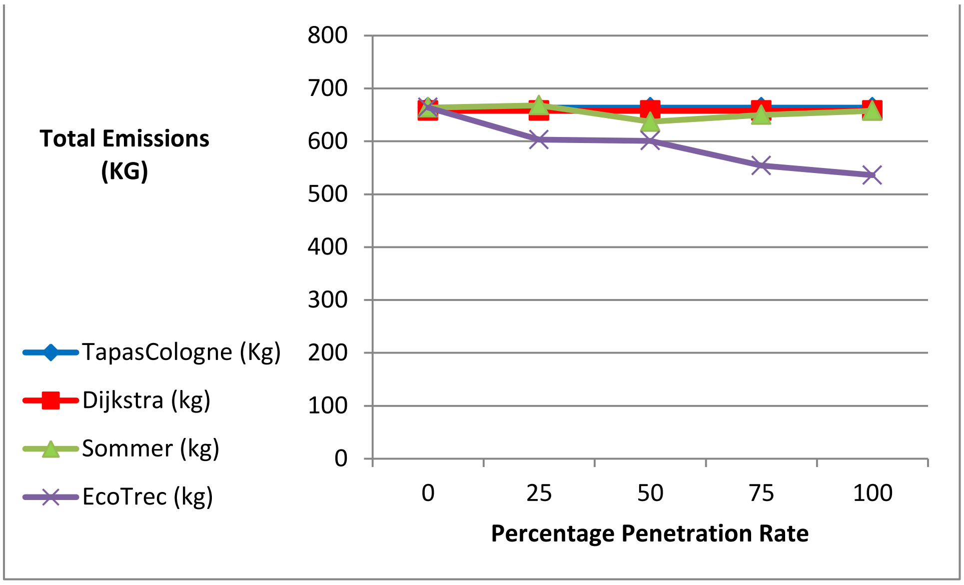

Figure 7-14 Scenrio1 Emissions generated by the vehicles for the different penetration rates

Table 7-3 Percentage of vehicles which have reached their destination for different penetration rates

Penetration Rate (%)	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
0	46.3	54	46.3	46.3
25	46.3	54	47.0	52.7
50	46.3	54	49.0	63.5
75	46.3	54	49.0	64.6
100	46.3	54	51.4	65.4

Table 7-4 Emissions generated by the vehicles for the different penetration rates

Penetration_Rate (%)	TAPASCologne (kg)	Dijkstra (kg)	Sommer (kg)	EcoTrec (kg)
0	664	658	664	664
25	664	658	668	603
50	664	658	637	601
75	664	658	650	554
100	664	658	658	536

As seen in Figure 7-13, the benefit EcoTrec brings in terms of emissions and percentage of vehicles to reach their destination increases linearly with the penetration rate.

As can be seen from the results EcoTrec outperformed the other VANET-based schemes on average by 25% in terms of percentage of vehicles to reach their destination. EcoTrec outperformed the other scheme at every percentage of penetration rate tested. In terms of emissions EcoTrec outperformed the other schemes by 12% on average. Individual T-tests were performed and confirmed that there is a significant statistical difference between EcoTrec's results and the results from the other schemes with 97.5% confidence interval.

7.3.1.2 COMPLIANCE RATE

The compliance rate was varied from 0%, 25%, 50%, 75% and 100%. This means that although 100% of the vehicles in this simulation are VANET equipped, and only the compliant vehicles follow the routes that were recommended to them by the different schemes.

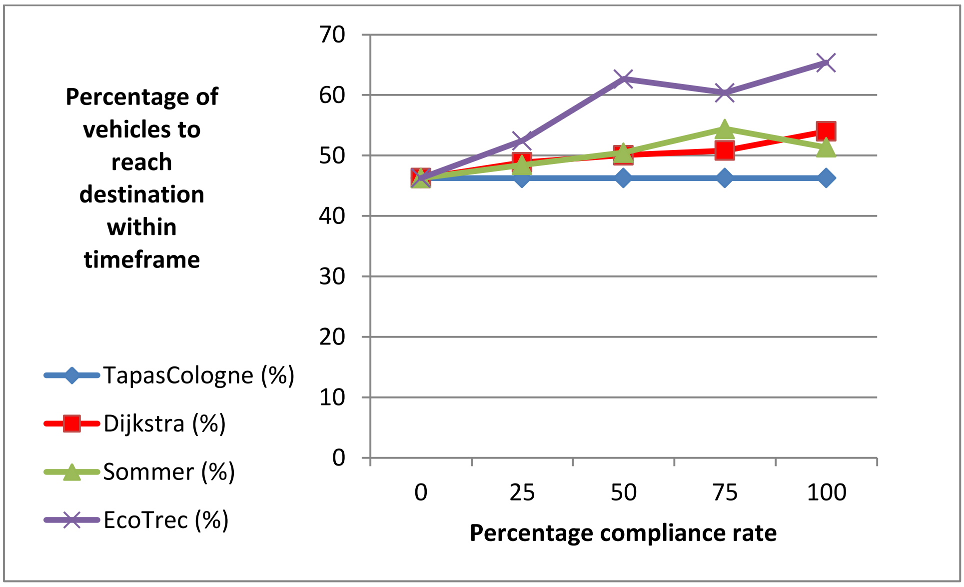

Figure 7-15 Percentage of vehicles which reached their destination between 6:00-6:15 under different compliance rates

As seen in both Figure 7-15 and Figure 7-16, EcoTrec improves its performance with increasing compliance rate both in terms of emissions and percentage of vehicles to reach their destination.

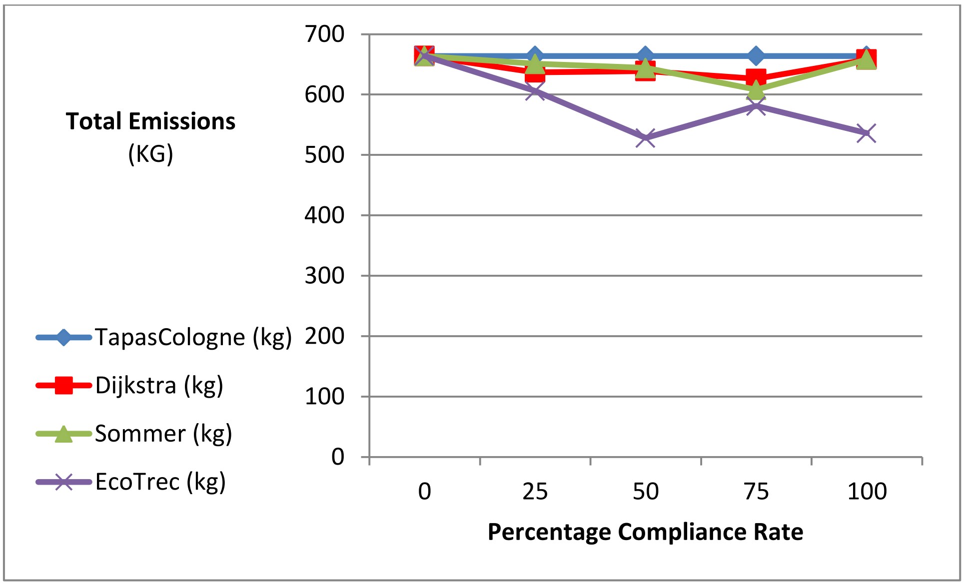

Figure 7-16 CO_2 Emissions generated by the vehicles for the different compliance rates

Table 7-5 Percentage of vehicles which have reached their destination for different compliance rates

Compliance Rate (%)	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
0	46.3	46	46.3	46
25	46.3	49	48.4	52
50	46.3	50	50.5	63
75	46.3	51	54.4	60
100	46.3	54	51.4	65

Table 7-6 Emissions generated by the vehicles for the different compliance rates

Compliance Rate (%)	TAPASCologne (kg)	Dijkstra (kg)	Sommer (kg)	EcoTrec (kg)
0	664	664	664	664
25	664	637	651	606
50	664	639	644	528
75	664	626	608	581
100	664	658	658	536

These results show how EcoTrec outperformed Sommer's proposed solution by 17% on average and Dijkstra's algorithm by 18% in terms of percentage of vehicles to reach their destination at different compliance rates. Individual T-tests were performed and confirmed that there is a significant statistical difference between the EcoTrec results and the results from the other schemes with a 97.5% confidence interval.

It is interesting to note that at 75% compliance rate we see an improvement in Sommer's solution. This is due to the fact that load balancing is not implemented and so 25% of vehicles not going the recommended route results in less congestion on some roads. However the results are still lower than those of EcoTrec as illustrated in Figure 7-15 and Figure 7-16.

In terms of emissions EcoTrec outperformed the other schemes by 12% on average. Individual T-tests were performed and confirmed that there is a significant statistical difference between these results and those of other solutions with 95% confidence interval.

7.3.2 Scenario 2- Influence of Different Traffic Sets

The second set of results is for the 1,500 m x 2,000 m map of Dublin illustrated in Figure 7-3. Four traces of approximately 450 vehicles were simulated using the 4 different rerouting mechanisms.

Table 7-7 Total Emissions in kg

	Original (kg)	Dijkstra (kg)	Sommer (kg)	EcoTrec (kg)
Dublin1	198	255	217	195
Dublin2	531	552	451	329
Dublin3	450	427	348	351
Dublin4	593	646	579	390

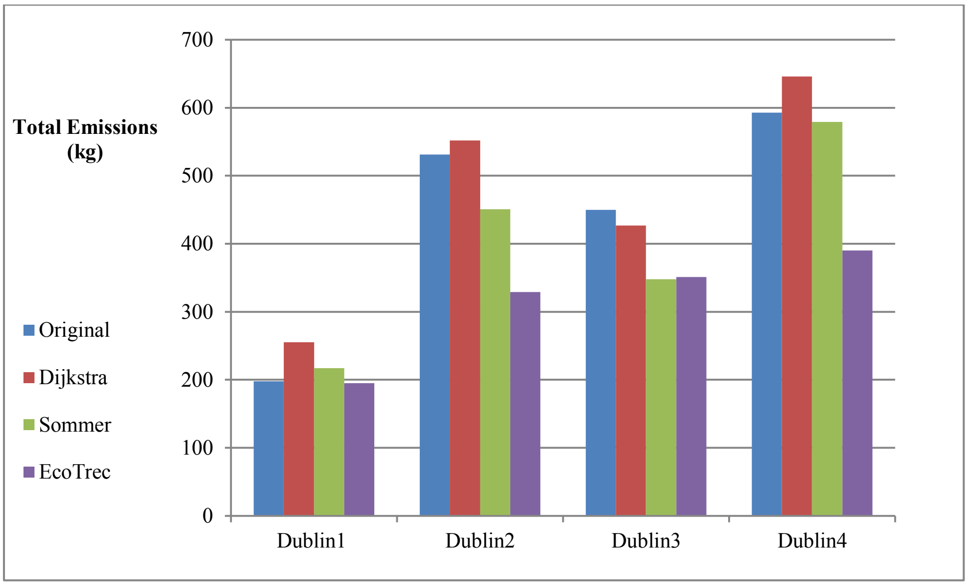

Figure 7-17 CO_2 emissions generated by the vehicles for scenario 2

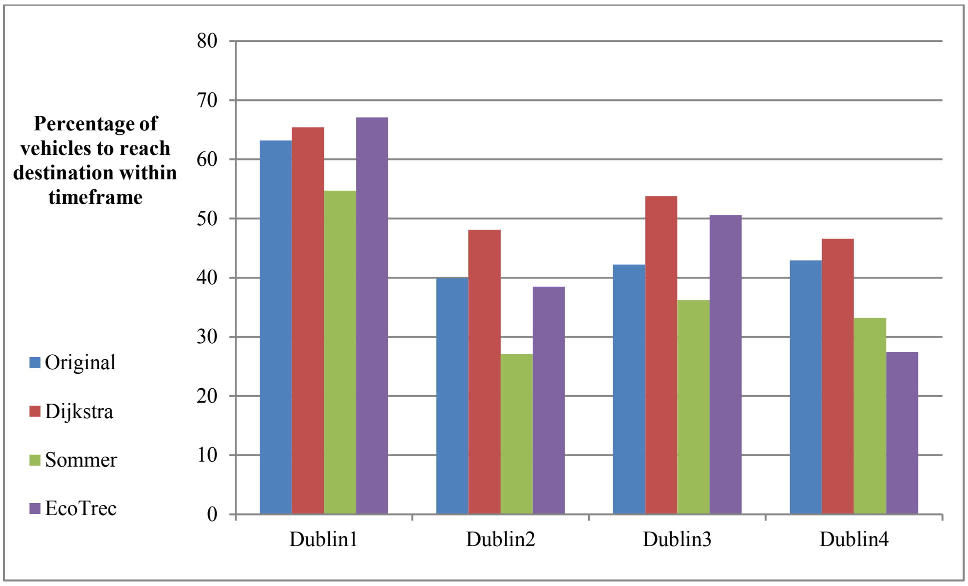

Figure 7-18 Percentage of vehicles which reached their destination

Table 7-8 Percentage of vehicles which have reached their destination

	Original (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
Dublin1	63.2	65.4	54.7	67.1
Dublin2	39.9	48.1	27.1	38.5
Dublin3	42.2	53.8	36.2	50.6
Dublin4	42.9	46.6	33.2	27.4

Figure 7-18 shows the percentage of vehicles which have reached their destination within the allotted time. Apart from the Dijkstra's algorithm, EcoTrec outperformed all the other schemes in the first three traces in terms of percentage of vehicles which reached their destination within the time frame. EcoTrec outperformed all the schemes including Dijkstra when Dublin 1 trace was used. When the results of all the traces are considered, on average EcoTrec outperformed the Sommer routing scheme by 18%.

Figure 7-17 shows the total amount of CO_2 produced during the simulation. EcoTrec outperformed all the other schemes in terms of emissions except for Sommer when Dublin 3 trace was used, but the difference was marginal (less than 1% only).

On average EcoTrec outperformed the TAPASCologne, Dijkstra and Sommer routing schemes in terms of emissions by 24%, 33% and 16% respectively.

Although better than the other solutions, EcoTrec's performance in Scenario 2 was not as good as in Scenario 1 in this scenario in terms of the percentage of vehicles reaching their destination in the given time. This could be due to the particular dynamics of the Dublin scenario as there is very heavy traffic on the roads entering the map at the start time. This was described when in the scenarios were introduced in section 7.2.3 The heavy traffic at the entrance roads would prevent traffic-aware rerouting from having a meaningful effect. However EcoTrec performed very well in terms of emission reduction and there is expected to be a trade-off between speed and emissions.

In this scenario there was no statistical advantage for EcoTrec in terms of travel time. However in terms of emissions the t-tests showed how EcoTrec was better than the original routes, Dijkstra, and Sommer with 95%, 99% and 90% confidence intervals, respectively.

7.3.3 Scenario 3- Influence of Map Size

The third set of results is for three different sized maps in Koln, a 2,000 m x 3,000 m, 3,000 m x 3,000 m and 3,000 m x 4,000 m map. The traces consider roughly 900, 1,400 and 1,200 vehicles respectively. They are labelled Koln1, Koln1.5 and Koln2 respectively.

Figure 7-19 shows the percentage of vehicles which have reached their destination within the allotted time. On average EcoTrec outperformed the TAPASCologne, routing schemes by 31% in terms of percentage of vehicles to reach the destination within the timeframe. It also outperformed both the Dijkstra and Sommer by 19% in terms of percentage of vehicles to reach the destination within the timeframe.

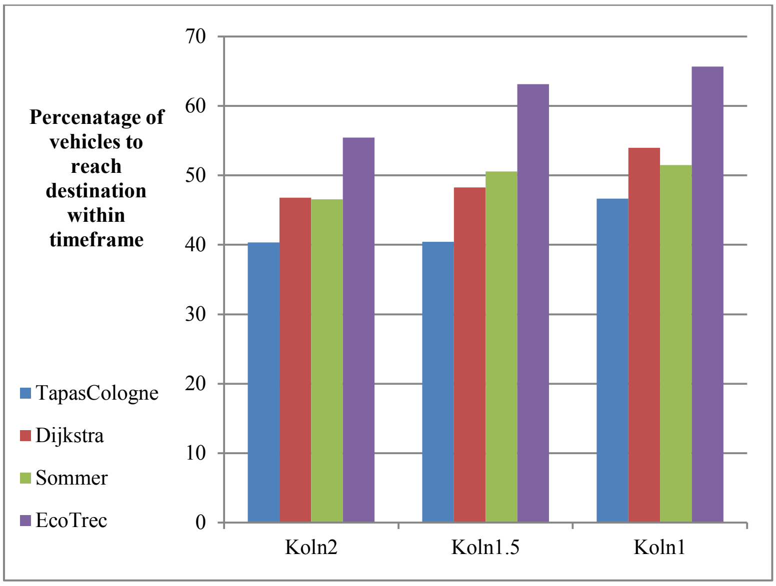

Figure 7-19 Percentage of vehicles which have reached their destination

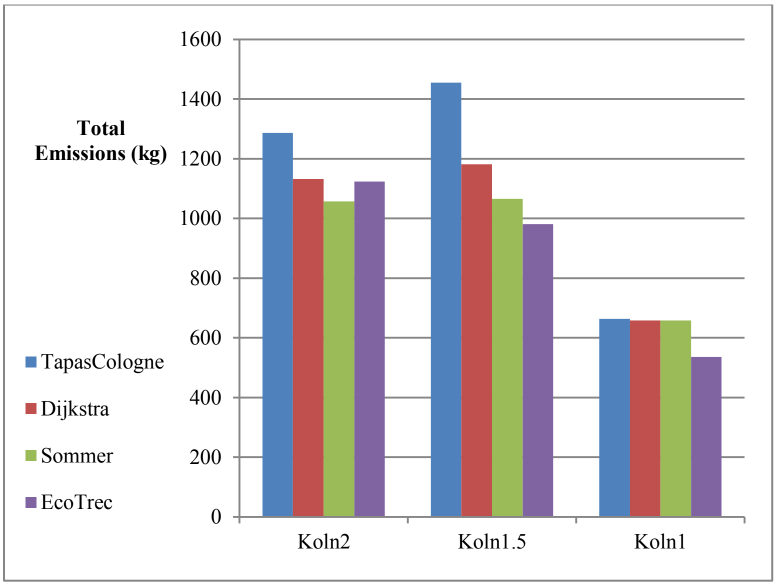

Figure 7-20 Total Emissions in kg

Table 7-9 Percentage of vehicles which have reached their destination

	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
Koln2	40.4	46.8	46.5	55.4
Koln1.5	40.4	48.3	50.6	63.1
Koln1	46.7	4.0	2.0	5.3

Table 7-10 Total Emissions in kg

	TAPASCologne (kg)	Dijkstra (kg)	Sommer (kg)	EcoTrec (kg)
Koln2	1287	1132	1057	1123
Koln1.5	1455	1183	1065	981
Koln1	664	658	658	536

Figure 7-20 shows the total amount of CO_2 emitted during the simulation. EcoTrec outperformed all the other schemes in terms of emissions except for Dijkstra in the Koln3x2 trace. On average EcoTrec outperformed the TAPASCologne, Dijkstra and Sommer routing schemes in terms of emissions by 21%, 12% and 7% respectively. EcoTrec did not perform the best in terms of emissions in the 3,000 m x 4,000 m map. This is due to the lower vehicle density. This map had a density of 100 vehicles per square kilometre compared with the other two which had densities of roughly 150 vehicles per square kilometre. Individual T-tests were performed and showed that in terms of the number of vehicles to reach their destination within the simulation time, EcoTrec outperformed TAPASCologne, Dijkstra and Sommer with a 95% confidence level.

7.3.4 **Scenario 4- Influence of Map Type**

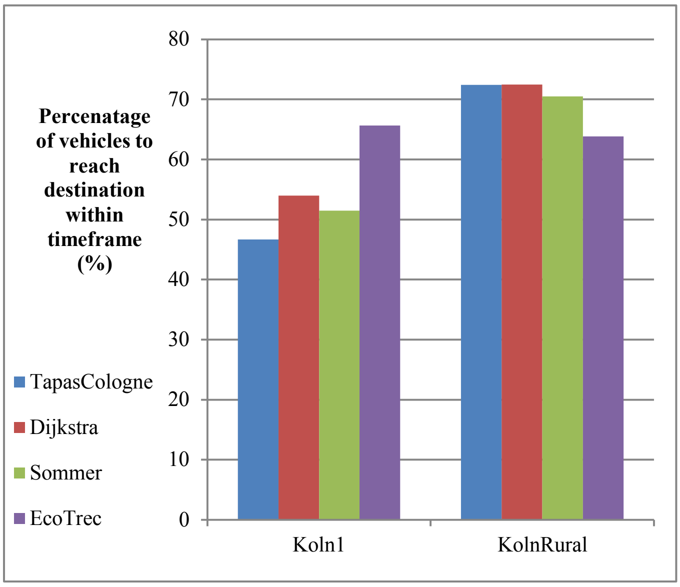

Figure 7-21 Percentage of vehicles which reached their destination

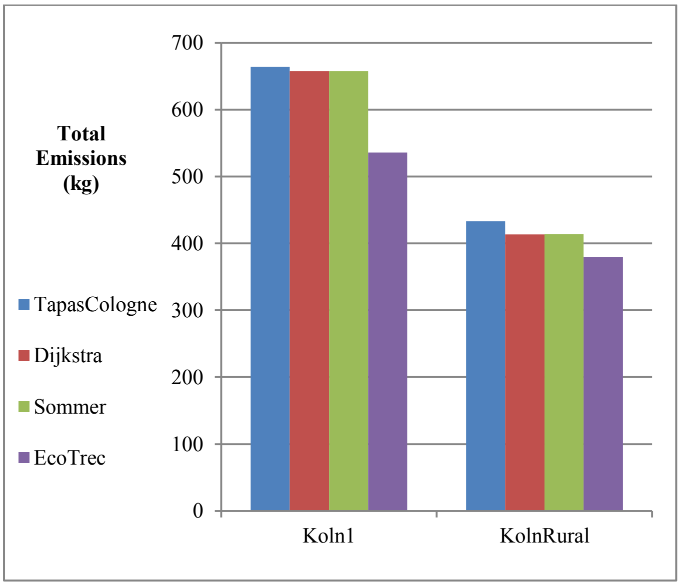

Figure 7-22 CO_2 emissions generated by the vehicles

Table 7-11 CO_2 emissions generated by the vehicles

	TAPASCologne (kg)	Dijkstra (kg)	Sommer (kg)	EcoTrec (kg)
Koln_rural	433	414	414	380
Koln_urban	664	658	658	536

Table 7-12 Percentage of vehicles which reached their destination

	TAPASCologne (%)	Dijkstra (%)	Sommer (%)	EcoTrec (%)
Koln_rural	72.4	72.5	70.5	63.8
Koln_urban	46.3	54.0	51.4	65.4

Figure 7-21 shows the percentage of vehicles which have reached their destination within the allotted time. EcoTrec scores the worst in this scenario, but the difference between EcoTrec and the other routing schemes in this scenario is 13.5%, 13.6% and 10.5% for TAPASCologne, Dijkstra and Sommer respectively.

Figure 7-22 shows the total amount of CO_2 produced during the simulation. EcoTrec scores the best in this scenario. EcoTrec outperformed the TAPASCologne, Dijkstra and Sommer routing schemes in terms of emissions by 12%, 8% and 8% respectively in this scenario.

Over the distances in the map with the low vehicle density, vehicle to vehicle communication is very difficult if not impossible and also traffic congestion rarely occurs. False positive readings of traffic congestion might be the reason for EcoTrec performing badly in this scenario. These readings occur when vehicles detect traffic congestion, which quickly clears or when the vehicles stop at a junction or traffic lights.

Note that the other VANET-based schemes also performed poorly. The knowledge of road roughness values and road gradients has a slight impact on emissions in these scenarios only.

This scenario suggests that the best results are obtained for urban situations when VANET communications are possible and there is potential for vehicular traffic congestion.

7.3.5 Discussion

The number of messages and the percentage of bandwidth used by the different schemes were looked at. On average the EcoTrec scheme sent approximately 300,000 messages in the Koln1 simulation, used in Scenario 1, Scenario 2 and Scenario 4. This corresponded to roughly 300 messages per vehicle or one message every 3 seconds. As each message is approximately 450 bits this accounts for 150 kbps. The table below shows the performance analysis. As can be seen every instance in well within the performance capabilities of 802.11p (~27 Mbps) [15]. Han et al. estimated the actual bandwidth of 802.11p as 6 Mbps so EcoTrec would use approximately 1.67% of the bandwidth available.

$$\frac{300{,}000\ messages\ x\ 450\ bits}{900\ seconds\ x\ 6{,}000{,}000\ bps}$$

$$= \sim 2.5\%$$

The Sommer proposed VANET-based scheme sent 200,000 messages in the same scenario, which was significantly less, but the number of messages of EcoTrec is well within the communication capabilities of 802.11p.

Table 7-13 Number of messages in each scenario

	Total Number of Messages	Total Number of Messages per Veh	Average Message Frequency (s)
	EcoTrec		
Koln2	415,000	345.8	2.6
Koln1.5	425,000	303.6	3.0
Koln1	300,000	333.3	2.7
Koln_rural	105,000	262.5	3.4

Overall in terms of the percentage of vehicles which reached their destination, EcoTrec outperformed the original routes and Sommer by 15% and 17%, respectively. EcoTrec was only outperformed by Dijkstra by 0.1%, the difference between these sets of data was not statistically significant, and so we can assume they are competitive with each other in terms of this metric.

Overall in terms of emissions, EcoTrec outperformed the original routes, Dijkstra and Sommer by 21%, 19% and 11% respectively.

7.4 Time-Ants Testing Simulation Environment

Time-Ants is an Innovative Temporal and Spatial Ant-based Vehicular Routing Mechanism. Time- Ants applies the ant colony optimization algorithm in the Time domain. Hence vehicles are more likely to use roads with higher throughputs at certain times. Load balancing is used to prevent flash crowding. This approach led to a higher overall throughput in terms of the amount of vehicles to reach the destination within the simulation time.

This section presents the simulation-based testing setup for the assessment of Time-Ants, An Innovative Temporal and Spatial Ant-based Vehicular Routing Mechanism for reducing traffic congestion.

Modelling and simulations were performed on the iTETRIS [308] platform. iTETRIS is described in greater detail in section 7.2.1

7.4.1 Time-Ants Simulation-based Modelling

Time-Ants was modelled as described in Chapter 5. This is composed of: vehicle models, road models, a time-dependent traffic model and a current traffic model. The vehicle model contains the vehicle's speed and position. The road model contains the traffic information for a road segment that the vehicle is on. The current traffic model contains the instantaneous traffic information in the area, whereas the time-dependent traffic model contains the traffic information collected throughout a whole day.

The proposed Time-Ants routing algorithm was compared against three alternative approaches: Dijkstra shortest path algorithm, commonly used by GPS road guidance systems [84], and against an 'original route', the vehicles stick to a predefined route, and in some tests against DNA an algorithm described Wu et al. [95] and the algorithm described in Sommer et al. [89] .

7.4.2 Time-Ants Maps

For testing 3 different maps were used, representing different types of urban areas, similar to the maps used by Yamashita et al. [315], a Manhattan grid type, a radial and ring network and a map based on a real road network.

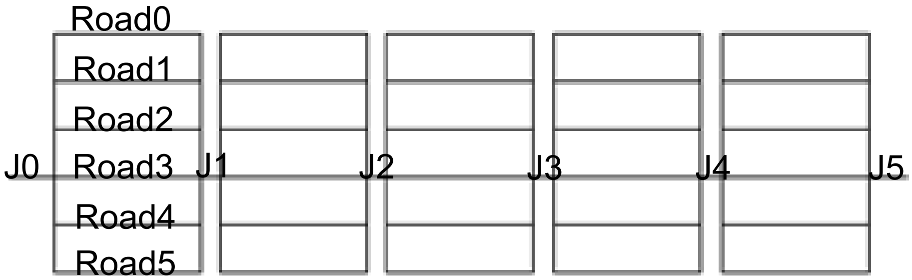

Figure 7-23 Manhattan Grid type map used for simulations

7.4.2.1 Map 1 – Manhattan Grid Map

A map similar to the one described in Wu et al. [95] and illustrated in Figure 7-23 was employed in these simulation-based testing. In this map there are 5 junctions (J1-J5), and each of the junctions is connected to the others by six road segments (Road0-Road5). The road segment lengths vary between 500m and 2,000m. The speed limits on these segments vary between 11 m/s (~40 kmph) and 35 m/s (~125 kmph). Each junction has a set of traffic lights. This will require some vehicles to stop at junctions to allow vehicles coming from a different direction.

7.4.2.2 Map 2 – Radial and Ring Map

The radial and ring type map is illustrated in Figure 7-24. There are 8 radial roads Ra0-Ra8. These radial roads cross at the very centre C0. There are also two radial roads surrounding the centre C1 and C2. At every junction there is a set of traffic lights. The speed limit on all roads is 13.9 m/s (~50 kmph). Each of the radial roads is 500m long in total with C0 exactly half way. The first ring C1 is located 85 m from C0, and the second ring C2 is located 175 m from C0. This map mimics the concentric rings found in many cities.

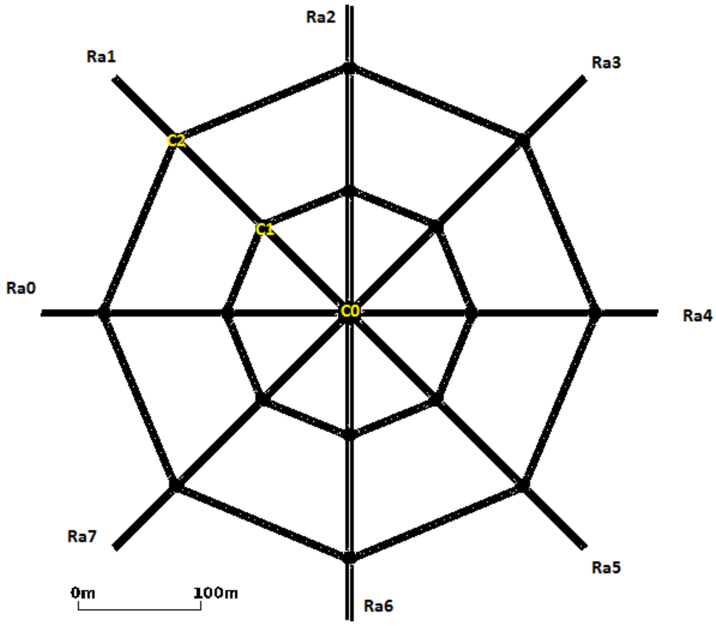

Figure 7-24 Radial and ring type map used for simulations

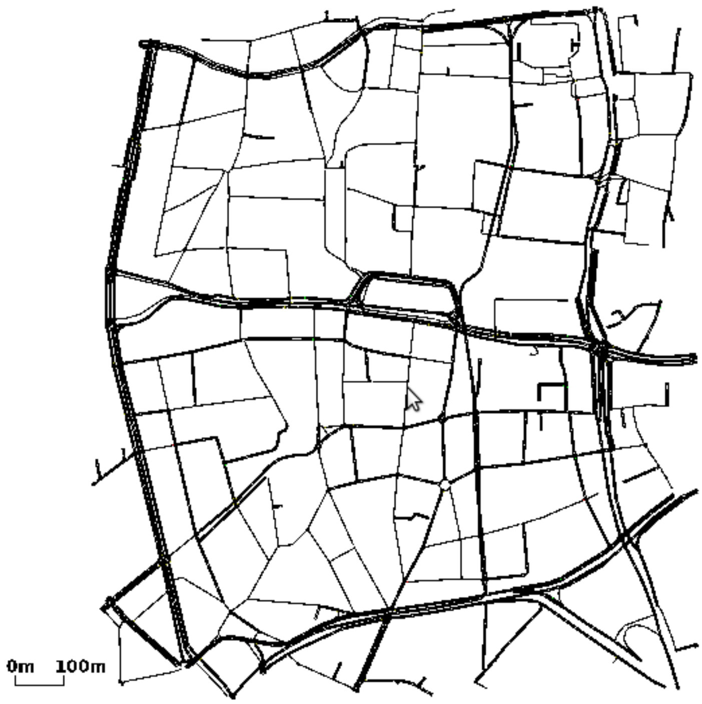

Figure 7-25 Realistic Map

7.4.2.3 Map 3 – Random Road Network Map

The third map is based on a section of TAPASCologne [13] at the coordinates latitude 50.92865 longitude 6.93948 to latitude 50.941358, longitude 6.95529. The map is roughly 1,000 m x 1,500 m in size and is shown in Figure 7-25. The TAPASCologne dataset is described in greater detail in section 7.2.2 This is a real map of an area of Cologne in Germany.

7.4.3 Time-Ants Testing Scenarios

The proposed algorithm was tested under a variety of headings: different maps, different numbers of vehicles, different penetration rates and different compliance rates. The assessment was in terms of the percentage of vehicles to reach the destination within the simulation timeframe. The average travel time of a scheme can be lower, but fewer vehicles might get to their destination. So in order judge the effectiveness of the different schemes, the percentage of the vehicles which got to their destination within the time-frame was recorded. Five different scenarios are considered to thoroughly explore the benefits and limitations of the Time-Ants algorithm.

7.4.3.1 Scenario 1 – Proof of Concept Testing

Initially 400 passenger cars are considered, which start driving into the Map 1 at time = 0; a new vehicle appears on the map every second. If no rerouting mechanism is employed, the cars take the first turn at each junction. Time-Ants was deployed according to the description in Chapter 5. The congestion threshold was set to 80% for these simulations.

The Time-Ants algorithm was tested against four different solutions: a mechanism which does not employ rerouting (the cars drive on the first turn on each junction – labelled "Original Routes" in Figure 7-26 and Table 7-15), Dijkstra lowest edge weight algorithm set to determine the fastest route (this will become congested if all the cars drive on it), the Dynamic rerouting algorithm (DNA) (described in the paper Wu et al. [95]) and an algorithm from Sommer et al. [89] .

DNA is a VANET-based rerouting algorithm based on the fact that each vehicle communicates its speed and the distance to the car in front of it to all the other vehicles. This information is used to determine the edge weights and employs the Dijkstra algorithm for determining the best route.

DNA uses equation (7-1) to score each road segment, in which Sr_i is the score of the segment $\boldsymbol{i}$ (graph edge); $\bar{S}_{\mathrm{i}}$ reflects the average vehicle speed on the road segment $\boldsymbol{i}$). $\bar{D}_{\mathrm{i}}$ - the inter-vehicle distance, $\bar{T}_{\mathrm{i}}$ - the road type of road segment $\boldsymbol{i}$ and $\bar{G}_{\mathrm{i}}$ - the road segment $\boldsymbol{i}$ length. k_j are weights and influence different metrics of the utility function.

$$Sr_i = k_1\bar{S}_i + k_2\bar{D}_i + k_3\bar{T}_i + k_4\bar{G}_i \qquad (7\text{-}1)$$

Table 7-14 DNA flavour weights

Flavour	k1	k2	k3	k4
DNA1	1	0	0	0
DNA2	0	1	0	0
DNA3	0.5	0.5	0	0
DNA4	0	0	0	1

Four DNA flavours are used in these tests, with the weights k1 through k4 indicated in Table 7-14.

7.4.3.2 Scenario 2 – Influence of Map Type

In the second scenario the map type was varied. There were 200 vehicles considered on Map 3 over a 900 second interval. There were 400 vehicles considered on Map 2, of which 200 vehicles were driving from Ra0 to Ra4 and 200 vehicles were driving from Ra2 to Ra6. For the "original routes" Time-Ants is compared against, the vehicles drive straight through junction C0.

7.4.3.3 Scenario 3 – Influence of Number of Vehicles

For this scenario Map 1 was chosen. The number of vehicle was varied between 200 and 500 in steps of 100 to test the effect of load on the system behaviour. Time-Ants was compared against the "original routes" and Dijkstra's algorithm.

7.4.3.4 Scenario 4 – Influence of Penetration Rate

This scenario consisted of running the simulations at varying penetration rates 0%, 25%, 50%, 75%, 100%. A 400 vehicle trace and Map 1 were used. Time-Ants was compared against the "original routes" and Dijkstra's algorithm.

7.4.3.5 Scenario 5 – Influence of Compliance Rate

This scenario consisted of running the simulations at varying compliance rates 0%, 25%, 50%, 75%, 100%. A 400 vehicle trace and Map 1 were used. Time-Ants was compared against the "original routes" and Dijkstra's algorithm.

7.5 Time-Ants Testing Results

7.5.1 Scenario 1 – Proof of Concept

The proof of concept testing, also reported in [316], aims at demonstrating that there is a benefit when using the proposed Time-Ants in terms of the percentage of vehicles to reach the destination when compared with other leading approaches. Map 1 is considered with 400 vehicles. The different iterations represent consecutive days of weekday traffic. Figure 7-26 and Table 7-15 show the results for various iterations of Time-Ants when compared against different flavours of DNA, Dijkstra, the mechanism with no rerouting ("original routes") and Sommer's algorithm.

As can be seen from Figure 7-26, the proposed Time-Ants outperformed the other solutions in all simulations in terms of percentage of the vehicles which reach destination within the time-frame of the simulation. For instance, the best performing DNA flavours, DNA1 performed worse than Time-Ants by 15% after the first iteration and 18% after the fourth iteration. Time-Ants gave a better score then the mechanism which employs no rerouting by 16% after the first iteration and 19% after the fourth iteration.

The DNA4 algorithm performed poorly as it sent all the vehicles along the shortest route distance-wise, without regard to speed limits or traffic congestion.

Table 7-15 Percentage of vehicles to reach destination during simulation

Iterations	1 (%)	2 (%)	3 (%)	4 (%)
Time-Ants	56.5	58.25	57.25	58
Original	48.75	48.75	48.75	48.75
Dijkstra	51.5	51.5	51.5	51.5
DNA1	49	49	49	49
DNA2	49	49	49	49
DNA3	49	49	49	49
DNA4	48.5	48.5	48.5	48.5
Sommer	49	49	49	49

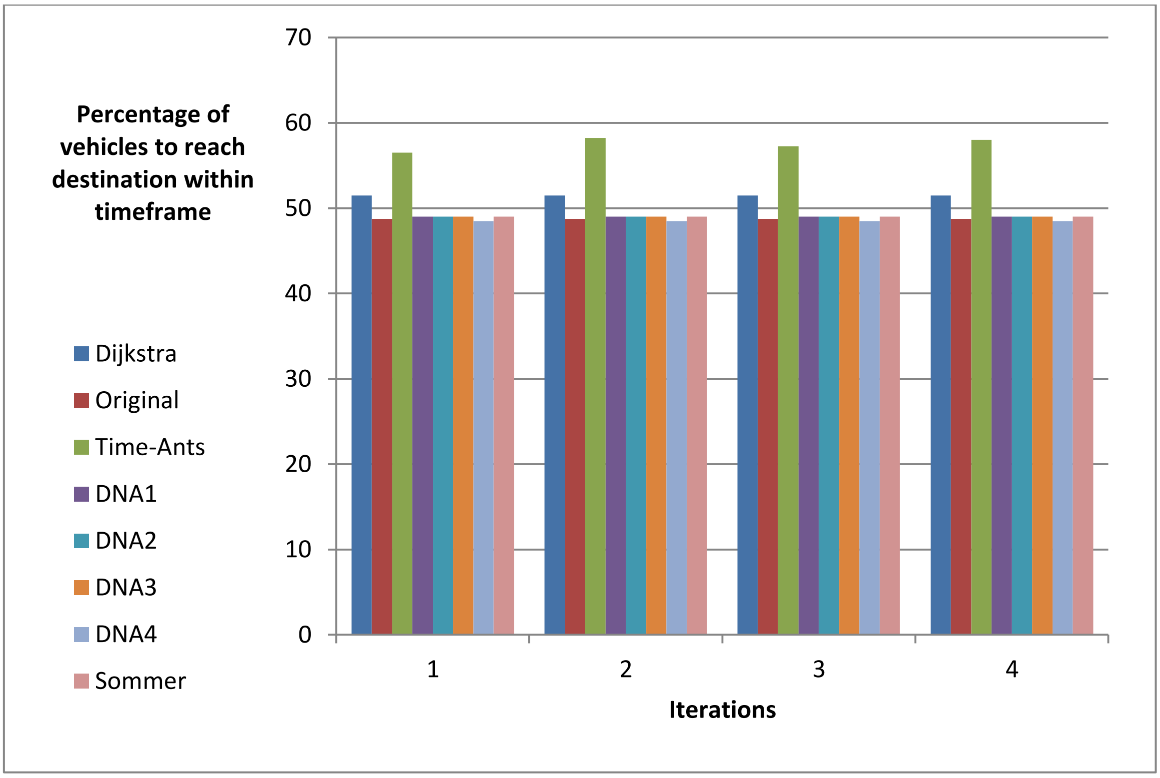

Figure 7-26 Percentage of vehicles which reached destination during simulation

Figure 7-26 shows an improvement of 19% in comparison with the baseline and 12%, 18% and 18% in comparison with Dijkstra, Sommer and DNA. These positive results of the Time-Ants algorithm are due to the fact that it considers load balancing and uses an innovative approach. Hence Time-Ants improves the results of the vehicle transportation, given the existing road network.

7.5.2 Scenario 2 – Influence of Map Type

The second set of results is for the map type comparison. This scenario was tested to show the effects of the map type on the different algorithms. Testing was ran on three different map types: Manhattan grid type, Radial and ring type and Random type.

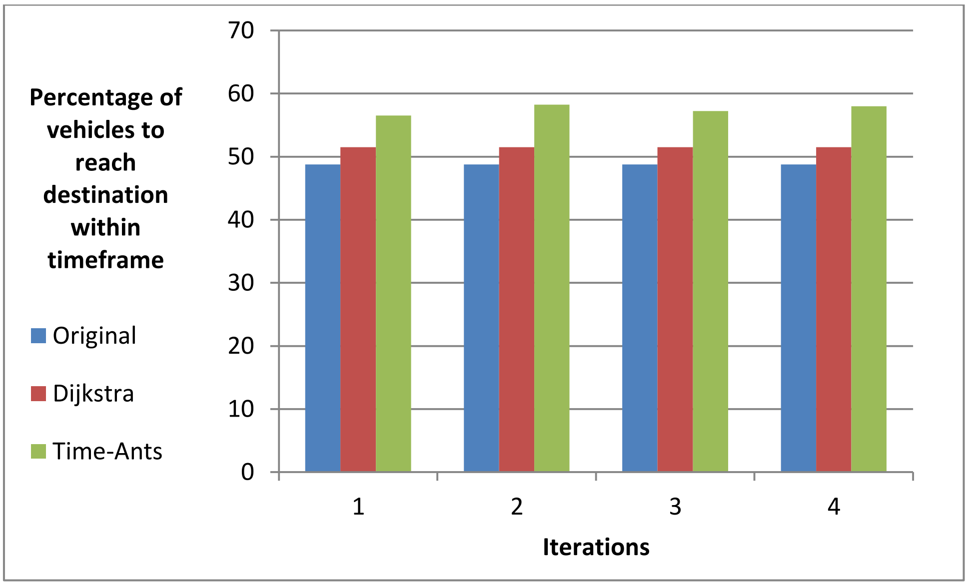

Figure 7-27 Percentage of vehicles to reach the destination within the timeframe for Map 1

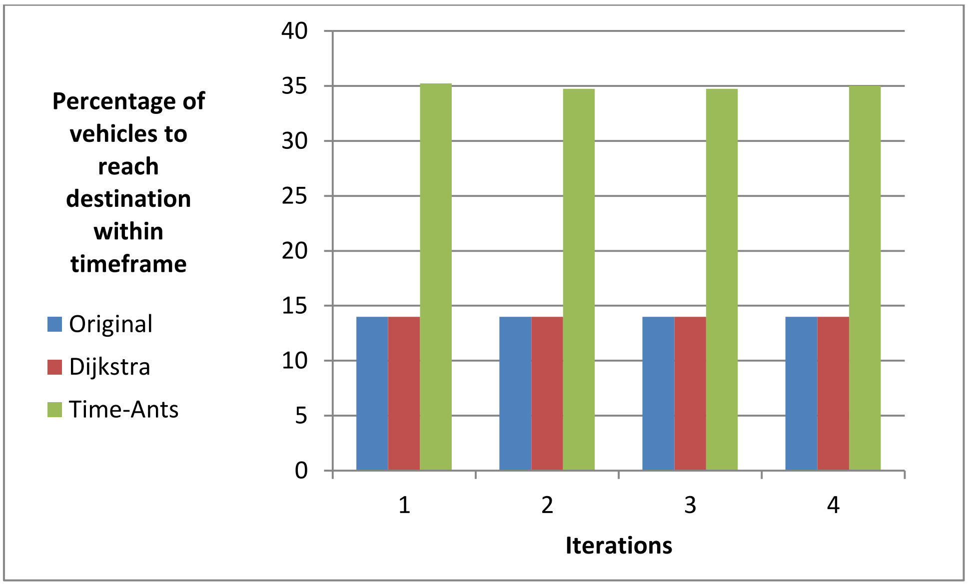

Figure 7-28 Percentage of vehicles to reach the destination within the timeframe for Map 2

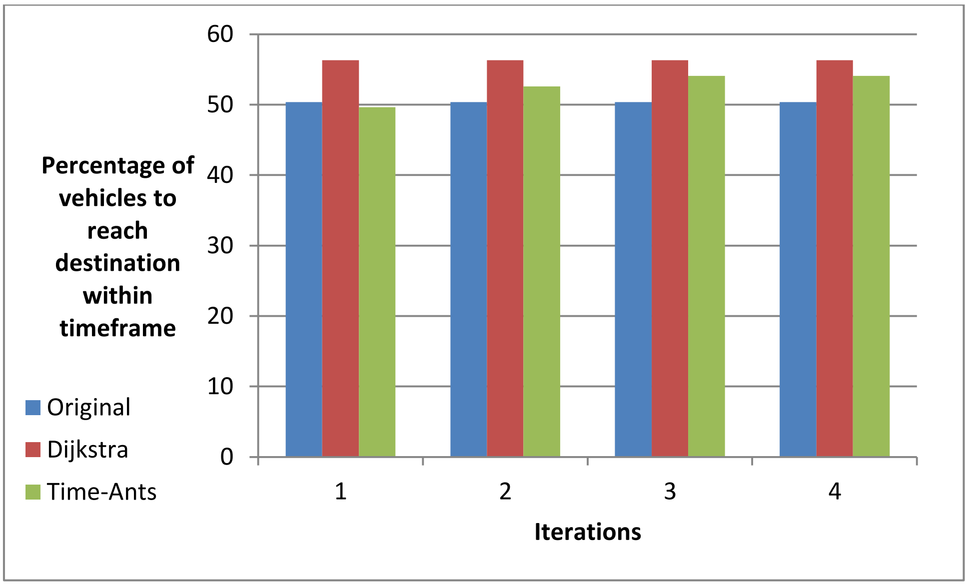

Figure 7-29 Percentage of vehicles to reach the destination within the timeframe for Map 3

Table 7-16 Percentage of vehicles to reach the destination within the timeframe for scenario 2

	Original (%)	Dijkstra (%)	Timeants1 (%)	Timeants2 (%)	Timeants3 (%)	Timeants4 (%)
Map 1 - Manhattan grid type	48.75	51.5	56.5	58.25	57.25	58
Map 2 - Radial and ring type	14	14	35.25	34.75	34.75	35
Map 3 - Random type	50.37	56.3	49.63	52.59	54.07	54.07

Figure 7-27 shows the percentage of vehicles to reach the destination within the timeframe for Map 1. Time-Ants outperforms Original and Dijkstra, by 16% and 10% respectively after the first iteration, and by 19% and 13% respectively after the fourth iteration.

Figure 7-28 displays the percentage of vehicles to reach the destination within the timeframe for Map 2. Time-Ants performs better than Original and Dijkstra, both by 152% after the first iteration, and both by 150% after the fourth iteration.

Figure 7-29 displays the percentage of vehicles to reach the destination within the timeframe for Map 3. Time-Ants is outperformed by Original and Dijkstra, by 2% and 12% after the first iteration. For the fourth iteration Time-Ants achieves a better result than Original by 7%, but achieves a worse result than Dijkstra by 4%.

For Map 1 Time-Ants achieved a better result than Dijkstra by 11.5% on average. For Map 2 Time-Ants outperformed Dijkstra by 150% on average and for Map 3 Time-Ants achieved a worse result than Dijkstra by 6.5% on average.

As can be seen from Figure 7-27 and Figure 7-28, Time-Ants performed quite well for Map 1 and Map 2, but poorly for Map 3, as seen in Figure 7-29. Map 3 contains only 200 vehicles so this could be factor, as there is less traffic congestion. Time-Ants seems to be more effective with increasing number of vehicles. This will become more apparent in the testing for different numbers of vehicles, presented in the next section.

7.5.3 Scenario 3 - Different Numbers of Vehicles

The goal of this testing scenario was compare the effect of the number of vehicles on the various algorithms.

Table 7-17 Percentage of vehicles to reach the destination within the timeframe for scenario 3

	Original (%)	Dijkstra (%)	Time-Ants1 (%)	Time-Ants2 (%)	Time-Ants3 (%)	Time-Ants4 (%)
200	35.5	40.5	44.5	38	40.5	38
300	44.33	48	55	51	49.33	52
400	48.75	51.5	56.5	58.25	57.25	58
500	51.6	53.6	62.8	59.6	56.8	59.2

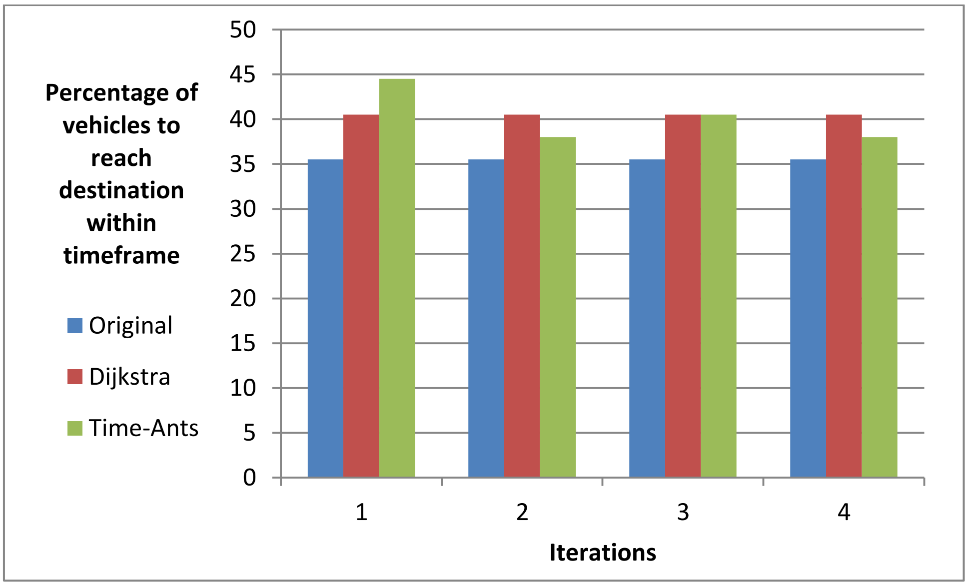

Figure 7-30 Percentage of vehicles to reach the destination within the timeframe for 200 vehicles

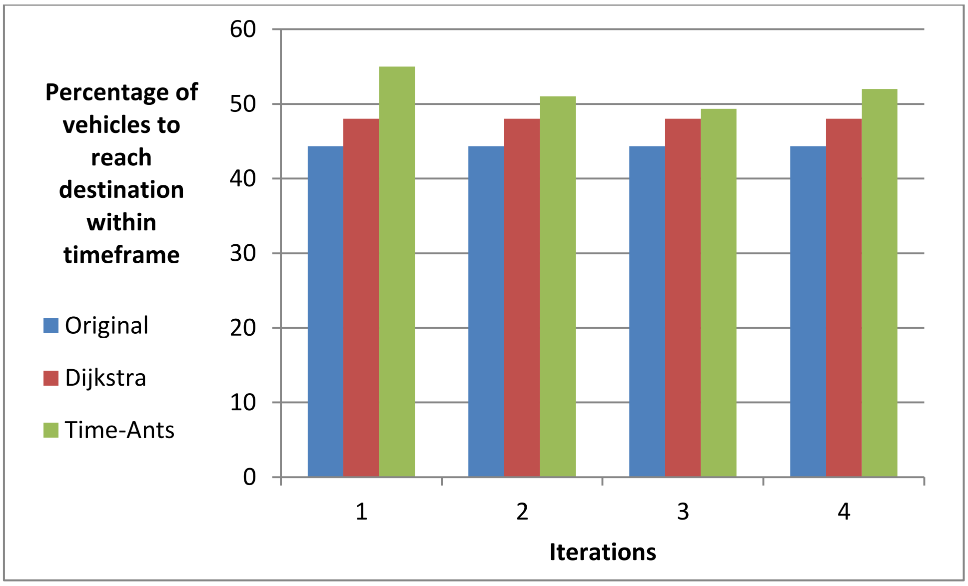

Figure 7-31 Percentage of vehicles to reach the destination within the timeframe for 300 vehicles

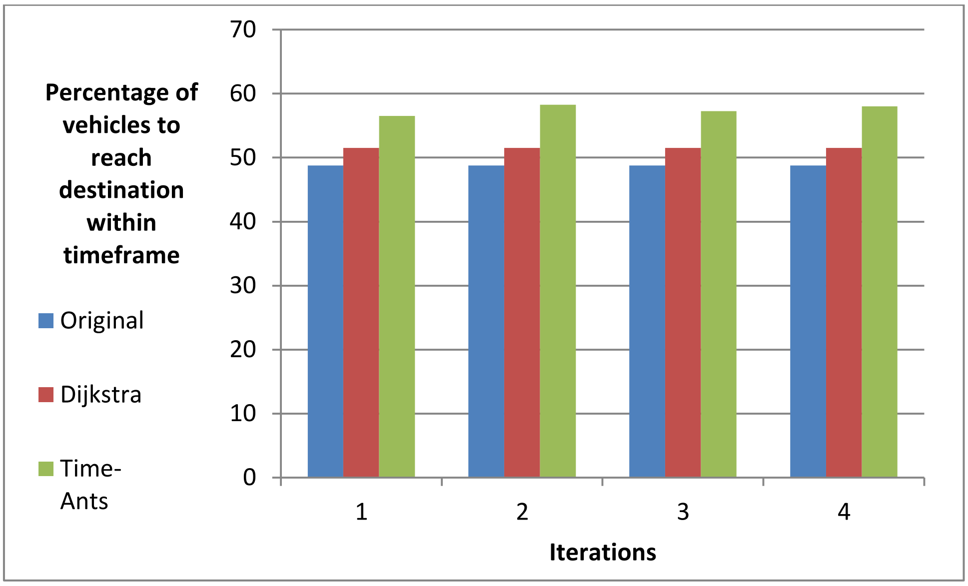

Figure 7-32 Percentage of vehicles to reach the destination within the timeframe for 400 vehicles

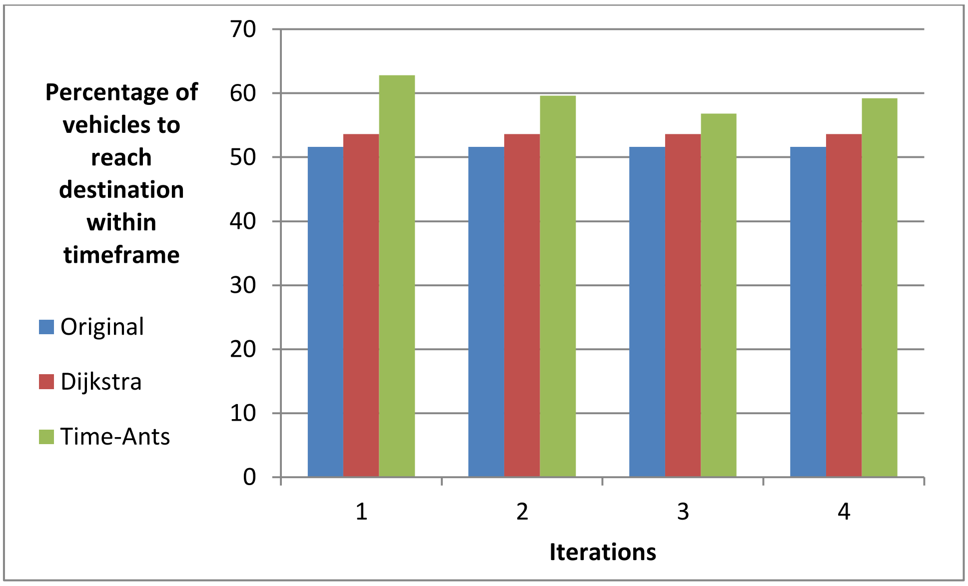

Figure 7-33 Percentage of vehicles to reach the destination within the timeframe for 500 vehicles

Figure 7-30 presents the percentage of vehicle to reach the destination within the timeframe for the trace of 200 vehicles. Time-Ants outperforms Original and Dijkstra, by 25% and 10% respectively after the first iteration. For the fourth iteration Time-Ants achieves a better result than Original by 7%, but achieves a worse result than Dijkstra by 6%.

Figure 7-31 displays the percentage of vehicles to reach the destination within the timeframe for the trace of 300 vehicles. Time-Ants performs better Original and Dijkstra, by 24% and 15% respectively after the first iteration, and 17% and 8% respectively after the fourth iteration.

Figure 7-32 illustrates the percentage of vehicles to reach the destination within the timeframe for the trace of 400 vehicles. Time-Ants attained a better result than Original and Dijkstra, by 16% and 10% after the first iteration and by 19% and 13% respectively after the fourth iteration.

Figure 7-33 displays the percentage of vehicles to reach the destination within the timeframe for the trace of 500 vehicles. Time-Ants outperforms Original and Dijkstra, by 21% and 17% after the first iteration and by 14% and 10% respectively after the fourth iteration.

In a brief summary Figure 7-30 presents the percentage of vehicle to reach the destination within the timeframe for the trace of 200 vehicles, Time-Ants performed better than Dijkstra by 0.5% on average for this metric. For the trace of 300 vehicles, as shown in

Figure 7-31, Time-Ants improves upon Dijkstra's result by 8%. The results for the trace of 400 vehicles is illustrated in Figure 7-32, in this case Time-Ants outperformed Dijkstra by 11.5%. Finally as shown in Figure 7-33, for the trace of 500 vehicles Time-Ants performed better compared with Dijkstra by 11%. Note the trend here in which the performance of Time-Ants improves with a larger amount of vehicles relative to the other schemes tested, this can be seen in Figure 7-34.

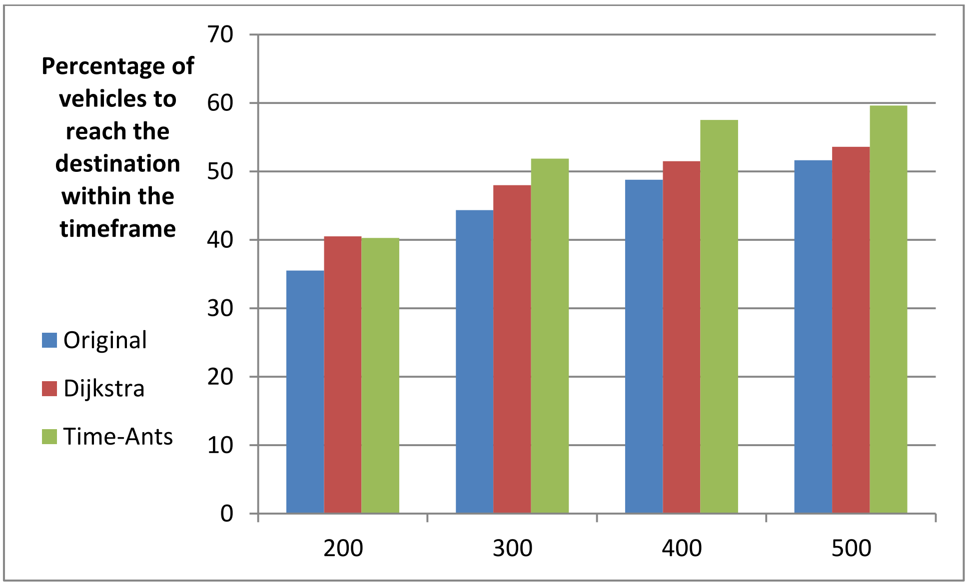

Figure 7-34 Average percentage of vehicles to reach destination within timeframe over four iterations

7.5.4 Scenario 4 - Different Penetration Rates

The goal of this testing scenario was compare the effect of different penetration rates on the various algorithms.

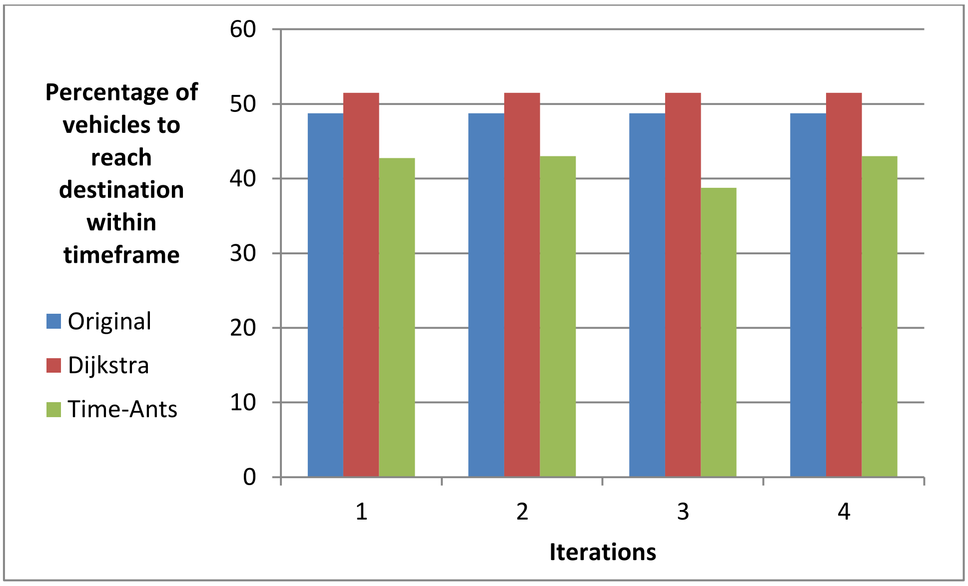

Figure 7-35 Percentage of vehicles to reach destination within timeframe for 75% penetration rate

Figure 7-35 shows the percentage of vehicles to reach the destination within the timeframe for the penetration rate of 75%. Time-Ants performed worse than Original and Dijkstra, by 12% and 17% after the first iteration and the same results after the fourth iteration.

Table 7-18 Results for different penetration rates

Penetration Rate (%)	Original (%)	Dijkstra (%)	Timeants1 (%)	Timeants2 (%)	Timeants3 (%)	Timeants4 (%)
100	48.75	51.5	56.5	58.25	57.25	58
75	48.75	51.5	42.75	43	38.75	43
50	48.75	51.5	39.5	39	39.75	40
25	48.75	50.75	44	43	42.5	40
0	48.75	48.75	48.75	48.75	48.75	48.75

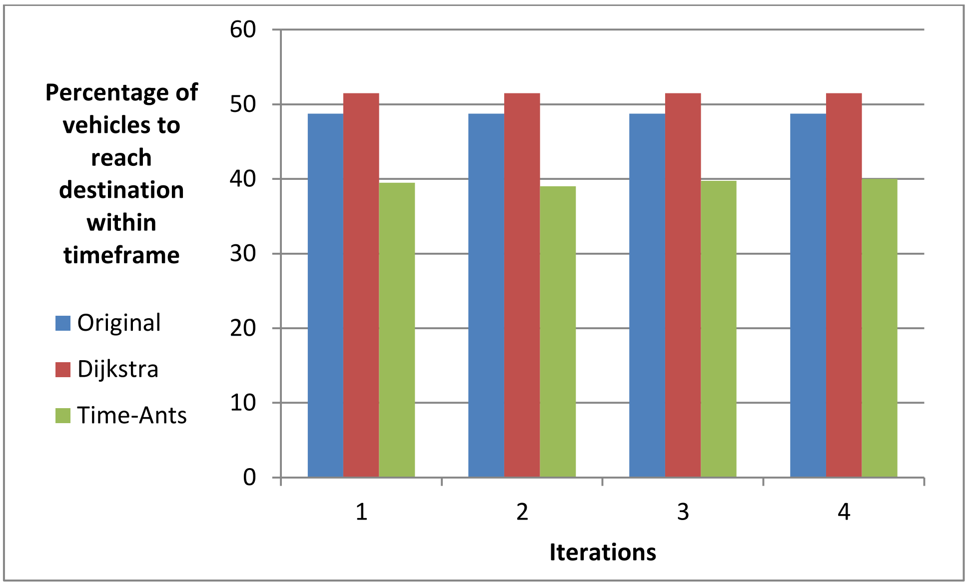

Figure 7-36 Percentage of vehicles to reach destination within timeframe for 50% penetration rate

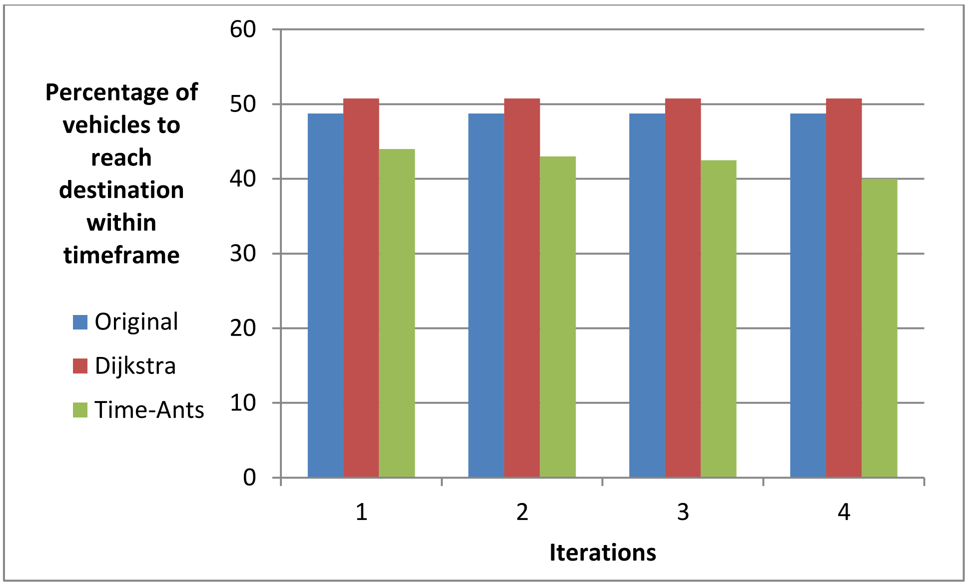

Figure 7-37 Percentage of vehicles to reach destination within timeframe for 25% penetration rate

Figure 7-36 displays the percentage of vehicles to reach the destination within the timeframe for the penetration rate of 50%. Time-Ants is outperformed by Original and Dijkstra, by 19% and 23% respectively after the first iteration and by 18% and 22% respectively after the fourth iteration.

The percentage of vehicles to reach the destination within the timeframe for the penetration rate of 25% is pictured in Figure 7-37. Time-Ants attained a worse result than Original and Dijkstra, by 10% and 13% respectively after the first iteration. For the fourth iteration Time-Ants is outperformed by Original and Dijkstra, by 18% and 21% respectively.

In a brief summary for the penetration rate of 75% Time-Ants is outperformed by Dijkstra by 19% on average, this is displayed in Figure 7-35. For the penetration rate of 50% Time-Ants achieved a better result than Dijkstra by 23% on average, as shown in Figure 7-36. Figure 7-37 depicts the results for the penetration rate of 25%, in which Time-Ants produced a worse result than Dijkstra by 16.5% on average.

From the results of the average over 4 iterations shown in Figure 7-38, it can be seen that Time-Ants does not perform well under different penetration rates. It performs worst at 50% showing that this is a scheme which rests upon a very high penetration rate.

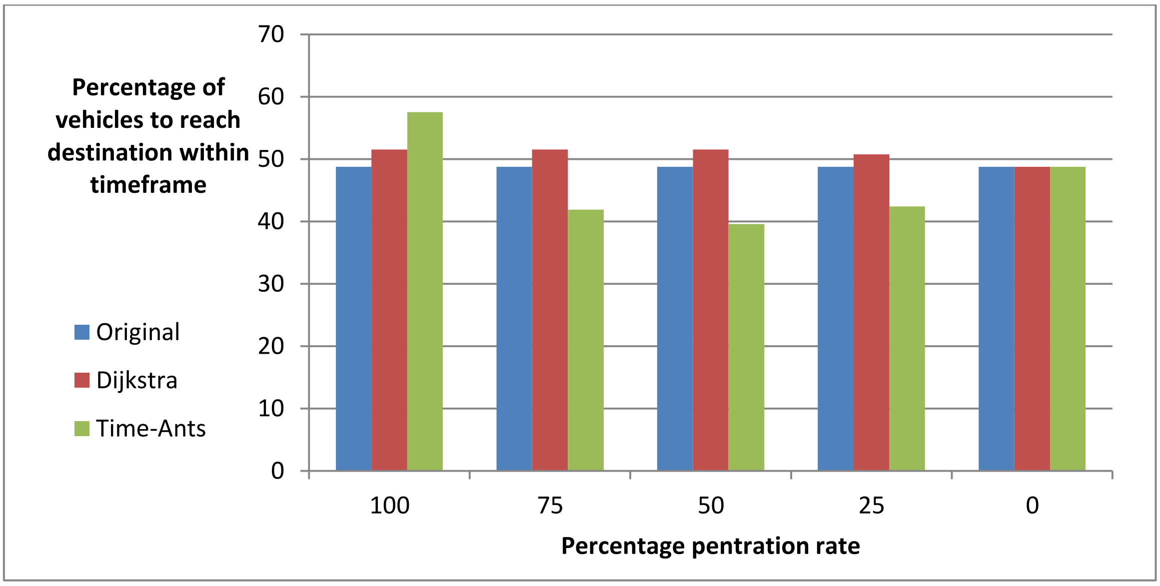

Figure 7-38 Average Percentage of vehicles to reach destination within timeframe for over different iterations for different penetration rates.

7.5.5 **Scenario 5 - Different Compliance Rates**

The goal of this testing scenario was compare the effect of different compliance rates on the various algorithms.

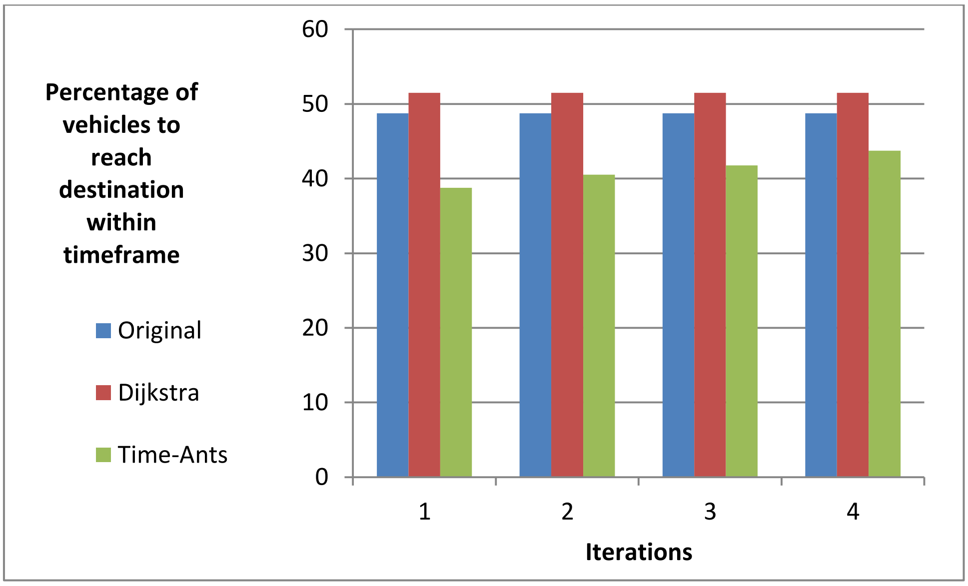

Figure 7-39 Percentage of vehicles to reach destination within timeframe for 75% compliance rate

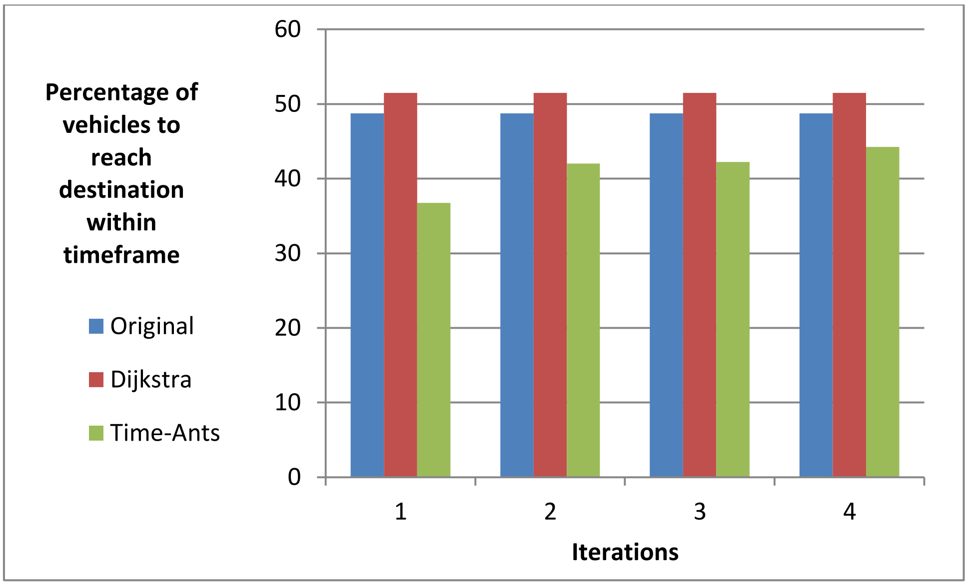

Figure 7-40 Percentage of vehicles to reach destination within timeframe for 50% compliance rate

Figure 7-39 shows the percentage of vehicles to reach the destination within the timeframe for the compliance rate of 75%. Time-Ants is outperformed by Original and Dijkstra, by 20% and 24% after the first iteration and by 10% and 15% respectively after the fourth iteration.

Figure 7-40 displays the percentage of vehicles to reach the destination within the timeframe for the compliance rate of 50%. Time-Ants performed worse in comparison with those of Original and Dijkstra, by 25% and 29% respectively after the first iteration and by 9% and 14% respectively after the fourth iteration.

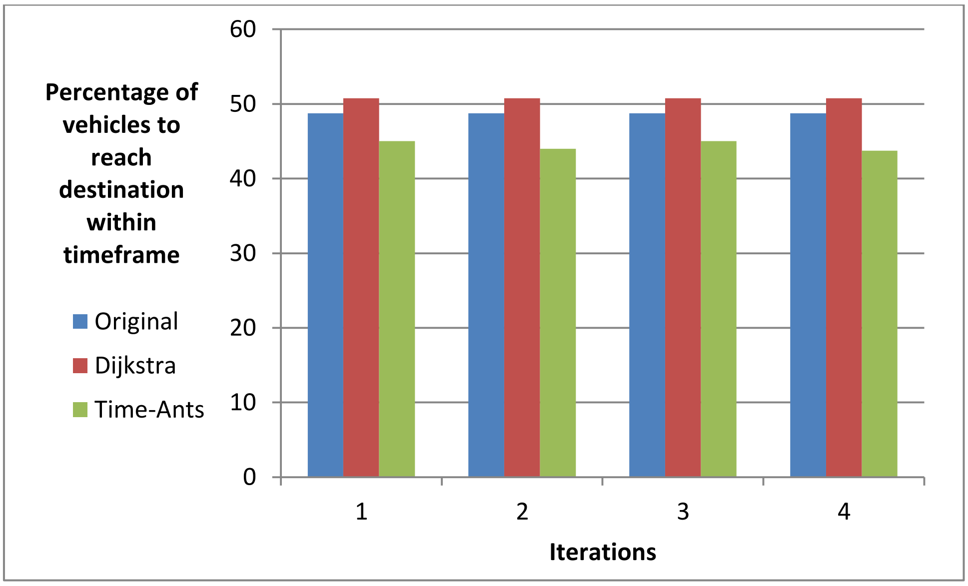

Figure 7-41 Percentage of vehicles to reach destination within timeframe for 25% compliance rate

Table 7-19 Results for different compliance rates

Compliance Rate (%)	Original (%)	Dijkstra (%)	Timeants1 (%)	Timeants2 (%)	Timeants3 (%)	Timeants4 (%)
100	48.75	51.5	56.5	58.25	57.25	58
75	48.75	51.5	38.75	40.5	41.75	43.75
50	48.75	51.5	36.75	42	42.25	44.25
25	48.75	50.75	45	44	45	43.75
0	48.75	48.75	48.75	48.75	48.75	48.75

Figure 7-41 depicts the percentage of vehicles to reach the destination within the timeframe for the compliance rate of 25%. The results from Time-Ants were surpassed by those of Original and Dijkstra, by 8% and 11% respectively after the first iteration. For the fourth iteration Time-Ants is outperformed by Original and Dijkstra, by 10% and 14% respectively.

In a brief summary for the compliance rate of 75% Time-Ants' score was less than those of Dijkstra by 20% on average, this is displayed in Figure 7-39. For the compliance rate of 50% Time-Ants was outperformed by Dijkstra by 20% on average, as shown in Figure 7-40. Figure 7-41 illustrates the results when the compliance rate was set to 25%. In this instance Dijkstra performed better than Time-Ants by 12.5% on average. Finally the average results for the different compliance rates can be seen in Figure 7-42.

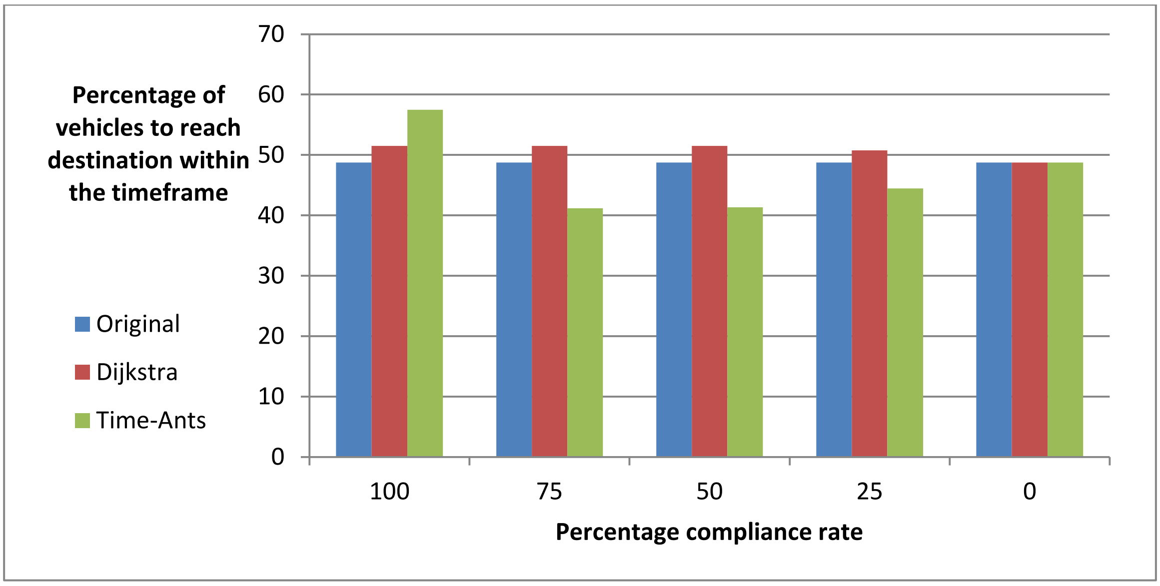

Figure 7-42 Average percentage of vehicles to reach destination for all compliance rates

7.6 Electric Vehicle Enhanced Dedicated Bus Lanes Testing Simulation Set-up

This section presents the settings for simulation-based testing which are performed to demonstrate the benefit of introducing E-DBLs in an urban environment. E-DBL proposes allowing electric vehicles access to bus lanes in order to improve road capacity reduce the congestion felt by electric vehicles without greatly impeding the journey times of buses.

For the simulations, the road traffic simulator SUMO [310] was used. SUMO is an open source microscopic traffic simulator, which simulates each individual vehicle as opposed to just traffic flows.

For the testing scenario a map of Dublin was obtained from the OpenStreetMap website in the form of an xml file [313]. The map size is 1,500 m by 2,000 m, and has the following coordinates: 53.333274, -6.291900 to 53.356862, -6.202507. Vehicle counts from induction loops in Dublin are available from the Dublin City Council website [314]. The junctions which contained induction loops are marked with Xs in Figure 7-43. Vehicle traces were constructed from the vehicle counts and five traces of different Monday mornings in January 2012 were made. In the first four scenarios vehicles were considered from 6:00 am to 6:15 am in the morning. These traces contained approximately 500 vehicles each. A rush hour scenario with 780 vehicles was also made. These vehicles were changed to varying percentages of Electric Vehicles (EVs) and Internal Combustion Engine vehicles (ICEs) during simulations. This took vehicles in Dublin from 8:30 am to 8:45 am in the morning. The vehicles were considered light passenger vehicles with engines between 1.4 and 2 litres in the SUMO simulations. The bus lanes were added to the map xml file manually using data from a map downloaded from the Dublin Institute of Technology (DIT) website [317]. This map is presented in Figure 7-44.

The bus arrival times were obtained from the timetables on the Dublin bus website [318]. These buses were then added to the vehicle trace. The energy consumption for EVs and fuel consumption for ICEs were recorded during the simulations.

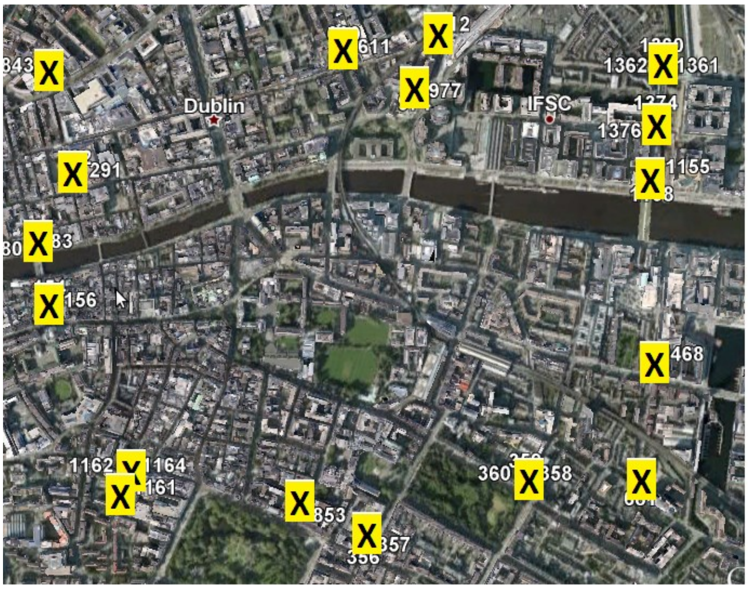

Figure 7-43 Map of Dublin City Centre with induction loops marked with Xs (Screenshot from Google-Earth [312])

In order to more accurately calculate fuel consumption, the gradients and roughness levels of the roads in the map were considered. The road gradients were obtained using Google Earth [312]. The heights of all road segment ends on the map were retrieved using the Google Maps APIs [295] and stored in a .cvs file. A Python script was then used to extract the length of all individual road segments and the heights of the start and end points of each segment, and calculate the gradients. These were then stored alongside map information in xml format. Appendix 1 includes the detailed procedure for computing these and the Python script employed.

The road roughness information was obtained from Dublin City Council in the form of IRI (International roughness index) and MPD (Mean depth profile) data. These were used to generate road roughness values of the major roads; the smaller roads' roughness was estimated from statistics obtained from the National Roads Authority [199].

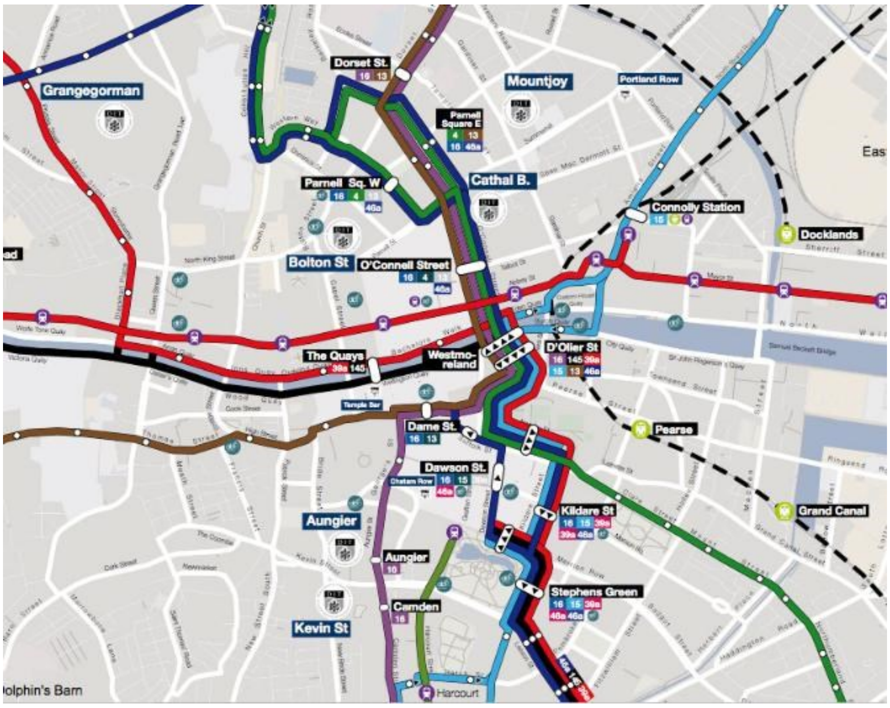

Figure 7-44 Map of Dublin City Centre with bus lanes [317]

Both the road gradient data and road roughness data were added to the map information.

The amount of energy the electric vehicles used was also calculated. The EVs energy computation was done similarly with that of basic passenger vehicles, the only difference being that their consumption was calculated in KWh instead of fuel litres.

MPGe is roughly 33.7 kWh [319]. 19.64 pounds of CO_2 in a gallon [320] = 8.9 kg. In HBEFA was used (CO_2*8.9)/33.7 to calculate the electricity consumed by the electric vehicles.

The ICE vehicles and the ICE buses were based on the basic passenger car P and the HDV models, both implemented in SUMO [202].

7.7 E-DBL Testing Results

Five scenarios were considered, a scenario for each of the vehicle traces. The five vehicle traces taken at similar times on different days for Dublin were considered with three different lane set-ups: all the lanes open to all traffic ('All lanes open'), dedicated bus lanes (DBL) and electric vehicle enhanced dedicated bus lanes (E-DBL). The percentage of vehicles, which were EV and ICE, respectively, varied between 0-100% in steps of 10%.

The bus times, the percentage of different vehicle types which had reached their destination, and the emissions were recorded for the five scenarios, for the three different lane schemes and for the different percentages of EVs. These results will now be discussed in details.

7.7.1 Bus Times

The average arrival times of buses were recorded for the five scenarios, with the three different lanes schemes, and for differing percentages of EVs. Scenario 1, 3 and 4 resulted in the same average travel time for buses of 378 seconds across all lane schemes and percentages of EVs.

Table 7-20 Journey times of buses in scenario 1, 3, 4

Bus journey times											
% EVs	0	10	20	30	40	50	60	70	80	90	100
All lanes open (s)	378	378	378	378	378	378	378	378	378	378	378
DBL (s)	378	378	378	378	378	378	378	378	378	378	378
E-DBL (s)	378	378	378	378	378	378	378	378	378	378	378

Scenario 2 resulted in average travel time for buses of 378 seconds for 'all lanes open' and 499 seconds for DBL. E-DBL returned an average travel time of 499 seconds for 0%, 10% and 40% EVs, with 378 seconds for the rest. Traffic congestion decreases as larger numbers of vehicles are allowed in the bus lanes.

Table 7-21 Bus journey times in scenario 2

Bus journey times											
% EVs	0	10	20	30	40	50	60	70	80	90	100
All lanes open (s)	378	378	378	378	378	378	378	378	378	378	378
DBL (s)	499	499	499	499	499	499	499	499	499	499	499
E-DBL (s)	499	499	378	378	499	378	378	378	378	378	378

Table 7-22 Bus journey times in scenario 5

Bus journey times											
% EVs	0	10	20	30	40	50	60	70	80	90	100
All lanes open (s)	394	394	394	394	394	394	394	394	394	394	394
DBL (s)	393	393	393	393	393	393	393	393	393	393	393
E-DBL(s)	393	393	393	393	394	393	393	395.3	394	394	394

In Scenario 5 more buses arrived for E-DBL for the simulations which considered the percentage of EVs in the total number of vehicles of 60%, 70%, 80% and 90%. This fact combined with the low average travel time compared with the other schemes makes E-DBL the best scheme in terms of bus travel times.

With the exception of Scenario 2, the bus travel times were not greatly affected by the different lane schemes. Heavy traffic congestion was the cause of the delays in Scenario 2.

7.7.2 ICEs and EVs

The following graphs, Figure 7-45 to Figure 7-53, show the percentage of vehicles which reach their allotted destination within the 6:00 to 6:15 timeframe in the case of Scenario 1-4 or the 8:30 to 8:45 timeframe in the case of Scenario 5. The first graph in each scenario shows the results for ICE cars and the second shows the results for EVs. The Dublin map from Figure 7-43 was used in all 5 scenarios.

7.7.2.1 Scenario 1

The results for Scenario 1 are now presented. This scenario contained 450 passenger vehicles.

Figure 7-45 shows the results of 30 simulations. Scenario 1 was run with the three different lane schemes for ten different percentages of EVs. The percentages of EVs varied from 0% to 100%, in steps of 10%. The percentages of ICEs to reach the destination were recorded. As can be seen from the results 'all lanes open' was the best lane scheme for ICEs, as expected. However E-DBL gave a slight improvement when compared with DBL. This amounted to 2.5% on average. T-tests confirmed that the two sets of results were statistically different with a 90% confidence interval.

This is significant as the scheme aims at improving travel times for EVs, not ICEs. This shows that E-DBL positively affects all traffic.

Figure 7-46 shows the percentages of EVs to reach their destination in Scenario 1 for the three different lane schemes for varying percentages of EVs. The total number of passenger cars which were EVs varied between 10% and 100% in steps of 10%. 'All lanes open' showed the best results, but E-DBL dramatically outperformed DBL. The statistical difference between the results for E-DBL and those of DBL was proven with t-test with a 99.9% confidence interval. This was shown to be a 27% improvement on average. The improvement increases with the percentage of EVs from 15% improvement at 10% to 32% at 90%.

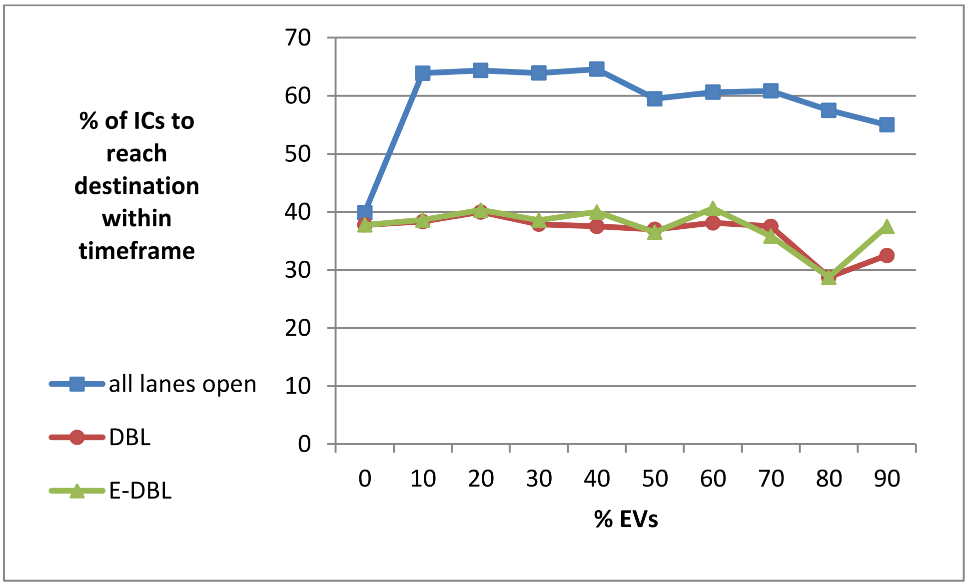

Figure 7-45 Percentage of Cars to reach destination in Scenario 1 under varying percentages of EVs.

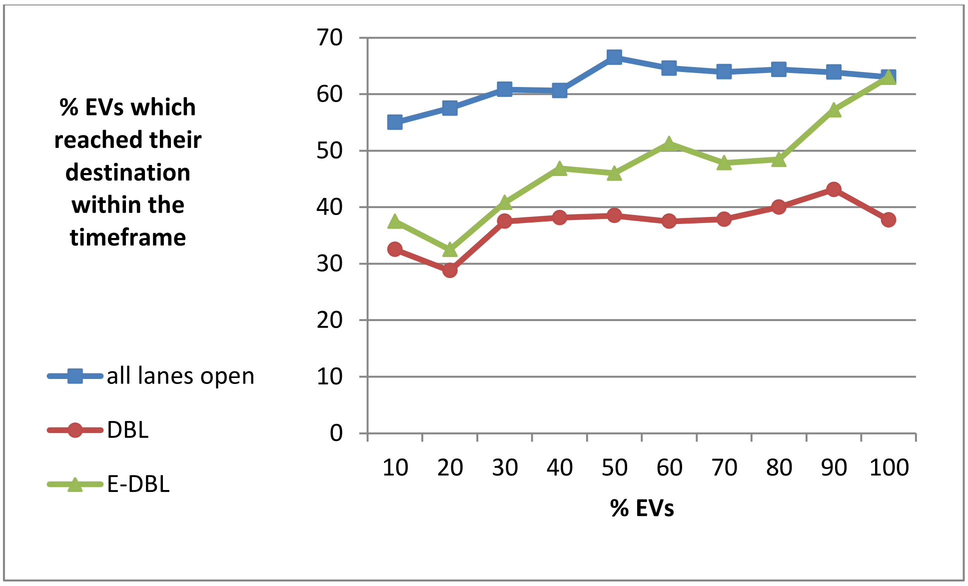

Figure 7-46 Percentage of EVs to reach destination in Scenario 1 under varying percentages of EVs.

7.7.2.2 Scenario 2

The traffic in Scenario 2 was slightly heavier, including in total 600 vehicles and used the same map. This resulted in increased traffic congestion and in a lower percentage of ICEs and EVs reaching their destination within the timeframe across all the schemes. In

Figure 7-47 we see a similar pattern to the results in Scenario 1 for percentage of ICEs reaching their destination. ‘All lanes open’ yields the best result with a slight improvement of E-DBL versus DBL. This improvement was 9% on average with greater improvement for the higher ratios of EVs. This difference was shown to be statistically significant with a 95% confidence interval.

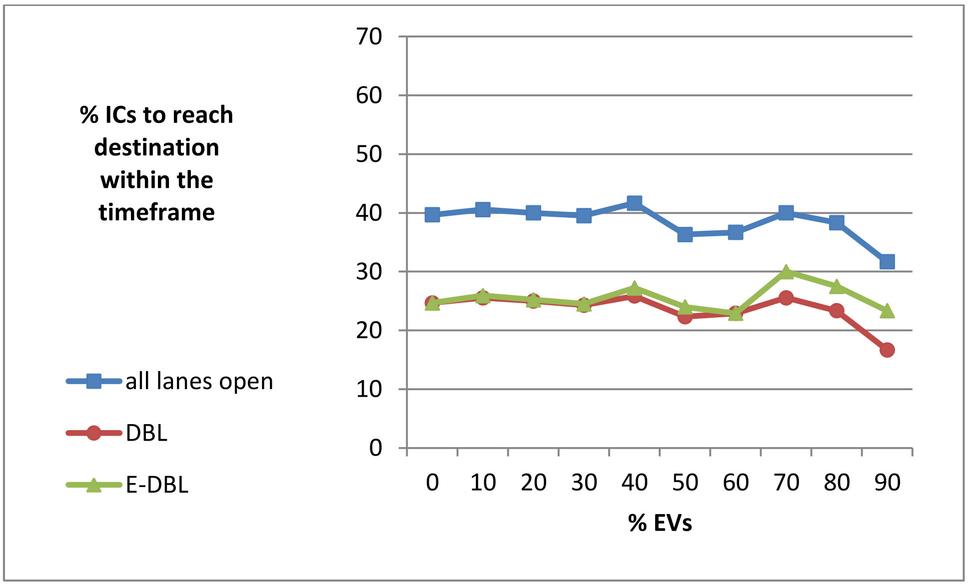

Figure 7-47 Percentage of Cars to reach destination in Scenario 2 under varying percentages of EVs.

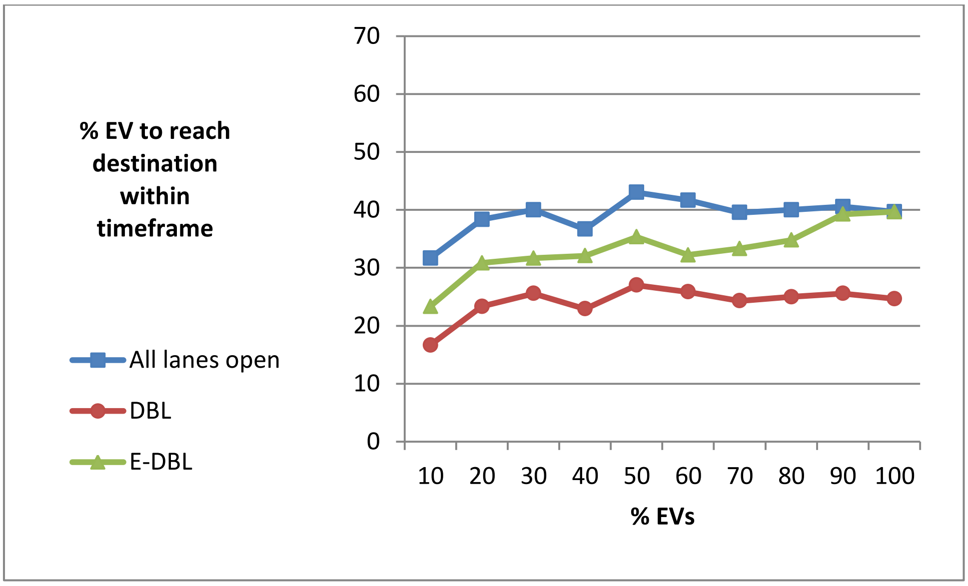

Figure 7-48 Percentage of EVs to reach destination in Scenario 2 under varying percentages of EVs.

Again the percentage of vehicles to reach their destination was lower for EVs as well, as can be seen in Figure 7-48. This was due to increased traffic congestion in Scenario 2, but similar patterns were seen. ‘All lanes open’ was the best policy in terms of percentages of vehicles to reach their destination.

E-DBL outperformed DBL in these sets of results as well. The improvement was slightly higher in Scenario 2 than in Scenario 1. This is due to increased traffic congestion. Using t-tests, the difference between DBL and E-DBL was shown to be statistically significant with a 99.99% confidence interval. On average E-DBL outperformed DBL by 38%.

7.7.2.3 Scenario 3

The results for passenger cars in scenario 3 will now be discussed. Traffic in Scenario 3 was also quite heavy, 530 passenger cars entered the map during the timeframe.

For the third time the same pattern is shown in Figure 7-49. ‘All lanes open’ being the best scheme with E-DBL results following and DBL performing worst. Due to the heavy traffic in scenario 3 E-DBL outperformed DBL by 8% only, with greater improvements for larger amounts of EVs. T-tests confirmed the statistical difference between the results for DBL and E-DBL with a 95% confidence interval.

The results for EVs in Scenario 3 further confirm the pattern of E-DBL being the better solution to DBL, as can be seen in Figure 7-50.

The results for E-DBL and DBL were shown to be statistically significant with a 99.9% confidence interval when t-tests were performed. On average E-DBL outperformed DBL by 40%, the difference was higher for higher percentages of EVs.

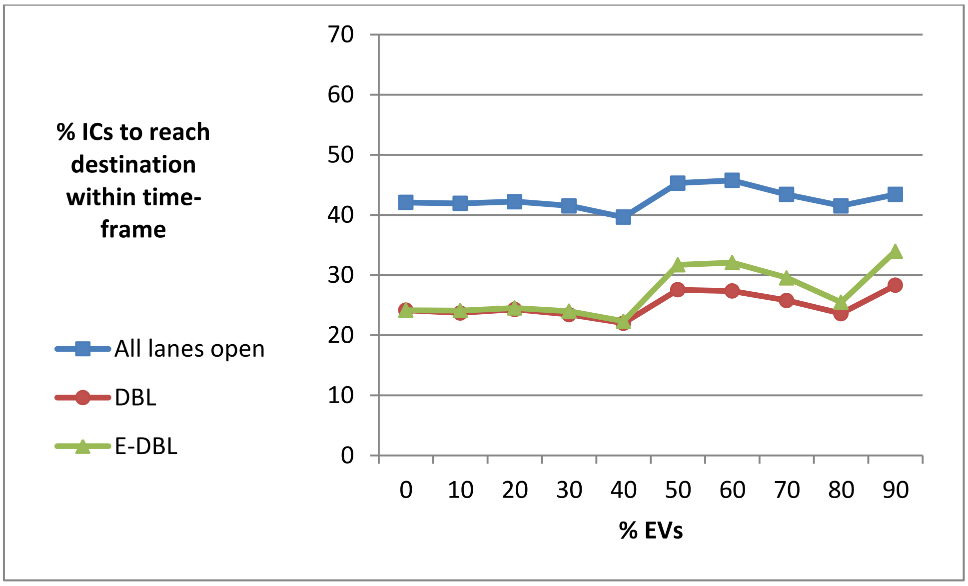

Figure 7-49 Percentage of Cars to reach destination in Scenario 3 under varying percentages of EVs.

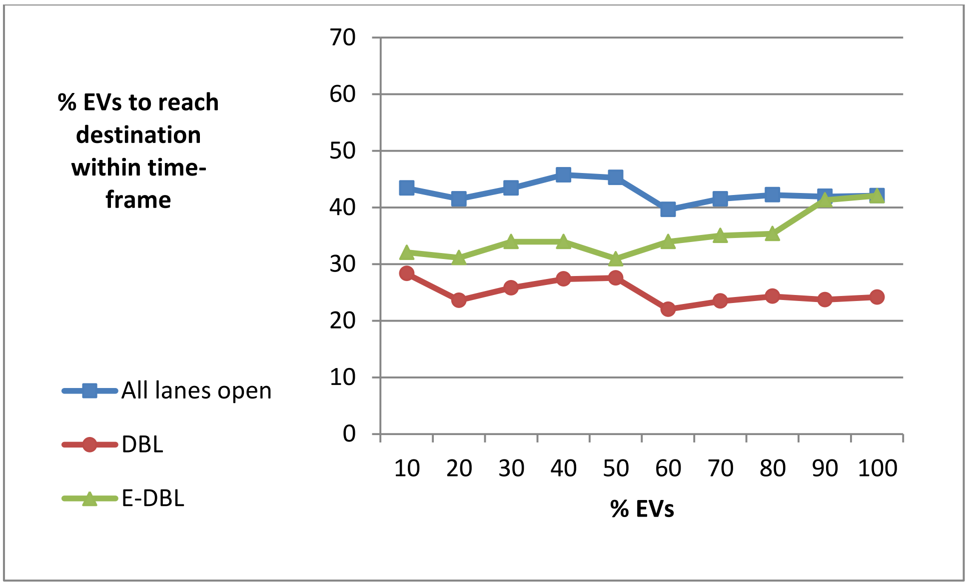

Figure 7-50 Percentage of EVs to reach destination in Scenario 3 under varying percentages of EVs.

7.7.2.4 Scenario 4

The results for passenger cars in Scenario 4 are discussed in this section.

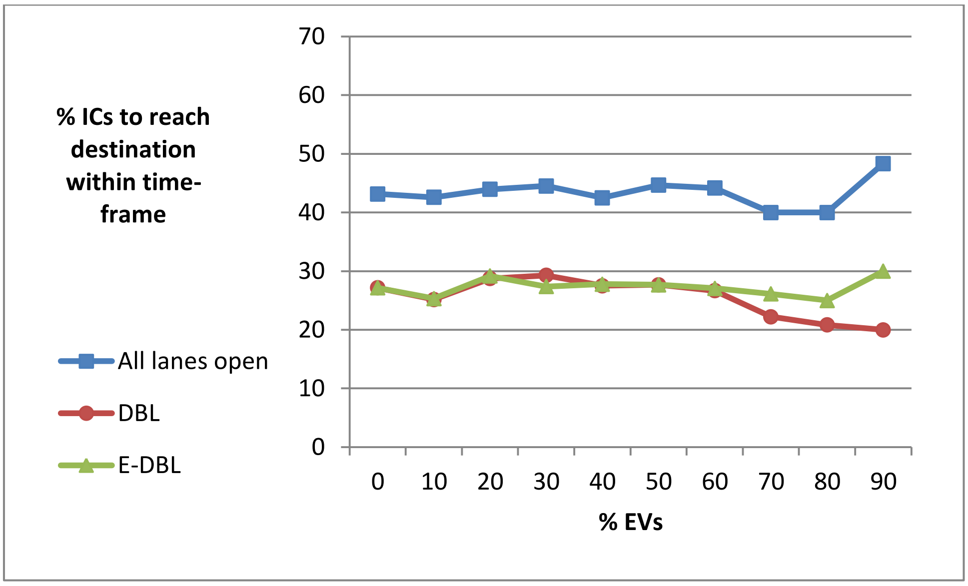

Figure 7-51 Percentage of Cars to reach destination in Scenario 4 under varying percentages of EVs.

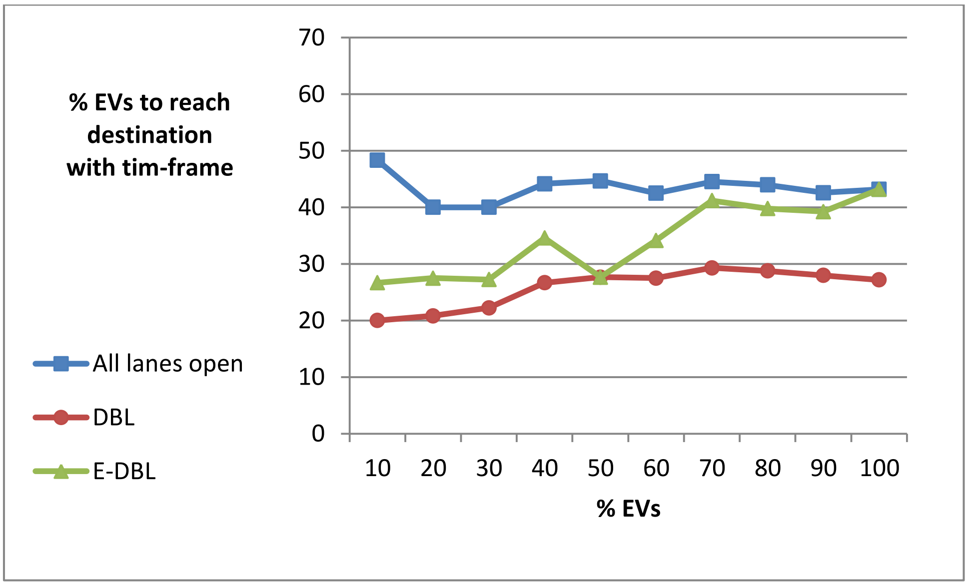

Figure 7-52 Percentage of EVs to reach destination in Scenario 4 under varying percentages of EVs.

This vehicle trace contained 600 vehicles. The Figure 7-51 shows one point where DBL outperforms E-DBL. Dynamic systems such as traffic road systems have an inherent degree of randomness. This explains the result for 30% EVs.

T-tests showed a statistical difference between the results for E-DBL and DBL with a 90% confidence interval and on average E-DBL outperformed DBL by 7%.

The results for EVs in Scenario 4, presented in Figure 7-52, show the same patterns as in the previous scenarios. Once again E-DBL outperforms DBL in terms of percentage of

EVs to reach their destination. T-tests confirmed a statistical difference with a 99.5% confidence interval. On average E-DBL outperformed DBL by 32%

7.7.2.5 Scenario 5 – Late morning scenario

Scenario 5 was a vehicle trace of Dublin from 8:30 am to 8:45 am, unlike the previous four scenarios, which used vehicle traces of Dublin from 6:00 am to 6:15 am in the morning. Due to rush hour taking place in Dublin at around 8:30 am, scenario 5 has 780 vehicles.

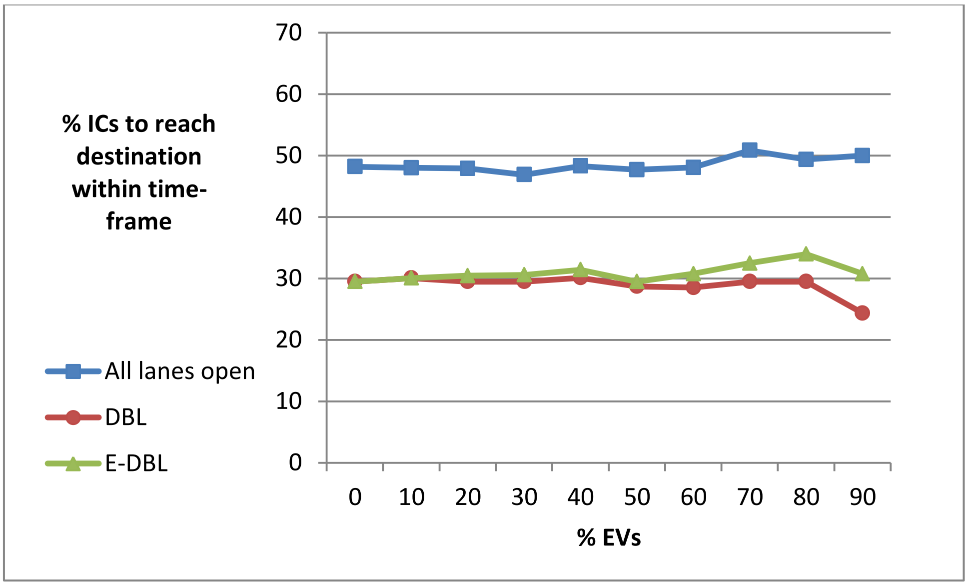

Figure 7-53 Percentage of ICEs to reach destination in Scenario 5 under varying percentages of EVs.

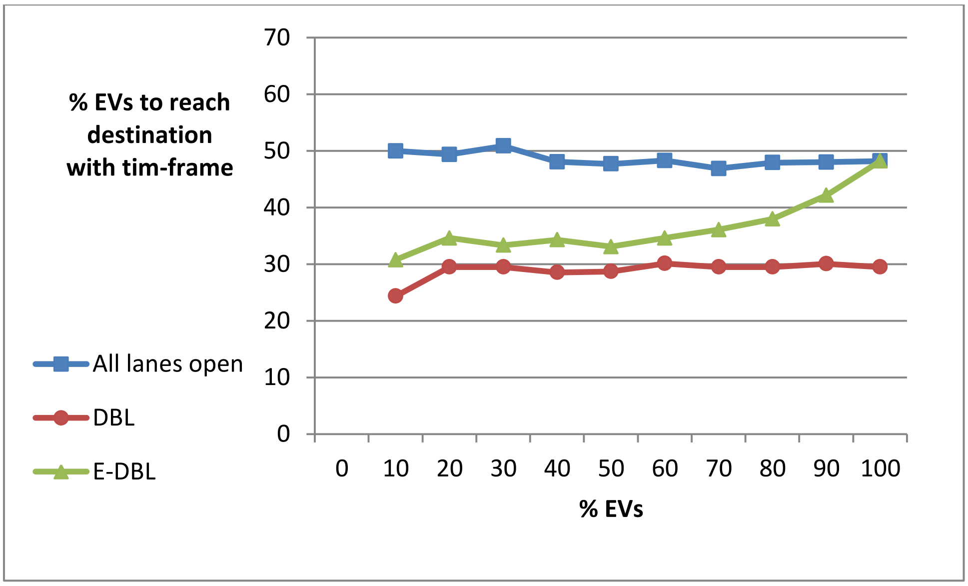

Figure 7-54 Percentage of EVs to reach destination in Scenario 5 under varying percentages of EVs.

Despite focusing on a different time, Scenario 5 resulted in similar patterns with E-DBL outperforming DBL by an average of 7% for the percentage of ICEs to reach their destination within the time-frame. This was confirmed by t-tests to be statistically significant with a 99% confidence interval. This is displayed in Figure 7-53.

Finally the same pattern is shown in Figure 7-54 for the results for EVs. An average improvement of 26% when E-DBL is employed is achieved in comparison with the case when DBL is used. The difference between these results is statistically significant with a 99.9% confidence interval.

As can be seen from these results opening bus lanes to all traffic is the best solution to congestion. However following the authorities' desire to maintain fast routes to public transportation via DBL, using E-DBL which opens the bus lanes to EVs is the next best solution as it reduces the congestion, not only for EVs, but the ICEs as well. This effect is magnified at increased rates of traffic congestion.

Table 7-23 Results of schemes in different scenarios at 50% EVs in terms of percentage to reach destination within timeframe

	All lanes open (EVs) (%)	All lanes open (ICEs) (%)	DBL (EVs) (%)	DBL (ICEs) (%)	E-DBL (EVs) (%)	E-DBL (ICEs) (%
Scenario 1	66.5	59.5	38.5	37	46	36.5
Scenario 2	43	36.3	27	22.3	35.3	24
Scenario 3	45.3	45.3	27.5	27.5	30.9	31.7
Scenario 4	44.7	44.7	27.7	27.7	27.7	27.7
Scenario 5	47.7	47.7	28.7	28.7	33.1	29.5

7.7.3 Emissions

The results for emissions from scenario 5 are shown in the next graph. These were computed using the emission calculation function available with SUMO.

As can be seen from Figure 7-55, the emissions do not vary greatly between the different lane schemes. The results do however decline as the percentage of EVs increases. This is obviously expected.

'All lanes open' has higher emissions than the other schemes due to more vehicles being able to move. As the percentage of EVs increases this effect drops. The biggest difference was at 30% when 'All lanes open' has 15% higher emissions.

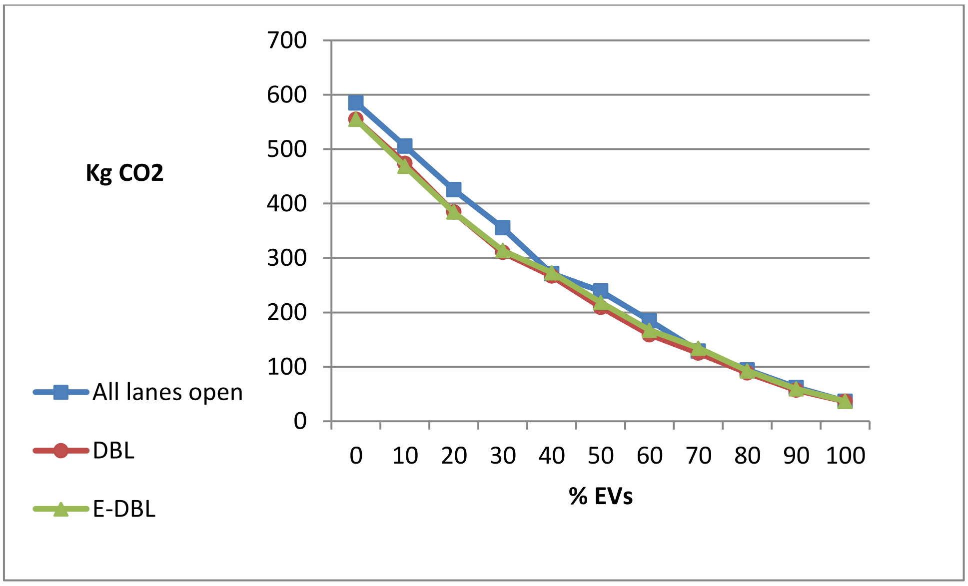

Figure 7-55 Emissions in Scenario 5

Table 7-24 Emissions in Scenario 5

Percentage EVs (%)	0	10	20	30	40	50	60	70	80	90	100
All (kg)	585	505	426	356	271	239	185	129	94	62	37
Bus (kg)	555	474	385	311	267	219	159	125	89	57	37
bus+evs (kg)	555	469	384	314	273	218	167	134	93	59	37

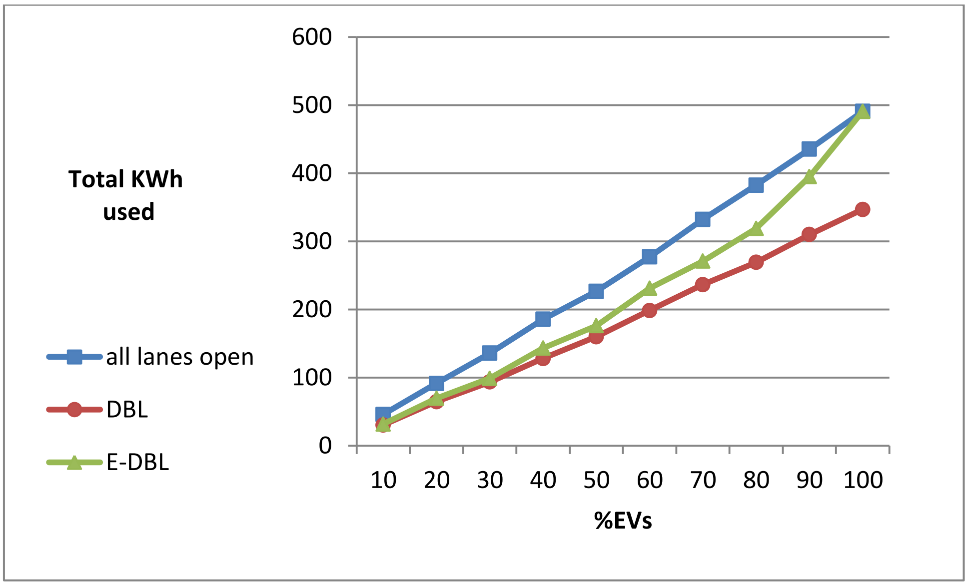

Figure 7-56 Energy used by EVs in Scenario 5

7.7.4 Energy Used by EVs

The results for the energy used by EVs will now be presented. As can be seen from Figure 7-56 all lanes open used the most energy, followed by E-DBL and DBL used the least. This is due to the fact that EVs do not use as much energy idling as ICs and the vehicles were not able to travel as far under DBL when compared with E-DBL. Distance travelled was the main input in terms of energy used by EVs in these tests.

Table 7-25 Energy used by EVs in Scenario 5

Percentage EVs (%)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
All (kWh)	45.8	91.3	135.7	185.4	226.6	277.1	332.2	382.5	435.4	490.7
Bus (kWh)	30.2	64.5	93.3	127.9	159.9	198.5	236.4	269.0	310.0	346.9
bus+EVs (kWh)	31.7	69.5	98.8	143.2	176.0	231.1	271	318.8	394.8	490.7

7.8 Testing Conclusions

This chapter presented the testing results of EcoTrec, a traffic and road characteristic aware VANET-based routing solution for reducing carbon emissions. EcoTrec was assessed in a variety of scenarios using the iTETRIS simulator. These scenarios varied the penetration rate and compliance rate, map type and size and considered urban and rural cases, and traffic traces from different days and times of day. Testing showed how EcoTrec outperformed the other vehicle routing schemes presented in this thesis in terms of emissions (up to 21% was saved vs the baseline) while it maintained a high percentage of vehicles to reach the destination with-in the timeframe (15% improvement vs the baseline). The best results were obtained for urban scenarios where there is high vehicle density and potential for road traffic congestion.

This chapter also presented the testing results of Time-Ants, a VANET-based ant-colony optimization algorithm which uses historical traffic data to improve traffic flows. This is a unique approach to dealing with traffic congestion as it employs ant behaviour and historical traffic data. The simulation-based testing performed has compared Time-Ants against a number of other VANET-based routing techniques including Sommer's [89] and various flavours of DNA [95]. Time-Ants was also tested under a variety of different metrics map type, number of vehicles and penetration and compliance rates. In terms of the percentages of vehicles to reach the destination, Time-Ants outperformed Dijkstra by 6% on average of running the algorithm, and the original routes by 11% on average. In the simulations where Sommer and DNA were tested Time-Ants helped more vehicles reach their destination within the timeframe by roughly 17% in all cases.

Finally this chapter tested the effects of a policy change involving the creation of dedicated bus lanes enhanced with Electric vehicles (E-DBL). Detailed simulation tests were performed with real data and real maps of Dublin, Ireland. In the tests E-DBL was compared against two other lane schemes, ‘all lanes open’ (all vehicles had access to bus lanes) and regular dedicated bus lanes (DBL). Tests have involved recording of energy consumption and journey times of buses, EVs and ICE passenger vehicles. The test results showed how road capacity was better used when employing the proposed E-DBL. The tests also showed good performance of E-DBL in terms of energy consumption. Significant benefits in travel time particularly for EVs were shown. This policy, if implemented could make EVs a much more attractive consumer choice.

Chapter 8 – Conclusions and Future Work

This thesis proposed several methods of reducing energy consumption by traffic systems by utilizing vehicle ad-hoc networks: VANET-Enabled Eco-Friendly Road Characteristics-Aware Routing for Vehicular Traffic (EcoTrec), An Innovative Temporal and Spatial Ant-based vehicular Routing Mechanism (Time-Ants) and Electric Vehicle Enhanced Dedicated Bus Lanes (E-DBL). A comprehensive survey of VANET technologies was also done, with particular emphasis on schemes related to vehicle routing.

This chapter will summarize these contributions in detail, and then indicate several directions for future works.

8.1 Problem Overview

Human-induced climate change is a critical issue at the moment. In order to help mitigate the magnitude of climate change, severely reducing greenhouse gases in all economic domains is imperative. The transport sector, as an important contributor to global gas emissions, should follow the same approach.

For instance, the United States (US) transportation sector's greenhouse gas emissions are expected to grow by about 10 percent by 2035, when they will account for 25% of the global emissions [321]. In 2011 the US road vehicles' CO_2 emissions share was 27.5% [322]. Another study showed that there were 2.9 billion gallons of fuel wasted during congestion in US urban areas in 2011 alone [323]. In the same period in Canada emissions for the transportation sector accounted for 24% of greenhouse gas emissions [324].

Traffic congestion contributes to pollution in built-up areas: a specialist report showed that children who live in high traffic areas are six times more likely to develop leukaemia and other cancers [8]. The constant low-level noise created by traffic was also shown to negatively affect children's blood pressure.

Traffic congestion also causes a lot of time-related stress for people who waste time in traffic. Studies have shown a correlation between increased time behind the wheel and increased blood pressure [9] and likelihood of obesity [10]. Another report showed that carbon monoxide levels are 10 times higher inside a car, so therefore large amounts of time stuck in traffic will negatively affect a person's health [8]. Gwilliam et al. [325] stated that in the developing world vehicles emit about 6% of particulate matter emissions (PM), yet because this is at ground level in urban areas, vehicles account for 32% of PM population exposure.

There are a lot of negative economic effects associated with traffic congestion; one example is the downtime for trucks and other commercial vehicles. Employing innovative communication-based solutions such as those making use of Vehicular Ad-hoc Networks (VANET) gives more accurate traffic prediction and wirelessly monitoring vehicle performance could help reduce the downtime for commercial vehicles, as mentioned in Ko et al. [326].

There is significant effort in research to produce intelligent solutions which can reduce traffic congestion. This thesis is part of that effort and has proposed VANET-based traffic management solutions to improve traffic congestion and emissions.

8.2 Thesis Contributions

8.2.1 EcoTrec

EcoTrec is a VANET-based Traffic and Road-characteristic aware routing mechanism for vehicles. Each vehicle acts as a data gathering node for traffic and road information. This information is retrieved via sensors on each vehicle and then distributed to neighbouring vehicles on the road by multi-hop communication. The vehicle uses this data to build models of the road network in terms of road quality and traffic congestion. The EcoTrec Algorithm recommends a new route which factors in load balancing. This approach was shown to improve fuel-efficiency without impeding on journey times. Testing showed how EcoTrec outperformed the other vehicle routing schemes presented in this thesis in terms of emissions (up to 21% was saved vs the baseline) while it maintained a high percentage of vehicles to reach the destination with-in the timeframe (15% improvement vs the baseline).

8.2.2 Time-Ants

Time-Ants is a swarm-based approach to reducing traffic congestion. In normal ant-algorithms, each ant leaves pheromone trails along its route so other ants can follow a good route. This is not directly applicable to vehicular traffic as this would approach would cause traffic congestion. Instead the proposed Time-Ants algorithm is used in both the time domain as well as the spatial domain. Markers are left at the roads with highest throughput at certain times of the day. The next day more vehicles are directed via VANET messaging to a more efficient route. Time-Ants was also tested under a variety of different metrics map type, number of vehicles and penetration and compliance rates. Time-Ants outperformed Dijkstra by 6% on average of running the algorithm, and the original routes by 11% on average. In the simulations where Sommer and DNA were tested Time-Ants helped more vehicles reach their destination within the timeframe by roughly 17% in all cases.

8.2.3 **E-DBL**

E-DBL is proposed as a way to improve uptake of electric vehicles. Electric vehicles are allowed onto the bus lanes, if there are only a small number of electric vehicles this will not affect bus journey times. The test results showed how road capacity was better used when employing the proposed E-DBL. The test also showed good performance of E-DBL in terms of energy consumption. Significant benefits in travel time particularly for EVs were shown. This policy, if implemented could make EVs a much more attractive consumer choice.

8.2.4 **Comprehensive Survey**

This thesis provides an extensive survey of issues associated with communication centred traffic management systems.

Firstly VANETs are introduced along with a survey of message routing and vehicle routing protocols which are used in VANETs. Next the 802.11 standards which can be used with VANETs are discussed, with particular attention paid to the 802.11p standard which was designed specifically for VANETs. A number of alternative technologies to VANETs are introduced and discussed such as 802.16 (WiMAX) and Cellular, Satellite and Optical communications,

VANETs are then examined under a number of headings. Data monitoring mechanisms, Data aggregation solutions, Inter-Vehicles coordination, IEEE 802.11p congestion reduction, Factors influencing emissions and fuel consumption, Swarm algorithms and finally VANET Services and Applications.

8.3 **Publications Arising from this Work**

8.3.1 **Journal Papers**

- Djahel, S., Doolan, R., Muntean, G. M., & Murphy, J. “A Communications-oriented Perspective on Traffic Management Systems for Smart Cities: Challenges and Innovative Approaches.” IEEE Communications Surveys & Tutorials, pp 1-1, 2014.
- R. Doolan, G. M. Muntean. “EcoTrec – A Novel VANET-based Approach to Vehicle Emission-saving and Congestion Reduction” IEEE Intelligent Transport Systems, 2015.

8.3.2 **Conference Papers**

- Doolan, Ronan, and Gabriel-Miro Muntean. "VANET-enabled Eco-friendly Road Characteristics-aware Routing for Vehicular Traffic." *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*. IEEE, 2013.
- Doolan, Ronan, and Gabriel-Miro Muntean. "Reducing carbon emissions by introducing electric vehicle enhanced dedicated bus lanes." *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014.
- Harris, C., Doolan, R., Dusparic, I., Marinescu, A., Cahill, V., & Clarke, S. (2014, May). A distributed agent based mechanism for shaping of aggregate demand on the smart grid. In *Energy Conference (ENERGYCON), 2014 IEEE International* (pp. 737-742). IEEE.
- Doolan, Ronan, and Gabriel-Miro Muntean. "Time-Ants: An innovative temporal and spatial ant-based vehicular Routing Mechanism." *Intelligent Vehicles Symposium Proceedings, 2014 IEEE*. IEEE, 2014.

8.4 **Future Work**

A list of potential subjects for future work arising from this research will now be discussed.

8.4.1 Vehicle Density and Penetration Rate

The sensitivity of the algorithm can be adjusted for vehicle density. If the vehicle density is very low there is no need to consider rerouting due to traffic congestion. As density becomes higher traffic congestion will become much more important than the road conditions.

Similarly the penetration rate can be taken into account as a low density of VANET nodes with a low penetration rate in the area could mean there is high traffic congestion. If there is a low penetration rate, the accuracy of the traffic conditions is less. Also if there is a very high penetration rate, load balancing is a lot more important for how vehicles are routed. The penetration rate would be calculated on the fly, by comparing the traffic flow with the node density.

The overhead will be maintained very low by employing a mechanism which decreases MaxHopCount logarithmically with the increase in number of vehicles. The time period ϕ will also depend on the node density.

8.4.2 Effect of Vehicle-Type Aware Rerouting on Trucks, HEV and EV. E-EcoTrec and ECOTRUC

Climate change has gained much attention in recent years. Despite it being a well published phenomenon, weaning civilization off fossil fuels is proving to be an immense challenge. One major issue is that people seem unwilling to switch from petrol driven vehicles to electric vehicles. This is mainly due to the very limited range of electric vehicles. Building on the previous work of EcoTrec this work could look at taking into account the individual characteristics of different vehicle classes. EV and HEV have limited range, require frequent charging and have regenerative braking. By recommending a more fuel efficient route the range of the vehicle may be extended. Trucks and buses are disallowed or unable to go on certain routes and are more susceptible to road roughness as a fuel parameter. The results show an increase in the typical mpg for the case of the trucks and the MPGe (miles per gallon equivalent) for the electric vehicles.

8.4.3 **Weather-aware Rerouting for Fuel-saving Purposes.**

This work could look at taking into account various weather parameters when calculating emissions and routing. The road roughness will change dramatically when there is rain or ice. The increased stopping distance may warrant a slower speed limit. Certain roads may become flooded or otherwise impassable. Wind speeds and directions will also have a large effect on emissions, as high speed side-winds may create dangerous scenarios which warrant slower speeds. This weather information could be gathered by individual vehicles and then distributed throughout the VANET to improve vehicular routing. Vehicles are already equipped with temperature sensors. High granularity maps with temperatures and wind speed and directions could be made from VANETs. Which roads are blocked due to flooding could easily be determined, as well as which roads are icy.

Weather will not only change the road conditions but also the traffic conditions. As noted by Dangel et al. [327] bad weather will increase the amount of traffic on the road as more people choose to drive instead of walk or cycle. Good weather could also dramatically affect traffic on weekends as people seek to go to beaches or parks. Drivers also drive slower during wet or icy conditions. For safety purposes they should also be recommended to drive slower during dangerous driving conditions.

8.4.4 Dynamic Assignment of lanes

As future work a VANET-based algorithm to dynamically assign lanes to vehicles could be developed. This would have the effect of encouraging fuel efficiency while making good use of the road capacity. As can be seen from the results dedicated bus lanes do not make efficient use of road capacity. Such an algorithm could also optimize light timing, to encourage fuel efficiency without substantially increasing emissions.

8.4.5 Eco-Ants

Future work will consider emissions as a parameter in a green extension of Time-Ants, which would minimize emissions instead of travel times. Time-Ants needs to be improved to perform better at different compliance and penetration rates. Note Time-Ants has to be updated to account for weekends which have different traffic patterns than week days.

Appendix 1

This appendix shows the python script which was used to calculate and append the gradients of each road segment of the SUMO simulation maps.

Firstly the locations of the road segment ends were retrieved.

Python file 1

```
#retrieve the gps coordinates of an openstreetmap file

from lxml import etree

from xml.dom.minidom import parseString

import xml.dom.minidom

import xml.etree.ElementTree as ET

import array

import sys



doc2 = etree.parse ( 'dublincc.net.xml' )

edges_2 = doc2.findall ( "edge" )

root2 = ET.Element('net')

yy = 0

zz = 0

for edge_2 in doc2.getiterator():

        #if edge_2.tag == "location":

        print 'hello'

        if edge_2.tag == "lane":

                edge_2.get( 'id' )

                E = edge_2.getparent()

                EE = E.getparent()
```

```
if EE.get( 'id' ) == "normal":
    lane = E.tag
    lane = ET.SubElement(edge,E.tag)
    Lanes = E.getchildren()
    for content in Lanes:
        shape = content.get( 'shape' )
        print shape
        S = shape.split()
        Point = []
        for i in range(len(S)):
            SS = S[i].split(",")
            lane = 'point'
            myattributes = {'lat': '','lon': ''}
#           lane = ET.SubElement(head,'point',attrib=myattributes)
            X = float(SS[0])
            Y = float(SS[1])
            lon1 = 6.739973 + X*((7.223808-6.739973)/34288.8) - 0.001
            lat1 = 50.772079 + Y*((51.148323-50.772079)/41946.86) - 0.0002
            lon2 = str(lon1)
            lat2 = str(lat1)
#           lane.set('lon',lon2)
#           lane.set('lat',lat2)
            Point1 = []
            if i == 0:
```

```
                Point1.append(lat2)
                Point1.append(',')
                Point1.append(lon2)
                Point1.append('|')
                point1 = ''.join(Point1)
                #print point
        if (i+1) == len(S):
                Point1.append(lat2)
                Point1.append(',')
                Point1.append(lon2)
                Point1.append('|')
                point2 = ''.join(Point1)
                Point.append(point1)
                Point.append(point2)
                point = ' '.join(Point)
                #       yy = yy + 1
                print point
```

Secondly the coordinates retrieved were parsed to google maps to retrieve the heights

EXAMPLE

http://maps.googleapis.com/maps/api/elevation/xml?locations=

50.9346348744,6.97201028604|

50.9347269916,6.97120640605|

50.9343176218,6.97320460588|

50.93459496,6.97215971712|

```
50.9337935316,6.97211442215|
50.9338098562,6.97116435651|
50.9337961328,6.97311951906
```

Finally the height information was used in another python script to calculate the gradients and enter them in the SUMO map

```
#this file adds the road gradients to a openstreetmap sumo file and outputs the result in a new openstreetmap file
from lxml import etree
from xml.dom.minidom import parseString
import xml.dom.minidom
import xml.etree.ElementTree as ET
import array
import sys



#print "this will be written to message.log"
f = open ("gradients.txt","r")

#Read whole file into data
data = f.readlines()

# Print it
#print data

# Close the file
```

```
f.close()

grad = -1;

doc = etree.parse ( 'busnet3.net.xml' )

edges = doc.findall ( "edge" )

root = ET.Element('net')


for edge in doc.getiterator():

    if  edge.tag == "location":

        location = edge.tag

        location = ET.SubElement(root,edge.tag)

        location.set('netOffset',edge.get( 'netOffset'))

        location.set('convBoundary',edge.get( 'convBoundary'))

        location.set('origBoundary',edge.get( 'origBoundary'))

        location.set('projParameter',edge.get( 'projParameter'))

    if edge.tag == "edge":


        #EE = E.getchildren()

        #head = 'edge'

        #myattributes = {'function': '','id': '','RoadRoughness': '1','RoadGradient': '0','from': '','to': '','priority': ''}

        #head = ET.SubElement(root,'edge',attrib=myattributes)


        #head = 'edge'

        #myattributes = {'function': '','id': '','RoadRoughness': '1','RoadGradient': '0','from': '','to': '','priority': ''}

        #head = ET.SubElement(root,'edge',attrib=myattributes)
```

```
        if edge.get( 'function' ) == "normal":
            head = 'edge'
            myattributes = {'function': '','id': '','RoadRoughness': '1','RoadGradient': '0','from': '','to': '','priority': ''}
            head = ET.SubElement(root,'edge',attrib=myattributes)
            head.set('function',edge.get( 'function' ))
            head.set('id',edge.get( 'id'))
            head.set('from',edge.get( 'from'))
            head.set('to',edge.get( 'to'))
            head.set('priority',edge.get( 'priority'))
            e = edge.getchildren()
            for E in e:
                lane = E.tag
                lane = ET.SubElement(head,E.tag)
                Lanes = E.getchildren()
            for content in Lanes:
                lanes = content.tag
                lanes = ET.SubElement(lane,content.tag)
                lanes.set('id',content.get( 'id' ))
                lanes.set('depart',content.get( 'depart'))
                lanes.set('maxspeed',content.get( 'maxspeed'))
                lanes.set('length',content.get( 'length'))
                lanes.set('shape',content.get( 'shape'))
                grad = grad + 1
            Grad = data[grad]
            head.set('RoadGradient',Grad)
```

```
        else:
            myattributes = {'function': '','id': '','RoadRoughness': '1','RoadGradient': '0'}
            head = ET.SubElement(root,'edge',attrib=myattributes)
            head.set('function',edge.get( 'function' ))
            head.set('id',edge.get( 'id'))


print "step5"
tree = ET.ElementTree(root)
tree.write('busnet5.net.xml')
xml1 = xml.dom.minidom.parse('busnet5.net.xml')
pretty_xml_as_string = xml1.toprettyxml()
#print pretty_xml_as_string
f = open('busnet5.net.xml', 'w')
f.write(pretty_xml_as_string)
f.close()
```

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