The evaluation and testing of mobile ITS interventions on speed compliance in the minibus taxi industry of South Africa

by

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Declaration

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Abstract

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Informal public transport in South Africa, dominated by minibus taxis is noted for poor compliance, and has been shown to disregard posted speed limits on long-distance trips. They go as far as driving over the differentiated speed limit of the lighter passenger vehicles used for private transport. This work compares and evaluates improvements in their speed compliance using two renowned interventions: automated Average Speed Enforcement (ASE), and auditory Intelligent Speed Adaptation (ISA). The feasibility of fuel economy existing as a self-regulatory incentive for speed compliant driving is investigated, together with the impact of each intervention on fuel consumption rates. The main findings were that with minibus taxis, ASE is not well understood and needs ISA as a complementary intervention, and safe driving can increase driver remuneration from fuel costs.

Average Speed Enforcement is an emergent alternative to instantaneous speed enforcement to improve road safety. This study involves a mixed methods approach in understanding driver response to the system on the R61 Between Beaufort West and Aberdeen in South Africa. A spatio-temporal quantitative study of speed compliance is conducted. Various speed metrics are measured prior to, and during enforcement, and ASE impact on crash risk and injury severity is also examined. These measurements are taken on the enforcement route and on control routes having similar characteristics. Two main modes of transport in the region are considered, namely minibus taxis and passenger vehicles. A qualitative study is also conducted to evaluate the relationship between speed compliance and understanding of the system. Results show that for passenger vehicles, the ASE system led to a reduction in mean speed on the enforcement and adjacent control routes. However, ASE appears to have no influence on minibus taxis, which could be linked to limited understanding on ASE operation.

This study also tests and evaluates the impact of an auditory ISA intervention, applied at various levels, on the speeding behaviour of the seemingly intransigent minibus taxi industry. The experiment evaluates the same ASE section on the R61, to which the minibus taxi drivers were seemingly impervious. Various speed metrics, as well as their statistical relevance and the effect sizes are evaluated. Results show that the auditory ISA intervention has a clear impact on speeding behaviour, both when applied at an audible level that can be drowned out by a radio, and even more so at a loud level. The impact on speeding is significant, with speeding frequency (both time and distance) reducing by over 20 percentage points. Also, although the drivers showed little or no behavioural change when driving on the ASE route, introduction of the ISA system resulted in significant changes bringing violation frequencies down to 47.4% from 81.2% on the enforcement route. These changes brought about lower fuel consumption rates especially with the ISA system, and drivers can increase their remuneration by a minimum of about 120% and by up to 214% from the fuel budget if they drive safely.

Uittreksel

Die evaluering en toetsing van mobiele Intelligente Vervoer Stelsel (IVS) ingrypings op spoed gehoorsaamheid in die minibustaxibedryf van Suid Afrika

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Informele publieke vervoer in Suid-Afrika, gedomineer deur minibus taxi's is bekend vir slegte gehoorsaamheid, veral met betrekking tot spoed beperkinge op lang afstand reise. Hulle gaan so ver as om oor die gedifferensieerde spoedlimiet van ligter passasiersvoertuie te gaan, wat gebruik word vir private vervoer. Hierdie werk vergelyk en evalueer verbeterings in hulle spoed nakoming deur gebruik te maak van twee bekende intervensies: outomatiese Gemiddelde Spoed Handhawing (GSH), en ouditiewe Intellegente Spoed Aanpassing (ISA). Die lewensvatbaarheid van ekonomiese branstof gebruik as 'n self-regulerende aansporing vir spoedlimiet handhaving word ondersoek, tesame met die impak van elke intervensie op brandstofgebruik. Die hoof bevindinge vir minibus taxi's was dat GSH nie goed verstaan is nie en benodig ISA as 'n komplimentêre intervensie, sowel as die feit dat veilige bestuur die drywer se vergoeding deur middel van laer brandstof kostes kan verhoog.

Gemiddelde Spoed Handhawing is 'n opkomende alternatief tot Intellegente Spoed Aanpassing met die hoop om padveiligheid te verbeter. Hierdie studie bevat 'n gekombineerdemetodes benadering om die bestuurders se reaksie met betrekking tot die sisteem op die R61 tussen BeaufortWes en Aberdeen in Suid-Afrika te bekom. 'n Tydruimtelike kwantitatiewe studie van spoed gehoorsaamheid is gedoen. 'n Verskeidenheid spoed statistieke is gemeet, voor, sowel as gedurende implimentering. Daar is ook gekyk na GSH se impak op botsingrisiko en beseringsintensiteit. Hierdie metings is geneem op die implimenteringsroete sowel as die beheerroete, elk met ooreenstemmende eienskappe. Die twee hoof

vervoermiddels in die omgewing is oorweeg, naamlik minibus taxi's en passasiersmotors. 'n Kwalitatiewe studie is gedoen om die verhouding tussen spoed gehoorsaamheid en begrip van die sisteem te evalueer. Resultate wys dat vir passasiersmotors, lei die GSH na 'n vermindering in gemiddelde spoed op die geïmplimeenteerde sowel as die ooreenstemmende beheer roete. Egter, blyk dit asof die GSH geen invloed het op minibus taxi's, wat gekoppel kan wees aan min/geen begrip oor die gebruik van die GSH sisteem.

Hierdie studie toets en evalueer ook die implak van 'n ouditiewe ISA intervensie, geimplimenteer op verskeie vlakke op die spoed gedrag van die onversetlike minibus taxi bedryf. Die eksperimente evalueer dieselfde GSH roete op die R61, waaraan minibus taxi bestuurders blyk om min aandag aan te gee. Verskeie spoed statistieke, sowel as hulle statistiese relevansie en die inpak van hul effekgroottes is geëvalueer. Resultate wys dat die ouditiewe ISA intervensie 'n duidelike impak het op spoed gedrag, beide wanneer dit geïmplimeenteer word op 'n hoorbare vlak wat sagter is as die radio, sowel as, en self beter wanneer, dit harder is as die radio. Die impak op die spoed is merkwaardig; die spoed frekwensie (beide spoed en afstand) verminder met meer as 20 persentasiepunte. Alhoewel die bestuurders min of geen gedragsverandering gewys het indien hulle op die GSH roete gery het nie, met die implimentering van die ISA sisteem het dit gelei tot merkwaardige veranderings in oortredings frekwensie; 'n daling na 47.4% vanaf 81.2% is opgemerk. Hierdie veranderinge het laer brandstofverbruik na gebring, veral met die ISA stelsel, en bestuurders kan hul vergoeding verhoog met 'n minimum van ongeveer 120% tot en met 214% van die brandstof begroting as hulle veilig ry.

Publications

The work in this manuscript has been published as follows:

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- N.A. Ebot Eno Akpa, M.J. Booysen, M. Sinclair, "Efficacy of novel interventions on speed compliance in the minibus taxi industry," *The South African Institute of Civil Engineers (SAICE) magazine*, September 2015 edition.
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- N.A. Ebot Eno Akpa, M.J. Booysen, M. Sinclair, "Auditory Intelligent Speed Adaptation for long–distance informal public transport in South Africa," submitted to *The IEEE ITS Transactions and Magazine.*

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Nomenclature

Acronyms and abbreviations

AAP	Active Accelerator Pedal
ACC	Advanced Cruise Control
ANPR	Automatic Number Plate Recognition
ASE	Average Speed Enforcement
ASOD	Average Speed Over Distance
COPERT	COmputer Programme to calculate Emissions from Road Transport
CTO	Comprehensive Traffic Observations
CR	Control Route
dB SPL	Decibel Sound Pressure Level
DID	Difference-in-Differences
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DJ	Density-Join
FC	Fuel Consumption
GPS	Global Positioning System
g/km	Grams per kilometre
HDOP	Horizontal Dilution Of Precision
HMI	Human Machine Interface
Hz	Hertz
ISA	Intelligent Speed Adaptation
ISE	Instantaneous Speed Enforcement
ITS	Intelligent Transport Systems
IVSS	Intelligent Vehicle Safety Systems
KDE	Kernel Density Estimation
km/h	Kilometres per hour
L/100km	Litres per hundred kilometres
OBD	On-Board Diagnostic
PV	Passenger Vehicle
SANRAL	South African National Roads Agency Limited
VMS	Variable Message Sign

List of symbols used

σ	Standard Deviation (SD)
v	Speed in km/h
V_x	Speed at xth percentile
$\%_x$	Percentile crossing at speed x
d	Route distance between consecutive GPS records in kilometres
R	Correlation Coefficient
N	Number of trips / Average sample size
EZ	Effect Size
SF	Speeding Frequency (%)
κ	Distribution kurtosis
γ	Distribution skewness
Δ	Change in metric *(final - initial)*
s_p	Pooled standard deviation
h	Kernel Density Estimation smoothing bandwidth

Chapter 1

Introduction

The African region accounts for almost 20% of the global traffic deaths but has less than 2% of registered vehicles worldwide. Compared with the rest of the world, Sub-Saharan Africa and South Africa in particular have very high road fatality rates [3, 4]. While fatalities for developed countries range from 2.7 in the UK to 5.2 in Australia, South Africa and its neighbours lie in the range of 27 to 32 in terms of the number of deaths per 100,000 inhabitants per year.

Accounting for 32% of deaths, road crashes are a major contributor to fatalities and injury in South Africa. A five year analysis of crash data (from 2005 to 2009) revealed that at least 14,000 people die annually on South African roads, in which at least 10,000 vehicles were involved [5]. The same study also found that human factors account for 86.4% of fatal crashes per year.

The minibus taxi sector of public transport is considered to be notoriously dangerous and is seen as the epitome of bad driving in South Africa. Of the 36 lives lost daily on roads, three are killed in taxi related incidents [6]. In addition, a study done by the Automobile Association in South Africa revealed that about 70,000 minibus taxi crashes occur annually. This indicates that taxis in South Africa amount to twice the crashes of all other passenger vehicles.

The crash/fatality statistics described and the role of human factors in their occurrence shows that there is a need to improve and expand existing speed calming measures. It also confirms that safety and efficiency are the biggest challenges in public transport [1]. This study contributes towards the need to improve safety by evaluating and testing ITS (Intelligent Transport Systems) technologies for speed compliance, and places more emphasis on minibus taxis which account for over 60% of the collective public transport market share [7, 8].

1.1 Background: Informal public transport

In this section, an overview of the unique operational dynamics within the minibus taxi sector is presented. It will suit readers who are oblivious to how the industry operates, and aid in understanding some of the challenges faced therein. The overview is especially significant because this informal industry operates on principles foreign to the developed world, partly because regulatory authorities have little control over its operations, which are usually characterised by unplanned and ad-hoc service delivery. Although the section focuses on South African public transport, similar logistic arrangements are operational in many other Sub-Saharan African countries.

The minibus taxi industry is a vibrant, yet partly informal sector of public transport. According to the Economic Development Department of South Africa, there were about 200,000 minibus taxis on South African roads in 2006, with an annual demand of about 23,000 more taxis since then [9]. Minibus taxis dominate the informal public transport sector and have shown remarkable growth over the last 20 years. In addition to being the most available mode of transport, they are also affordable to the majority of the working population. More than 16 million passengers use minibus taxis everyday [8]. In 2008 the industry held 67.9% of the collective public transport market share, the rest of which is predominantly held by buses and trains [7]. Although metered taxis exist, they only provide a marginal share of public transport.

Despite the huge demand for minibus taxis, it is lagging behind in the application of ITS safety solutions for the improvement of its services and the overall ITS network. Although the minibus taxi sector is well known to its operators and users, policy makers and researchers are not always aware of the mechanisms and procedures involved due to the informal and organic evolution of the industry. According to a recent study by the Trans-African Consortium, the majority of taxi owners in Sub-Saharan Africa manage to cover operation costs, but cannot afford to adequately maintain and upgrade their fleets. As a result, they tend to compromise on safety and quality. Due to the high number of fatalities involving minibus taxis, in 1999, a special maximum speed limit of 100 km/h was set for minibus taxis in South Africa, 20 km/h lower than the norm on highways. However, it has been found that the differentiated speed limit is impractical and difficult to enforce [10]. Safety measures that can provide lasting and reliable solutions to this difficulty need to be investigated.

There are five distinct stakeholders that make up the informal transport industry; owners, drivers, passengers, taxi associations, and regulatory authorities. There are over 80,000 minibus taxi owners in South Africa, and the industry employs around 300,000 people, mostly drivers. A taxi driver spends on average 8.8 hours per day on the road, drives an average of 8,000 kilometres per month, and works an average of 6.33 days per week [11]. This corresponds to ten hours per week more than the average legal limit in the EU [12].

Minibus taxis in South Africa have two main functions; they are used for long distance transport with trips measuring over 1200 km, and urban transport with trip distances of 20 - 50 km. The role that minibus taxis play in the urban transport network falls somewhere between that played by metered taxis (cabs) and urban buses in the developed world.

The long-distance taxis perform a function similar to that of coaches in the developed world. Although these two functions have different logistic and operating mechanisms, the vehicles and drivers are the same. Drivers who complete urban trips ferrying passengers from Monday morning to Friday afternoon are usually the same drivers who complete long distance journeys over the weekend. For urban transport, drivers lease the vehicles from the owners, and have to earn a certain sub-minimum to make the business viable, creating an incentive to overload the bus and complete as many trips as possible, leading to speeding and reckless behaviour. The owners have no control over the way their vehicles are used, and have little control over the flow of cash. For long-distance driving, the driver is given fixed payments and fuel funds for the trip by the owner [13].

This thesis focusses on long-distance transport and considers the route between Cape Town (in the Western Cape province) and Mthatha (in the Eastern Cape province) along the N1 and R61. Despite the presence of Average Speed Enforcement (ASE) systems and police patrols on this route, it continues to experience high crash rates and fatalities resulting from several causes, mainly speeding. Figure 1.1 shows the route with colour-coded speeds recorded for one journey.

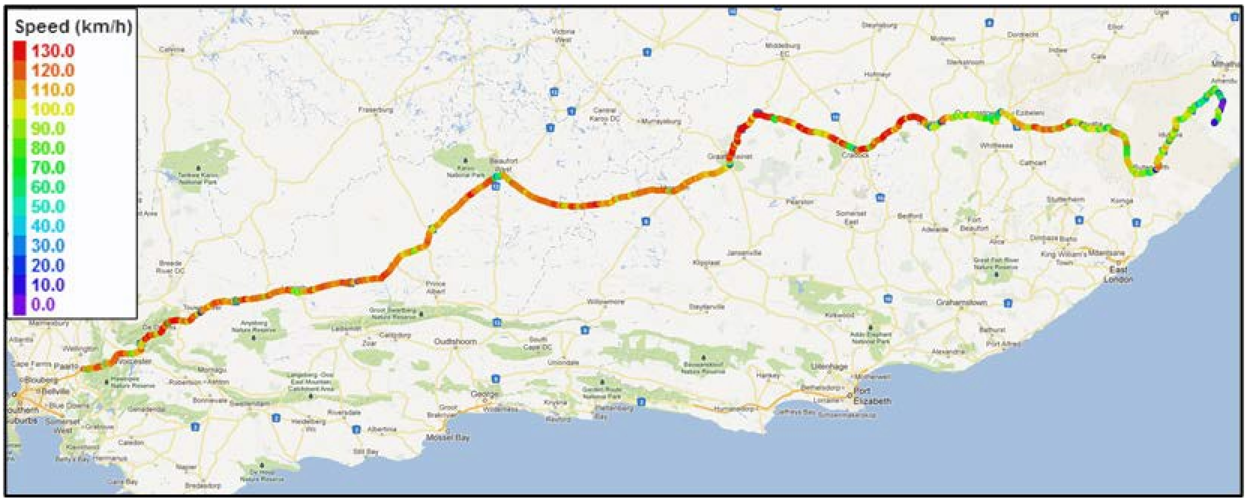


Figure 1.1: The long-distance route from Cape Town to Mthatha

A permit system exists for long-distance taxis. At festive seasons and Easter holidays, more permits are assigned, since many travellers go home during these periods. Passengers who intend to go on a long-distance trip, typically for a funeral, festive season, or for a holiday, must pre-arrange a "contract" with one of the minibus owners. The cost of the contract is fixed and includes delivery and collection at agreed locations. This 1200 km one-way trip normally starts on a Thursday or Friday evening around sunset, and ends with the return trip on a Monday morning before sunrise to allow passengers to start work on time. To make ends meet, especially on the longer routes during the festive seasons, some taxi drivers work 24 hour shifts. A concerning peculiarity of the weekend long-distance trips is that the driver often hands over control of the vehicle to a willing passenger when he inevitably suffers from fatigue during the trip. This passenger is not necessarily licensed to drive the vehicle, and may not even have experience in doing so [13]. Given this background, the investigation of ITS safety and efficiency solutions is necessary for the minibus taxi industry.

1.2 ITS road safety interventions

ITS is a generic term referring to the integrated application of communication, control and information processing technologies to transport systems with the aim of saving lives, time, money, energy and the environment [1]. The main drivers of ITS adoption are efficiency, safety, and environmental impact reduction.

This section presents an overview of various ITS systems aimed at improving road safety by assisting in the driving task and minimising the probability of human errors. Several ITS systems have been developed with the main purpose of improving road safety. Although some ITS systems are primarily developed for driving comfort, such as Advanced Cruise Control (ACC) systems, these also have road safety consequences. ITS safety systems – broadly classified as Intelligent Vehicle Safety Systems (IVSS) – fall under two main categories, namely: [14]

1. Infrastructure-related systems.
2. Vehicle-based systems.

Infrastructure-related road safety systems include traffic signals and the systems that coordinate them, weather warning systems, safe speed alert systems on a given road communicated through Variable Message Signals (VMSs), re-routeing guidance systems, and speed enforcement systems. In South Africa, speed enforcement systems are a common and direct form of infrastructure-related safety systems implemented using cameras. Two main speed enforcement systems exist, namely:

1. Instantaneous Speed Enforcement (ISE)
2. Average Speed Enforcement (ASE)

ISE systems use single point-based cameras to monitor and report speed compliance at precise locations or zones, while ASE systems perform the same function over longer distances using camera pairs. The main advantage of ASE systems over ISE systems is the enforcement of speed limits and uniform traffic flow over distances.

Vehicle-based safety systems include Fatigue/Distraction Warning Systems, Collision Avoidance Systems, Electronic Stability Control systems, and Intelligent Speed Adaptation (ISA) systems. Table 1.1 shows vehicle-based safety systems used to prevent unsafe situations or actions in the course of driving.

This study focuses on the evaluation ASE and ISA systems. ASE is chosen both for its known positive effects on safety, speed compliance and traffic flow, and for its relative novelty and expansion within South Africa compared with other existing safety measures. On the other hand, though uncommon to the minibus taxi industry, ISA systems – specifically auditory ISA systems – are chosen for their proven success in improving

Table 1.1: Vehicle-based safety systems

Source: Institute for Road Safety Research (SWOV) [15]

Category	Name	Abbrev.	Effect
Vehicle Control	Electronic Stability Control	ESC	Autonomous system that prevents skidding when manoeuvring or at a bend
	Lane Departure Warning System	LDWS	Warns when crossing the road marking (via video in vehicle)
	Lane Keeping System	LKS	Intervenes when crossing the road marking (via video in car and servo-assisted steering)
Prevention of offences	Intelligent Speed Adaptation	ISA	Gives information about speed limit, warns of exceeding the limit, or intervenes when speeding
	Electronic Vehicle Identification	EVI	Locates and follows a vehicle in the network; can for instance be used for 100% chance of apprehension when speeding
	Electronic Data Recorder (black box)	EDR	Registers all sorts of driving behaviour. Can be used both for punishing (possibly linked to Automatic Policing) and rewarding (e.g. via insurance bonuses)
Support for observing, interpreting situations	Collision Avoidance System	CAS	Warns or intervenes when a (moving) object is detected in front of the vehicle (also pedestrians)
	Vehicle detection at intersections	–	Warns or intervenes when crossing traffic is detected
	Night time vision system	–	Improves night time vision, and thus timely detection of pedestrians/cyclists
Temporarily diminished fitness to drive	Fatigue/Distraction Warning System	–	Detects deviations from normal brain activity, eye movements, or driving behaviour (e.g. in combination with smart card) and warns or intervenes

speed compliance, and for the fact that they are relatively easier to implement. Unlike most infrastructure-related systems, ISA systems have the unique advantage of improving road safety continuously, since the system gets activated anywhere as soon as a threshold speed is exceeded. The next section gives a brief outline of existing literature, evaluation procedures, and outcomes applicable to ASE and ISA systems.

1.3 Literature synopsis

This section presents a summary of the current state-of-the-art techniques for GPS data mining towards the investigation of operational trends. It summarises various techniques recommended for the evaluation of ITS benefits and their respective outcomes, with specific reference to ASE and ISA systems, which are the interventions of interest in this study. A brief synopsis on fuel consumption as an incentive for safe driving and the type of models involved is also presented.

Vehicle data used in this research is primarily collected using GPS devices. Various rules and algorithms exist for the reliable mining of GPS data, towards the understanding of driver behaviour and logistic patterns. The identification of trips, trip ends, routes taken and stops are particularly important aspects to consider when investigating operational trends. Density-based clustering algorithms such as DBSCAN and DJ-Clustering have been widely used in different ways to extract information from GPS data [16].

1.3.1 ASE synopsis

ASE provides both congestion alleviation and environmental safety through speed compliance enforcement [17]. ASE systems are commonly referred to as ASOD (Average Speed Over Distance) systems in South Africa. The ASOD system is similar in many ways to ASE systems and also uses camera pairs equipped with ANPR (Automatic Number Plate Recognition) technology to detect vehicle registration numbers. Images of the number plates are taken at an initial camera location (the entry cabinet) and also at any subsequent camera location (the exit cabinet). Character recognition is done through image processing techniques, followed by the retrieval of vehicle information from a central database. The known distance between the cameras and the time taken to travel between both cameras is used to calculate the average speed of the vehicle along the section. A fine is issued if the calculated average speed is higher than the legal enforcement threshold of the vehicle on a given road. Camera visibility is enhanced through roadside notifications at the entry and exit cabinets.

ASE systems have been operating in certain parts of the developed world for a reasonably long time. The first instance was a trial form installed in the Netherlands in 1997 which ran for five years before permanent installation in 2002. However, the post-implementation evaluation of ASE systems is a relatively new research topic. There is still a general lack of a credible body of research on its effects on speeding patterns in different regions. This applies particularly to the African context where they have been in operation for less than half a decade. Besides South Africa, which launched one of its first ASE systems in November 2011, there is no documented literature on the implementation of average speed enforcement in other Sub-Saharan African countries, the majority of which rely on police patrols, rumble strips and speed humps to control speed [18]. South Africa launched one of its first ASOD systems in November 2011 on the R61: a 71.6 km stretch of road between Beaufort West and Aberdeen [19]. Since then, progressive deployment of ASOD systems on South African roads, especially in the Western Cape province has followed. By the end of December 2014, the road distance covered with ASE within the province totalled 423.2 kilometres.

Most post-implementation evaluation studies on ASE systems were carried out in Europe where systems have been running for a long time. The methods applied evaluate data for one or more years before and during enforcement on the enforcement route. Results showed a general reduction in mean speed, 85th percentile speed, and speed variation, with speeds typically below or at the posted speed limit [17]. However, critical aspects lacking in these evaluation attempts are the evaluation of control routes and the isolation of transport modes during analysis and investigation.

Media reports on ASE systems in South Africa indicate that they have been effective in road safety improvement. This is evidenced by the number of speed fines reported to have been issued as well as the reduction in traffic injuries, particularly fatalities. However, the availability of concrete microscopic evidence to substantiate its supposed benefits is absent, and needs to be investigated. With over three years of actively running systems, a detailed post-implementation evaluation is essential to check if the system is delivering the expected results of speed compliance across the different modes of transport at their respective speed limits on the enforcement route and adjacent control routes. Such evaluation schemes can be used to fine-tune and improve existing systems, and provide feedback for subsequent rounds of ITS deployment.

1.3.2 ISA synopsis

Besides simulative and predictive studies [20], there are no records of real-life ISA system effects on minibus taxis and passenger vehicles in South Africa. Although some vehicles come with different forms of built-in ISA systems, most of these systems are yet to be applied in the minibus taxi sector.

Several forms of ISA systems exist and have been found to significantly improve road safety [21], and three different criteria can be used to classify them [22]; the warning/control type, the calculation of the system threshold speed, and the user interface. Road safety is measured through the ability of the system to regulate speed.

Previous research has shown that a strong correlation exists between speed, crash rate, and injury severity. The knowledge of this has led to the integration of ISA systems in vehicles, since they hold the promise of ensuring speed compliance continuously. In-vehicle speed adaptive technological devices for road safety have been researched since the 1980s. Many ISA research projects have been conducted in several countries and various Human-Machine Interface (HMI) solutions have been tested. These HMIs are activated once a set threshold speed – usually the speed limit – is exceeded, and can be informative (visual), warning (speech/non-speech auditory warnings), or haptic/intervening channels that limit the speed of the vehicle [23].

Simulation and real-life trials conducted so far have shown positive results irrespective of the HMI solution used. However, the extent of its contribution to speed management varies in terms of effectiveness, acceptability and policies within the test environment/region. Haptic feedback implemented through Active Acceleration Pedals (AAP) have been shown to be more effective but are generally the least acceptable, while visual feedback HMIs have turned out to be the most acceptable system but not equally effective [24]. On the other hand auditory warnings/messages are very intrusive and are sometimes difficult to ignore. Unlike visual feedback, auditory feedback poses less of a distraction while driving, and in addition, it is more effective. Hence, auditory warning systems seem better at bridging the gap between effectiveness and acceptability. Most modern systems usually end up combining visual and auditory feedback.

The implementation of ISA systems has mostly been restricted to private vehicles. This research explores its effectiveness on public transport minibus taxis, through a mandatory non-speech (buzzing) auditory feedback system. Previous implementations have tested vehicles for different fixed speed thresholds on different routes and at different times, with systematically adjusted buzzing/beeping intervals and loudness levels.

1.3.3 Fuel consumption and emissions synopsis

The COPERT model (COPERT IV) is used for the estimation of fuel consumption and emissions. COPERT stands for **CO**mputer **P**rogramme to calculate **E**missions from **R**oad **T**ransport. Development on COPERT is funded by the European Environmental Agency, with scientific and technical support from the Laboratory of Applied Thermodynamics in Greece. It incorporates results of several research and policy assessment projects which are used to calculate emissions of important pollutants from road transport for almost all vehicle classes.

Several models have been formulated to estimate fuel consumption and emissions for different vehicle types through GPS data mining. These models can be broadly classified as macroscopic, mesoscopic or microscopic models, where each is related to a certain scale and accuracy. Microscopic models are more accurate but computationally expensive and data intensive. Macroscopic models are often related to large scale emissions and are least accurate. On the other hand, mesoscopic models are more flexible and address medium scale emissions by adjusting microscopic or macroscopic models to a mesoscopic scale. Different models will be explored with specific focus on their advantages and disadvantages within different contexts.

One of the main advantages of ASE and ISA systems is their ability to indirectly reduce fuel consumption and pollutant emissions. Literature provides some evidence on the positive impact of ASE on vehicle emissions and fuel consumption. However, studies investigating such outcomes are sparse and have largely originated from regions where improved air quality was an underlying objective of the implementation of ASE systems [17]. Research on ISA systems showed that significant reductions in fuel and emissions are possible without drastically affecting travel time [25].

Using the COPERT model, environmental impact is measured through the ability of these interventions to reduce fuel consumption and emissions. Another factor that many minibus taxi drivers may not be exactly aware of is the extent to which their behaviour affects fuel use. This research also investigates possible financial gains on fuel when posted speeds are adhered to on long-distance journeys.

1.4 Dissertation statements and hypotheses

Dissertation statement 1:

ASE is not entirely effective in improving overall speed compliance.

Hypothesis 1.1: The behaviour of different modes of transport towards ASE is different and should not be generalised.

Hypothesis 1.2: Low compliance with ASE in the informal public transport sector is linked to lack of understanding of ASE system operation.

Dissertation statement 2:
ISA can improve speed compliance for non-compliant modes of transport.

Hypothesis 2.1: Soft and loud auditory ISA warning systems can improve speed compliance at different degrees of impact, with loud systems being more effective.

Hypothesis 2.2: Auditory ISA systems activated at fixed speeds can have significant effects on speed compliance improvement in the informal public transport sector.

Dissertation statement 3:
ASE and ISA interventions reduce fuel consumption.

Hypothesis 3.1: For drivers in the informal public transport sector, there is a significant financial advantage from speed compliance.

1.5 Research Objectives

The following objectives have been set towards the investigation of the aforementioned hypotheses:

Research objective 1:
To survey drivers and investigate general operational patterns in long-distance trips completed by minibus taxis.

Research objective 2:
To conduct a post-implementation evaluation on the impact of Average Speed Enforcement implemented through the Average Speed Over Distance system on minibus taxis and passenger vehicles at a microscopic scale.

Research objective 3:
To evaluate the impact of auditory ISA warning systems on minibus taxis and compare these with ASE effects.

Research objective 4:
To estimate fuel consumption and emissions for minibus taxis, and investigate the impact of ASE and ISA systems on fuel economy and emissions.

1.6 Contributions

The evaluation of ITS technologies is important for justifying the need for future investments in the system under evaluation, and highlights the urgency for developing/testing more efficient ones. This is even more relevant in South Africa, given the high violation and crash rates linked to speeding, despite the active enforcement of existing interventions. Cognisant of this, the main contribution of this research is to serve as feedback for the improvement of existing systems, and provide insight to pre-implementation evaluation endeavours for systems that are yet to be deployed.

The scientific rigour associated with the evaluation of existing ASE technologies is relatively low [17]. Firstly, evaluation studies have been generalised for all vehicle types and modes of transport. Secondly, the impact on control routes relative to enforcement routes have not been quantified in any evaluations. This study addresses these two gaps in literature with specific reference to ASE in South Africa. The evaluation process in this study isolates minibus taxis used for public transport and privately owned passenger vehicles from other modes of transport. In particular, the evaluation is conducted not only on the enforcement route, but also on adjacent and distant control routes to quantify the extent to which the benefits of the system diffuse across the road network.

Monitoring of minibus taxis has mainly focussed on local/urban trips. Most studies on minibus taxis have equally concentrated on this function since it is evidently the most common. However, the monitoring of minibus taxis engaging in long-distance public transport also needs attention because of speeding and fatalities. The implementation of ISA systems in informal public transport vehicles is relatively new, talk less of a meaningful evaluation of any trials. This research provides details on the behavioural dynamics behind long-distance trips and how an auditory ISA system can be used to improve safety and reduce emissions. Therefore, outcomes on auditory ISA implementation in the minibus taxi industry are provided to serve as evidence for an in-vehicle intervention that could improve compliance and safety in the industry. The ISA system configuration featured a fixed speed system tested at two different sound pressure levels – 'soft' and 'loud'.

A qualitative study was also conducted through interviews with minibus taxi drivers. This was done to understand the drivers, how they conduct long-distance trips in the industry, and for cross validation with behavioural patterns observed from the quantitative GPS traces. Most drivers typically fall in the 31-40 age group, and drive at least six days a week for about nine to twelve hours each day.

With regards to fuel consumption, drivers may be aware of the general role that erratic driving and excessive speeding play, but are still oblivious to their precise impact on fuel cost and the extent to which ISA systems can assist in fuel economy. This research provides evidence to these aspects towards road safety improvement.

1.7 Scope of work

In this dissertation, ITS safety and speed compliance interventions on minibus taxis and passenger vehicles are evaluated. The evaluation is centred around the inference of safety from speed probe data, and the evaluation of ASE and auditory ISA interventions. The impact of speed compliant driving on fuel use for minibus taxis is also investigated.

The evaluation of ASE was done on the system along the R61 between Beaufort West and Aberdeen, and considered surrounding control routes. Passenger vehicles and minibus taxis were involved in ASE evaluation. Historical tracking information obtained from TomTom was used to analyse passenger vehicles. For minibus taxis, ten vehicles operating within the Western Cape province under the Stellenbosch Taxi Association were monitored using GPS tracking devices in real-time. Ethical clearance was obtained for the involvement of minibus taxis in this research.

After data for ASE evaluation was collected, ISA system activation was launched. A passive auditory ISA system was used as opposed to active voluntary and mandatory ISA systems. Auditory ISA was tested only on the minibus taxis. A buzzer was used to provide the interface, and drivers were warned when a fixed threshold speed was exceeded. The fixed threshold speeds were set remotely with the consent of the taxi owners, who informed their drivers about the activation. Emphasis was on the impact of the ISA system on driving behaviour with respect to speeding, and not so much on driver experience and acceptability. Fuel consumption estimates were computed for the minibus taxis using individual vehicle specifications and travel speed obtained from the GPS traces.

It should be noted that the knowledge of minibus taxi drivers on the relationship between speeding and fuel economy was not investigated in this study. Emphasis was placed on the feasibility of fuel economy as an incentive for speed compliant driving, and on the extend to which ITS interventions such as ISA affect fuel consumption in the minibus taxi industry.

1.8 Research Overview

Chapter 2 presents a comprehensive review of the literature for improving road safety with ASE and ISA systems, and their impact on fuel consumption. Many camera-based ASE evaluation schemes have been conducted on different roads with different speed limits and different subjects. The impact of these systems on speed compliance and crash rates will be discussed. Likewise, a number of simulation and field ISA trials have been implemented with diverse ISA elements. Their impact on speed compliance will be discussed in this chapter as well.

Chapter 3 describes the methods used, the choices made and the procedures taken to evaluate the effectiveness of ASE systems and the newly proposed ISA system. Data collection methods, software design methods, mathematical models used, and implementation issues encountered will be discussed in this chapter.

Chapter 4 presents all the results and graphs obtained during the study. The behaviour of passenger vehicles and minibus taxis on the ASE and control routes routes is compared within suitable pre and post-implementation time frames. Results for soft and loud warning ISA systems implemented on minibus taxis are presented together with results comparing ISA and ASE effects on various speed variables, and on fuel consumption.

Chapter 5 discusses the results in more detail, paying keen attention to existing policies and how the measures can be implemented for best practice based on the observed results in Chapter 4.

Chapter 6 concludes the work by validating the hypotheses from Chapter 1 using the results from Chapter 4. The main findings and contributions of the work in this dissertation are provided.

Chapter 2

Literature Survey

The relationship between speeding and crash risk/severity has been the topic of many studies. Speed is clearly the most important determining factor of crash risk and injury severity, since it affects driver reaction and response time, the energy involved at impact [26, 27], and the time it takes a vehicle to come to a complete stop [28]. Nilsson's power model [29] is probably the most popular model that quantifies the relationship between speed and crash frequency. His model suggests an exponential relationship between speed and crash risk/severity. Another mathematical model, developed by Aarts in [26], suggests that a 1% decrease in speed corresponds to a 13% decrease in crash probability.

In order to reduce crash risks and severity, the impact of novel ITS technologies such as Average Speed Enforcement (ASE) and Intelligent Speed Adaptation (ISA) systems have been developed to improve speed compliance. This chapter presents documented ASE and ISA effects on speed compliance, and the impact of these countermeasures on fuel economy.

2.1 Post-evaluation of ASE benefits

ASE systems have been operating in certain regions for about seventeen years. The first instance was a trial form installed in 1997 in the Netherlands, which ran for five years before permanent implementation in 2002. In 2000, England launched its first permanent implementation after running trial versions for a year [17]. Besides South Africa, there is no documented literature on the implementation of average speed enforcement in Sub-Saharan Africa. The majority of Sub-Saharan African nations rely on police patrols, rumble strips and speed humps to control speed [18]. In November 2011, the Western Cape Provincial Government of South Africa launched its first ASE system – known as the ASOD system – on the R61; a 71.6 km stretch from Beaufort West towards Aberdeen [19]. This became the first of several phases of ASE system deployment within the province along the N1 and R61.

Media reports on ASE systems indicate that they have been effective in improving road safety. This is evidenced by the number of speed fines issued and the reduction in road fatalities. The evaluation of the effectiveness of ASE systems is, however, a relatively new research topic. This applies particularly to the African context, where ASOD systems have been operational for less than half a decade. Hence, there is still a general lack of a credible body of research on the extent of its effects on speed management in different regions, and the availability of concrete evidence to substantiate its supposed benefits [17].

2.1.1 ASE, speed compliance and crash rates

This section summarizes outcomes based on studies carried out in Europe where the impact of ASE systems have been evaluated in detail. A number of studies have been conducted, which evaluate the impact of ASE on speed compliance (shown on Table 2.1). Soole et al. compiled recommendations for best practice in ASE [30], and a concise literature survey of ASE evaluation in Europe [17]. The aim of their research was to monitor compliance with posted speed limits on enforcement routes. They also investigate the evidence of the effectiveness of ASE systems through comparison with other countermeasures, driver perception and cost-benefit analyses. Previous studies on some enforcement routes revealed that average speed enforcement reduced the mean and 85th percentile speeds by upto 33%. In addition, speed variation from the posted speed limit was reduced with speeds typically below or at the posted speed limit. Their findings support ASE as a complementary measure to existing speed management measures, which should focus on roads with historically high crash rates. Nevertheless, they conclude that ASE is a more reliable and cost-effective approach to speed enforcement, and is widely accepted by road users. Table 2.1 shows a summary of ASE system evaluations and effects of the system on speed compliance. The studies are shown by year for evaluations conducted between 2000 and 2013.

A reduction in crashes and injury severity due to the deployment of speed enforcement countermeasures rests on the assumption that these countermeasures have significant effects on vehicle speeds. Table 2.2 shows a summary of ASE system effects on crash rates and injury severity. The studies are shown by year for evaluations conducted between 2000 and 2013. Studies with similar sources to those shown in Table 2.1 were obtained under the same experimental conditions.

According to the Western Cape government in South Africa, ASOD systems also have a positive effect on speeding patterns [19]. A macroscopic evaluation of the ASOD system on the R61 was conducted in 2012. Prior to ASOD enforcement, a total of 509 crashes were reported, 75 of which were fatal crashes. The specific time frame before ASOD implementation during which these crashes occurred is not mentioned. During ASOD enforcement, between November 2011 and November 2012, no fatal crashes were reported. The proportion of vehicles driving above the speed limit of 120 km/h dropped from 39% to 26%, and the percentage of vehicles driving below the speed limit increased from 61% to 74%. Moreover, the number of speed fines issued decreased from 2558 in January 2012 to 157 in August 2012 [19].

Table 2.1: Summary of ASE effects on speed

Study	Location & System details	Main findings
Cascetta and Punzo, 2011 [31]	Naples (Italy); permanent ASE on A56; 80 km/h speed limit	Comparing 1 week pre with 1 week post installation data: mean speed reduced from 80.8 km/h to 71.7 km/h; proportion of speeding vehicles reduced from 51.6% to 17.4% (66.3% reduction); proportion of vehicles speeding excessively (over 40 km/h) reduced from 1.2% to 0.1% (91.7% reduction); speed variance reduced from 18.1 km/h to 12.1 km/h (33.1%); reductions were greater during free-flow conditions than during peak-hours; findings consistent across the majority of A56 sections (some sections with irregular road alignment showed smaller reductions or increased speed variations).
Thornton, 2010 [32]	Various road types and locations in England; permanent and temporary ASE.	On the 70 mph section with ASE, 60% of vehicles were observed within a 5 mph range (compared with 60% of vehicles travelling within a 15 mph range on a similar stretch of road without ASE). On a 50 mph section with temporal ASE during roadworks, 60% of vehicles were observed within a 3 mph range
Collins, 2010 [33]	Cambridge (England); permanent ASE on A14; Different speed limits by vehicle and road type	Six ASE routes were investigated. Average speeds reduced on 4 routes, but increased on 2 routes (1 mph and 5mph). 85th percentile speeds reduced on 4 routes, unchanged on 1 route, and increased by 3 mph on 1 route. In first 3 years of operation only 1077 infringements issued (0.0002% of vehicles travelling on the enforcement sections). Overall speed variation reduced with only 0.1% exceeding the 70 mph limit.
Vysionics ITS, 2010 [34]	Nottingham (England); permanent ASE on A610 (30 mph limit) and A6514 (40 mph limit)	Comparing 3 years prior to 3 years post installation; 85th percentile speeds reduced from 44 mph to 40 mph (9.1%) on the A6514 and 39 mph to 30 mph (23.1%) on the A610; average speed reduced from 33 mph to 24 mph (27.3%) on the A610.
Vysionics ITS, 2010 [34]	Northampton (England); permanent ASE on A43 (50 mph limit) and A428 (60 mph limit)	Comparing 3 years prior to 3 years post installation; 85th percentile speeds reduced from 58 mph to 45 mph (22.4%).
Cameron, 2008 [35]	Victoria (Australia);permanent ASE on Hume highway;100-110 km/h limit	Average daily offence rates were between 1-2%, with estimated daily traffic volumes of about 100,000 vehicles.
Stephens, 2007 [36]	Exeter (England); M5 Junctions 29-30 (50mph speed limit); temporary ASE during roadworks.	Throughout period of the roadworks, 95th percentile speeds reduced to less than 55 mph; difference between 95th percentile and average speeds reduced from 16 mph to 6 mph; an average of only 45 infringements per week (from an average traffic volume of 210,000 per week).
Stefan, 2006 [37]	Vienna (Austria); A22 Tunnel with Permanent ASE; 80 km/h limit for cars and 60 km/h limit for HDV	Passenger vehicle speeds reduced by 10 km/h during daytime conditions and 20 km/h during night-time conditions; heavy vehicle speeds reduced by 15 km/h during daytime conditions and 20 km/h during night-time conditions; about 40,000 infringements in first year of operation (from a traffic volume of 29 million vehicles during same period) representing an offence rate of 0.14%.
Schwab, 2006 [38]	Rhone Valley (France); temporary ASE on A7; 90 km/h and 110 km/h limits	During the 90 km/h phase: 80% of motorists drove at less than 100 km/h; during the 110 km/h phase: 90% of motorists drove at 115 km/h or less; overall: 68% of speeding motorists below 10 km/h over the speed limit.
Gains et al., 2005 [39]	Various locations in Nottingham and Northampton (England)	Average speeds reduced by 1.6 mph; 85th percentile speeds reduced by 3.6 mph; proportion of vehicles exceeding the speed limit reduced by 53%; The system was reported as being particularly effective in reducing the number of vehicles exceeding the speed limit by more than 15 mph.
Stefan, 2005 [40, 41]	Rotterdam (Netherlands); Permanent ASE on A13 (80 km/h speed limit reduced from 100 km/h)	Free-flow average speeds reduced by 15–20 km/h; average speed reduced from 100 km/h to 80 km/h for passenger vehicles and 90 km/h to 80 km/h for heavy vehicles; speed variation and 85th percentile speeds also reduced (exact amounts not detailed); violations reduced from 4.6% to 0.6% on weekdays and 0.9% on weekends – estimated traffic volume of 124,000 vehicles per day.

Table 2.2: Summary of ASE effects on crash rates

Study	Location & System details	Main findings
Collins, 2010 [33]	Cambridge (England); permanent ASE on A14; Different speed limits by vehicle and road type	Compared 5 years pre-installation with 13 months post-installation (excluding construction/maintenance period): significant reduction in rate of Personal Injury Collisions (PIC) from 70.4/year to 41.5/year (41.1%); reduction in collisions per million vehicle-kilometres (PIC/mvkm) from 0.119 to 0.068 (42.8% reduction; compared to the national average of 0.169); severity index of crashes reduced from 13% to 2% (84.6% reduction); no fatalities in first 13 months of full-operation. More recent data (3 years post-implementation) shows a 65.4% reduction in serious injury crashes and a 20.2% reduction in minor injury crashes.
Stephens, 2007 [36]	Exeter (England); M5 Junctions 29-30 (50mph speed limit); temporary ASE during roadworks	During 5 month roadworks period there were no injury crashes. In similar periods, three years prior to enforcement, the average number of injury crashes was 2.3 (this reduction was however not statistically significant).
Keenan, 2002 [42]	Nottingham (England); a trial system on the M1	Casualty crashes reduced by 36.4% in the first year of implementation.
Stefan, 2006 [37]	Vienna (Austria); A22 Tunnel with Permanent ASE; 80 km/h limit for cars and 60 km/h limit for HDV	Comparing 3 years prior to 2 years post installation: all injury crashes reduced by 33.3%; fatal and serious injury crashes reduced by 48.8% (no fatalities in first two years of system operation); minor injury crashes reduced by 32.2%. It was noted that the tunnel had lower average crash rates compared with other sections of the motorway.
Cascetta and Punzo, 2011 [43, 31]	Naples (Italy); permanent ASE on A56; 80 km/h speed limit	Comparing equivalent 8 months pre to 8 months post installation: significant reduction in injury crashes of 38.8% (from 116 to 71) and fatal crashes from 4 to 0.
Vysionics ITS, 2010 [34]	Nottingham (England); permanent ASE on A610 (30 mph limit) and A6514 (40 mph limit)	Comparing 3 years prior to 7–8 years post installation (adjusted to 3 years equivalent): across all routes KSI (Killed or Seriously Injured) crashes reduced by 65%; KSI crashes reduced by 53% on the A6514 and 45% on the A610; PIC crashes reduced by 46% on the A6514 and 60% on the A610; fatalities reduced from 6 to 1 on the A6514 and from 3 to 0 on the A610.
Vysionics ITS, 2010 [34]	Northampton (England); permanent ASE on A43 (50 mph limit) and A428 (60 mph limit)	Comparing 36 months prior to 61 months post installation (adjusted): KSI crashes reduced by 77.9% on the A43 (annual average reduced from 2.67 to 0.59) Comparing 50 months prior to 50 months post installation: KSI crashes reduced by 85.2% on the A428 (annual average reduced from 6.5 to 0.96; fatalities from 2.9 to 0.24, seriously injured from 3.6 to 0.72).

In general, the literature shows that ASE systems are effective countermeasures for improving speed compliance and crash rates/severity, bringing about comparatively low speed violation rates. However, previous studies only focus on enforcement routes with little reference to the impact on control routes close to the enforcement routes. In addition, the impact of ASE systems is generalized for all modes of transport and vehicle types, despite the existing variety. In this study, minibus taxis used for public transport are isolated and their response to ASE is investigated, and compared with passenger vehicles. Furthermore, this investigation is carried out on the R61 enforcement route and also on adjacent control routes.

2.2 ISA systems

2.2.1 ISA system classification and characterisation

Different variants of ISA systems have been developed and deployed. Differences between these systems range from their components and mechanisms of operation to the interface through which they interact with users. Carsten and Tate [22] found that all ISA systems can be broadly classified and characterised in terms of three different criteria. These are: user control of the system; the calculation of the system speed limit; and the user or human machine interface (HMI). In addition, other factors that characterise ISA systems are the test environment/subjects, the scale of deployment, and the test duration.

User control

User control types are either advisory/informative, voluntary or mandatory in nature. They are the mechanisms to which the user responds when the ISA system is triggered. Advisory systems simply inform the driver about the current speed limit, or give a warning when the speed limit is exceeded. They do not physically prevent the vehicle from exceeding the speed limit. Voluntary and mandatory systems both come with speed regulators that warn the driver or physically prevent the vehicle from exceeding a specific threshold speed limit. However, the degree to which drivers have control over the system may vary. While voluntary systems can be switched off, regulated or overruled by the driver, mandatory systems do not give the driver options to shut down or regulate its operation.

ISA threshold speed systems

ISA system threshold speeds can either be programmed as fixed, variable, or dynamic threshold speed systems. For fixed threshold speed systems, only one speed limit will activate the ISA system regardless of the road, weather or traffic conditions. Usually the selected speed is either the posted speed limit or some other acceptable speed. Variable threshold speed systems are set to the posted speed of the current road. These have the ability to cater for specific areas with lower permanent speed limits such as pedestrian crossings. ISA systems can determine variable speeds in many ways. The most popular method is through the use of roadside transponders or beacons which transmit wireless signals to the vehicles. Alternatively, autonomous systems in the vehicles equipped with GPS devices and digital maps can be used to adjust the system threshold speed to match the posted speed of the current road. Dynamic threshold speed systems are complex forms of variable threshold speed systems, with extended functionality and operational requirements. In addition to varying threshold speeds according to roadway posted speeds, dynamic systems adjust the threshold speed based on other travelling conditions such as weather or traffic. In most cases, the user has no control over the threshold speed system irrespective of whether the control type is advisory, voluntary or mandatory.

Human machine interfaces (HMIs)

Several HMIs have been incorporated in different ISA systems to provide a platform for interaction with the user. The main functional modes of ISA systems in terms of their HMIs are informative/advisory, warning, intervening, and automatic control [44]. Informative HMI systems are the simplest form of HMIs which primarily advise the driver on the value of the current speed and the prevailing speed limit. They are mostly visual, and do not physically prevent the driver from exceeding the threshold speed limit. Warning HMI systems provide auditory or tactile warnings to the driver when the system threshold speed is exceeded. They are usually auditory in nature, but could also include head-up displays, dash-mounted LED displays, and haptic warnings among other forms. Haptic warnings occur as virtual rumble strips or through stiffening of the accelerator pedal. Intervening HMI systems act upon the vehicle control system to prevent the system threshold speed from being exceeded. However, the driver may exceed the threshold speed by applying a stronger counter force. Active Accelerator Pedals (AAP) are the most predominant form of intervening HMI systems. Automatic control systems are intervening systems which ignore driver requests for speeds beyond the threshold speed. In other words, they are intervening systems which do not respond to a stronger counter force on the accelerator pedal.

HMIs are closely related to the type of user control programmed in the ISA systems. Voluntary systems, for instance, require additional interface components such as on-off switches and kick-in mechanisms that permit drivers to overrule the ISA system by pressing hard on the accelerator pedal [45].

Experimental design factors

Other factors that characterise ISA systems are the test environment, scale and duration. ISA systems have been investigated in two main test environments: simulation environments and real life environments. Simulation studies are conducted with drivers using driving simulators. Some simulation studies are conducted without drivers or vehicles by using traffic simulation studies or software packages. Real-life tests are conducted with drivers through on-road or field trials. Although most real-life tests involve system installation in privately owned vehicles, some tests are done on selected drivers using instrumented vehicles dedicated to such studies. With regards to the scale of deployment, tests are either small-scale or large-scale, while with regards to duration, tests are either long-term or short-term based.

Many simulation and real-life studies have been conducted with drivers in different regions, most of which were short-term and small-scale based. As with all simulation studies, results may show evidence of bias through the use of artificial trial environments where risk perception and task demands may vary from those in real life environments [46]. Despite this possibility, validation studies have shown that the majority of behavioural effects observed in real life environments are also observed in simulation environments, and that driving performance during simulation satisfactorily emulates real traffic [47, 48, 49].

In order to get a comprehensive picture of long-term and large-scale deployment benefits, researchers often use traffic simulation studies. Promising results have accompanied these simulation experiments, and suggest that ISA systems will have significant impact on fuel economy, emissions, and safety of both equipped and non-equipped vehicles [45]. On the other hand, real-life large-scale studies conducted in Sweden, France and the UK continue to serve as examples of successful ISA systems, in terms of effectiveness and acceptability, although most of them were not sustained over a long-term [50].

Effectiveness versus Acceptability

From simulation and real-life trial experiments, there is little doubt as to the effectiveness of ISA systems. Unfortunately, user acceptance over a long-term and on a permanent basis needs to be resolved. Mandatory intervening ISA systems have been the most effective in ensuring speed limit compliance. However, they face high resistance in terms of driver acceptance. Some drivers found that mandatory systems impose high levels of mental demand [51] while others described their driving experience with the system as stressful [52]. After driving vehicles with mandatory ISA systems, some drivers expressed feelings of vulnerability, frustration, and low system satisfaction [51, 53]. In some experiments, these feelings were so strong that 38% to 70% of drivers refused to have mandatory intervening ISA systems installed in their cars irrespective of the cost. [54]. Informative and warning mandatory systems are slightly more acceptable to consumers, however, studies have shown that they are significantly less effective in ensuring speed compliance [55, 54, 56, 57]. Results in one field test revealed that 29% of drivers did not lower their speed at all, and 39% found the system annoying. In an attempt to improve driver acceptance, voluntary systems (that the driver can disable) were used. Unfortunately, the percentage of time during which such systems are used is very low, and drivers tend to disable the system when it will have the largest impact [58, 59].

Blum and Eskandarian identified universal mandatory control and false alarm rates as the two main factors that limit user acceptance of ISA systems [45]. They suggest that consumer acceptance can be improved by non-technical means such as education, policy making, and economic incentives without compromising so much on efficiency and safety issues. In addition, they suggest the use of technical approaches such as system adaptability that allows the driver to enter preferences for system operation, and also allows the driver to customise the timing of warning messages.

Despite the aforementioned acceptability hurdles, there have also been strong motivators for the use of ISA systems. The concept of ISA which gradually gained ground in Europe (where ISA systems originated) is of an advisory system that provides persistent feedback to the driver whenever the speed limit is exceeded. A strong motivator for the use of ISA systems came from strict enforcement of speed limits and the issuing of speed fines, especially in France [50]. Enforcement was so rigorous that drivers did not mind using a system that will keep them from trouble with authorities.

2.2.2 Outcome of ISA trials

This section presents some noteworthy real-life and simulation ISA trials and their outcomes. ISA system effects on driving speed, crashes, traffic and the environment will be discussed. These effects may vary significantly depending on the user control, the threshold speed system, the HMI used, and the penetration rate of the ISA system in vehicle fleets. Due to the mixed nature of ISA system tests in terms of the HMI used, those that incorporate non-speech auditory warning HMIs will be emphasised, and outcomes will be presented based on the scale and time when the experiment was conducted.

ISA in Sweden

Sweden pioneered the large-scale deployment and testing of real-life ISA systems. In earlier systems, roadside transponders were used to transmit speed limits. However, digital maps are currently becoming the preferred approach to providing speed limit information. This is not surprising considering the fact that developments in telematic technologies are widely known. Between 1999 and 2002, the Swedish National Road Administration (SNRA) conducted a large-scale research in the cities of Umeå, Borlänge, Lidköping and Lund, from which a number of studies on intervening systems have ensued [60, 61]. Variable speed ISA systems were used. A non-speech warning HMI with visual displays was tested in Umeå with over 10,000 drivers recruited, while AAPs and advisory systems were tested in the other towns. The aim of the research was to:

- study driver behaviour and how they used the system;
- study the impact of the system on road safety and the environment;
- learn ways on how to integrate the system in vehicles;
- investigate user acceptance and prospects of the system for ITS on a large-scale.

In the Umeå study – mostly carried out in 2001 – about 5,000 vehicles were driven by over 10,000 drivers on roads with speed limits of 30, 50, and 70 km/h. Vehicle integration with ISA components was facilitated by Volvo. Surveys and interviews were also conducted throughout the trial period. It was observed that average speeds on 50 km/h roads were around 50 km/h with violations below 55%, and 85th percentile speeds between 57 and 63 km/h. For 70 km/h roads, average speeds were around 70 km/h and violations of about 50%. Drivers exceeded the speed limit on most 30 km/h roads, especially the isolated ones, with violations of upto 85% and maximum speeds of about 50 km/h.

In general, it was found out from the study that road injuries could reduce by up to 20% if all vehicles were equipped with ISA systems. In addition, user acceptance levels were high. Most users were of the opinion that ISA penetration rates systems should increase and become compulsory in urban areas so that equipped vehicles did not stand out in traffic by driving at slower speeds. The SNRA is currently developing and testing measures for instituting regulations for ISA, and defining economic incentives for the purchase and use of ISA systems.

ISA in France – LAVIA

The first ISA road test conducted in France in 1982 was a small-scale voluntary real-life trial [58]. It was a variable speed ISA system whose speed limit was set manually. In 2001, a large-scale ISA project called LAVIA was launched and carried on till 2006. The LAVIA ISA system equipped vehicles with fixed speed limit systems, with warning HMIs, and active speed limiters that had voluntary and mandatory user control options that could limit the fuel supply if the speed limit was exceeded [62]. The goals of the experiment were as follows:

- Assess user acceptance and usage patterns for different control options;
- Assess change in individual driving behaviour;
- Measure reductions in speed and and its effect on speed compliance;
- Measure detrimental effects of the system such as reduced vigilance (underloading) and distraction;
- Assess global collective impacts on safety through simulation using field data.

A 7% reduction in mean speed was observed over all road network types when an auditory warning was used. Results also showed that voluntary and mandatory control types were more effective in speed compliance but were endured more reluctantly by users compared with the warning systems. LAVIA also achieved a fatality reduction of up to 17%, thus showing that it could improve safety.

Small-scale ISA trials

The effects of ISA systems on driving behaviour and road safety have been investigated extensively in several European countries. These investigations have been carried out using driving simulators, instrumented vehicles, and real-life trials. Table 2.3 shows a summary of different ISA studies, all of which involved private vehicle drivers.

Table 2.3: Overview of small-scale experimental ISA studies

	Study	Control	Speed	HMI
Driving simulator	UK, 2000 [63]	Mandatory	Dynamic	Intervening
	Finland, 2001 [64]	Mandatory	Fixed	Warning
	Netherlands, 2005 [65]	Voluntary	Variable	Informative & Intervening
	Netherlands, 2007 [66]	Mandatory	Variable	Informative & Warning
	UK, 2014 [67]	Mandatory	Variable	Informative, Warning & Intervening
Instrumented vehicles	Netherlands, 1999 [68]	Mandatory	Variable	Warning
	Finland, 2001 [57]	Mandatory	Variable	Informative & Intervening
Real-life	Denmark, 2001 [51]	Mandatory	Variable	Informative & Warning
	Australia, 2006 [69]	Voluntary	Variable	Informative, Warning & Intervening
	Belgium, 2007 [70]	Voluntary	Variable	Intervening
	Spain & Hungary, 2008 [24]	Mandatory	Variable	Visual, Warning, Intervening

Almost all results point in the same direction, showing reductions in mean speed of about 2 to 7 km/h, as well as reductions in speed variance, speeding frequency, and violations. The extent to which each system improves speed compliance and safety depends on the implementation, with intervening and mandatory systems being more effective. The ISA systems had their largest effects on the highest speeds, which was also observed from reductions in 85th percentile speeds. Only in [64] which investigated the effect of ISA systems on icy roads was there an increase in mean speed. It was found in [24] that there was no long-lasting effect on speeds after system deactivation, and more drivers wanted to keep the warning HMI over the visual and intervening AAP HMIs.

Besides driver distraction and overloading associated with ISA systems, one other potential drawback to the widespread use of ISA systems is the foreseen increase in travel time. However, some studies have show that if all vehicles in urban areas were equipped with ISA systems (i.e., a high system penetration rate), an improvement in traffic flow is likely, which will bring about a reduction in average travel time and congestion [60].

2.3 Fuel consumption

A number of studies have shown that the main variables that affect fuel consumption are speed and acceleration, with speed having more direct effects [71, 72, 73]. While most models also take vehicle parameters into account, others are independent of vehicle parameters but dependent on road parameters such as gradient [73]. Another characteristic common to these models is that driving at optimal speeds improve fuel consumption significantly. In addition to evaluating the effects of fuel consumption due to the ASE and ISA interventions, fuel consumption estimation is used to investigate the financial gains drivers will accrue should they drive safely, which could also provide an incentive for speed compliant driving behaviour.

2.3.1 Model types

Depending on the level of accuracy required, and the scale involved, fuel consumption models can be classified as microscopic, mesoscopic or macroscopic models [74]. Microscopic and mesoscopic models are the best developed and most used models since they often take speed and acceleration as inputs, yielding more accurate results [75]. Figure 2.1 taken from the official website of the Center for Environmental Research and Technology in Bourns College of Engineering shows each category and examples of the parameters that are plausible [76].

Macroscopic models are commonly used in the estimation of large scale emissions such as over an entire town or city. They are mainly based on average speeds of traffic flow and as such do not account for vehicle/driver-specific operational conditions or transient speed variations. Calculations in such models tend to be simplified, and meant for large scale applications, with low accuracy for individual vehicle dynamics. Typically, transport planning models are first used to determine the average speed and total vehicle mileage for the network being considered followed by a computation of average fuel consumption and emission rates [77]. Macroscopic models usually provide a single emission rate for each average speed level, while assuming that all vehicles pollute similarly under an average range of speeds [78]. Examples include MOVES and its predecessor MOBILE6 [79], and

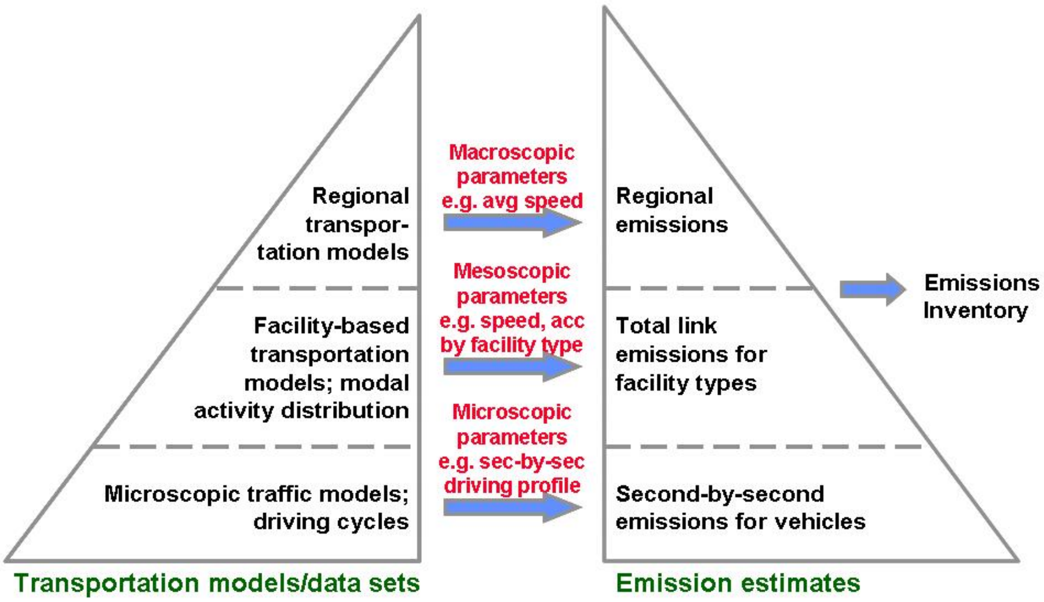


Figure 2.1: Transport pyramid

Source: Center for Environmental Research and Technology, Bourns [76]

COPERT [80] which simplify driving patterns and take parameters such as average speed, road types, and vehicle specifications into account.

Microscopic models are based on instantaneous parameters computed for individual vehicles or individual traffic links. They require more detailed individual vehicle parameters and speed measurements. In addition, the models are built with high temporal precision, capturing transient variations in speed, and as such are usually more costly and computationally expensive [71, 73]. However, they cannot be used to estimate emissions from temporally sparse data. An example is the VT-Micro model used to compute mode specific fuel consumption and emission rates [81]. Another example is the COPERT Micro model which is similar to the macroscopic model, but applied at a microscopic scale per traffic link [82].

Mesoscopic models are usually built on microscopic models with the aim of reducing cost and time in computing fuel consumption and emissions, while retaining the accuracy of the model. They can also be developed from macroscopic models used at a mesoscopic scale, depending the nature of fleet data. They are usually trip-oriented and use instantaneous or average speed and acceleration to estimate synthetic driving cycles, such as in the VT-Meso model [83]. The VT-Meso model uses average travel time, number of vehicle stops per unit distance, and average stop duration to partition the drive cycle into deceleration, idling, acceleration and cruise portions. Mesoscopic models are therefore more suitable since they guarantee both accuracy and computational speed, and can be used for sparse and inconsistent fleet data.

2.3.2 Speed compliance, ITS and fuel consumption

Studies have shown that driving speed plays a significant role in fuel consumption [72]. Reductions in fuel consumption and emissions can be brought about by improving traffic flow, and the lowering of high speeds to an optimum level [60]. The ability of interventions to promote speed compliance implies that they can also reduce fuel consumption, especially for habitual offenders. However, the size of reductions may vary depending on the level of intervention and the drivers involved.

Details on fuel consumption within ASE sections in South Africa are yet to be investigated. However, a number of studies have shown that compared with other sections, ASE sections are characterised by lower fuel consumption and emission rates [32]. Compared with unenforced sections, for an average car, ASE improved fuel consumption by 2.07 km/L when 70 mph (112.7 km/h) limits were enforced, and by 6.77 km/L when 50 mph (80.5 km/h) limits were enforced.

Similarly, little research has been carried out on the impact of ISA systems on fuel consumption on the minibus taxi industry in South Africa and Africa in general. However, one study which estimated the cost savings that can be achieved by implementing active ISA systems in South Africa such as AAPs showed that between R18.7 billion and R51.2 billion will be saved annually [20]. Fuel consumption, vehicle maintenance, and road accident costs were identified as the greatest contributors to this prediction. Savings particularly linked to minibus taxis are still unknown since the prediction considered all motorised modes of transport in a typical urban setting.

In addition to the impact of interventions on fuel consumption, this thesis also investigates projected reductions in fuel cost due to speed compliant driving, and the resultant financial gains which could act as an inherent incentive for safe driving in the impervious minibus taxi industry.

2.4 Summary

From the literature, it can be concluded that both ASE and ISA interventions are good speed compliance, emission reduction, and safety improvement measures. ASE systems reduced violation rates significantly on enforcement routes, while ISA systems reduced the proportion of time spent driving above the ISA speed. However, one interesting observation is that these expected improvements may not always be guaranteed. While ASE is spatially limited, ISA on the other hand has the effectiveness versus acceptability problem. In addition, the lower the ISA speed, the more difficult it is to have ISA systems accepted, while the higher the ISA speed, the more difficult it is to ascertain ISA effects.

It was also observed that responses to these interventions may vary for different regions and test groups. In addition, most trials and studies test the interventions on private drivers and passenger vehicles used for private transport. Little attention is given to the response of drivers for other motorised modes such as public transport.

Although improvements in the vibrant minibus taxi public transport industry can be expected, considering the improvements from literature, it will nevertheless be relevant to investigate their unique response to these interventions, and evaluate the extent to which they affect speed compliance and safety. The next chapter presents the methods and procedures followed to conduct this investigation.

Chapter 3

Methodology

From the existing literature presented in Chapter 2, it was observed that ASE evaluation involved pre and post data comparison and analysis. It was also observed that ASE should not exist as the primary intervention. This chapter describes the ASE evaluation procedure, and also describes the implementation and testing of ISA as a supporting intervention. The chapter also includes the software design process and details on the computation of fuel consumption. Evaluation routes, test participants and data sources (both qualitative and quantitative) are also presented in this chapter.

The ITS evaluation cycle (shown in Figure 3.1) proposed in the ITS handbook [1] is adopted for the evaluation of ASE, and for the testing of the ISA system, taking into account the constraints of data availability and implementation dates. For ASE, the focus will be on post-implementation evaluation with the aim of generating feedback for the improvement of existing and future systems. On the other hand, ISA testing will serve as pre-implementation information towards its deployment as an alternative or supporting intervention.

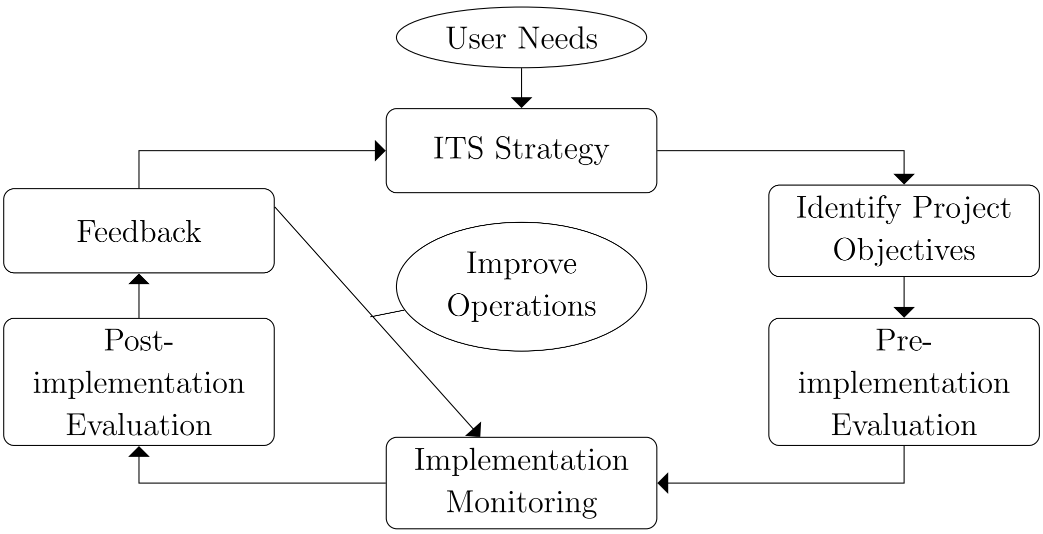


Figure 3.1: The ITS evaluation cycle (PIARC ITS handbook [1])

3.1 Evaluation routes

This study considered the ASE routes along the N1 and R61, taken by most minibus taxis for long-distance travel. As of December 2014, five sections were equipped with ASE systems. The ASE system between Beaufort West and Aberdeen was the first to be commissioned in November 2011, and was chosen for evaluation based on its longevity of operation, permitting a longer post-implementation period for comparison.

According to [1], the evaluation process also needs to consider control routes. Figure 3.2 shows the enforcement and control routes considered in this study, all of which are bidirectional single carriageways. Sections of the evaluation routes are shown in Figures 3.3 and 3.4 for the R61 and N1 respectively. The enforcement route (ER I) between Beaufort West and Aberdeen, and three control routes (CR I, CR II, and CR III) without ASE are evaluated. CR III (between Hanover and Colesburg, not shown in Figure 3.2) is situated North of the N1 with a distance of 240 km from ER I. Control routes CR I and CR II were chosen such that their geometric characteristics and traffic conditions were similar to those of the enforcement route.

Although rarely used by minibus taxis, CR III is frequently used by passenger vehicles, and is chosen to compare driver behaviour farther from ASE with driver behaviour close to, and within ASE routes. While CR III is different from the other evaluation routes due to its paved shoulders and higher average daily traffic, it was found suitable for investigations farther from ASE on the N1 and R61.

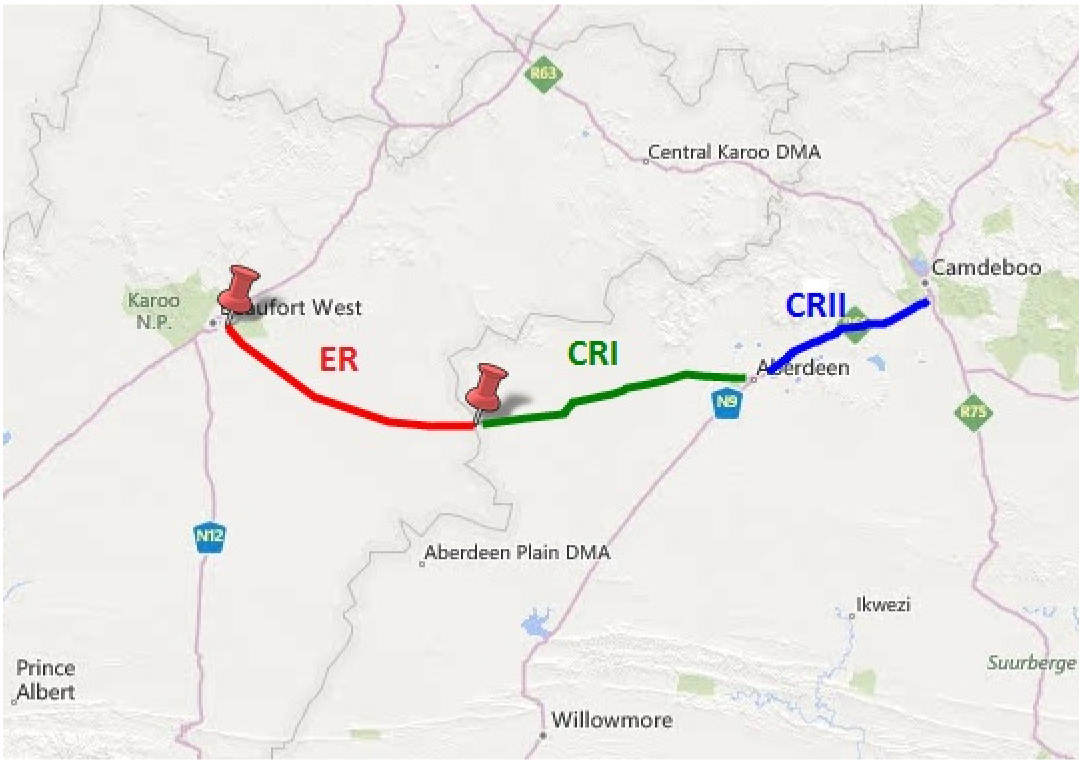


Figure 3.2: R61 evaluation routes
Source: Bing Maps Provider

Figure 3.3: Road section of R61

Figure 3.4: Road section of N1

Source: Google street view 2015

No information could be found to confirm the number of minibus taxis that complete the Cape Town to Mthatha route every weekend, but estimates from the traffic department put the figure at around 300 minibus taxis passing through on a Friday night. This was confirmed by the BP filling station in Beaufort West. Through interviews with the rank marshals and owners, it was also established that 17 minibus taxis from Stellenbosch (about 40 km from Cape Town) complete this journey regularly, with an estimated average of eight per weekend. To get a more accurate estimate, an observation was conducted on a Friday in December 2014 whereby minibus taxis travelling from Cape Town through the N1 were counted. The observation ran for twelve hours at the Shell service station in Worcester on the N1. Over 1,500 minibus taxis were identified, with a peak traffic flow rate of 5.5 taxis per minute. Figure 3.5 shows the minibus traffic counts recorded over time. Most of these trips are taken for holidays, funerals, or other ceremonies [84] by numerous passengers living and working the Western Cape but hail from the Eastern Cape Province.

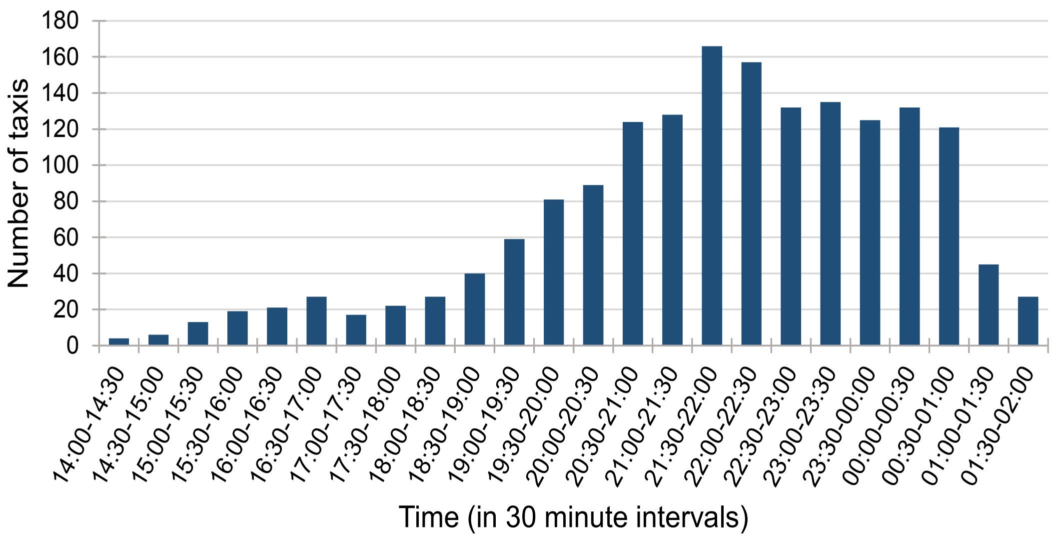


Figure 3.5: Traffic count of minibus taxis from Cape Town to Mthatha over twelve hours

3.2 Test participants and data sources

Two independent test groups were considered for quantitative analysis, namely, passenger vehicle drivers, and minibus taxi drivers. These two groups served as primary data sources in this study.

The first test group consisting of passenger vehicle drivers represents fleet monitoring for vehicles mainly used for private transport with a maximum speed limit of 120 km/h. Data for this group was collected from TomTom Traffic Stats [85]. TomTom obtains data from a number of sources including tracking devices, navigation devices, fleet management devices, and other solutions to which sophisticated data fusion algorithms are applied to achieve high accuracy information and detailed road coverage.

The second test group consisting of minibus taxi drivers represents vehicles used for public transport. Data was obtained from tracking devices installed by MiX Telematics in ten minibus taxis with the permission of the taxi owners. These taxis operate within the Cape Winelands District under the Stellenbosch/Kayamandi Taxi Association. Although data was gathered from taxis within the same association, each owner has a set of contracted drivers who usually work across different minibus taxi associations. Typically, at least two drivers can drive a specific taxi; the owner and his designated/contracted driver(s) [84, 13]. Despite the multiple drivers per taxi, vehicular driver identification was not enabled for this study. In addition, the taxis were not equipped with data-loggers, but each transmitted data to an online data server allowing continuous localisation of the vehicle in real time. The device in each taxi had integrated GPS reporting, and speed-triggered buzzers which served as ISAs. The GPS reporting system was programmed to provide time, location and speed at a nominal frequency of 1Hz.

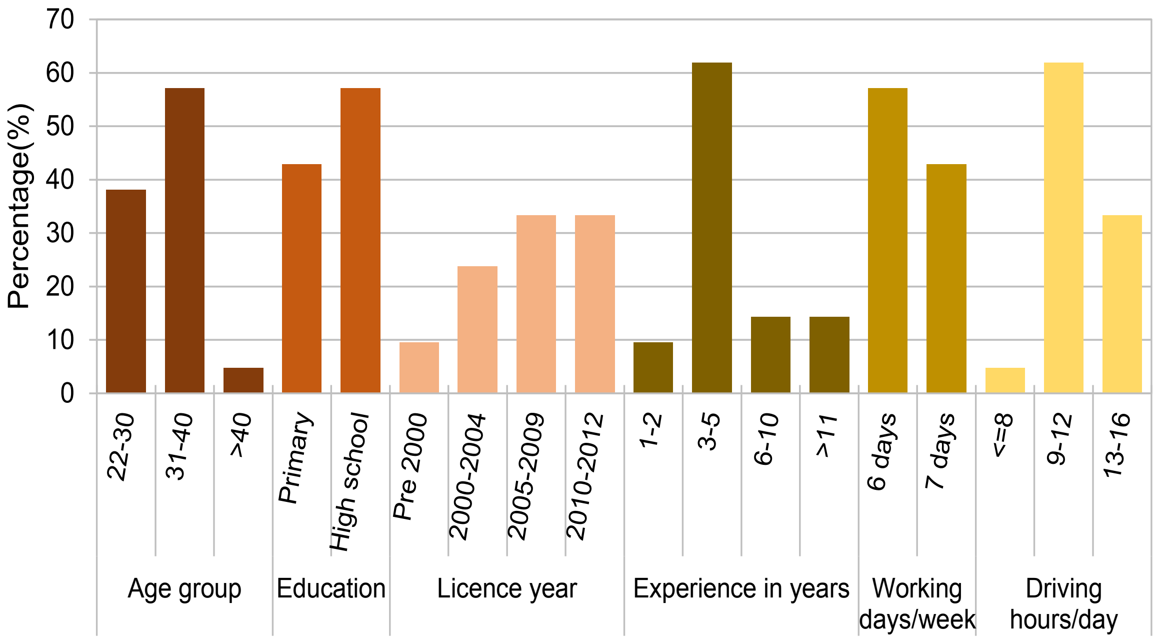


Figure 3.6: Taxi driver information

Figure 3.6 shows demographic information collected from a survey on twenty minibus taxi drivers who frequently complete long-distance trips over the weekend. It shows that most drivers fall in the 31 – 40 age group and drive at least six days a week for about nine to twelve hours each day.

Qualitative data was collected through interviews with these drivers to determine their level of understanding of ASE. Only drivers who frequently drove through the N1 and R61 routes between Cape Town and the Eastern Cape Province were interviewed. Based on their understanding of ASE, taxi drivers were grouped into three categories. The first category represents drivers who understood how the ASOD system operates and where it was deployed along the route. The second category represents drivers who understood how the system operates, but were unaware of its location along the route. The third category represents drivers who neither understood how the system operates nor where it was deployed along the route. These categories are used in Section 4.2.2 where results on driver perception and awareness are presented.

Other secondary data sources used in this study include traffic counts data along the enforcement and control routes, traffic fines issued along the enforcement route, and accident reports data on the enforcement route. The traffic counts data reported by the South African National Roads Agency Limited (SANRAL) is used to verify and validate the TomTom data, while the traffic fines levied on the tracked taxis were used to verify and validate the GPS data. Accident reports data obtained from the Western Cape Provincial Government was used to investigate the impact of ASE on crash rate and crash severity for both passenger vehicles and minibus taxis.

3.3 Evaluation metrics

The metrics used to assess and quantify the results are presented in this section. The metrics are listed in Table 3.1, which also identifies the interventions where each metric is applied.

Computation of mean speed

There are two types of mean speeds in traffic engineering: *time mean speed* (v_t) and *space mean speed* (v_s) [86]. Time mean speed is the arithmetic mean of the speed of vehicles through a point on a highway during an interval of time, while space mean speed is the harmonic mean speed of vehicles through a section of a highway obtained by dividing the total distance travelled by two or more vehicles by the total time required by these vehicles to travel that distance. The time mean speeds are given by:

$$v_t = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{3.1}$$

where
n = number of vehicles through a point on the highway
v_i = speed of the ith vehicle (km/h)

The space mean speed is given by:

$$v_s = \frac{nL}{\sum_{i=1}^{n} t_i} \tag{3.2}$$

where
n = number of vehicles through the section
L = Length of the highway section (km)
t_i = travel time of the ith vehicle (hours)

For the purposes of this study, space mean speed will be used since it considers an entire section, and also to validate comparisons between minibus taxis and passenger vehicles since TomTom uses the same approach for mean speed computation. In the rest of this manuscript the space mean speed is denoted as $\boldsymbol{v}$ for simplicity. In cases where a particular trip needs to be inspected for compliance with the posted speed limit over a given section, Equation 3.2 is still applied with $n = 1$.

Computation of speeding frequency

Speeding Frequency (SF) is the proportion of time spent above or below a given speed, expressed as a percentage [57, 87]. This metric was extended to also consider distance-based speeding frequency. For this study, we were more interested in speeds above a certain threshold (v_T). It was computed per vehicle trip over a given road section from successive GPS records. The time-based speeding frequency is given by:

$$SF(Time) = \frac{t_{SF}}{t_{Total}} * 100, \qquad with \;\; t_{SF} = \sum_{i=1}^{N-1} t_{i,i+1}, \; for \; \frac{d_{i,i+1}}{t_{i,i+1}} > v_T \tag{3.3}$$

where t_{Total} is the time taken to travel through the road section, while $d_{i,i+1}$ and $t_{i,i+1}$ are the distance and time between two consecutive GPS records from an ordered list N that constitutes a trip.

Computation of speed distribution

Kernel Density Estimation (KDE) [88] was used to compute the probability density function of GPS speed samples recorded along a road section over a specific time interval, from which speed distribution parameters such as skewness and kurtosis could be inferred. For n independent speed observations $(x_1, ..., x_n)$ from a random variable of GPS records X, the kernel density estimator $\hat{f}_h(x)$ for a density value $f(x)$ at a given speed x is defined as:

$$\hat{f}_h(x) = \frac{1}{nh} \sum_{i=1}^{n} K(\frac{x - x_i}{h}) \tag{3.4}$$

where h is a positive non-zero smoothing parameter called the bandwidth, and the function K is the kernel for which a Gaussian function was used given by:

$$K(t) = \frac{1}{\sqrt{2\pi}} e^{(-0.5t^2)}, \quad -\infty < t < \infty \tag{3.5}$$

Table 3.1: List of metrics used

Metrics		ASE	ISA	Fuel	Ref.
Speed (km/h)					[25, 57, 68]
	Space mean speed (v)	✓	✓	✗	
	Maximum	✓	✓	✗	
	SD – Standard Deviation (σ)	✓	✓	✗	
	V_{75} – 75th Percentile speed	✓	✓	✗	
	V_{85} – 85th Percentile speed	✓	✓	✗	
	$\%_{120}$ – 120 km/h percentile crossing	✓	✓	✗	
	$\%_{110}$ – 110 km/h percentile crossing	✗	✓	✗	
	$\%_{100}$ – 100 km/h percentile crossing	✓	✗	✗	
	SF (Time) – Time spent speeding (%)	✗	✓	✗	
	SF (Distance) – Distance spent speeding (%)	✗	✓	✗	
	Distribution - Peak	✓	✓	✗	
	Distribution - Kurtosis (κ)	✗	✓	✗	
	Distribution - Skewness (γ)	✗	✓	✗	
Travel time (minutes)					[25, 60]
(for a given section)	Mean travel time	✗	✓	✗	
	Minimum	✗	✓	✗	
	SD – Standard Deviation (σ)	✗	✓	✗	
	Percentiles	✗	✓	✗	
COPERT fuel consumption					[25, 73]
(L/100km)					
	Average consumption	✓	✓	✓	
	Minimum consumption	✓	✓	✓	
	Maximum consumption	✓	✓	✓	

3.4 ASE evaluation

Time differentiation was performed on the enforcement and control routes. This involved a 'before' and 'during' enforcement analysis for each route. Results from time differentiation on the enforcement route are expected to show reduction in travel speeds during ASOD enforcement. Similar results are also expected of CR I considering its proximity to the enforcement route though to a lesser extent, while CR II and CR III should show little or no impact due to enforcement.

Spatial differentiation was also performed with the aim of determining the impact of the ASOD system on the control routes relative to the enforcement route. This involved 'in' and 'out' of ASOD section analysis before and during enforcement. Between the enforcement route and CR I, results from spatial differentiation before enforcement are expected to be similar while results during enforcement are expected to be slightly different. Between the enforcement route and CRs II and III, spatial differentiation results are expected to be similar before enforcement but different during implementation. Nevertheless, it is well understood that despite these expectations, the riding quality and general traffic patterns of the routes over time could lead to different results.

Date ranges were chosen while taking the implementation date of November 2011 and data availability into account, depending on the mode of transport. Table 3.2 shows a summary of date ranges and route characteristics. Query distances refer to the distance over which data was collected, which was a function of the maximum distance allowed by the TomTom server for a specific route. For passenger vehicles, two years prior to installation were compared with two years after installation of the system. On the other hand, there was no data for minibus taxis before enforcement on the R61 since tracking only started in November 2013. As a result of this data availability constraint, only spatial differentiation analysis during enforcement was performed for the minibus taxis. In addition, the minibus taxis rarely travel along CR III. As a result spatial differentiation analysis was not possible for minibus taxis on CR III. For ASE evaluation of minibus taxis, six months worth of probe data between December 2013 and May 2014 was used.

Difference-in-Differences (DID) analysis

The Difference-in-Differences estimator is a common tool used in quantitative research to evaluate the effect of public interventions on treatment and control groups [89]. DID analysis requires data measurements at two or more periods in time, and relies on an underlying assumption that the average outcomes for the treatment and control groups will both follow parallel paths over time before the introduction of the intervention.

In this study, a naïve approach to DID analysis is applied where changes in speed metrics measured before and during enforcement on each evaluation route are compared. DID analysis applies only to passenger vehicles since there was no data for minibus taxis before the ASE intervention. Also, based on the underlying assumption of DID estimation, changes in speed metrics along the control routes are expected to be linear before enforcement.

Table 3.2: Time frames and route characteristics for ASE evaluation

		Passenger vehicle	Minibus taxi
	Before	Jun 2009-Jun 2011	-
Enforcement	During	Dec 2011-Dec 2013	Nov 2013-May 2014
Route I (70 km)	Query distance (km)	70	70
	Speed limit (km/h)	120	100
	Before	Jun 2009-Jun 2011	-
Control	During	Dec 2011-Dec 2013	Nov 2013-May 2014
Route I (70 km)	Query distance (km)	52	52
	Speed limit (km/h)	120	100
	Before	Jun 2009-Jun 2011	-
Control	During	Dec 2011-Dec 2013	Nov 2013-May 2014
Route II (42 km)	Query distance (km)	42	42
	Speed limit (km/h)	120	100
	Before	Jun 2009-Jun 2011	-
Control	During	Dec 2011-Dec 2013	Nov 2013-May 2014
Route III (60 km)	Query distance (km)	50	50
	Speed limit (km/h)	120	100

3.5 ISA implementation

3.5.1 ISA elements and system operation

Unlike ASE evaluation which involved both modes of transport, ISA systems were tested on minibus taxis only. The three main ISA elements of user control, threshold speed, and HMIs in operation are presented here.

User control and customisation of the system were disabled, making the system mandatory. Mandatory systems were chosen over voluntary systems to apprehend the full effect of having the system running continuously.

A fixed speed system was used throughout the experiment. After running a number of trials at different thresholds, the final threshold speed was set at 110 km/h. The speeds were set remotely, with the consent of the taxi owners, who informed their drivers about the activation. Fixed speed systems were used over variable and dynamic systems on the basis of their simplicity, and also to minimise driver distraction and overloading associated with mandatory ISA systems [57, 90]. A 110 km/h threshold is reasonably high, compared with the legal speed limit of 100 km/h. Motivations behind this choice were two-fold, namely, the managing of acceptability and effectiveness. On one hand, the issue of acceptability cannot be overlooked when dealing with ISA systems, and on the other hand, the effectiveness of enabled ISA systems should be measurable. Firstly, it should be noted that this was a real–life experiment with no intentions to disrupt the logistics of passengers and operators. This study focused on long–distance trips made by minibus taxis which are also involved in urban travel – characterised by lower speeds. As such, the threshold had to be high enough to maximise acceptability and to prevent the system from being triggered during urban trips. Secondly, as presented in previous chapters, most taxis travel at average speeds of about 110 km/h or more, with standard deviations of about 14 km/h for certain sections on the Cape Town to Mthatha route. Setting the device at a threshold speed of 110 km/h thus allows assessment of the system's effectiveness at realistic travel speeds.

The HMI used was a non-speech warning system implemented with a buzzer. The warning was a persistent auditory tone that sounded ten seconds after the fixed threshold speed had been exceeded consistently, and stopped immediately after the speed had dropped below the threshold. At maximum volume, the sound pressure level (SPL) was set at 90 dB SPL within a 10 cm range, and had a frequency of 5 kHz.

3.5.2 Experimental procedure

After collecting six months worth of data with the ASE system, ISA activation was introduced from June 2014. Table 3.3 shows the buzzer activation timeline followed in this study. The evaluation was based on the intensity of the warning signal compared with an inactive period (i.e., the six months period before any ISA system activation, with ASE only). Two warning intensity levels were tested; 'soft' and 'loud'. Unlike the loud warning, the soft warning could be ignored or drowned out by increased radio volume or noise. Two months worth of data was used for the inactive (ASE only) and soft warning periods, while only one month was used for the loud warning period as a result of drivers and owners requesting to have the system deactivated.

Table 3.3: ISA activation timeline

Period	ISA speed	Intensity	Active group
Dec 2013 – 05/06/2014	-	-	All inactive
06/06/2014 – 08/07/2014	120	soft	A1
09/07/2014 – 31/07/2014	-	-	All inactive
01/08/2014 – 01/10/2014	110	soft	A1
02/10/2014 – 02/12/2014	-	-	All inactive
03/12/2014 – 16/02/2015	110	soft	A2
17/02/2015 – 12/03/2015	100	soft	A2
13/03/2015 – 13/04/2015	110	loud	A2
14/04/2015 – Present	-	-	All inactive

All taxis: 7001, 7000, 6001, 6000, 5000, 4000, 3001, 1001, 1000.
A1: 3001, 6000, 6001, 7000, 7001. A2: 1000, 3001, 4000, 6000, 7000.

The first set of successive ISA tests involving active group A1 was a trial case where only the soft warning system was activated. Subsequent ISA activation and deactivation periods involving active group A2 were the central periods in this study since loud and soft warnings were tested.

Analysis involved calculating the descriptive statistics of speeding behaviour for all vehicles. Next, differences in behaviour due to ISA system activation and buzzing intensity were verified. An assessment was further conducted as to whether differences brought about by the ISA system were significant; this was carried out through independent samples t-tests. The t-tests were done for the pre-ISA activation period versus both the soft and loud intensity periods. No t-tests were done for the soft versus loud intensity periods since the objective was to investigate ISA system effects against the ASE intervention.

An independent samples t-test does not inform on the magnitude of the observed effects. In order to gain insight into this magnitude, the effect size (EZ) was calculated separately for the different speed-related metrics using Cohen's equation [91] as follows:

$$EZ = \frac{M_2 - M_1}{s_p} \tag{3.6}$$

where M_2 and M_1 are metric means, and s_p is the pooled standard deviation (for two independent samples) given by

$$s_p = \sqrt{\frac{(N_2 - 1)\sigma_2^2 + (N_1 - 1)\sigma_1^2}{n_1 + n_2 - 2}} \tag{3.7}$$

where N_1 and N_2 are the number of observations or trips, and σ_1 and σ_2 are the metric standard deviations.

3.6 Fuel consumption

This section describes the use of the COPERT model to estimate emissions and fuel consumption for minibus taxis in South Africa. It incorporates results of several research and policy assessment projects which are used to calculate emissions of important pollutants from road transport for almost all vehicle classes. It is generally accepted that the motor vehicle emissions in South Africa resemble those of Europe, allowing for the use of common European transport emission models such as COPERT [92, 93, 94, 95]. The COPERT model was applied at a mesoscopic scale since transient effects could not be measured due to GPS data sparsity and inconsistency; Subsection 3.7.5 explains how this issue is dealt with.

3.6.1 Vehicle characteristics and COPERT equations

Table 3.4 shows vehicle characteristics for the Toyota Quantum used in the study. The COPERT model classifies vehicles according to engine capacity, weight and emission control technology, i.e. within the correct COPERT vehicle category.

Table 3.4: Minibus taxi characteristics

Descriptor	Category/Value
Fuel type	Diesel
Cylinder capacity	2494cm^3 (2.5D)
Fuel capacity	70 litres
Emission technology	Euro II
Gross laden mass	3150 kg
Licensing mass	2035 kg
Towing capacity	1400 kg
Height	2285 cm
Width	1880 cm
Max speed	$\approx$ 155 km/h

Based on these characteristics, the following fuel consumption factor (FC) expressed as a function of speed(v) for light-duty diesel vehicles applies [96],

$$FC(v)\ [g/km] = 0.0198v^2 - 2.506v + 137.42,\ \mathrm{R}^2 = 0.422 \tag{3.8}$$

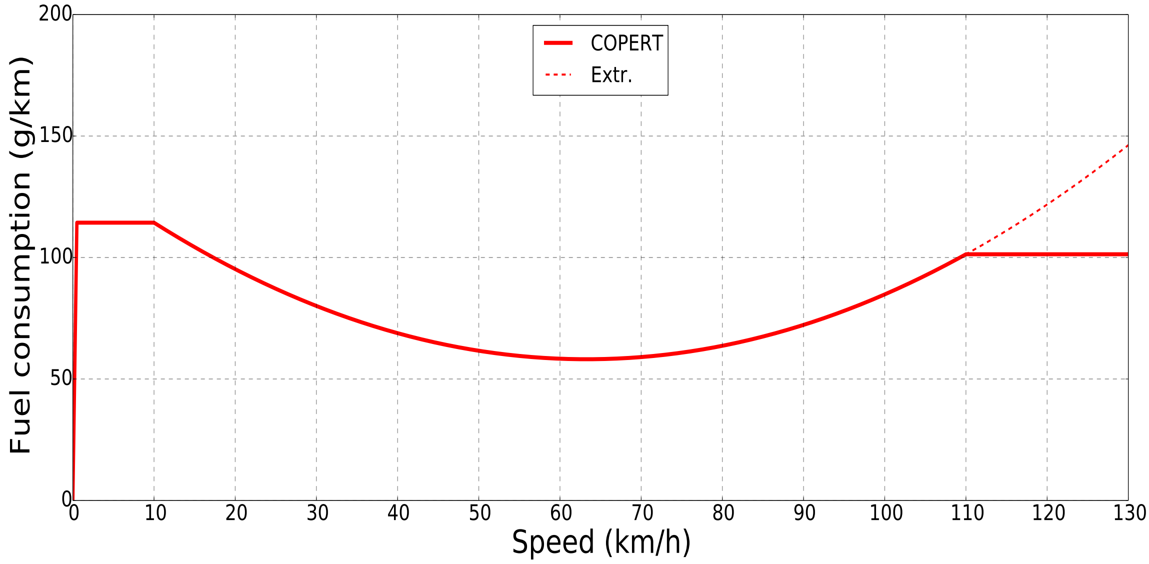


Figure 3.7: COPERT fuel consumption plot for diesel LDVs
Source: Category exhaust emissions from road transport [96]

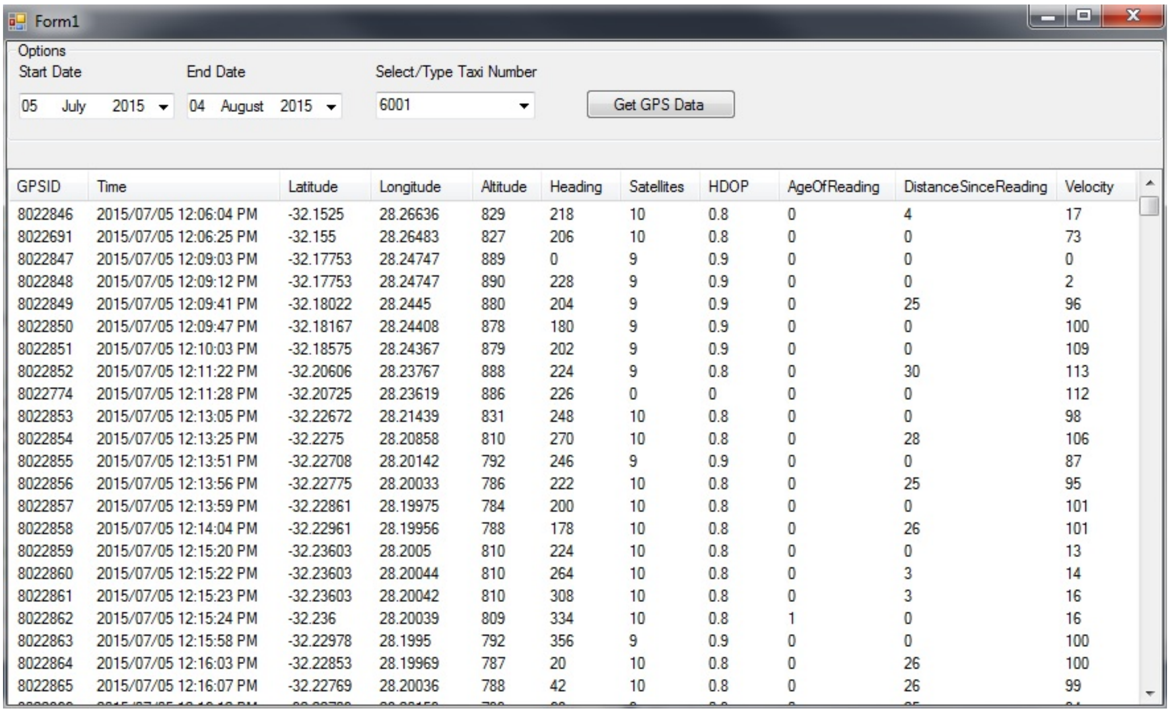
Figure 3.7 shows the relationship between speed and fuel consumption for light duty diesel vehicles based on the COPERT model. Since the COPERT model estimates a constant fuel consumption value for speeds above 110 km/h, and minibus taxi drivers usually drive above 110 km/h on the evaluation routes, an extrapolation of the quadratic function used for lower speeds was assumed for speeds above 110 km/h, and analysed alongside the COPERT model. This extrapolation agrees with a number of predictions on the general relationship between speed and fuel consumption [73, 97], proven mainly from passenger and light duty vehicles.

3.7 Software design

This section presents the software modules and processes developed for the mining and analysis of minibus taxi data.

3.7.1 GPS data acquisition

In this study, GPS tracking devices were used to collect minibus taxi data. Each GPS receiver collected timestamps, latitudes, longitudes and speed information. The devices also collected relevant information such as altitude, heading/bearing, number of satellites in view and HDOP (Horizontal Dilution of Precision) for each record. Each GPS device was connected to a data server in which data was stored and ready to be queried. Figure 3.8 shows a visual studio web interface which was developed to download GPS data. It also shows the form in which data was downloaded, which was then saved for offline analysis. A unique ID was assigned to each GPS record per tracking device.



Form1

Options

Start Date: 05 July 2015 | End Date: 04 August 2015 | Select/Type Taxi Number: 6001 | Get GPS Data

GPSID	Time	Latitude	Longitude	Altitude	Heading	Satellites	HDOP	AgeOfReading	DistanceSinceReading	Velocity
8022846	2015/07/05 12:06:04 PM	-32.1525	28.26636	829	218	10	0.8	0	4	17
8022691	2015/07/05 12:06:25 PM	-32.155	28.26483	827	206	10	0.8	0	0	73
8022847	2015/07/05 12:09:03 PM	-32.17753	28.24747	889	0	9	0.9	0	0	0
8022848	2015/07/05 12:09:12 PM	-32.17753	28.24747	890	228	9	0.9	0	0	2
8022849	2015/07/05 12:09:41 PM	-32.18022	28.2445	880	204	9	0.9	0	25	96
8022850	2015/07/05 12:09:47 PM	-32.18167	28.24408	878	180	9	0.9	0	0	100
8022851	2015/07/05 12:10:03 PM	-32.18575	28.24367	879	202	9	0.9	0	0	109
8022852	2015/07/05 12:11:22 PM	-32.20606	28.23767	888	224	9	0.8	0	30	113
8022774	2015/07/05 12:11:28 PM	-32.20725	28.23619	886	226	0	0	0	0	112
8022853	2015/07/05 12:13:05 PM	-32.22672	28.21439	831	248	10	0.8	0	0	98
8022854	2015/07/05 12:13:25 PM	-32.2275	28.20858	810	270	10	0.8	0	28	106
8022855	2015/07/05 12:13:51 PM	-32.22708	28.20142	792	246	9	0.9	0	0	87
8022856	2015/07/05 12:13:56 PM	-32.22775	28.20033	786	222	10	0.8	0	25	95
8022857	2015/07/05 12:13:59 PM	-32.22861	28.19975	784	200	10	0.8	0	0	101
8022858	2015/07/05 12:14:04 PM	-32.22961	28.19956	788	178	10	0.8	0	26	101
8022859	2015/07/05 12:15:20 PM	-32.23603	28.2005	810	224	10	0.8	0	0	13
8022860	2015/07/05 12:15:22 PM	-32.23603	28.20044	810	264	10	0.8	0	3	14
8022861	2015/07/05 12:15:23 PM	-32.23603	28.20042	810	308	10	0.8	0	3	16
8022862	2015/07/05 12:15:24 PM	-32.236	28.20039	809	334	10	0.8	1	0	16
8022863	2015/07/05 12:15:58 PM	-32.22978	28.1995	792	356	9	0.9	0	0	100
8022864	2015/07/05 12:16:03 PM	-32.22853	28.19969	787	20	10	0.8	0	26	100
8022865	2015/07/05 12:16:07 PM	-32.22769	28.20036	788	42	10	0.8	0	26	99

Figure 3.8: GPS data extraction web interface

3.7.2 Map matching

Mapping and map matching tools used in this study were built with the GMap.NET control. The GMap.NET control is a cross platform open source framework for geocoding and routing from several map providers [98]. The GMap.NET control supports a number of maps such as OpenStreetMap, ArcGIS, Google, and Bing maps. Based on the needs and purposes of this study, Google maps were used extensively for their detailed road coverage of the evaluation routes. Bing maps were also used as an alternative to Google maps in cases where Google map functions were unresponsive. Development was done in C#, with some analysis results generated using Python. Figure 3.9 shows the data analysis interface developed for this study with trip generation, fuel consumption, ISA analysis, and percentile calculation features. The trip generation function assigns a unique ID to each trip and provides descriptive statistics such as the trip direction, departure time, arrival time, mean speed, duration, distance, number of stops, and the number of GPS records. The ISA analysis function takes a collection of trip IDs, identifies the period in ISA trial timeline during which the trip was made, and computes their ISA metrics such as speeding frequency. Some GMap.NET classes and functions specifically relevant to the study are elaborated in Appendix B.

3.7.3 Mining of trips and trip ends

The identification of trips completed between two reference points from raw GPS records was fundamental in the trip mining process. Once this identification is successful, impor-

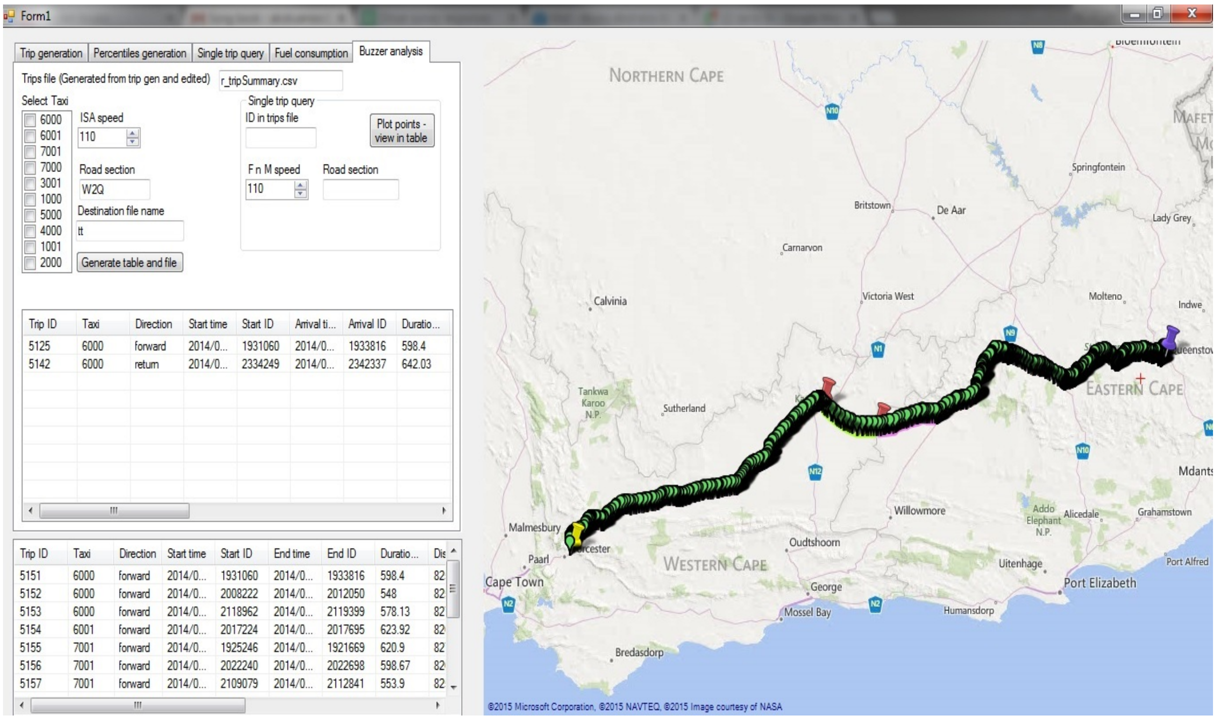


Figure 3.9: Data analysis interface

tant variables such as trip duration and the route taken are also revealed. Other variables such as speed profiles and trip ends need to be computationally derived from the records. However, the first step to processing raw GPS records is the elimination of bad records and quality inspection of reliable records. Here, algorithms for the identification of trips and trip ends are presented, while subsection 3.7.5 explains the validation process.

Trip mining

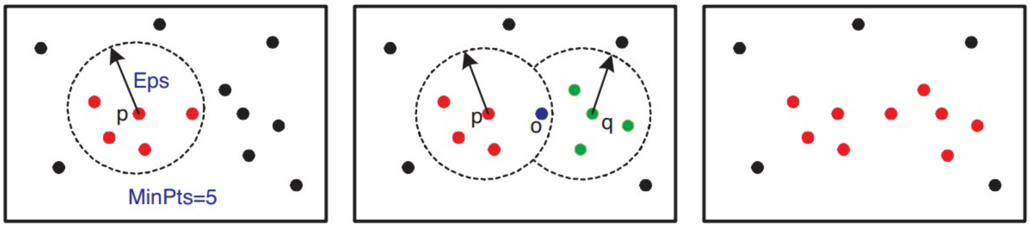
The data analysis interface was designed such that users could specify two reference points (one departure and one destination point) by clicking on the map, or by typing the known coordinates. Forward trips (departure to destination) were distinguished from return trips (destination back to departure) since they may likely have different characteristics for minibus taxis. The 'forward' algorithm generated all trips – and their respective records – taken from the departure point to the destination point for selected taxis over a specified time frame. The trips were generated for all routes between the reference coordinates. As such an additional feature ensuring the selection of trips on the desired route was included based on the expected trip characteristics. In almost all cases, this was the route with the shortest path between the reference points. The 'return' algorithm was similar to the 'forward' algorithm except for the switch in reference points. Further details on the algorithms and methods used to refine trip records are explained in Appendix B.1 to avoid divergence from the subject matter.

Trip ends and stops

After collecting the records of a trip, trip ends were identified. The identification of trip ends was necessary to correlate and measure their effect on trip speed profiles and travel time. A trip end flag was set when two successive records had zero speeds, were less than 0.02 km apart, and had a time stamp difference of over three minutes. Both records resulting in a trip end were considered as trip end records. It does not suffice to consider zero speed records as trip ends or stops since these may only last for a short while hence not representative of an actual stop location.

It is possible for multiple trip ends to exist in close proximity. Records resulting in such trip ends were clustered and considered as a single trip end. The DJ-Cluster (**D**ensity and **J**oin clustering) algorithm was applied on all trip end records for the identification of trip end clusters [99, 2]. The DJ-Cluster algorithm was chosen over the K-Means algorithm because the number of stops along a route are not fixed or known, and it was chosen over the common DBSCAN algorithm for efficient memory usage and speed [99]. Although the DJ-Cluster algorithm is density-based, time related components were captured through the initial detection of trip ends.

Besides its use in trip end cluster identification, another primary use of the DJ cluster algorithm was in the identification of regular stop locations from a collection of records obtained from several trips over a specified time interval.



(a) *Density – N(p)* (b) *Density – Joinable* (c) *DJ – Cluster*

Figure 3.10: DJ clustering concepts (Zhou et al [2])

The DJ-Cluster algorithm is illustrated in Figure 3.10. Firstly, the neighbourhood of each point is calculated, which consists of points within distance *Eps*, given that there are at least *MinPts* in the neighbourhood. If this condition is not met, the point will be labelled as noise. If any two neighbourhoods share at least one point, both are joined and treated as a single neighbourhood.

For the identification of trip end clusters, the initial neighbourhood distance (*Eps*) was set to 0.3 km, and the minimum number of records (*MinPts*) per neighbourhood was set to three. The number of clusters returned by the algorithm plus the number of points labelled as noise ("stand-alone trip end records") were considered as the number of stops in the course of the trip. The *Eps* and *MinPts* were chosen considering the evaluation routes with the characteristic high speeds, data consistency issues, and the fact that data was collected for long-distance trips which were treated independently. Generally, stops along the evaluation routes were expected to be few given the inactivity in its surroundings.

On the other hand, the identification of regular stop locations from several trips discarded trip end records labelled as noise, using the same input parameters (*Eps = 0.3 km, MinPts = 3*). In this case, *MinPts* could be varied depending on the level of detail required, with an increase in *MinPts* returning the most regular stops.

3.7.4 Fuel estimate computation

Based on the vehicle characteristics, the following COPERT emission factor equation for fuel consumption (FC) in g/km expressed as a function of speed (v) in km/h applies;

$$FC(v) = \begin{cases} 114.34, & v < 10 \\ 0.0198v^2 - 2.506v + 137.42, & 10 \leq v \leq 110 \\ 101.34, & v > 110 \end{cases} \tag{3.9}$$

For the extrapolated quadratic function, fuel consumption (FC) in g/km was estimated as a function of speed (v) in km/h, with an upper limit of the domain set at the maximum recorded speed v_{max} = 150 km/h.

$$FC(v) = \begin{cases} 114.34, & v < 10 \\ 0.0198v^2 - 2.506v + 137.42, & 10 \leq v \leq v_{max} \end{cases} \tag{3.10}$$

Given a list of N ordered GPS records that constitute a trip, the fuel consumption in grams is calculated as follows:

$$FC[in\ grams] = \sum_{i=1}^{N-1} FC(v_{i,i+1}) * d_{i,i+1} \tag{3.11}$$

where $FC(v_{i,i+1})$ is the fuel consumption factor in Equation 3.8, $v_{i,i+1}$ is the average speed between records i and i+1 in km/h, and $d_{i,i+1}$ is the distance between records i and i+1 in km. The fuel consumption in litres was calculated by dividing the fuel consumption in grams by the diesel density of 832 grams per litre.

Two methods were used to calculate distances between consecutive records, namely, the Havesine distance, and the Google Route distance. In most cases, the Google Route distance was used for its accuracy since it incorporates windings. However, due to the computational payload associated with the Google Route distance computation, Havesine distances were used for consecutive records which were less than 100 metres apart.

It should be noted that Equation 3.11 is applied based on the assumption that the GPS records defining a trip explain/capture all stops in the course of the trip. If all stops are not captured, which could be as a result of missing data, then the average speed between the consecutive records involved will be inaccurate. The probability of this inaccuracy was minimised by applying the 1 Hz nominal recording frequency to the GPS receiver.

3.7.5 Data validation

Passenger vehicles – Traffic counts speed data

Over 6000 TomTom data samples were collected on the enforcement and control routes along the R61, before and during ASE enforcement. TomTom data is collected from a range of high quality data sources such as live PNDs (Personal Navigation Devices), in-dash navigation and business solutions, on which sophisticated data fusion is applied to achieve high accuracy and detailed road coverage. However, since relatively few vehicle owners possess TomTom devices (especially before ASE), sample sizes obtained for this dataset were potentially too small. To verify the TomTom data, it was compared with speed data obtained through electronic traffic counting devices equipped with inductive loop technology. Time mean speeds were used to calculate speeds at the traffic count stations. As a result, direct comparison with TomTom mean speeds could be misleading except at the exact location of the stations. Nevertheless, standard deviations in TomTom speeds were significantly low (< 3 km/h) except on CR I with a standard deviation of 7.5 km/h. The comparison was aimed at observing the trend in the speeds before and during ASE, checking for consistent increase/decrease in both datasets from before to during. The TomTom data was found to be consistent with the traffic counts data, except on CR III where CTO speeds decreased while TomTom speeds increased during ASE. Details of this comparison are presented in Appendix A.

Minibus taxis – ASOD system captured data

The GPS tracking devices were programmed to provide information at a nominal frequency of 1Hz. Ideally, at least 6500 records per trip were expected along the enforcement route, CR I and CR II at the 1Hz nominal frequency. However, due to filtering and data loss, not all successive records were captured at this frequency. Of the 402 trips collected for ASE evaluation, an average of 60 records were collected per trip through the enforcement route, CR I, and CR II. Although accurate, GPS devices are subject to both systematic and random errors [100]:

- Systematic errors that affect accuracy may occur due to a low number of satellites in view, a high horizontal dilution of precision (HDOP) which relates to satellite orientation on the horizon and its impact on position precision, and other factors such as poor antenna placement.
- Random errors may occur due to signal blockage, atmospheric effects, multipath signal reflection, satellite orbit, and other factors such as receiver defects.

Systematic error effects were minimised by removing GPS records with less than five satellites in view and HDOPs greater than one. On the other hand, the effects of random error were difficult to address. Statistical smoothing techniques or visual inspection of data can be used to identify random errors [101]. Polygons surrounding each route were used to minimise the effect of random errors. Only records within the polygons were used.

To validate the minibus tracking data, average speeds captured by the ASOD system were compared with average speeds calculated from the GPS traces. The ASOD system's speeds were obtained from twelve fines levied on minibus taxi drivers between December 2013 and March 2014. Timestamps on each fine with their corresponding average speed were mapped to GPS-calculated average speeds with the same timestamps. To compute the average speed from GPS traces, two GPS reference records closest to the arrival and departure points of interest were selected from the list of GPS records defining a trip. For each trip, a 2km tolerance radius was defined around each point of interest to minimise wide variations in the location of reference records. Trips with no GPS records in the specified radius were excluded from the analysis. This ensured a maximum deviation of 4km in travel distance from the fixed route distance. GPS average speed for each trip was calculated using the known distance and travel time between the reference records. A maximum percentage error of 0.85% was measured between ASOD and GPS average speeds.

3.8 Summary

This chapter began with a brief outline of the ITS evaluation life cycle, explaining where the the ASE evaluation and ISA tests conducted in this study fit in. It then defined the scope of the study – the evaluation routes and participants – supporting the choices made in each case. Procedures and data analysis methods pertaining to ASE post-implementation and ISA pre-implementation were also presented. Particularly important in this chapter were explanations on data collection and the software design procedures implemented, together with procedures on how fuel consumption was estimated, and how data validation was ensured. The next chapter presents results on the impact of each intervention on driving patterns, and supports these results with qualitative information collected through interviews with the drivers.

Chapter 4

Results and Investigation

The investigation and analysis of results covers ASE evaluation on the enforcement and control routes, followed by the ISA trial evaluation on the Beaufort West to Aberdeen stretch. The chapter then proceeds with an ASE and ISA comparative analysis on the enforcement route, and CR I, after which detailed fuel consumption results are presented, and concludes with a summary of the findings.

4.1 Long-distance informal public transport

Before dealing with the actual outcomes on interventions and incentives, this section presents results on useful operational patterns observed in the minibus taxi industry, which will help to understand the industry better. The data was collected from our sample of ten minibus taxis throughout the year 2014. The 830 km route from Worcester (80 km from Stellenbosch) to Queenstown in the Eastern Cape was considered.

A total of 245 forward trips and 239 return trips were completed by the taxis during the year 2014. Average travel times of 593 and 566 minutes were measured for the forward and return trips respectively. Figure 4.1 shows the number of forward trips (leaving Worcester), and the number of return trips (leaving Queens Town) taken per day of the week. The results strongly agree with driver survey outcomes, where it was found that departures from Cape Town are mostly done on Thursday or Friday, while return trips are done on Sunday. In addition, Figure 4.2 shows the distribution of departure times (from Worcester), and distribution of departure times (from Queenstown) by hour of the day. Given the approximately 53 minutes journey from Stellenbosch to Worcester, the results agree with the survey responses which show that drivers typically depart from Stellenbosch between 5 - 8PM. The time at which they depart from the Eastern Cape (shown in Figure 4.2) also agrees with survey results, with a remarkable peak in the 19th hour (6 - 7PM). Finally, Figure 4.3 shows the number of long-distance trips completed per month. It shows that most trips are taken during the festive season (in December and January), followed by school holidays (in June and July), and Easter holidays (in April).

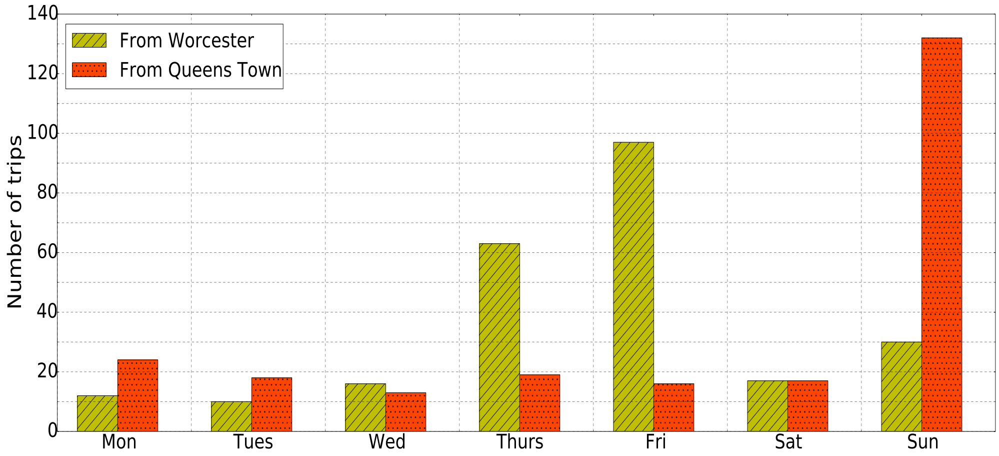


Figure 4.1: Departures per day

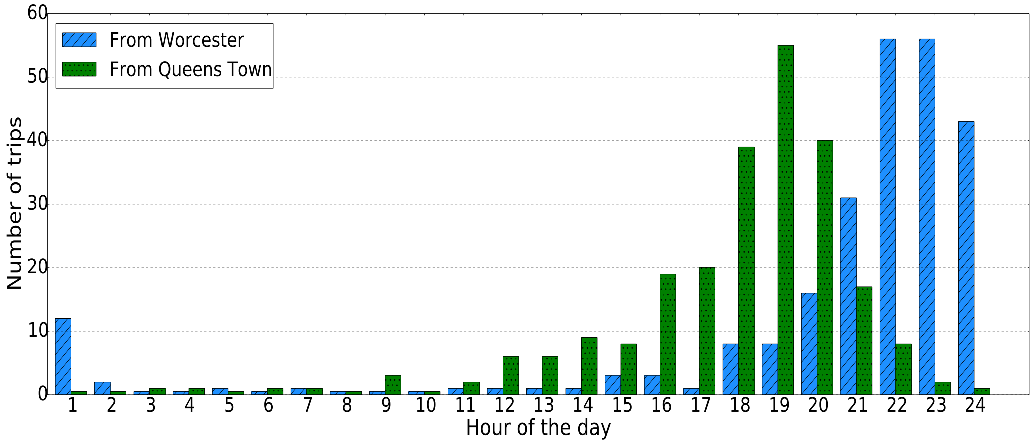


Figure 4.2: Departures per hour of the day

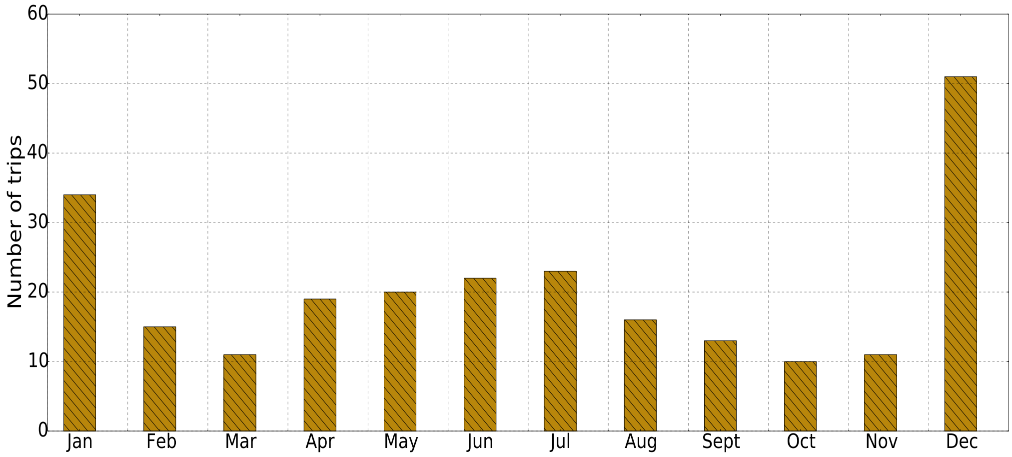


Figure 4.3: Long-distance trips per month in 2014

4.2 ASE evaluation

4.2.1 Speed compliance results

More than 6000 GPS samples obtained from passenger vehicles along the evaluation routes were analysed. For minibus taxis, 402 trips identified from GPS records over six months were analysed. Figure 4.4 shows speed percentile plots for passenger vehicles and minibus taxis for each route and time. An overall reduction in speed for passenger vehicles (PV) on the enforcement and control routes is observed during enforcement. Percentiles for the enforcement route and CR I are similar during ASOD enforcement, while for the same time interval, percentiles for CR II and CR III are significantly higher. For minibus taxis, percentiles show no significant changes between the enforcement and control routes during enforcement. Speed statistics obtained for passenger vehicles are summarized in Table 4.1 for time and spatial differentiation, while Table 4.2 shows the spatial differentiation results of taxis against those of passenger vehicles during enforcement.

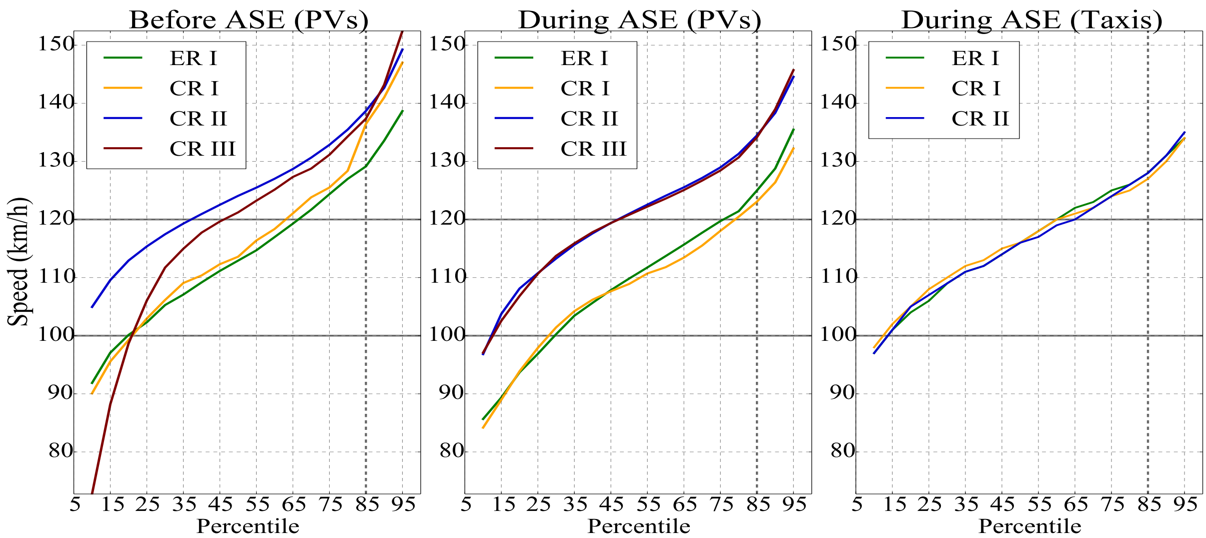


Figure 4.4: Speed percentiles for passenger vehicles (PV) and taxis

Table 4.1: Spatio-temporal comparison for passenger vehicles

		N	Mean	V_{85}	$\%_{120}$	$\%_{100}$	Δ_{mean}	Δ_{85}	Δ_{120}
Enforcement	Before	306	110	129	66	20			
	During	1389	105	124	75	30	-5	-5	9
CR I	Before	101	109	136	64	20			
	During	528	102	123	80	28	-7	-13	16
CR II	Before	2000	121	138	38	6			
	During	3500	117	134	48	13	-4	-4	10
CR III	Before	94	111	137	46	21			
	During	200	115	134	47	13	4	-3	1

Note: N = average sample size; Mean = mean speed; V_{85} = 85th percentile speed; $\%_{120}$ = 120 km/h percentile crossing; Δ = difference between During and Before. All speeds are in km/h.

Table 4.2: Spatial differentiation for taxis versus passenger vehicles

		N	Mean	V_{85}	$\%_{120}$	$\%_{100}$	Δ_{mean}	Δ_{85}	Δ_{120}	Δ_{100}
During	Enforcement	1389	105	124	75	30				
	CR I	528	102	123	80	28	-3	-1	5	-2
	CR II	3500	117	134	48	13	12	10	-27	-17
	CR III	200	115	134	47	13	10	10	28	-17
During (Taxis)	Enforcement	402	110	128	60	14				
	CR I	402	112	129	60	13	2	1	0	-1
	CR II	402	114	128	65	14	4	0	5	0

Note: N = number of trips for taxis and average sample size for passenger vehicles; Mean = mean speed; V_{85} = 85th percentile speed; $\%_{120}$ = 120 km/h percentile crossing; $\%_{100}$ = 100 km/h percentile crossing; Δ = difference between Control and Enforcement. All speeds are in km/h.

A more concise analysis of the results is made possible by applying Difference-in-Differences (DID) analysis on the passenger vehicle data. But before going into the actual results, the DID assumption is verified. Figure 4.5 shows mean speed measurements along each control route from 2009 to 2011. These measurements were obtained from the CTO traffic counts made available by SANRAL, and are shown in detail with respect to data availability. It is observed that mean speeds on CR II and CR III follow fairly parallel paths over time before Average Speed Enforcement on the enforcement route, which satisfies the underlying DID assumption. On the other hand, CR I is not affected in a similar manner, suggesting that it could have been subjected to unbalanced treatment during the evaluation period.

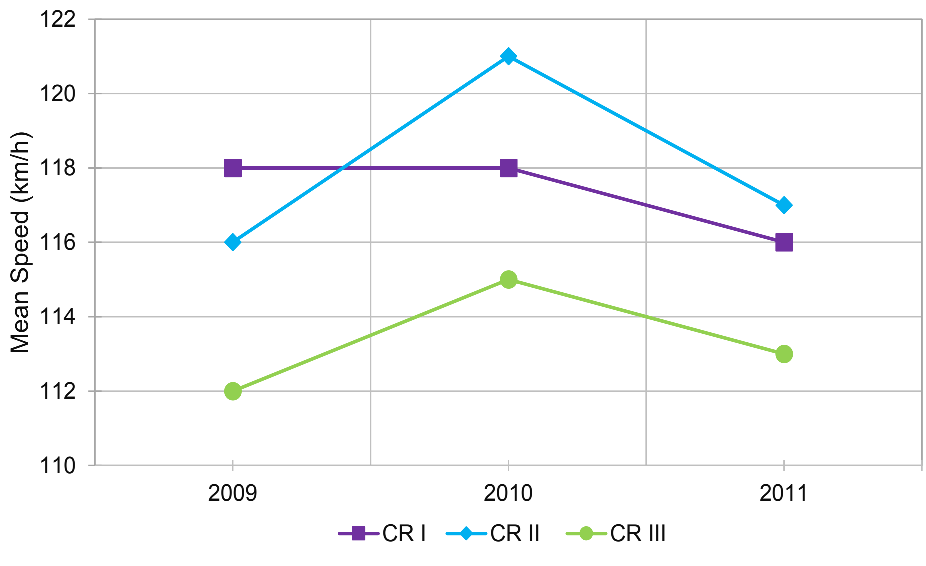


Figure 4.5: Mean speed by year on control routes

Moving on to the results, Figure 4.6 shows DiD analysis results obtained from mean and percentile speeds. Negative changes in mean and 85th percentile speeds indicate a reduction in speeding, while positive changes in percentile crossings indicate that the number of recorded speeds above the speed limit decreased. Except for CR III, an overall reduction in speeding is observed for passenger vehicles on the enforcement and control routes. This is evident from their more negative DID values.

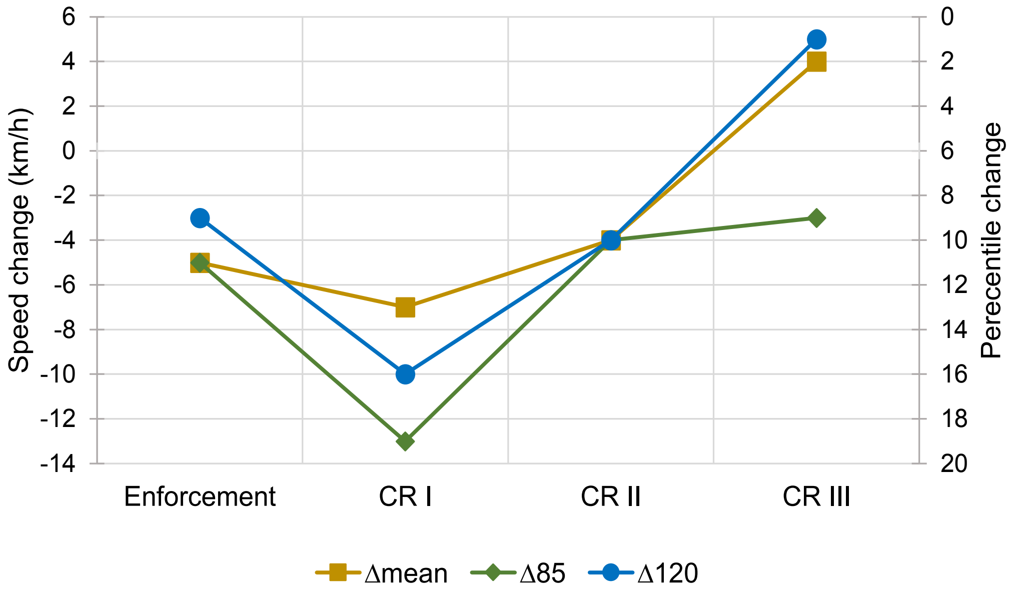


Figure 4.6: Difference-in-Differences analysis for passenger vehicles

For minibus taxis, mean and percentile speeds show no significant changes between the enforcement and control routes during enforcement. This can be observed in Figure 4.7 which shows minibus taxi results against passenger vehicle results during enforcement. In addition to their comparatively higher speeds, their tangential transitions from Enforcement route to farther control routes are gradual and opposite to that of passenger vehicles.

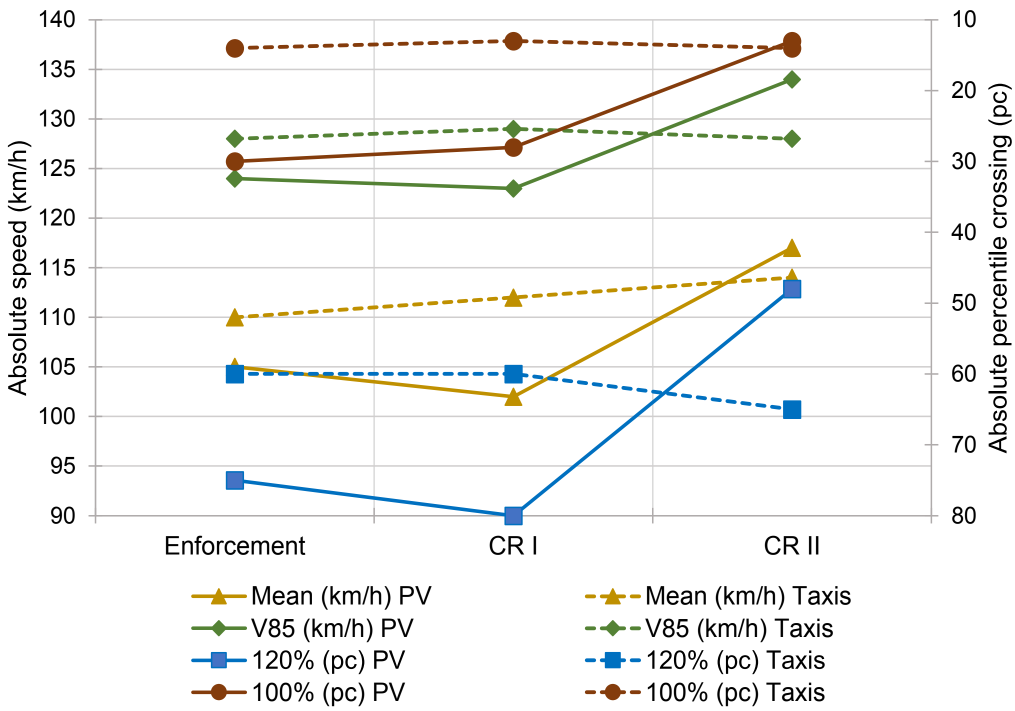


Figure 4.7: Passenger vehicles versus taxis during enforcement

Passenger vehicles

As shown in Table 4.1, the ASOD system appears to have had an impact on passenger vehicles along the enforcement route. Mean speed reduced by 5.5 km/h from 110.7 km/h before enforcement. The 85th percentile speed also reduced by 5 km/h, which corresponds to a 4% reduction. In addition, the percentile at the 120 km/h legal speed limit increased from 66% to 75% which suggests that passenger vehicles spent more time driving below the legal speed limit on the enforcement route. CR I also shows positive results for passenger vehicles. Mean speed reduced by 6.9 km/h from 108.5 km/h before ASOD implementation. The 85th percentile speed reduced by 13 km/h, corresponding to a 10% reduction. In addition, the percentile at the 120 km/h legal speed limit increased by 16% indicating that drivers adhered to the legal speed limit more often. On CR II, mean speed reduced by 4 km/h from 121 km/h before enforcement. The 85th percentile speed reduced by 4 km/h, corresponding to a 3% reduction. The percentile at the 120 km/h legal speed limit increased by 10% indicating that drivers adhered to the legal speed limit more often. The time differentiation results for passenger vehicles show that speed profiles on the enforcement and control routes improved. However, improvements on the enforcement route and CR I were better than those on CR II and CR III. It should also be noted that these improvements on the enforcement route and CR I occurred despite the fact that their speed profiles before enforcement were already significantly lower than those of CR II and III.

An examination of Figure 4.4 gives a general picture of the spatial differentiation results. During enforcement the enforcement route and CR I have similar speed profiles. During enforcement, CR II and CR III also have similar speed profiles. At any given percentile, the difference in speed from the enforcement route and CR I to CR II and III is about 10 km/h. Before enforcement however, this difference in speed is lower and inconsistent which shows a higher degree of similarity and the absence of average speed related enforcement. Coupled with observations from the time differentiation results, it is observed that the ASOD system influenced drivers to comply with speed limits along the enforcement route and on CR I, but not on a further control route such as CR II or even further away such as CR III.

Two concerns arise from the time and spatial differentiation results. Firstly, between the enforcement route and CR I, it is observed that during enforcement, CR I shows a slightly better level of compliance with the speed limit. The average speed is 3.6 km/h lower than that of the enforcement route, and the 85th percentile speed is 1 km/h lower than that of the enforcement route. Speed profiles for CR I were expected to improve, but not to an effect magnitude greater than the enforcement route. It is speculated that this may be due to the poor road condition of CR I before enforcement, leading to routine maintenance during the enforcement period in 2012 and 2013. This strongly agrees with results in Figure 4.5 where an anomaly in CR I was already evident. During maintenance, which typically last for two months in a year, speed restrictions are set at 100 km/h, with occasional Stop/Go closure delays [102, 103]. The second point of concern is that CR II and III also show a slight overall reduction in speeds which was not expected. This could be as a result of national road safety campaigns carried out on roads with high death tolls.

Factors responsible for this reduction in speeds could to some extent be responsible for the reduction in speeds along the enforcement route, which may have nothing to do with the ASOD system. Nevertheless, the reduction in speed compliance along the enforcement route is better than that on CR II and III, suggesting that the ASOD system has a measurable effect.

Minibus taxis

Currently, the posted speed limit for minibus taxis on the enforcement and control routes is 100 km/h. But percentiles in Figure 4.4 show that only about 15% of all recorded taxi speeds are within this legal speed limit. Furthermore, besides a lower variation in speed for the minibus taxis, the speed profiles of minibus taxis are very similar to, or higher than those of passenger vehicles. This finding conforms to studies in [13], which presents similar results for three other road sections. In addition, Table 4.2 shows that the mean speed of minibus taxis during enforcement on all the evaluated routes is at least 110 km/h, which is similar to the average speeds of passenger vehicles before enforcement. It is also observed from the spatial differentiation results that there appear to be no significant differences in driving behaviour at the enforcement and control routes due to very low percentile and mean speed changes. Figure 4.8, which shows speed distribution plots for GPS speeds recorded on all routes also confirms this finding: mean speeds are at 110 km/h on the enforcement route, 112 km/h on CR I and 114 km/h on CR II. The standard deviations are at 14.7 km/h on the enforcement route, 13.1 km/h on CR I, and 13.7 km/h on CR II. From these results, it appears that minibus taxis are not influenced by the presence of the ASOD system along the R61. Also, the similarity between minibus taxi speeds during enforcement and passenger vehicle speeds before enforcement along the enforcement route and CR I is an indication that performing time differentiation analysis on minibus taxis using pre-ASOD implementation data may show little or no significant changes.

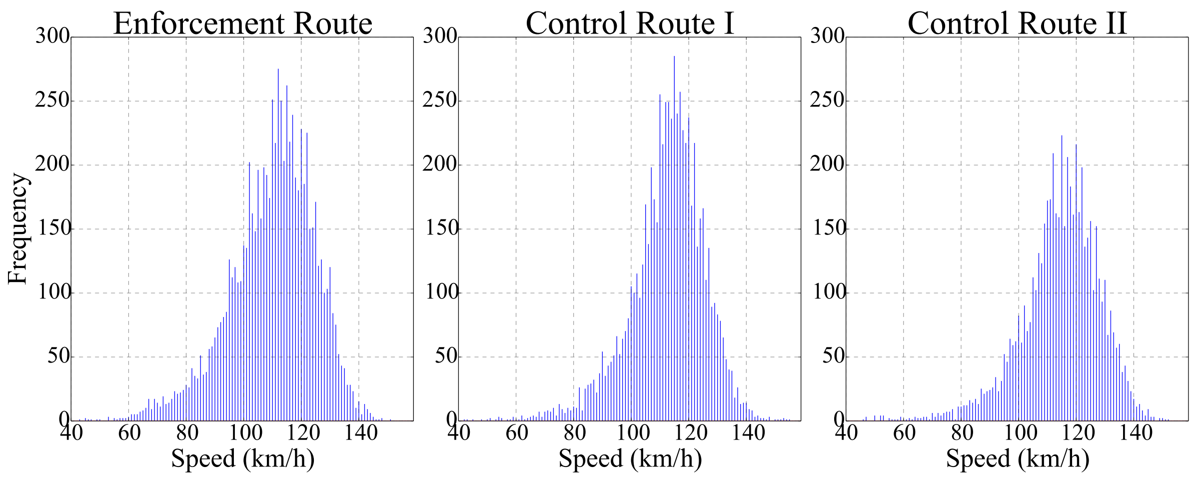


Figure 4.8: Speed distribution within the enforcement and control routes for taxis

A further investigation on individual trips along the enforcement route was conducted for each minibus taxi. The results show that most drivers did not comply with the 100 km/h legal speed limit. Table 4.3 shows a summary of system violations detected from the probe data, for each tracked taxi. Results are expressed as a percentage of trips with an average travel speed beyond a specified threshold. The thresholds start at the 100 km/h speed limit and end at 120 km/h, with 5 km/h increments.

Table 4.3: Trip-based violations summary for taxis

Taxi ID	*N*	*SL* (%)	*SL+5* (%)	*SL+10* (%)	*SL+15* (%)	*SL+20* (%)
6000	74	81	71	62	53	32
6001	49	78	67	53	35	16
7000	32	75	56	31	16	0
7001	53	91	76	57	30	13
3001	56	80	77	64	50	21
1000	60	83	75	58	35	17
5000	30	83	77	57	47	33
4000	28	85	79	68	36	11
1001	20	70	60	35	20	15

Note: *N* = number of complete trips through ASOD system. *SL* = Speed limit of 100 km/h. *SL+10* = 110 km/h. *SL+10 (%)* is the percentage of trips with average speed greater than 110 km/h.

Using average speed, results show that at least 70% of trips taken by each taxi exceed the 100 km/h legal speed limit. For one taxi, up to 33% of the trips completed have average travel speeds greater than 120 km/h. While these results show that ASOD enforcement has little or no impact on minibus taxis, they also support findings in [10] on the impracticality and enforcement difficulties associated with differentiated speed limits. Interviews with the taxi drivers revealed that although all are aware of the 100 km/h speed limit, they nevertheless consider 120 km/h as the limit that governs their choice of speed.

4.2.2 Driver perception and awareness

Twenty drivers who regularly travel along the R61 were interviewed as part of a qualitative survey. This section presents outcomes of the survey related to ASOD systems. All drivers were aware of their legal speed limit of 100 km/h and of the location of speed cameras along the route. Eighty percent (16) of the drivers claimed that the presence of cameras caused them to adhere to speed limits within the vicinity of the camera, while 20% (4) claimed not to be influenced by the presence of cameras because they usually adhered to speed limits. Drivers were then asked if they understood how the ASOD system works. Only two (10%) of the twenty drivers understood the concept of ASE and knew how the ASOD system operates. Drivers who understood how the system operates also knew where it was deployed along the road. Eighteen drivers (90%) neither knew about the deployment of the ASOD system nor how they operated. Four of these eighteen drivers admitted that they were advised by traffic officers to spend a minimum travel time on the road, below which they will get fined. These drivers were nevertheless placed in the third category of oblivious drivers since they neither understood how the system works nor could identify the system along the route.

The high percentage of unawareness of the ASOD system suggests that cameras at the beginning and end of the enforcement section could have been viewed as instantaneous speed cameras, which measure instantaneous speed just in the vicinity of the camera, and not over the entire distance between them. This was verified by investigating only the

GPS speeds within three hundred metres of camera B (camera between Beaufort West and Aberdeen). Camera A (just outside Beaufort West) was not included in this analysis due to comparatively low speeds which can be attributed to its proximity to residential areas. Figure 4.9 shows the speed distribution within three hundred metres of camera B against that on the enforcement route. The results are normalised on a 0 to 1 scale based on the number of observations. The mean speed within three hundred metres of camera B is 60 km/h which is 50 km/h less than the mean speed on the enforcement route, despite no noticeable differences in the road condition. Moreover, in the vicinity of camera B, over 95% of speed records are below the 100 km/h speed limit, showing that minibus taxi drivers view the intervention as an instantaneous speed enforcement (ISE) system.

Thus, despite the proven advantage of ASE systems to improve the speed uniformity along enforcement routes [17], and the general improvement in compliance due to ASOD system deployment [19], most trips completed by minibus taxis prove otherwise due an apparent misunderstanding of ASE.

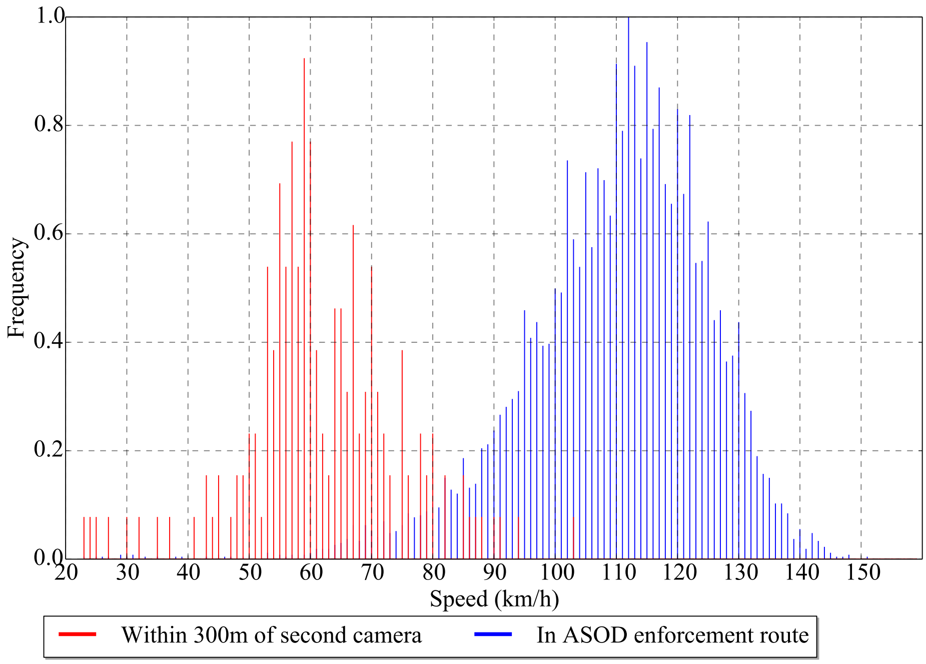


Figure 4.9: Speed distribution: Vicinity of Camera B against enforcement route

4.2.3 Effect on crash risk and injury severity

A high incidence of crashes on a particular road is often the reason behind the implementation of ASOD systems. Reduction in crash rates due to the implementation of ASOD systems rest on the assumption that their effect on speed compliance improvement is significant. It is therefore necessary to investigate their impact on crash rates. To this end, crash data within the enforcement route between January 2008 and September 2014 was provided for analysis by the Western Cape department of Transport. A time-based analysis around the enforcement date of November 2011 was applied with pre-implementation and post-implementation periods of two years. The analysis was conducted for minibus taxis and passenger vehicles for crashes primarily linked to human error due to speeding.

Comparing two years before enforcement (June 2009 – June 2011) to two years during enforcement (December 2011 – December 2013) on the enforcement route, all crashes increased by 9.6% (from 83 to 91). Despite the increase in reported crashes, fatalities decreased by 79.5% (from 39 to 8), serious injuries decreased by 58.5% (from 53 to 22), and minor injuries decreased by 50% (from 106 to 53). Crash severity involving the two vehicle types considered in this study were queried separately; results are shown in Figure 4.10.

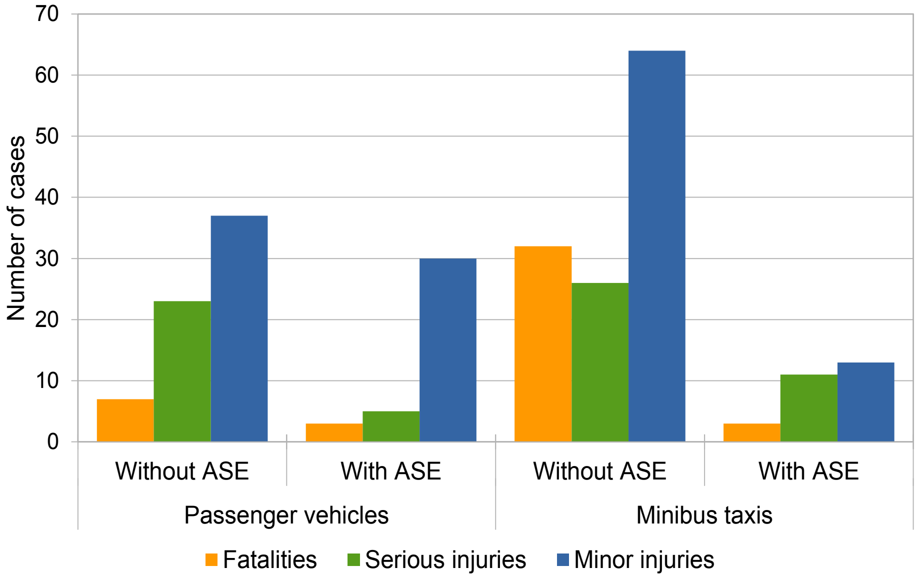


Figure 4.10: Injury severity with and without enforcement for passenger vehicles and taxis

For passenger vehicles, the number of reported crashes decreased by 2% (from 49 to 48). Severity was also reduced; fatalities decreased by 57.1%, serious injuries decreased by 78.3%, and minor injuries decreased by 18.9%. For minibus taxis, the number of reported crashes increased by 38.1% (from 21 to 29). Nevertheless, an impressive decrease in severity is observed; fatalities were reduced by 90.6%, serious injuries decreased by 57.7%, and minor injuries decreased by 79.7%. Given the lack of any other changes in the road system over this time, it is possible to conclude that the ASOD system has had a notable in impact in the reduction of fatalities and injuries.

It should be noted that the fatality results presented were measured over a fixed period of time. As such, effects due to regression-to-the-mean in road accident data were not taken into consideration. While results show that the deployment of the ASOD system was effective, subsequent measurements may reveal different statistics which are not necessarily or solely linked to the ASOD system.

4.3 The ISA trial

Testing of the ISA system in minibus taxis was carried out around three different time settings, chosen relative to the chronology in which the ISA activation timeline unfolded. The primary period of interest was the time during which the loud system was activated, which ran for a month; from 13th March to 13th April 2015. The second period of interest was the time during which the soft system was active. For this, two months' worth of data (12th January to 12th March 2015) was used in the evaluation process. The third period of interest was the period during which the ISA system was inactive and only the ASE intervention was operational. From the six months' worth of data, two months (February and March 2014) were used for the evaluation process. This section presents results comparing speed profiles from these three time frames along the 140 km route from Beaufort West to Aberdeen (i.e., ER I and CR II combined). First, it begins by presenting important behavioural perceptions of the participating drivers.

4.3.1 Pre-implementation survey outcomes

Preliminary survey results from twenty regular long-distance drivers, carried out through interviews are discussed here. The surveys were designed to compile driver demographics, assess the viability of ISA system deployment, and assist in determining the appropriate selection of system settings. A summary of responses is shown in Figure 4.11 which shows that 90% of participants knew about the 100 km/h speed limit. The remaining 10% assumed the outdated 120 km/h speed limit to be in place. Furthermore, 70% of the surveyed drivers felt that ISA systems were necessary and would be effective especially for safety reasons, while 30% were sceptical and felt that the interventions could be a distraction to the normal driving process. Most drivers admitted that they sometimes drive above the speed limit, with 40% of the participants having no particular reasons for speeding while 20% of the participants attributed speeding to lateness.

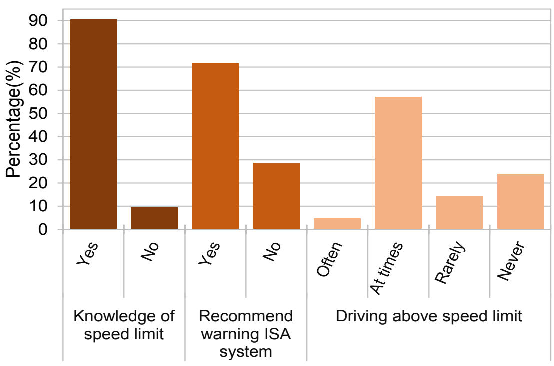


Figure 4.11: Survey responses on perception of the speed limit and ISA system

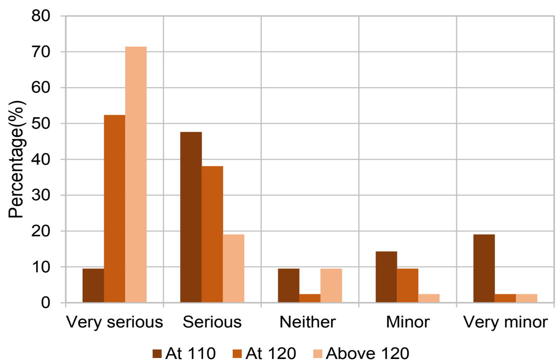


Figure 4.12: Perception on the severity of exceeding the 100 km/h speed limit

With regards to perceptions on speed severity, participants were grouped in one of five categories for three different speed levels above the 100 km/h speed limit. The results are shown in Figure 4.12. Thirty percent of the participants considered driving at 110 km/h on a route with a posted speed limit of 100 km/h of little (minor) or no consequence (very minor). Another 10% considered it neither serious nor minor. For most participants, only speeds at or above 120 km/h were considered serious and intolerable. These results show that setting fixed speed ISA systems at the speed limit of 100 km/h will be characterised by low acceptability.

4.3.2 Driving speed

Three metrics of driving speed that illustrate driving behaviour are mean speed, standard deviation and maximum speed. The metric changes are plotted in Figure 4.13 and recorded in Table 4.10, showing effect sizes with respect to results obtained before ISA activation.

The results show that the introduction of auditory ISA systems have the ability to reduce mean speed by up to 3 km/h even for soft advisory-type buzzing. Despite this reduction for soft buzzing, the statistical analysis results were insignificant (p<0.05), suggesting that with regards to mean speed, soft buzzing results in very little behavioural change compared with the pre-ISA activation period. This is substantiated by the observation that mean speeds both before ISA and during soft buzzing were higher than the ISA fixed speed of 110 km/h. On the other hand, the mean speed for loud buzzing was just 1 km/h higher than the fixed ISA speed (probably higher due to the ten second time lag before buzzing starts). The mean speed for loud buzzing had a statistically significant difference compared with the pre-ISA activation period (p<0.05), which means that loud buzzing had a significant impact on mean speed. Moreover, the loud buzzing system resulted in lower variations in speed from the ISA speed, with a standard deviation (SD) of 9.5 km/h. It is worth noting that after the ISA trials, drivers started reverting to normal driving patterns with speed variations and mean speeds higher than the loud buzzing period, but not at the same level as before ISA activation.

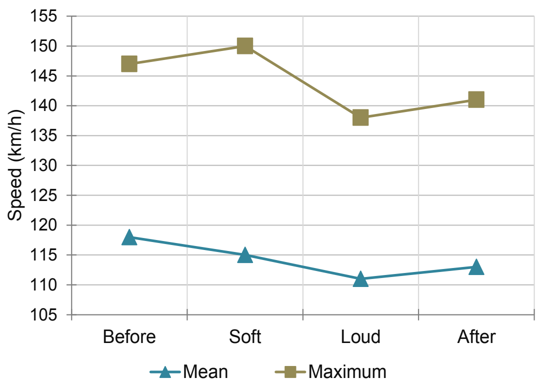


Figure 4.13: Driving speed metric changes

Table 4.4: Driving speed metrics (km/h)

	Trips	Mean	SD	Maximum	EZ
Before	33	118	9.6	147	–
Soft	27	115	11.7	150	-0.377
Loud	20	111*	9.5	138	-1.063
After	19	113	12.5	141	–

* Statistically significant difference from inactive system (p<0.05)

The ISA system effect sizes weighted against the number of observations show that loud buzzing is more effective at reducing mean speeds than soft buzzing. Based on the effect size magnitudes of mean speed reduction, the impact due to loud buzzing (EZ = 1.063) is almost three times the impact due to soft buzzing (EZ = 0.377. It should be noted that with the ISA system active along the enforcement route, the vehicle is under the influence of two interventions – ASE and ISA. As was observed in the previous section, ASE had little or no effect on driving, with about 64% of trips completed through the enforcement route with average speeds above 100 km/h. This suggests that the results obtained after introducing the soft and loud warning are primarily due to the activated ISA system.

Table 4.5: Percentage of trips per mean speed interval

		Mean speed intervals (km/h)			
	Trips	$v > 120$	$115 < v \leq 120$	$110 < v \leq 115$	$v \leq 110$
Before	33	39	27	18	15
Soft	27	29	18	29	22
Loud	20	0	20	40	40
After	19	21	26	21	32

Table 4.5 shows disaggregate results of the percentage of trips completed in the specified mean speed intervals. Results show that the loud warning system was more effective than the soft warning system. With the loud warning system, 40% of trips were completed with mean speeds below the ISA speed, and 80% with mean speeds below 115 km/h on the complete enforcement route and CR I stretch. On the other hand, the pre-ISA period had the lowest proportion of trips with mean speeds below the ISA speed, and up to 39% of trips with mean speeds over 120 km/h. However, with the soft buzzing system, there seems to be a non-monotonic distribution in trip proportions over the four intervals, indicating that it was occasionally overridden or ignored by drivers. A similar pattern from the soft buzzing system is observed after the ISA trials, showing that the soft buzzing system is not as effective as the loud buzzing system in ensuring speed compliance. Once the loud ISA system is deactivated, drivers revert to less compliant driving, though not as severely as before ISA activation, which agrees with findings in [24].

4.3.3 Speed percentiles

Speed percentile rankings are a further metric used to quantify driving behavioural changes, and have been used in previous studies to measure the effectiveness of ISA systems [70, 67]. This section presents 85th percentile speeds, and speed limit percentile crossings for the different evaluation periods and warning intensities. Figure 4.14 shows the percentile plots while Figures 4.15 and 4.16 show important percentile changes due to the introduction of ISA warnings.

For soft and loud warnings, speeding above the fixed ISA speed start at the 43rd and 40th percentiles respectively, while prior to ISA activation, speeding starts earlier at the 30th percentile. As shown in Figure 4.14, before the ISA fixed threshold of 110 km/h, there are no noticeable changes that can be attributed to the ISA system. A further representation of this is shown on the 110 km/h crossing of Figure 4.16 which shows a low percentile before ISA activation, but very similar percentiles for the soft and loud systems.

The largest effect of loud buzzing can be observed at higher speeds; percentile changes between inactive and loud warning are higher at speeds above 120 km/h. However, the

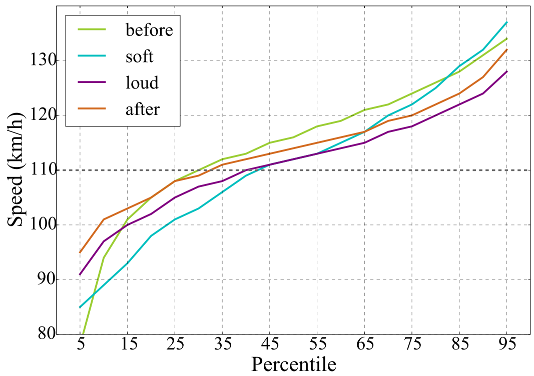


Figure 4.14: Speed percentiles

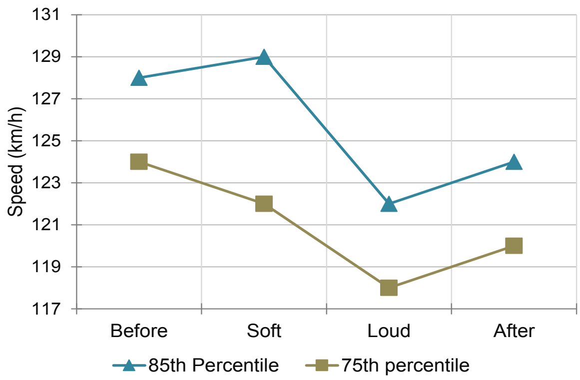


Figure 4.15: 85th and 75th percentiles

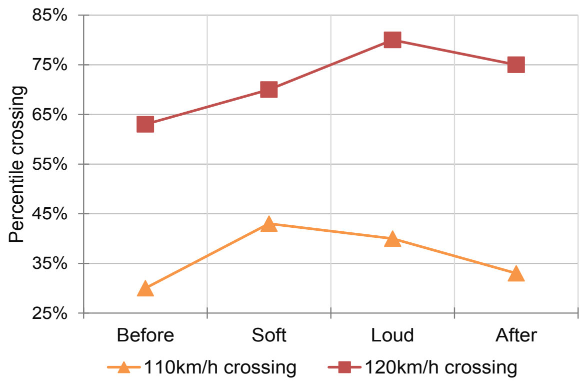


Figure 4.16: Percentile crossings

contrary is true for the soft warning system with percentiles becoming very similar to or higher than those of the inactive system. Again, this shows that the loud warning system was more effective, while the soft warning system though effective was more likely to be overridden.

From the percentile plot of the soft warning system, it is observed that once the ISA threshold of 110 km/h is exceeded, speeds begin to increase abruptly, and at higher rates. This agrees with findings in [67] where a similar response to warning ISA systems was observed. It turns out that auditory warnings irritate drivers [45], so once the ISA system is triggered, they would prefer to endure the warning for much higher speed rather than endure the same warning at or around the ISA threshold. This characteristic is not observed with the loud buzzing system, probably because it tends to be more difficult to ignore.

4.3.4 Speed distribution

Another metric that was investigated was the speed distribution obtained for each evaluation period. Kernel Density Estimation (KDE) smoothing using Gaussian kernel functions was applied to each distribution with a smoothing bandwidth of 0.05 as shown in Figure 4.17, and a Scott smoothing bandwidth of 0.25 as shown in Figure 4.18. The Scott smoothing bandwidth (computed from the standard deviation and number of speed records) was used as an optimal bandwidth for normally distributed data [104]. Figure 4.17 will be referred to for more accurate results, since it retains most of the original information due to its low smoothing bandwidth.

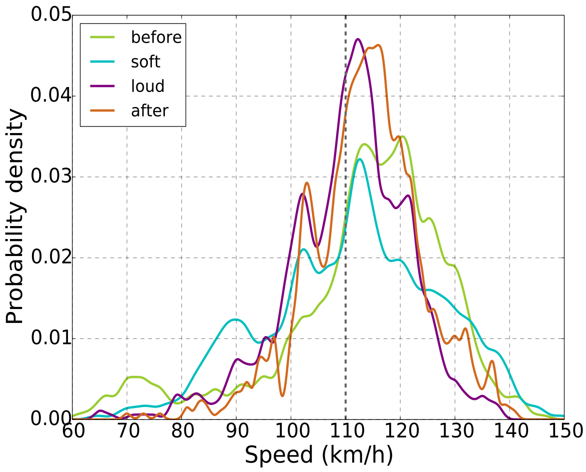


Figure 4.17: Speed distribution (BW = 0.05)

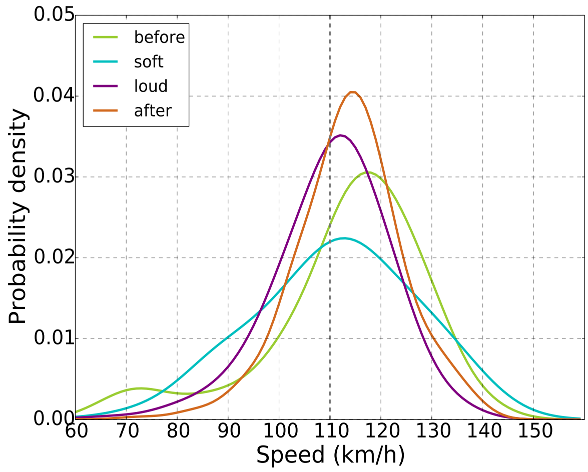


Figure 4.18: Speed distribution (BW = 0.25)

Table 4.6: Descriptive statistics of speed distribution

	Peak (km/h)	Mean (km/h)	Skewness	Kurtosis
Before	120	118	-1.11	1.21
Soft	112	115	-0.28	-0.18
Loud	112	111	-0.74	1.63
After	116	113	0.05	-1.89

Prior to ISA activation, a negatively skewed distribution is observed with a skewness of -1.11, peaking at 120 km/h with a kurtosis of 1.21, and with a mean speed of 118 km/h. Both soft and loud warning system distributions are also negatively skewed with skewness values of -0.28 and -0.74 respectively. In addition, they both have peaks at 112 km/h with kurtosis values of -0.18 for the soft warning distribution, and 1.63 for the loud warning distribution. The high peak and consequently high kurtosis observed for the loud buzzing distribution is evidence of a compensation effect from drivers due to the ISA system. This is more evident in Figure 4.18. Due to the fixed ISA threshold speed of 110 km/h, habitual speeders tend to drive at or around 110 km/h more often than normal, which is clearly demonstrated by the loud buzzing system. Interestingly, effects of the ten seconds delay before buzzing can also be observed especially in Figure 4.17. This can be seen from the plateau between 115 km/h and 120 km/h for both soft and loud warning distributions. Although both audible notifications have an impact, the soft warning did not restrict speeding as much as the loud warning system did, especially for higher speeds. Compared with the soft warning distribution, the loud warning distribution has a higher kurtosis value and a more negative skewness, both of which explain the former assertion. The negative skewness values are an indication that minibus taxi drivers are more prone to driving at higher speeds, pushing the distribution curves rightwards. Only after the ISA trials is a more positive skewness value observed. However, this is coupled with a negative (platykurtic) kurtosis which which indicates a relatively flat distribution.

4.3.5 Speeding frequency

Speeding frequency (SF) is the proportion of time spent driving above or below a given speed limit. Some studies have found it to be among the best metrics for quantifying the effects of ISA systems [57, 87]. In this study we measured speeding frequency based on the proportion of time spent driving above the fixed ISA speed, and also include the proportion of the total distance covered above the fixed ISA speed (110 km/h).

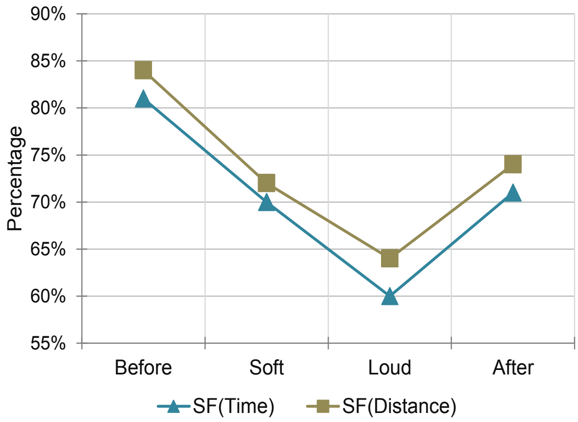


Figure 4.19: Changes in speeding frequency

Table 4.7: Speeding frequency

		Time			Distance		
	Trips	SF (%)	SD	EZ	SF (%)	SD	EZ
Before	33	81	20.5	–	84	19.4	–
Soft	27	70*	27.7	-0.458	72*	27.5	-0.512
Loud	20	60*	24.6	-0.950	64*	25.4	-0.917
After	19	71	22.9	–	74	22.4	–

* Statistically significant difference from pre-ISA activation ($p<0.05$)

Unlike mean speeds, both soft and loud warning systems have statistically significant impacts on speeding frequency. The observations are illustrated in Figure 4.19, and summarised in Table 4.7, which shows that the soft warning system reduced time-based speeding frequency to 70%; 11 percentage points less than before ISA activation. Moreover, loud buzzing reduced time-based speeding frequency by 21 percentage points with an effect size magnitude of 0.950; more than twice the 0.458 effect size due to the soft warning system. Uniformity of time and distance-based speeding frequency changes between different intensity levels is also observed. This indicates that for each evaluation period and intensity level, epochs of average speeds above the fixed ISA speed computed between consecutive records were similar.

Previous results have shown that driver compliance with posted speed limits depends on the value of the speed limit. Irrespective of the ISA system used, lower posted speeds result in higher speeding frequencies, while higher posted speeds result in lower speeding frequencies [105, 67]. In this study, a similar trend was seen whereby the fixed ISA speed of 110 km/h – which happens to be 8 km/h less than the mean speed with the inactive ISA system – resulted in fairly high speeding frequency changes for both soft and loud warning systems. Reductions in speeding frequency due to ISA implementation can be further appreciated from the remarkable increase in speeding frequency observed after ISA deactivation.

Table 4.8: Percentage of trips per speeding frequency interval

	Time-based (%)				Distance-based (%)			
Interval (%)	Before	Soft	Loud	After	Before	Soft	Loud	After
SF< 50	9	18	30	21	9	18	25	21
$50 \leq SF < 60$	3	4	15	11	0	0	15	0
$60 \leq SF < 70$	9	18	20	11	9	11	20	11
$70 \leq SF < 80$	6	11	15	11	3	22	10	11
$80 \leq SF < 90$	27	26	10	31	27	22	15	41
$SF \geq 90$	45	22	10	15	51	26	15	15

In Table 4.8, the number of trips are shown in six percentage intervals for each ISA system. Results indicate that the ISA system affected most drivers, with the loud system being more effective. In the time-based results, 45% of trips before activation have speeding frequencies above 90%, compared with 22% and 10% for soft and loud buzzing systems respectively. There is a noticeable jump in speeding frequencies before ISA activation between the 80-90% speeding frequency interval; 72% (27+45) of trips stay above the ISA fixed speed of 110 km/h at least 80% of the time. Introducing the ISA system reduced this percentage to 48% for soft buzzing, and 20% for loud buzzing. Furthermore, a comparatively higher proportion of trips with the loud buzzing system spend less than 50% of the time above the ISA speed. On the other hand, while the soft buzzing system shows improvement compared with the period before ISA activation, most of its trips are still characterised by high speeding frequencies. These results are further supplemented with the scatter plot of time-based speeding frequency versus mean speed shown in Figure 4.20. The plot shows that the drivers are generally habitual speeders whether speed adaptive technology is present or not. It can be observed for the loud buzzing system that even at comparatively low mean speeds, 35% of the trips had speeding frequencies over 70%, which is an indication that drivers kept triggering the ISA system over a large portion of the journey.

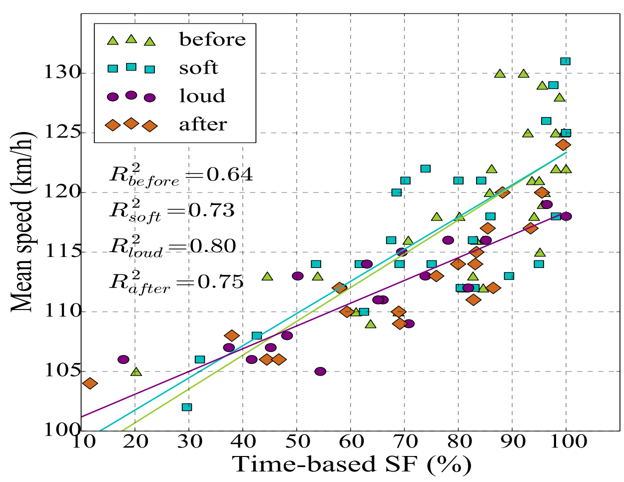


Figure 4.20: Mean speed and speeding frequency scatter

4.3.6 Travel time

In this section, the ISA system effects on travel time are quantified. An average travel time of 70 minutes was obtained before ISA activation. During the activation period, the computed average travel times were 73 minutes for soft buzzing and 76 minutes for loud buzzing. Table 4.9 shows these results. The t-tests revealed that both soft and loud buzzing travel times were statistically different (p<0.05) from those before ISA activation, with effect size magnitudes of 0.507 and 1.021 respectively.

Table 4.9: Travel time results

		Time (in Minutes)			
	Trips	Mean	SD	Minimum	*EZ*
Before	33	70	5.81	62.05	–
Soft	27	73*	6.04	62.48	-0.507
Loud	20	76*	5.98	66.92	-1.021
After	19	75	4.77	68.12	–

* Statistically significant difference from pre-ISA activation (p<0.05)

Together with the computed mean speeds, these results suggest that auditory ISA systems set at a 110 km/h threshold can improve road safety and speed compliance. A consequent increase in travel time of about six minutes (8.6%) is observed along the Beaufort West to Aberdeen stretch. This corresponds to a cumulative increase in travel time of about 50 minutes over the whole 1200 km long-distance route. Considering the fact that under 20% of participants attributed speeding to time restrictions, the 8.6% increase in travel time should not be a significant trade-off to speed and safety.

According to the TomTom online route planner, without any traffic delays or stops, it takes normal passenger vehicles 84 minutes to travel this route, corresponding to an average speed of 100 km/h [106]. Assuming that vehicles adhere to an average speed of 110 km/h on this route, travel times should not be less than 76 minutes, which corresponds to the mean travel time achieved with the loud ISA system. This result shows that the ISA system had an effect on driver behaviour, causing them to drive around the ISA threshold speed.

4.4 ASE versus ISA

From the independent ASE evaluation and ISA tests, one observation is that although ASE brings about lower crash rates and injury severity for minibus taxis, it falls short in ensuring speed compliance in the same industry, for which ISA systems seem to provide a more reliable solution. This section gives a more in-depth view on the effect of ASE and ISA systems on minibus taxis. It picks up from the ISA tests in section 4.3 and considers the loud warning system as the representative ISA system. The comparison focusses on the enforcement route and CR I.

4.4.1 Driving speed and speeding frequency

Table 4.10 gives an aggregate summary of key speed metrics. The number of trips with the ASE and ISA interventions are one less than the number of trips in section 4.3 where the complete Beaufort West to Aberdeen route was considered. This is because the reference records for one of the trips was not identified by the trip generating algorithm after separating the enforcement route and CR I.

The results shows significant differences between ASE and ISA, especially on the enforcement route with a 7.7 km/h reduction in mean speed, and a 9 km/h reduction in the 85th percentile speed after ISA is introduced. Average speeding frequency also shows similar trends with ASE having higher values in time and distance-based results for both routes. Effect sizes computed with respect to the intervention-free period on the control route shows higher effect size magnitudes when ISA is introduced.

Table 4.10: Speed and speeding frequency metric summaries

				Speed metrics (km/h)				Average SF (%)	
Route	Intervention	Trips	EZ	Mean	SD	Max.	V_{85th}	Time	Distance
ER	ASE	32	0.07	118.3	11.2	147	130	82	84
	ISA	19	-0.46	110.6	9	138	121	59	61
CR	Neither	32	–	117.3	17	141	127	79	81
	ISA	19	-0.40	110.8	15.2	138	121	57	60

Speed and travel time percentiles

Speed percentiles in Figure 4.21 show an increasing divergence between ASE and ISA speed profiles as speed increases, with the ASE system characterised by higher speed profiles on both routes. These results also reflect on the travel time percentile profiles, showing longer travel times with the ISA system.

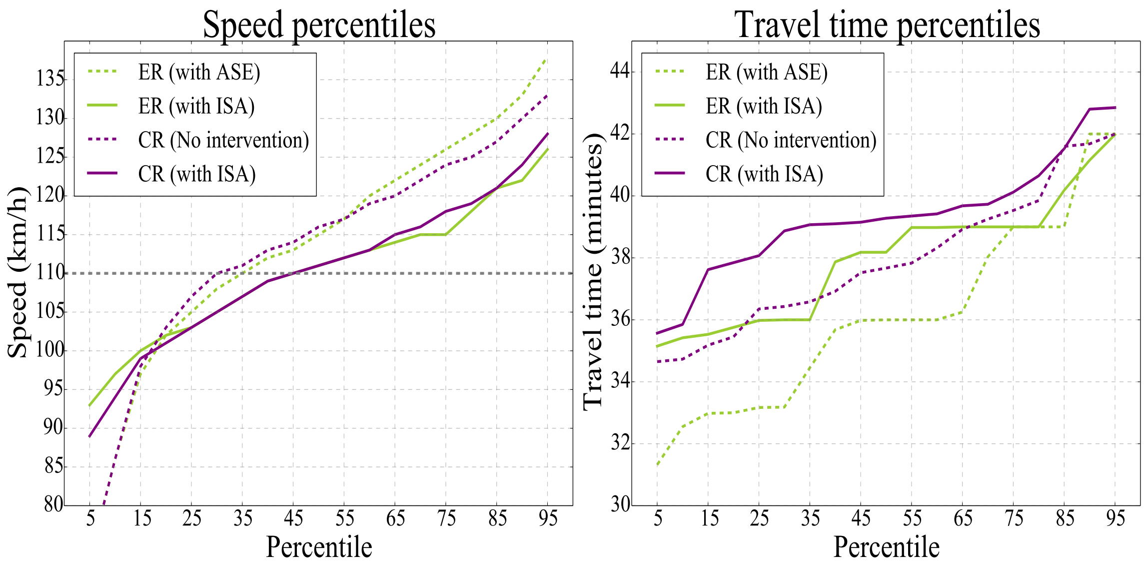


Figure 4.21: Speed and travel time percentiles

Violation rates

A detailed disaggregate analysis of mean speeds is shown in Table 4.11 with the 110 km/h violation frequency. These results are further elaborated in Figure 4.22. The proportion of trips completed with mean speeds above 110 km/h are higher for ASE than for ISA. However, ISA threshold violations (average speeds above 110 km/h) on the enforcement route with ASE is at 81.2%; 9.4 percentage points lower than on the control route with no intervention. Considering violations at the legal speed limit of 100 km/h shown in 4.22, it is observed that the proportion of trips completed above 100 km/h are above 90%, and are the same for both interventions. This shows that although ASE is less effective than ISA at improving speed compliance with minibus taxis, fixed-speed ISA systems can only guarantee speed compliance at the set threshold.

Table 4.11: Percentage of trips per mean speed interval

			Mean speed intervals (km/h)			
Route	Intervention	Trips	$v > 120$	$110 < v \leq 120$	$v \leq 110$	Violations*
	ASE	32	40.6	40.6	18.8	81.2
ER	ISA	19	5.3	42.1	52.6	47.4
	Neither	32	46.9	43.7	9.4	90.6
CR	ISA	19	10.5	42.1	47.4	52.6

* Refers to trips that exceed the ISA speed of 110 km/h.

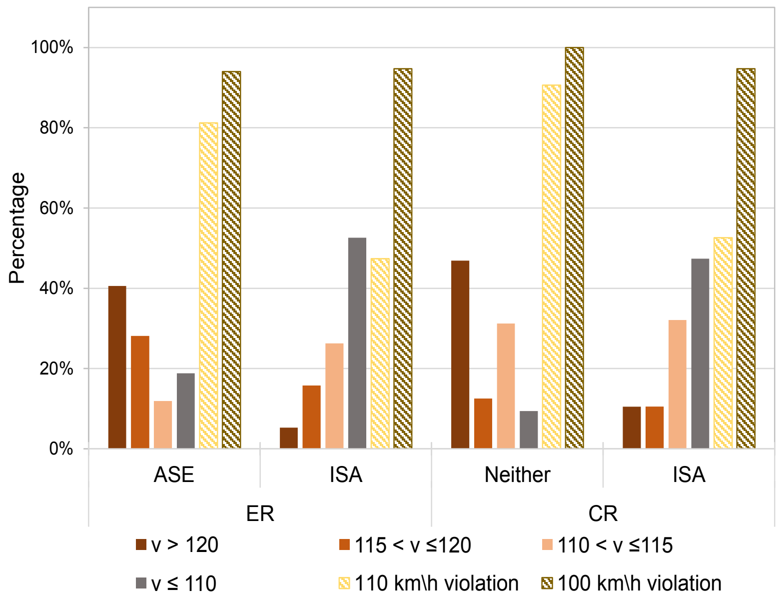


Figure 4.22: Speeding and system violation rates

Speeding frequency

Time and distance-based speeding frequency results are shown in Figures 4.23 and 4.24 respectively, with six intervals of interest for each intervention and route. The results show that with ASE alone, high speeding frequencies are more common on both the enforcement and control routes, but less common when ISA is introduced. Similarly, low speeding frequencies are more common when ISA is introduced, than with ASE alone. Uniformity between time and distance-based speeding frequency results is also observed which shows that average speed instances above 110 km/h computed from consecutive GPS records were similar.

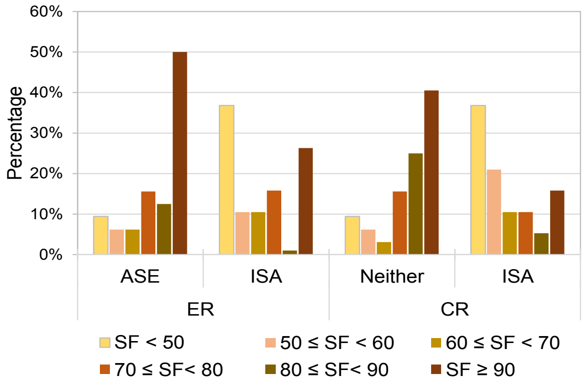


Figure 4.23: Speeding frequency (time)

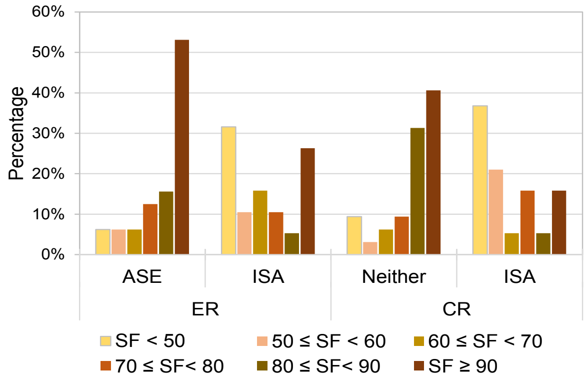


Figure 4.24: Speeding frequency (distance)

Mean speed and speeding frequency scatter

Furthermore the relationship between space mean speed and time-based speeding frequency is explored. In Figure 4.25 the scatter plots and regression lines on the enforcement and control routes for each intervention are shown. Individual trips are plotted as separate points. These plots show that the drivers are generally habitual speeders even in the presence of an intervention. This is evident from the presence of many points situated on the top right quadrant of the graph. On the enforcement route the ASE intervention has a steeper slope indicating that introducing ISA is more effective in ensuring speed compliance. Similarly, on the control route, with no intervention, the slope is slightly higher than that of the ISA system. This occurs because with no intervention, the control route has a higher proportion of trips with low speeding frequencies than the ASE intervention on the enforcement route.

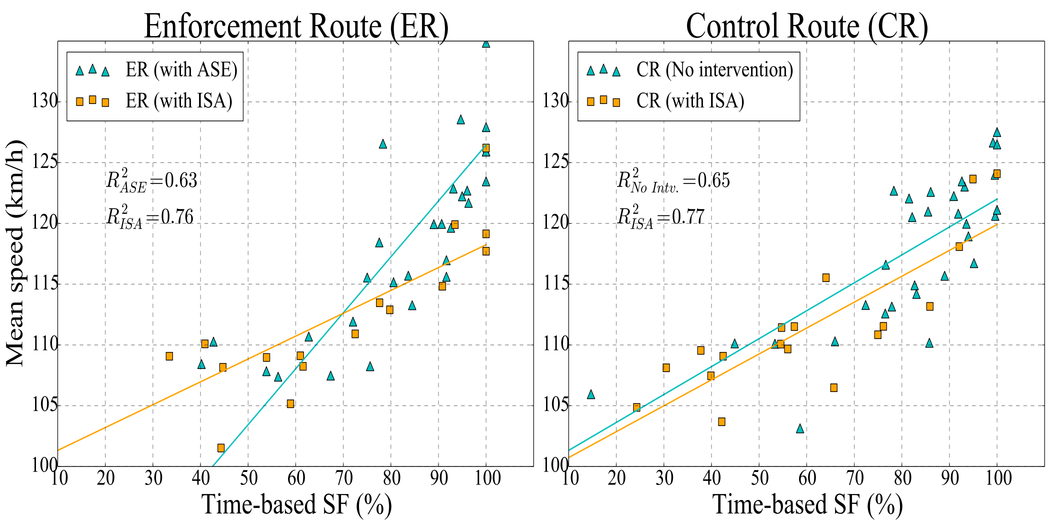


Figure 4.25: Mean speed versus time-based speeding frequency

4.4.2 Speed distribution

Using Gaussian kernel functions, Kernel Density Estimation (KDE) was applied to estimate speed distributions over the entire speed range. The Scott smoothing bandwidth of 0.25 was used for each distribution. From the results shown in Figure 4.26, it is observed that all four distributions are negatively skewed, with the ASE distributions being more negatively skewed, while all kurtosis values are leptokurtic (more positive than that of a normal distribution). More interestingly, it is observed that with the introduction of ISA, the distribution means reduce on both routes, showing that, in this study at least, ISA contributes towards speed compliance more than ASE.

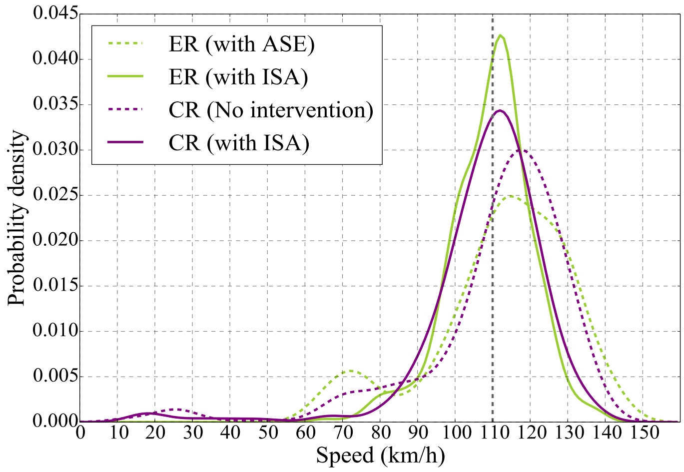


Figure 4.26: KDE Speed distribution for ASE and ISA interventions

On the enforcement route, the skewness values are -0.9 for ASE and -0.6 with ISA, and the kurtosis values are 0.4 for ASE and 1.2 with ISA. On the control route, the skewness values are -2.2 for ASE and -2.7 with ISA, and the kurtosis values are 5.9 for ASE and 11.4 with ISA. On each route, kurtosis values for ASE are lower than those with ISA, indicating the impact of the ISA system causing drivers to spend more time around the ISA speed. The high peak and consequent high kurtosis of both ISA distributions show that the system had a compensatory effect on driving especially around the ISA speed of 110 km/h. The slight deviation of the ISA distribution peaks from the 110 km/h mark is also evidence of the effect of the ten seconds time lag before buzzing starts. Results show that the ISA system was more effective at achieving speed compliance than ASE on the enforcement and control routes.

4.5 Fuel consumption

Studies have shown that driving speed plays a significant role in fuel consumption [72]. The ability of interventions to promote speed compliance implies that they can also reduce fuel consumption, especially in the case of habitual offenders. Using the COPERT model, fuel consumption estimates (in litres) and fuel consumption rates (in L/100km) were calculated for each trip through the entire 140 km stretch from Beaufort West to Aberdeen. The computed average fuel consumption estimates for the inactive, soft and loud buzzing systems were 16.42, 16.40, and 16.17 litres respectively, corresponding to fuel consumption rates of 11.73 L/100km for the inactive ISA system, 11.71 L/100km for the soft buzzing system, and 11.55 L/100km for the loud buzzing system. These changes (although seemingly small due to the high ISA speed) show lower fuel consumption with the loud ISA system. In addition, these estimates can have cumulative effects over the entire journey of 1200 km between Cape Town and Mthatha. Similar to the mean speed results, average fuel consumption before ISA activation and during soft buzzing are very similar, while that with the loud buzzing system is more distinct.

Table 4.12: COPERT versus Quadratic function

	COPERT		Quadratic			
	Litres	Rate (L/100km)	Litres	Rate (L/100km)	$\lvert\Delta_{Litre}\rvert$	$\lvert\Delta_{Rate}\rvert$
Inactive	16.42	11.73	20.31	14.51	3.89	2.78
Soft	16.40	11.71	19.86	14.19	3.46	2.48
Loud	16.17	11.55	17.91	12.79	1.74	1.24

The quadratic extrapolation of the COPERT model for speeds above 110 km/h yielded higher fuel consumption values. The computed average fuel consumption estimates for the inactive, soft and loud buzzing systems were 20.31, 19.86, and 17.91 litres respectively, corresponding to fuel consumption rates of 14.51 L/100km for the inactive ISA system, 14.19 L/100km for the soft buzzing system, and 12.79 L/100km for the loud buzzing system. Two significant observations can be made from these results. Firstly, besides the fact that fuel consumption values are higher than those of the actual COPERT model, the loud buzzing system results in a lower fuel consumption rate compared with the inactive and soft systems which show similar results. Secondly, the observed fuel consumption values are another indication of the fact that minibus taxi drivers often exceed their prosecution speed of 110 km/h. Should they adhered to the speed limit, there will be no differences between the COPERT model and the assumed quadratic extrapolation. Table 4.12 gives a summary of the average fuel consumption parameters for the different ISA system states, and the absolute difference between the COPERT model and its extrapolated quadratic curve. Even with the loud buzzing ISA system, an absolute difference of 1.24 L/100km is computed between the fuel consumption rates, although significantly less that of the inactive and soft buzzing systems computed as 2.78 L/100km and 2.48 L/100km respectively. Based on these results and the known quadratic relationship between speed and fuel consumption, results obtained from the COPERT model probably represent a lower limit in terms of fuel consumption for minibus taxis.

A further investigation was conducted on the relationship between COPERT fuel consumption and mean speed (shown in Figure 4.27). In Figure 4.27, an intersection and subsequent divergence of the regression lines is observed around the ISA fixed speed of 110 km/h. This is indicative of the effect of the ISA system. Moreover, with the loud buzzing system, a steeper slope is observed. This shows that reduction in fuel consumption with ISA systems depends on the ability of the system to reduce mean speed. Evaluating the loud system at its computed mean speed of 111 km/h corresponds to 16.2 litres, while before ISA activation fuel consumption at its computed mean speed of 118 km/h corresponds to 16.4 litres.

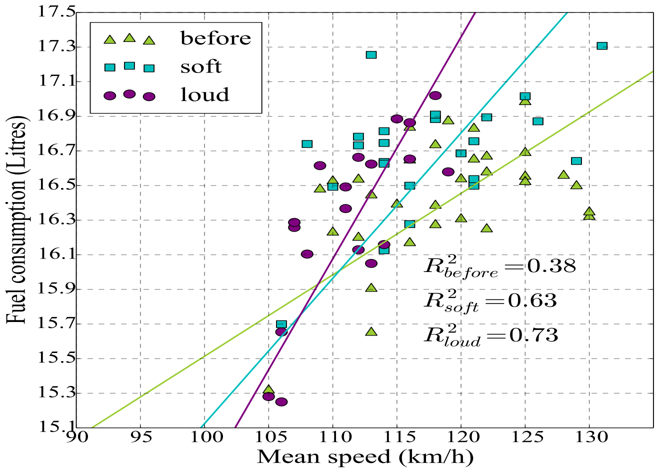


Figure 4.27: Mean speed and fuel consumption scatter

Fuel consumption estimates were also calculated for each trip through the enforcement route and CR I. On the enforcement route, computed average fuel consumption estimates were 11.98 L/100km for ASE and 11.65 L/100km with the ISA system. On the control route, the computed average fuel consumption estimates were 11.96 L/100km for no intervention and 11.59 L/100km with the ISA system. Compared with the control route with no intervention, ASE shows little or no change in the fuel consumption rate. However with the ISA system, average fuel consumption rate on the enforcement route improved by 3%.

Assuming that drivers keep to a constant speed of 110 km/h, the maximum fuel consumption rate will be 12.19 L/100km (101.34 g/km), which happens to be the maximum rate for light duty vehicles based on the COPERT model. This also explains why the ISA speed fixed at a 110 km/h does not result in remarkable reductions in fuel consumption rates. However, comparing the fuel consumption of speed compliant trips with the worst non-compliant trips reveals interesting results. With the ISA system active, some drivers were able to keep fuel consumption rates on the enforcement route as low as 9.9 L/100km, corresponding to a 2.06 L/100km (17.2%) improvement compared to the 11.96 L/100km average, and a 2.29 L/100km (18%) improvement compared to the 12.19 L/100km maximum rate. On the other hand, the minimum fuel consumption rate observed on the enforcement route with ASE is 11.41 L/100km which corresponds to a 5% improvement compared with the 11.96 L/100km average on the control route without enforcement, and a 6% improvement compared with the 12.19 L/100km maximum rate.

Table 4.13 shows a summary of fuel consumption metrics for both the COPERT model and its quadratic extrapolation for higher speeds. With the quadratic model, a minimum fuel consumption rate of 10.03 L/100km was observed on the enforcement route, which corresponds to a 4.43 L/100km (30.6%) improvement when compared with the 14.46 L/100km average on the control route with no intervention. For ASE on the enforcement route, a minimum fuel consumption rate of 11.88 L/100km was observed, corresponding to a 2.58 L/100km (17.8%) improvement compared with the 14.46 L/100km average on the control route with no enforcement.

Table 4.13: Fuel consumption metric summaries for ASE and ISA

		COPERT (L/100km)		Quadratic (L/100km)	
		Enforcement Route	Control Route	Enforcement Route	Control Route
ASE*	Min	11.41	10.80	11.88	10.80
	Avg	11.96	11.96	14.97	14.46
	Max	12.18	12.18	20.86	16.94
ISA**	Min	9.91	9.86	10.03	9.86
	Avg	11.67	11.59	13.33	12.82
	Max	12.18	12.18	17.33	16.03

* ASE on the enforcement route: No intervention on control route.
** ISA on both the enforcement and control routes.

For each trip, a driver typically gets R500 as payment, and a fixed fuel budget of R3500 from the owner of the taxi. The 17.2% improvement in fuel consumption with the ISA system could result in an increase in driver remuneration by about 120% from the fuel budget, while the 30.6% improvement can bring about in a 214% increase in driver remuneration. Also, the 5% improvement in fuel consumption with the ASE system could result in an increase in driver remuneration by about 35% from the fuel budget, while the 17.8% improvement results in a 125% increase in driver remuneration. This significant financial gain from lower fuel consumption shows that it can act as an incentive for safe driving in the minibus taxi industry. A minimum increase in remuneration of 120% per trip can be expected, with the possibility of a 214% increase in remuneration as well.

4.6 Summary

This chapter began with an overview of operational patterns in the minibus taxi industry, followed by an evaluation of ASE effects on passenger vehicles and minibus taxis. It was discovered that fatalities and injury severity on the enforcement route decreased, with certainty that ASE – being the primary intervention on the route – was the main contributor towards the improvement. In addition, with regards to speed limits, passenger vehicles were generally compliant, while minibus taxis on the other hand showed little or no change in behaviour on all evaluation routes. A pre-evaluation of the ISA system followed, first on the entire Beaufort West to Aberdeen route, and subsequently through separate examination of the enforcement route and CR I. In both cases, the ISA system proved to be a potential intervention for speed compliance. From the fuel consumption results, it was observed that drivers could increase their remuneration should they adhere to the speed limit. Although not verified in this study, this massive return in remuneration can serve as an incentive to speed compliant driving.

The next chapter expands on analysis of the results. Based on the observations, it considers strategies for best implementation of ITS interventions within the minibus taxi industry, which could serve as relevant feedback for improvement.

Chapter 5

Discussion

The aim of this study – as pointed out in earlier chapters – is to evaluate the impact of existing ITS interventions on speed compliance, and test the impact of in-vehicle ITS interventions on speed compliance in minibus taxis used for long-distance public transport. Addressing the issue of speed compliance is specifically relevant to the minibus taxi industry which is noted for high crash incidents attributed primarily to human factors such as aggressive driving and low speed compliance rates. Average Speed Enforcement (ASE), which is one of South Africa's solutions to road fatalities and speed compliance awareness was investigated. Auditory Intelligent Speed Adaptation (ISA) – an ITS technology uncommon to the minibus taxi industry – was also tested as an alternative that could work where existing interventions fall short. Finally, the possibility of fuel consumption savings as an incentive for speed compliance was investigated independently, and in relation to the ASE and ISA interventions.

5.1 ASE and speed compliance

The ASE system along the R61 is currently the main measure to counter speeding between Beaufort West and Aberdeen. Questions may arise as to whether improvements in speed compliance of passenger vehicles can be attributed to the system. Answers to these questions are especially relevant since a net decrease in overall speed was observed not only on the enforcement route, but on the control routes as well, although at different proportions. It should be noted that high death tolls on provincial routes before enforcement have led to the systematic intensification of existing countermeasures and the launching of road safety campaigns during the enforcement period, which may have directly influenced speed compliance. However, this is impossible to quantify. The most common countermeasure on this route before ASE was police patrols, which in itself is very limited, with one study indicating that only about 3 out of every 10,000 speed limit infringements are detected by the police [107]. Despite these patrols, mean speeds and 85th percentile speeds were high before the introduction of ASE, coupled with high crash rates and injury severity. Evidence of the impact of the ASOD system is demonstrated by the fact that during enforcement, speed compliance of passenger vehicles on the enforcement route is better than that on CR II with a lower 120 km/h percentile and a mean only 3 km/h lower than the 120 km/h speed limit. Also, despite the existence of the ASOD system amidst other countermeasures, the fact that these changes occur during enforcement indicate that the system could be actively responsible for speed compliance.

The main advantage of the ASE systems over other countermeasures is the reduction in mean speed, 85th percentile speed and low speed variability along enforcement routes [17]. As with other countermeasures, it is also associated with a reduction in overall crash rates and injury severity. According to [108], the ultimate objective of all road safety measures is to reduce the expected number of crashes or injury severity. On the other hand, behavioural studies become more relevant when specific causes need to be identified or verified. For passenger vehicles, improvement in speed compliance is reflected in a corresponding decrease in fatalities and injury severity on the enforcement route. With the introduction of the ASOD system, its combined effect with other countermeasures along the enforcement route appears to have led to a decrease in fatalities and injury severity for both passenger vehicles and minibus taxis, hence satisfying the ultimate objective of road safety measures.

The importance of modal isolation in ITS evaluation

From this study, it is also observed that different modes of transport may respond differently to existing countermeasures for several reasons. While passenger vehicles generally comply with speed limits, our sample of minibus taxis rarely comply. Although the number of fatalities and injury severity decreased for both modes of transport, the number of reported crashes increased for minibus taxis, coupled with very high offence rates during enforcement. This suggests that the presence of the ASOD system may not influence driver behaviour for some modes of transport as expected, but could still lead to a reduction in crash severity and fatalities.

The discrepancy in speed compliance between passenger vehicles and minibus taxis shows that generalisation of the outcomes of road safety measures for all modes of transport could be misleading. Although countermeasures appear to be effective, some vehicle types may be under-represented in the overall results. The evaluation of ITS interventions should therefore not be generalised or simply segmented according to vehicle types, but individual modes of transport should also be considered where possible.

Minibus taxis and compliance on ASE routes

Four factors that could influence the effect size of ASE on speed compliance and crash rates/severity are identified in [108]. It should be noted that the individual effect of each factor is not as outstanding as the effect due to their interaction with each other. These factors are:

1. The choice of evaluation routes and times.
2. The country in which the study (and the enforcement) was conducted.
3. The type of publicity that followed enforcement.
4. The visibility of the enforcement.

The choice of evaluation times and routes is a very important factor since it determines the quality of the study and how these choices may affect the results. In chapter three, the choice of evaluation routes and times was discussed and was done such that their impact on evaluation outcomes was minimised as much as possible. The routes were chosen around the enforcement route on the R61 which was launched in November 2011, and which is the oldest ASE system on the long-distance route. Two year periods before and during enforcement covering the same number of months were chosen as evaluation times for passenger vehicles. One aspect with regards to evaluation times which may have the greatest toll on result quality is the minibus taxi evaluation times which were only available during enforcement, with six months worth of data for evaluation. Nevertheless, except for the subsequent comparison between both modes, passenger vehicles and minibus taxis were analysed independently.

Being a transitional/developing country, South Africa has and is still facing a number of challenges towards the adoption and progress of ITS technologies. This supports findings in [109] on the indispensability of regional factors when dealing with ITS. Low acceptance rates, marginal penetration, abuse of existing structures, and the neglect of ITS safety interventions manifested in several ways including speeding are but a few challenges.

ASE systems either use fixed (visible) or mobile (hidden) speed cameras; the latter being the most common and most effective [108]. All ASE cameras along the N1 and R61 are fixed and visible. Visibility is further enhanced by roadside text notifications at the entry and exit cabinets of each system. The low speed compliance of minibus taxis can therefore not be largely attributed to system visibility. However, as was observed in the results, minibus taxi drivers treat ASE regions more like instantaneous speed camera regions, adhering to speed limits only within close proximity to the cameras.

From the results of this study there is a high possibility that poor speed compliance from minibus taxi drivers is related to their poor understanding of how the ASOD system operates. This could be a combination of non-explicit roadside warnings, the lack of more comprehensive publicity campaigns, or the lack of driver education through sensitisation programmes. From the surveys conducted through interviews with the drivers, it was observed that although most of them are aware of the 100 km/h speed limit, they nevertheless consider 120 km/h as the limit that governs their choice of speed. In addition, it was observed that the maximum level of education for an average driver was Grade 10 (Equivalent to an ordinary level certificate). Although the effects of driver education on accident involvement has been found to be little [110], novel approaches that could play a significant role in the aptitude of minibus taxi drivers in understanding general ITS concepts need to be considered [111].

The quality and mode of information release along the road can also have an impact on compliance [112]. The ASOD system gantries and roadside notifications along the N1 and R61 are very visible. Current notifications feature an "Average Speed Enforcement" warning, the speed limit of 120 km/h (for passenger vehicles), and a 2D camera graphic. However, in order to improve compliance and capture a wider audience, roadside notifications may need to be less textual and more graphic, capturing ASE elements of distance coverage and differentiated speed enforcement.

By the end of December 2014, five phases involving the deployment of ASOD systems in the Western Cape Province were completed. Web-based reports and media releases accompanied the launch of each phase. Despite the widespread availability of information on the deployment of ASE systems, there is still an apparent need for local publicity through the dissemination of information via a wider range of media options in ways that will be understood by the general public. There are no guarantees that most drivers will come across web-based reports and media releases, and even if they do, these may not be clearly understood. Driver educational and sensitisation programmes can assist in this regard. For instance, while conducting interviews with the drivers, those who where oblivious to the operation of ASE systems were given a thorough explanation on the important concepts. This was done keeping in mind that the underlying goal of ASE is to improve compliance, reduce fatalities, and not necessarily to raise revenue from infringements [30]. It is strange to realise that drivers in possession of public transport licences may not understand ASE concepts and how the system operates. This is one of the challenges to be dealt with in transitional/developing countries. If minibus taxi drivers were educated on how safety measures such as the ASOD system operates, this could improve safety.

Other reasons for poor speed compliance from minibus taxis could be attributed to driving exposure or the frequency with which they travel the route. Each taxi in this study travels along the ASE enforcement route at least twice a month, while most passenger vehicles might travel along this route only twice in a year. The effect of travel frequency on speed compliance and safety in the minibus taxi industry still needs to be investigated. Nevertheless, one study found that most professional drivers identified familiarity with a given road as one of the factors that make the driving task appear easier, leading to negligence, which could have severe repercussions [113].

As stated in [10], another reason for poor compliance could be the impracticality and difficulty associated with differentiated speed limits, which restricts minibus taxis to a speed limit of 100 km/h and passenger vehicles to a speed limit of 120 km/h on the same route. From the results, this may not be the main reason since some taxis have offence rates of over 30% with average speeds above 120 km/h along the enforcement route.

The job requirements of a minibus taxi driver – which requires that they arrive at certain times irrespective of when they depart – is another factor that could contribute to poor speed compliance. Other reasons could result from ineffective enforcement regimes which fail to prosecute all motorists, or failure of the ANPR cameras in detecting vehicles altogether. Investigation of these reasons was beyond the scope of this study, which focussed on the evaluation of ASE, ISA, and fuel economy as a likely incentive for safe driving.

5.2 ISA and speed compliance

Given the need for ASE systems to coexist with other complementary interventions, and its apparent shortcomings with minibus taxis, ISA systems were tested as an intervention that could work towards improving speed compliance. Analysis began by comparing the effect of different warning intensities against pre-ISA activation results on the whole Beaufort West to Aberdeen stretch, followed by a further comparison of ASE with the most effective ISA trial on the enforcement route and CR I.

Reaction to different warning intensities

A mandatory speed notification was introduced at two different loudness levels (soft and loud). The ISA threshold speed was fixed at 110 km/h; 10 km/h higher than the speed limit for minibus taxis, but lower than their usual average speed on the route, thus high enough to capture effects due to the ISA system.

With the soft ISA system, drivers exceeded the speed limit less often, but were able to ignore the warning as well. As a result, high maximum speeds were recorded for each trip, and the speed distribution still showed a long tail towards the higher speeds. In addition, the soft ISA system appeared to be least effective at higher speeds; this was indicated by the high maximum speeds per trip, and high 85th percentile speed of 129 km/h, higher than that of both the inactive and loud ISA systems. Nevertheless, mean speed throughout the enforcement route and CR I decreased by 3 km/h, and the proportion of trips completed by drivers with mean speeds below the set ISA threshold were higher compared with the pre-ISA activation results. On average, the soft ISA system also reduced speeding frequency from 81% to 70%. Compared with the pre-ISA activation period, the proportion of trips completed by drivers with low speeding frequencies increased. However, similar to findings in [67], many trips were still completed with high speeding frequencies since habitual speeders will prefer to endure the warning for speeds that are much higher than the threshold speed once the ISA system has been triggered.

The loud warning system had a huge impact, reducing speeding frequency from 81% to 60%, and reducing the mean speed by 7 km/h, with lower maximum speeds recorded per trip. Interestingly, no trips had average speeds above 120 km/h, and up to 40% of trips had mean speeds below the ISA speed. The largest effects of the loud system were observed at higher speeds. This is evident from the low 85th percentile speed observed, despite its similarity to percentile speeds measured before ISA activation at lower speeds. These results correspond to findings in [24], on the effects of auditory ISA systems on speed. The loud system also caused drivers to drive around the ISA speed more often, confirmed with the low speed variance around the ISA speed and the low proportion of trips with high speeding frequencies.

From this study, it can be concluded that actively running auditory ISA systems installed in minibus taxis for public transport can provide speed compliance and safety solutions within the minibus taxi industry. Both loudness levels were effective at improving speed compliance. However, a clear distinction can be seen in the extent to which each level affects driver behaviour. This is supported by the observation that all trips taken while the loud ISA system was active were affected. Although effect magnitudes may vary for different road types and regions, the loud system has similar positive trends with earlier auditory ISA studies, and with ISA systems that implement other intervening human interfaces like the AAP [51, 60]. On the other hand, not all trips taken while the soft ISA system was active were affected by the system. The soft ISA system has similar trends with informative ISA systems since it can be suppressed or ignored by habitual speeders, and is more effective with drivers who are more speed conscious.

The investigation into travel time showed that both ISA systems increased travel time. On average, the loud ISA system brought about a six minutes increase in travel time over the 140 km long route between Beaufort West and Aberdeen. Cumulatively, this corresponds to an increase in travel time of about 50 minutes assuming the same road characteristics over the whole 1200 km long-distance route. One of the main reasons given by drivers for speeding intentionally was that they are usually late and need to hurry. This is partly due to the nature of their job within the industry whereby the more trips you make with as many passengers as possible, the more you earn [13]. Hence among other factors like irritation and driver overloading, increase in travel time could be one hurdle to ISA system acceptance. This study focused on the effectiveness of the ISA system on speeding and speed compliance. It did not evaluate user acceptability and experience in much detail. However, from the pre-implementation survey outcomes, it was found that 70% of drivers recommended warning ISA systems for speed limit notification and safety purposes. Like most informative and voluntary ISA systems, the soft system seemed to have a high level of acceptance [45]; only one driver complained about it during system activation. On the other hand, like most mandatory intervening systems the loud system seemed to have a very low level of acceptance [45]; one month into the activation period of the loud ISA system, most drivers insisted that it be deactivated, while in some vehicles, drivers tampered with the system rendering them untraceable and unresponsive to ISA activation.

ISA on ASE enforcement and control routes

As the most effective ISA trial, results from the loud ISA system were compared with the ASE system on the enforcement route and CR I. The main finding was that with regards to the minibus taxi industry, an improvement in speed compliance can be achieved with ISA systems rather than through ASE. With the known proportionality between speed compliance and crash risk [26, 27], this also implies that road safety can be improved with ISA systems than through ASE systems for the minibus taxi industry, and possibly for other road users as well. As explained in the previous chapter, investigation into the low compliance associated with Average Speed Enforcement showed that most minibus taxi drivers did not understand how the system operated and what was expected of them within the enforcement zone. On the other hand, the ISA system was well understood by drivers as an intervention that is triggered in response to exceeding a certain speed.

Mean speeds, percentiles, speeding frequencies, and speeding distributions measured on both the enforcement and control routes were similar while ASE was active on the enforcement route. Not only were they similar, but were characterised by high speed violation frequencies. Violation frequencies (average speeds above ISA threshold) of 81.2% and 90.6% were measured on the enforcement and control routes respectively. This also shows that despite the high violation frequencies, vehicles were more compliant on the enforcement route than on the control route as would be expected. On the other hand, while the ISA system was active, average speed violation frequencies decreased, and were shown to comply closely with the ISA threshold speed of 110 km/h. Violation frequencies of 47.4% and 52.6% were measured on the enforcement and control routes respectively. This is 33.8 percentage points less than violation frequencies with ASE on the enforcement route, and 38 percentage points less than violation frequencies on the control route. Over 90% of trips violated the 100 km/h legal speed limit for both ASE and ISA interventions. The improvement in speed compliance results observed with the ISA system set at a 110 km/h threshold suggests that ISA systems set at the legal speed limit of 100 km/h could equally be influential in improving speed compliance and safety. The foreseen improvement with a 100 km/h ISA threshold is expected to be slightly less than that observed in this study since – as noticed in variable speed ISA studies – drivers tend to be less compliant when ISA thresholds are reduced especially for informative and warning HMIs [108, 67].

5.3 The fuel consumption incentive

According to the COPERT model, the optimal speed of diesel light duty vehicles lies between 60 - 70 km/h. This corresponds to a fuel consumption rate around 7.0 - 7.2 L/100km. However, minibus taxi drivers rarely drive within the optimal speed range on long-distance trips. Moving to the speed limit of 100 km/h, the corresponding fuel consumption rate is 10.3 L/100km, compared with 12.2 L/100km at a speed of 110 km/h which the drivers usually exceed as was observed in the results. These observations imply that drivers can save significantly on fuel cost should they adhere to the speed limit. On the contrary, from the multiple trips completed by minibus taxis with high speeds, it is evident that this incentive is ignored and not taken advantage of, or drivers are just oblivious to it. Fuel savings is therefore a good incentive to present when addressing speed compliance in the minibus taxi industry.

Furthermore, the introduction of the loud ISA system not only improved speed compliance, but also reduced fuel consumption. Unlike ASE, the benefit of auditory ISA to minibus taxis is twofold; safety and fuel economy. With ISA, fuel consumption rates as low as 9.9 L/100km were observed with an average consumption rate of 11.5 L/100km. With ASE, low fuel consumption rates were around 11.4 L/100km with an average consumption rate of 11.7 L/100km. Compared with the 12.9 L/100km standard consumption rate at 110 km/h, both systems show improvements in fuel consumption, with ISA being more effective. Moreover, drivers can increase their remuneration by over 100% from the fixed fuel budget for long-distance trips if they adhere to the speed limit. This also confirms the need for awareness campaigns and education of drivers in this vibrant industry on the importance of speed compliance to the economic viability of the industry.

The COPERT model tends to suppress the real effect of driving speeds above 110 km/h on fuel consumption. Its extrapolated quadratic function was used to gain insight to the anticipated fuel consumption levels at higher speeds. It was realised that the 120% increase in remuneration from the COPERT model is significantly less than the 214% increase projected from the quadratic estimation function. This is indicative of the fact that the 120% increase is probably the minimum increase in remuneration that could be expected for speed compliant driving on long-distance trips in the minibus taxi industry. Savings on fuel cost are therefore a potential incentive that could encourage speed compliant driving among minibus taxi drivers.

5.4 Summary

The Western Cape government in South Africa reported significant improvements in speed compliance as a result of the ASE system on the R61. However, from this study, it is likely that minibus taxis which frequent this route do not contribute significantly to the observed improvements in compliance. As such, the evaluation of ITS interventions should not only be generalised, but should also isolate the different modes of transport to observe more unique underlying trends. In addition, the implementation of ITS interventions needs to consider regional factors such as driver access to information. From the surveys and speed distribution profiles, it is clear that drivers are not well informed and knowledgeable enough on the operation of infrastructure-related ITS interventions such as ASE.

Furthermore, as the minibus taxis have shown, ASE should not exist as the sole ITS intervention. Other interventions like ISA have proven to be suitable complementary measures. Even the spatio-temporal activation of auditory ISA systems along ASE enforcement routes could improve speed compliance and safety. Moreover, implementing ISA technologies come with other advantages such as lower fuel consumption rates, and the availability of fleet information due to the ubiquitous nature of GPS data.

Chapter 6

Conclusion

The minibus taxi industry has been noted for low compliance levels and aggressive driving, and has been shown to disregard posted speed limits on long-distance trips, leading to high crash rates. This study set out to understand how the industry conducts long distance trips, and to evaluate the impact of existing ITS interventions such as Average Speed Enforcement (ASE) on them, compared with passenger vehicles used for private transportation. Among other existing ITS interventions, the ASE system was chosen because it is relatively new, is growing in popularity, and has already demonstrated some degree of success in South Africa. Given the spatial limitation of ASE systems, the study also sought to test auditory Intelligent Speed Adaptation (ISA) systems on minibus taxis as a potential complementary ITS intervention. Finally, the impact of each intervention on fuel consumption was investigated, together with the possibility of it becoming a self-regulatory incentive for safe driving. The general theoretical literature on ITS safety measures for informal public transport is inconclusive on several vital questions which this study sought to answer such as:

- Does the presence of ASE systems influence drivers to comply with speed limits?
- Could auditory ISA systems be a solution to low speed compliance in the impervious minibus taxi industry?
- Are there financial gains to be had from lower fuel consumption if drivers comply with speed limits?

6.1 Empirical findings

This section provides a synthesis of the empirical findings in Chapter 4, with respect to the Average Speed Enforcement, Intelligent Speed Adaptation and fuel consumption, making reference to the dissertation hypotheses stated in Chapter 1.

6.1.1 The effectiveness of ASE in improving speed compliance

Passenger vehicles seemed generally compliant and adjusted positively to the ASE intervention, with average speeds along the enforcement route reducing from 110 km/h before enforcement to 105 km/h during enforcement. In addition, the two control routes closest to the enforcement route showed reduction in mean speeds, while average speeds on the control route farthest from the enforcement route increased. The 85th percentile speeds reduced on all evaluation routes with the best improvements observed along the enforcement route (5 km/h reduction) and the nearest control route (13 km/h reduction). On the other hand, minibus taxis do not seem to be affected by the ASE system. Although pre-implementation data was not available, the post-implementation analysis showed that mean speeds of at least 110 km/h were computed for all evaluation routes, which is 10 km/h higher than their legal speed limit. In addition, percentile profiles on all three evaluation routes were almost indistinguishable, leading to the conclusion that the ASE system on the enforcement route was not as effective in ensuring speed compliance. From our sample of taxis, it was also observed that over six months, 70 to 91% of all trips completed by each taxi exceeded their 100 km/h speed limit along the enforcement route.

It could be argued that despite the 100 km/h speed limit, a 10 km/h tolerance has been set in the ASE system, which means that minibus taxis with a computed average speed of 110 km/h along the enforcement route will be deemed compliant. However, from the results, 31 to 68% of all trips completed by each taxi drove at an average speed above 110 km/h along the enforcement route. From the generally compliant nature of passenger vehicles coupled with low compliance from minibus taxis, it can be concluded that the ASE system is not entirely effective in improving overall speed compliance. Despite their differentiated speed limits, minibus taxis had speed profiles even higher than those of passenger vehicles along the enforcement route and adjacent control route. These observations support Hypothesis 1.1 which states:

Hypothesis 1.1: The behaviour of different modes of transport towards ASE is different and should not be generalised.

Interestingly, from the compliant passenger vehicles, it is probable that the ASE system on the enforcement route influenced driver behaviour on the adjacent control route to some extent. Besides road maintenance – which only lasted a while – there is no better explanation for improvements on the adjacent control route during enforcement, than that the ASE system, which happens to be the main intervention in the region. The influence of the ASE system on the adjacent control route is further indicated by the fact that low speed compliance was observed on a farther control route.

A survey conducted by interviewing twenty regular long-distance minibus taxi drivers revealed that 90% of the drivers neither knew about the deployment of ASE systems nor how they functioned. This was also confirmed by the discrepancy in speed distribution results observed between the enforcement route and a 300 metre radius from the ASE camera location. As a result Hypothesis 1.2 also holds, which states:

Hypothesis 1.2: Low compliance with ASE in the informal public transport sector is linked to lack of understanding of ASE system operation.

Most minibus taxi drivers treat the cameras at the entry and exit point of ASE routes as Instantaneous Speed Enforcement (ISE) cameras. This in itself shows that visibility of the ASE system is not among the main reasons for low compliance, given the sudden adjustment in driver behaviour at camera locations.

6.1.2 The effectiveness of ISA in improving speed compliance

With both soft and loud auditory ISA systems, there were fewer trips with high speeding frequencies compared with the pre and post-ISA activation periods. While almost half the trips before ISA activation had speeding frequencies greater than 90%, less than a quarter of the trips with soft and loud ISA systems spent over 90% of the time driving above 110 km/h. Average time-based speeding frequencies of 70% and 60% were measured for the soft and loud buzzing systems respectively. This shows significant improvement compared with an average time-based speeding frequency of 81% before ISA activation.

During ISA activation, mean speeds on the Beaufort West to Aberdeen route also reduced compared with the pre-ISA activation period. Almost 40% of trips had average speeds above 120 km/h before ISA activation: for the same speed interval, 30% of trips were observed at over 120 km/h with the soft warning system, while no trips were observed at over 120 km/h with the loud system. Furthermore, introducing the ISA system increased the proportion of trips that drove below or at the ISA fixed threshold of 110 km/h: 22% of trips with the soft warning system, and 40% with the loud warning system, in contrast to 15% prior to ISA activation. It can therefore be concluded that auditory ISA systems set at audible intensity levels can improve speed compliance. In addition, the two intensities tested in this study showed that their impact on speed compliance varied, with the loudest system yielding the best compliance results. This supports Hypothesis 2.1 which states:

Hypothesis 2.1: Soft and loud auditory ISA warning systems can improve speed compliance at different degrees of impact, with loud systems being more effective.

Furthermore, with regards to speed compliance for minibus taxis on the ASE and adjacent control routes, auditory ISA systems have proven to be more effective than the ASOD system. Before ISA activation, the proportion of trips with average speeds above 110 km/h were 81.2% and 90.6% on the control and enforcement routes respectively. Despite the relatively low compliance rates in both cases, this shows that taxis were more compliant on the enforcement route than on the control route. However, when the loud ISA system was introduced, mean speeds are shown to comply closely with the fixed ISA threshold speed. In addition, the proportion of trips with average speeds above 110 km/h were 47.4% and 52.6% on the enforcement and control routes respectively, showing a significant reduction compared with no ISA system. The ISA system is therefore a good complementary intervention on ASE routes, ensuring speed compliance for non-compliant or partially compliant modes of transport such as the minibus taxi industry. This confirms Hypothesis 2.2 which states:

Hypothesis 2.2: Auditory ISA systems activated at fixed speeds can have significant effects on speed compliance in the informal public transport sector.

6.1.3 Fuel consumption and safe driving

The introduction of the ISA system not only improved speed compliance, but also reduced fuel consumption compared to the ASE system alone. Hence for minibus taxis, the ISA system does not just provide safety as an incentive, but fuel economy as well. Moreover, drivers can increase their remuneration by at least 120% from the fixed fuel budget if they adhere to the speed limit. This agrees with Hypothesis 3.1 which states:

Hypothesis 3.1: For drivers in the informal public transport sector, there is a significant financial advantage from speed compliance.

Should drivers know about the magnitude of these fuel savings from speed compliant driving, it could act as a self-regulating incentive for safe driving. This brings us to driver assistance systems such as auditory ISA systems, which can help in this regards. The lowest fuel consumption rates were measured while the ISA system was active. Compared with the 12.9 L/100km standard consumption rate at 110 km/h, the ASE system also brought about some improvement, but not as much as the ISA system.

6.2 Theoretical and policy implications

Most of the outcomes of this study support findings from other studies, especially for auditory ISA systems. The ASE outcomes support existing theory, except for minibus taxis, which rarely comply, and as a result do not contribute to the generally acclaimed success of the ASE system. One particular oddity with ASE was in the realisation that for passenger vehicles, compliance on the adjacent control route seemed better than on the enforcement route; an observation which can be partially attributed to regular maintenance on the control route. However, this is entirely based on expectation, since existing theoretical evidence does not refer to the effect of ASE systems on control routes. With regards to auditory ISA systems, aspects of its effectiveness in speed compliant driving relate well with existing theories, such as low speed variation and mean speeds close to the ISA speed. However, similar to many studies, the acceptance of auditory ISA systems is still prominent, though not as severe as that associated with active ISA systems such as AAPs.

Policies regarding Average Speed Enforcement may need to be heightened to improve speed compliance especially for minibus taxis. Best practice strategies in speed enforcement need to be put in place to harness the benefits of ASE across the different modes of transport. In addition, investments in ITS safety measures will have to consider vehicle-based interventions such as ISA especially for public transport vehicles, to ensure road and environmental safety on a wider scale.

6.3 Limitations of the study and recommendations for future research

This section discusses the limitations of the study. It also highlights recommendations for future research directly observed from the study, and recommendations stemming from its identified limitations.

The main limitations encountered in this study were:

- Limited passenger vehicle data.
- Small sample size of minibus taxis.
- Accurate, but sparse GPS data from taxis.
- The investigation was carried out over a relatively short term.

Only TomTom data was used to investigate ASE compliance patterns for passenger vehicles, since attempts to obtain other data sources failed. Although accurate, the number of samples obtained for some routes were particularly small. On the other hand, this study primarily involved ten minibus taxis, and data from the taxis was collected over 18 months. As such, there is a need to consider large-scale projects that run for longer periods in the future. Evaluation and testing of the ASE and ISA interventions at such magnitudes will undoubtedly give more credibility to the outcomes. Such large-scale implementation will definitely not be limited to passenger vehicles and minibus taxis only, but may include other modes of transport. In the light of large-scale evaluation on a long-term basis, a number of aspects have to be taken into account, such as the challenges that come with the management of large datasets, and the effects of ISA penetration on traffic, other road users and the environment. The penetration of GPS and ISA devices can result in little need for camera-based ASE systems since speed data can easily be retrieved from each vehicle over any enforcement route of interest. Moreover, such implementations come with many other advantages due to the ubiquitous nature of GPS data, and opens doors for more advanced implementation solutions.

The GPS device was programmed to receive data at a rate of 1Hz (i.e., per second). However, systematic and random errors demanded data filtering, which resulted in sparsity and irregularity of the received records. As such, detailed metrics such as acceleration, and the use of more accurate fuel consumption models were not realised. Taking these data constraints into account, the COPERT model was used in this study since it only requires vehicle specifications and speed as the dynamic parameter. However, it comes with the limitation of under-representing higher speeds, which was addressed through extrapolation. While there is need for more detailed geographic data to get accurate fuel consumption estimates from GPS data, it will be preferable to use in-vehicle fuel consumption reporting systems such as On-Board Diagnostic (OBD) devices synchronised with the GPS device. This highlights the need for more accurate GPS datasets for future investigations, and the implementation of more accurate fuel consumption models for minibus taxis. With further regard to vehicular technologies, another aspect not considered in this study that could improve comparison results is the implementation of driver identification, which assigns trips to a specific driver within the GPS dataset. This is important because a single taxi can have at least two drivers, and behavioural studies often need to know the response of an individual to a given intervention.

Future work will require a comprehensive examination of driver perception, experience and acceptability, conducted for each intervention considered. Safety aspects of ISA systems such as driver underloading (loss of awareness due to the presence of automated systems), overloading/distraction, and the interaction of drivers with other road users need to be taken into account.

Variable speed ISA systems are another option to explore with minibus taxis especially when analysing both urban and long-distance trips. In this study, fixed speed ISA systems were appropriate since the focus was on long-distance trips.

The investigation into fuel consumption as an incentive also needs more attention. In this study, driver knowledge on the relationship between speed and fuel consumption was not investigated. The study only examined the impact of interventions on fuel consumption, and the possible financial savings that could come from safe driving for minibus taxi drivers. As a result, the correlation between their knowledge of fuel economy and safe driving needs to be established. This also highlights the importance of driver education and awareness endeavours on road safety and ITS technologies.

6.4 Concluding remarks

To ensure high compliance with speed limits, it has been found that ASE systems cannot exist as the sole intervention. The results in this study also confirm this. The Western Cape government in South Africa reported significant improvements in speed compliance as a result of this ASE system on the R61. However, from this study, it is likely that minibus taxis which frequent this route do not contribute significantly to this observed improvements in compliance. This therefore suggests ISA technologies could be a complementary intervention to existing ASE interventions. Further, there is clearly a need for driver education on how the ASE systems operate, especially for minibus taxi drivers. However, the hurdles of user acceptance of ISA systems need to be overcome. Issues with ISA acceptance could be mitigated by educating drivers on the benefits associated with ISA systems, and ITS interventions in general. Further research also needs to be done to narrow down system requirements which may hinder acceptance. Nevertheless, the prospects of simplified auditory ISA technologies in the informal public transport sector are high, considering the advantages observed in this small-scale study, and it can be concluded that the apparent intransigence of the minibus taxi industry is partially due to a lack of understanding. Lack of compliance with ASE can be overcome – at least temporarily – through ISA.

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Appendices

Appendix A

TomTom versus Traffic Counts data

The Tables below (A.1 - A.4) compare mean speed and 85th percentile speeds of TomTom data and traffic counts data for verifying the consistence of TomTom data. The Tables show TomTom data for the enforcement and control routes before and during Average Speed Enforcement on the enforcement route. The traffic counts show annual data for light duty vehicles on the enforcement and control routes.

Table A.1: Enforcement Route (**Code:** 5055)

	Dates	N	Mean speed (km/h)	V_{85} (km/h)
TomTom (before)	Jun 2009 – Jun 2011	306	110.7	129
TomTom (during)	Dec 2011 – Dec 2013	1389	105.2	124
CTO 2011	Jul 2011 – Dec 2011	111904	110.9	128
CTO 2012	Jan 2012 – Oct 2012	175408	108.7	124

N = Samples (for TomTom), Number of vehicles (for CTO), V_{85} = 85th percentile speed
Note: CTO on the Enforcement Route was discontinued on the 20th of October 2012.

Table A.2: Control Route I: Border to Aberdeen (**Code:** 5016)

	Dates	N	Mean speed (km/h)	V_{85} (km/h)
TomTom (before)	Jun 2009 – Jun 2011	101	109	136
TomTom (during)	Dec 2011 – Dec 2013	528	102	123
CTO 2009	Whole year	203492	118.1	134
CTO 2010	Whole year	227384	118.0	134
CTO 2011	Whole year	236635	116.1	132
CTO 2012	Whole year	244917	112.8	128
CTO 2013	Whole year	251400	112.9	128

N = Samples (for Tomtom), Number of vehicles (for CTO), V_{85} = 85th percentile speed

Table A.3: Control Route II: Aberdeen to Graaff Reinet (**Code:** 889)

	Dates	N	Mean speed (km/h)	V_{85} (km/h)
TomTom (before)	Jun 2009 – Jun 2011	2000	121	138
TomTom (during)	Dec 2011 – Dec 2013	3500	117	134
CTO 2009	Whole year	505581	116.2	136
CTO 2010	Whole year	531882	121.5	148
CTO 2011	Whole year	511243	117.6	138
CTO 2012	Whole year	525976	113.7	130
CTO 2013	Whole year	544300	113.6	130

N = Samples (for Tomtom), Number of vehicles (for CTO), V_{85} = 85th percentile speed

Table A.4: Control Route III: Hanover to Colesburg (**Code:** 064)

	Dates	N	Mean speed (km/h)	V_{85} (km/h)
TomTom (before)	Jun 2009 – Jun 2011	94	111	137
TomTom (during)	Dec 2011 – Dec 2013	200	115	134
CTO 2009	Whole year	453135	112.5	128
CTO 2010	Whole year	470758	115.2	130
CTO 2011	Whole year	440527	112.9	128
CTO 2012	Whole year	435258	109	124
CTO 2013	Whole year	457551	109.8	122

N = Samples (for Tomtom), Number of vehicles (for CTO), V_{85} = 85th percentile speed

Appendix B

Detailed software design

This part of the appendix gives detailed information on the implementation behind the analysis software used for minibus taxis. In section 3.7, an overview of the software setup was presented, describing how the GPS data was downloaded from the MixTelematics data server through a web server interface implemented on the Visual Studio Express platform in C#.

Trips were the fundamental unit for analysis in this research, and their generation from the raw GPS records was of particular importance. Figure B.1 shows a basic flow diagram of the trip generation process, used to compute and analyse the different metrics of interest. It begins with the user specifying which taxis need to be investigated, over a desired period of time depending on data availability, and the selection of a route section by specifying its departure/destination coordinates. After the initialisation stage comes the choice of generating forward and/or return bound trips, each with its unique call to allow for flexibility.

The ‘forward’ algorithm generates trips from the identified departure to destination coordinates. The tolerance radius (set in kilometres) defines a region around the specified terminal coordinates from which the closest trip record is chosen. The algorithm begins by reading the static pre-downloaded GPS records of all selected taxis. When record closest to the departure coordinate is found, subsequent records are saved until a record closest to the end coordinate is found. At this stage, the list of saved records constitute a trip on which a lot of processing is done (discussed in the next section). After processing the data, the necessary updates and resets are made to initiate the capture of another trip. The process ends when all taxi data has been read or beyond the specified time frame. The ‘return’ algorithm is similar to the ‘forward’ algorithm just described except for the swap between departure and destination coordinates.

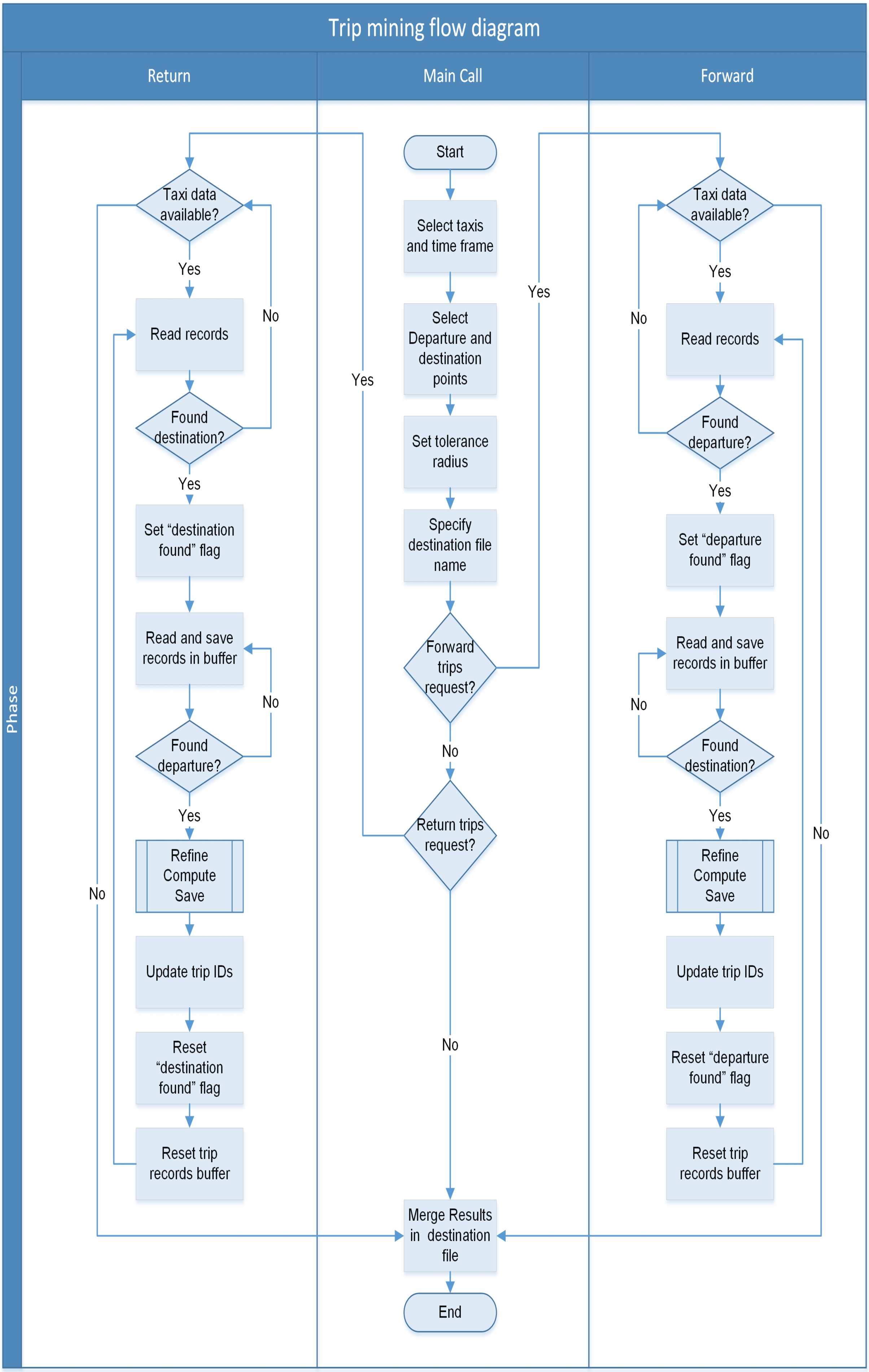


Figure B.1: Trip mining/generation flow diagram

B.1 Refine, Compute and Save

This section describes modules in the *Refine-Compute-Save* sub-process executed in the forward and return calls of the flow diagram in Figure B.1.

Many routes could exist between two points. The *Refine* process functions like a filter ensuring that only the desired trips are chosen. Three solutions, which can be applied individually or in combination were considered in this regard, namely;

- Polygon enclosure of the desired route.
- Choose route with the shortest path.
- Average number of records per trip.

In this study, polygons enclosing the evaluation routes were used to specify the trips of interest. It also served as a means to identify and exclude outliers in the final list of records defining a trip. For longer routes such as the Worcester to Queens Town query, trips that took the shortest path with a number of records per trip within 10% of the average were chosen. This also depends on the assumption that minibus taxi drivers tend to take the shortest path more often.

The *Compute* process extracts required metrics from valid trips identified by the *Refine* process. Metrics related to travel time, speeding frequency, and fuel consumption are calculated here. One of the computations done is the identification of stops using the DJ-Clustering algorithm presented in the next section.

The *Save* process simply organises the trip variables and computed metrics into an ordered dataset for further analysis.

B.1.1 DJ-Clustering algorithm

The pseudo code of the DJ-Clustering algorithm used for identifying stops and clusters is show below. It takes as arguments a list of identified trip end coordinates *(S)*, the maximum neighbourhood radius *(Eps)*, and the minimum number of points required in a neighbourhood *(MinPts)*.

```
while there are one or more unprocessed trip ends t in sample S do:
  Find density-based neighbourhood N(t) of trip end t with respect to Eps and MinPts
   if the neighbourhood N(t) has no neighbour then
     Label t as a stop.
   else if N(t) shares a trip end with an existing cluster then
     Merge N(t) and its 'density-joinable' clusters.
   else
     Create a new cluster with N(t).
   end if
end while
```

Appendix C

Online dashboard and ISA hardware

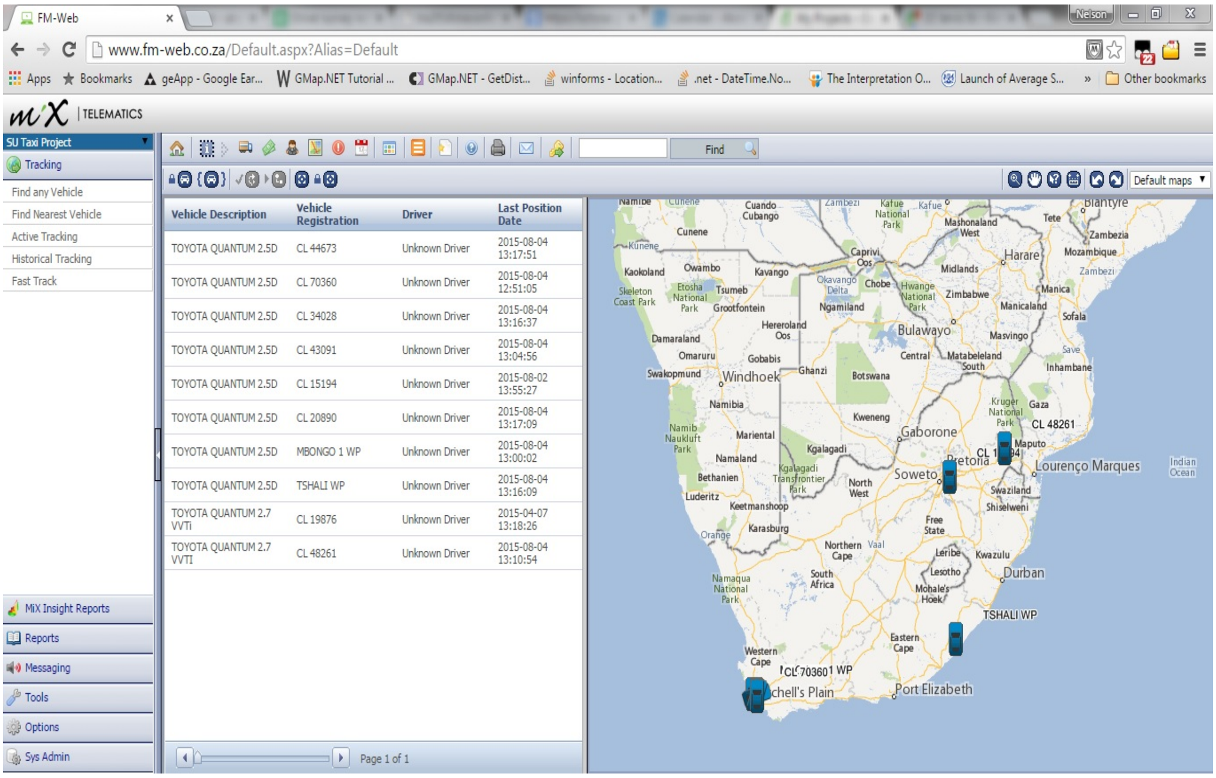
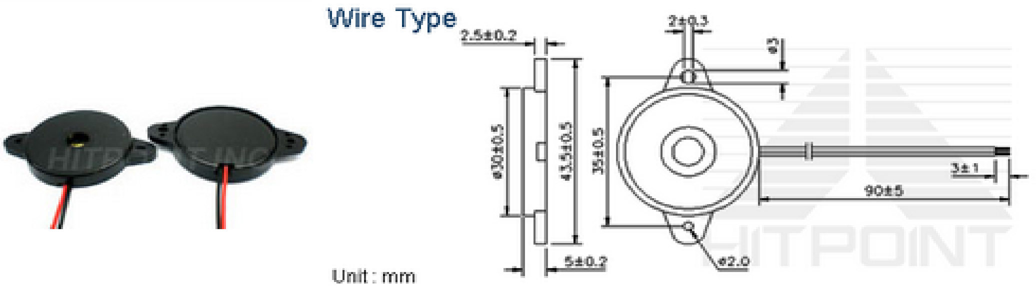


Figure C.1: MiX Telematics online tracking dashboard

Figure C.1 shows MiX Telematic's online tracking dashboard for the ten minibus taxis. It provides vehicle location in real time, and can be used to generate reports on driving behaviour.

DIMENSIONS AND MATERIAL

RoHS



ELECTRICAL CHARACTERISTICS

Oscillation Frequency	4.5 ± 0.5	KHz
Operating Voltage	30	Vp-p
Rated Voltage	5.0	Vp-p
Current Consumption	1.5 at Rated Voltage	mA
Sound Pressure Level	90 at 10 cm	dB
Capacitance	20000 ± 30% at 120 Hz	pF
Operating Temperature	-20 ~ +90	℃
Storage Temperature	-30 ~ +100	℃

VOLTAGE/ CURRENT / SOUND PRESSURE

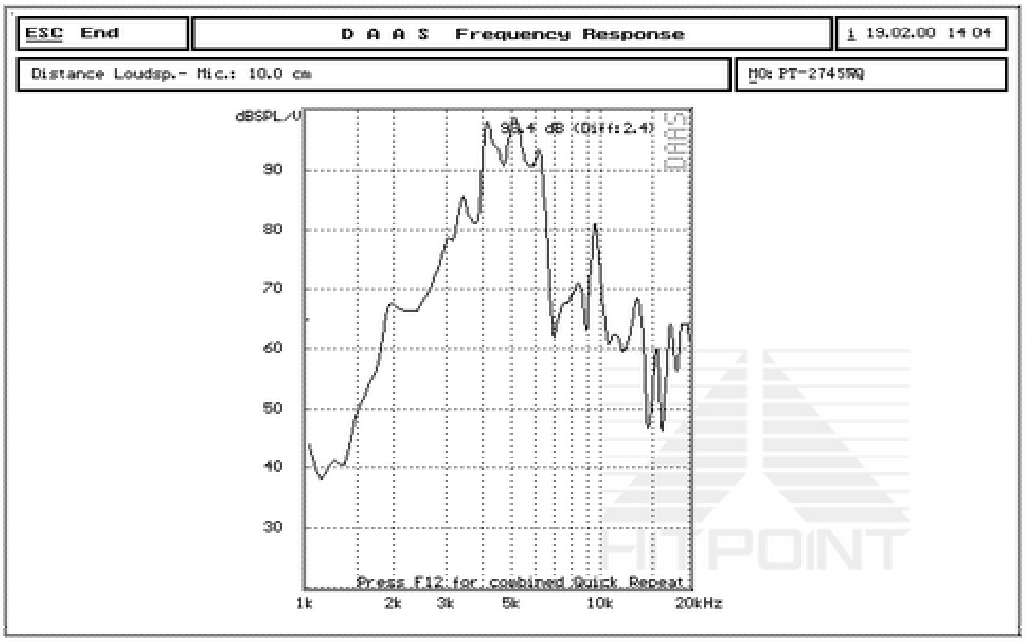


Figure C.2: Specifications of the device used for auditory ISA