

Traffic control centre optimisation through applied intelligent weigh-in- motion

A de Coning

 **orcid.org/0000-0001-7960-3119**

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Promoter: Prof A Hoffman

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Student number: 20270186

Declaration

I, Arno de Coning, hereby declare that the thesis entitled "*Traffic control centre optimisation through applied intelligent weigh-in-motion*" is my own original work and has not already been submitted to any other university or institution for examination. The work forms part of the patent (WO 2015/052662 A1) filed by the North-West University.

Arno de Coning

Student number: 20270186

Abstract

Title: *Traffic control centre optimisation through applied intelligent weigh-in-motion*

Transport logistics are of utmost importance in all countries because they ensure that goods are efficiently delivered to businesses and thus assist in trade facilitation. A country such as South Africa, where the primary economic hub is landlocked, requires road freight transport of these goods in the forms of trucks. Freight transport by road is regulated to ensure safe transport and to protect the road infrastructure because it is one of the largest resources a country requires for GDP growth (it is a South African asset valued at South African rand (ZAR) 1 trillion).

Mass regulations specify maximum permissible axle loads, total gross vehicle mass and a minimum drive axle mass. Vehicle compliance is tested by means of Overload Control Centre (OCC)s, primarily known as Traffic Control Centre (TCC)s, strategically situated on the freight corridors. A typical setup has a weigh-in-motion (WIM) scale that directs a vehicle to a static scale if its mass falls within a threshold. The static scale determines whether the vehicle is overloaded and, if so, the vehicle owner is prosecuted. Non-overloaded vehicles are allowed to return to the corridor and proceed on their journey.

There are currently inefficiencies in this system because each TCC operates in isolation, not sharing information with the previous or next TCC. As a result, the same vehicle can be weighed multiple times on a journey, even if it is loaded legally. Current annual reports indicate that 75,95% to 78,05% of vehicles that are statically weighed are not overloaded. Being weighed increases delays and costs in their logistic supply chains.

The proposal was to design a system that would remove the isolation of data between TCCs and implement an artificial intelligence model to predict whether a vehicle is overloaded and should be statically weighed or not. Successful implementation will result in much fewer statically weighed vehicles per annum, and decrease supply chain

turnaround times.

A case study was conducted in the South African TCCs at Mantsole and Heidelberg. Layout and operational flows were investigated to ensure full insight into current operations. Interventions in the current system are proposed to ensure data sharing between stations. These interventions include collecting data from the current systems to use as inputs to the proposed artificial intelligence (AI)-based algorithm.

Implementation of data sharing between stations will ensure that an intelligent decision can be made about whether a vehicle should be statically weighed while travelling along the freight corridor. In this discussion, the first TCC where the vehicle is statically weighed is called Station 1, while the second station, where an improved decision must be made, is called Station 2. The decision will be made using normalised to legal threshold mass from the WIM, actual vehicle combination mass (AVCM), and static scale measurements at Station 1. Algorithm values are normalised to legal thresholds to ensure the models will remain relevant if legislation changes or when applied in another country with different legislation. The next station uses a normalised travel time taken from benchmarked travel times combined with the WIM mass.

As all the variables available to make the decision (overloaded or not) are noisy, a simple rule-based decision would make many mistakes. Since AI techniques have been found to improve the quality of decision-making when more than one noisy variable is available, we applied AI techniques to improve the quality of decisions resulting from a simple rule-based approach. Data was collected between Mantsole and Heidelberg TCC, accurately linked, and used as training data sets.

The use of a random forest AI model reduced the percentage of non-overloaded vehicles that were statically weighed in the worst case from 76,64% (average) to 0,03% while sending 0% of overloaded vehicles incorrectly to the corridor. This model had slightly better performance when compared with the artificial neural network (ANN) implementation. Implementation of the model will therefore drastically reduce the number of legally loaded vehicles that are weighed statically.

The financial benefits of implementation would be considerable for several stakeholders. There would also be operational benefits for cargo owners, transporters, road users, clients, road agencies, cross border operations, TCCs, toll concessionaires, heavy vehicle operators and the National Treasury of South Africa. The potential benefits are compared to the operational costs of the proposed system for funding by the Treasury.

The novel contributions of this work are, firstly, the operational and system design for data sharing between TCCs in South Africa. Secondly, the development of a data simulator and AI techniques for training with historic data to reduce the number of statically weighed vehicles without increasing the risk of vehicle overloading represent a major innovation in this field. Thirdly, an estimated economical cost-benefit model was developed to indicate the potential benefits to the sector if the concept is implemented.

Keywords: *Freight corridor, Freight logistics, Overload control, Weigh station, Traffic Control Centre, TCC, Overload Control Centre, OCC*

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List of Acronyms

AI	artificial intelligence
ANPR	automatic number plate recognition
ANN	artificial neural network
ALPR	automatic license plate recognition
AVCM	actual vehicle combination mass
BI	business intelligence
CCM	cold chain management
CPU	central processing unit
CSIR	Council for Scientific and Industrial Research
csv	comma-separated values
DC	distribution centre
DOT	Department of Transport
e-screening	electronic screening
ESAL	equivalent standard axle load
F/U	functional unit
FS	Free State
GDP	gross domestic product
GPS	global positioning system
GPU	graphics processing unit
GVM	gross vehicle mass
HSWIM	high-speed weigh-in-motion
IOT	internet of things

IR infrared
I/F interface
IWIM intelligent weigh-in-motion
kg kilogram
km kilometre
km/h kilometres per hour
kNN k-nearest neighbours
KZN KwaZulu-Natal
LEF load equivalence factor
LSWIM low-speed weigh-in-motion
LPR license plate recognition
MCP McCulloch-Pitts
MSU mass sensor unit
N national road
N3TC N3 Toll Concession
NB northbound
NHVAS National Heavy Vehicle Accreditation Scheme
NTBs non-tariff barriers
OCC Overload Control Centre
OCR optical character recognition
PBSs performance-based standards
PPP public-private partnership
lbs pounds
RFID radio frequency identification
RFT Random Forest Tree
RTMC Road Traffic Management Corporation
RTMS Road Transport Management System
ROI return on investment
RTCs road traffic crashes
RTIs road traffic injuries
SA South Africa

SATC Southern Africa Transport Conference
SADC Southern African Development Community
SANRAL South African National Roads Agency SOC Limited
SANS South African National Standard
SB southbound
SCM supply chain management
SEK Swedish krona
SLA service level agreement
SQ status quo
SVM support vector machine
TCC Traffic Control Centre
TRACs Trans African Concessions
URS user requirement statement
USA United States of America
USD United States dollar
VAT value added tax
VWIM Virtual Weigh-in-Motion
VWS Virtual Weigh Station
WIM weigh-in-motion
XML extended markup language
ZAR South African rand

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will never be forgotten.

Chapter 1

Introduction

There can be economy only where there is efficiency - Benjamin Disraeli

Start with the Why - Simon Sinek

The reason that the rich were so rich, Vimes reasoned, was because they managed to spend less money - Terry Pratchett

This chapter explains the background to the problem at hand, overviews the research conducted, and discusses the contribution of the thesis. The chapter concludes with a chapter overview.

1.1 Introduction

Economic growth minimises poverty levels, increases economic confidence and develops the sector, as well as developing human skills [1]. Economic growth in South Africa took a drastic downturn at the end of 2017 and in early 2018, downgrading South Africa's economy to "junk" status and increasing its value added tax (VAT) [2–4]. During an economic downturn, it is extremely important to ensure efficient spending and efficient implementation of the current processes and systems, since the resultant cost savings make more funds available for essential services to the population, such as additional medical facilities, educational centres and infrastructure.

International and regional trade are required to increase economic growth and effective logistics operations facilitate the required trade, both locally and globally [5–7]. These operations apply to rail [8, 9], maritime corridors [10], air transport [11], and road transport, which all form part of multi-model supply chains [12]. Efficient transportation of goods within the supply chains improves delivery speed, service quality, operational costs, and turnaround time [13].

South Africa is critically dependent on growing its exports to support its economic growth [14–16]. Many of the Southern African Development Community (SADC) region, however, are landlocked, which makes those countries dependent on road and rail transport to ensure the supply chain is fully operational [5, 17]. Unfortunately, the condition of the rail infrastructure has declined over the past few decades [18], and it will require considerable investment for the current infrastructure to become a viable large-scale transportation platform again [19, 20]. The focus must therefore be on road transport to deliver freight within the SADC region. Figure 1.1 indicates that in terms of tonne-km 79% of corridor freight transport is currently on the road, with only 21% travelling by rail [21].

Road transport is the dominant mode of land transport for export goods, including mining, agricultural, and manufactured goods. The quality of the national road network therefore has a tremendous impact on the effectiveness of the trade corridors that link

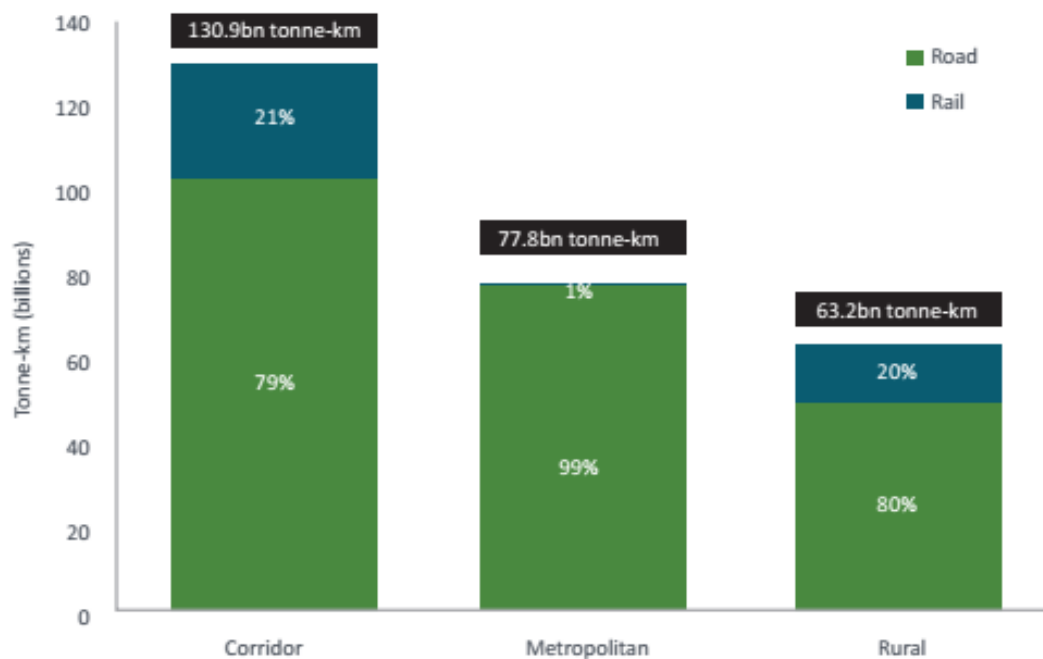


Figure 1.1: Topological division of general freight transport (South Africa 2014) [21]

areas of production with sea ports. Road infrastructure [5], border post operations [22], and regional law enforcement efficiency are of the utmost importance to the region's supply chains [23]. A ripple effect can be seen when inefficiencies, irregular operational patterns, non-tariff barriers (NTBs), and corruption creep into the supply chains.

An investigation was therefore necessary to determine the current state of freight logistics within the South African context for all the stakeholders involved.

1.2 Freight logistics in South Africa

Freight logistics in the South African context have to take the whole SADC region into account because there are extensive cross-border freight movements on multiple freight corridors. These corridors include routes over the whole of sub-Saharan Africa, as can be seen in Figure 1.2. The North-South Corridor is more than 10 500 kilometre (km),

with 18% of the corridor in South Africa [24].

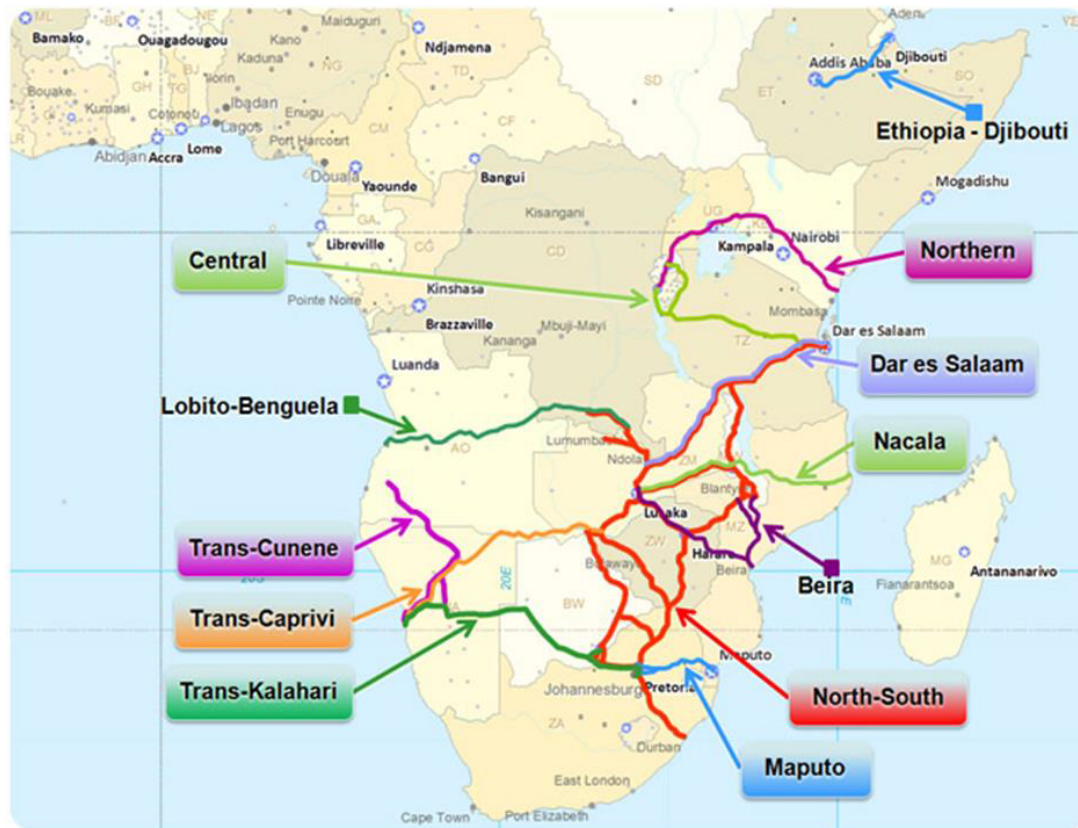


Figure 1.2: Freight corridors in sub-Saharan Africa [25]

Previous studies have emphasised the importance of an efficient north-south corridor for the region [24]. The importance of a high quality road network ensured that historic investment, annual maintenance, and upgrades have made the South African road infrastructure into an asset worth one trillion South African rand (ZAR) [26]. This infrastructure is a catalyst for commerce and economic growth in the SADC region. It is therefore essential to protect it.

Mechanisms have been set in place to protect the infrastructure: Government regulations stipulate the maximum loading capacity of axles, the minimum mass on the drive axle, and the load limits on a vehicle's tyres [27]. It has been estimated that the damage to the road network is ZAR600 million (1997 value) annually [27], and the CSIR stated at the time that ZAR2 155 million was spent per annum on road construction and maintenance [28]. Inflation over the years puts the annual damage at over ZAR1 500

million [29] and the CSIR estimates annual construction and maintenance costs at over ZAR5 500 million, without taking into account the increase in heavy vehicle traffic on the South African roads. This estimated cost is based on only repairing a road after damage has taken place, and does not consider the additional impact of poor road conditions on the general population, and on maintenance cost increases. The national Department of Transport (DOT) stated in [27, p. 99]: "It is therefore essential that effective law enforcement be carried out throughout South Africa in order to stop this economic sabotage and protect the country's most valuable asset – its road network".

One mechanism for infrastructure protection is a weighbridge at a Traffic Control Centre (TCC). These TCCs are typically constructed on freight transportation corridors where the heavy vehicles volumes are high [27, 30]. Some of these TCCs to screen vehicles by means of a weigh-in-motion (WIM) scale, which is usually installed in the road pavement or in a dedicated screening lane at the TCC. A WIM scale can quickly determine whether the vehicle likely to be within the permissible limits by weighing the vehicle while it is still in motion. The TCC has to have a static scale to more accurately determine the loads on the axles and the actual vehicle combination mass (AVCM) of the vehicle when it is stationary [30]. A vehicle is directed to the static scale to be weighed if the WIM reading is close to its permissible threshold. The static scale's measurement is the only one that can be legally used to prosecute the driver of a vehicle that is overloaded. A WIM scale may not be used for prosecution purposes because it has inherit inaccuracies due to the vehicle dynamics while in motion.

Multiple TCCs have been constructed across South Africa to protect the road infrastructure. They are in most cases implemented on toll roads and are run by the various toll concessionaires that service the national and regional roads. Their one mayor drawback is that each centre works in complete isolation from the centre up- or downstream on the same corridor [5,31]. The national road corridors are displayed in Figure 1.3.

Unfortunately, the logistics sector's profit margins are small and competition is ruthless, therefore some transporters overload their vehicles to gain additional income on a trip, without thinking of the consequences for the road infrastructure. Damage to the

road infrastructure has an extreme impact on other industries and the economy of a country. The economy can come to a complete halt if the transport industry is no longer functional.

Studies have shown that 60% of road damage can be caused by only 15–20% of vehicles' being overloaded [28], and vehicles overloaded by 20% can shorten the life of a road pavement by more than 50% [32]. Unfortunately, what currently happens is that the 80–85% of freight vehicles that are legally loaded are significantly delayed at multiple TCCs because their load is close to the legal limit.

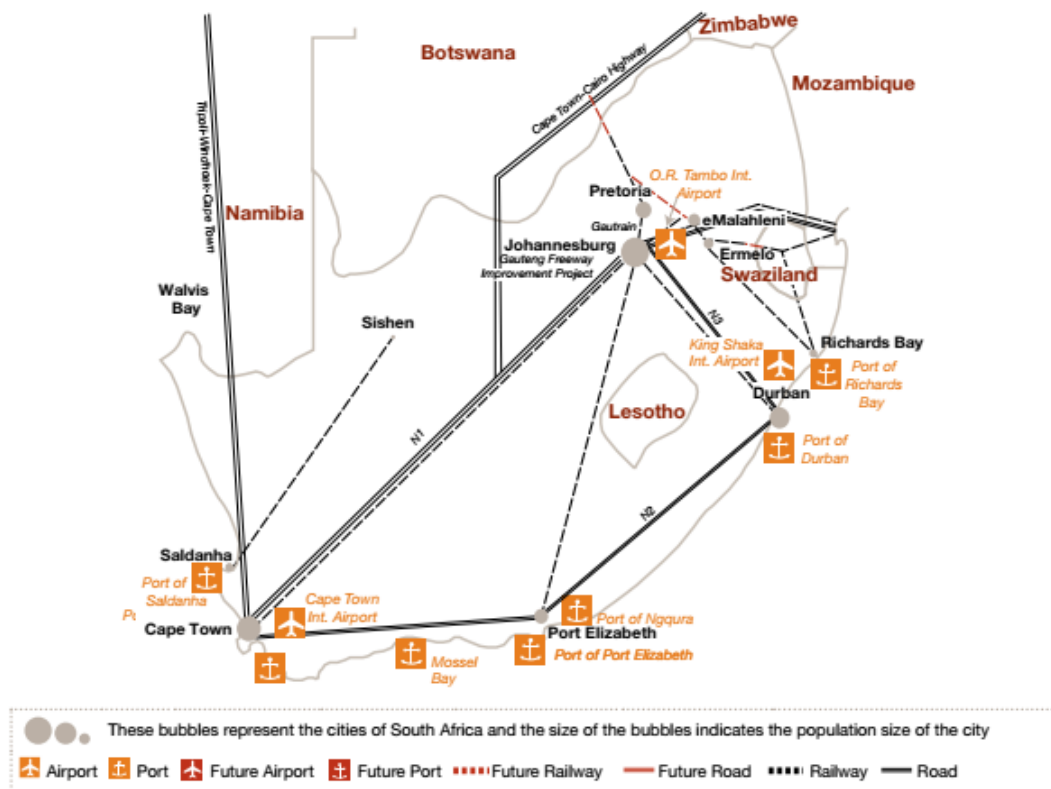


Figure 1.3: Primary corridors in South Africa [17]

1.3 Shortfalls and drawbacks of the current system

There are shortfalls in the current overload management system that negatively impact legally loaded freight vehicles in transit along the corridor. The shortfalls are listed below and will be considered in more depth in the literature review conducted in Chapter 2.

- TCCs are isolated from communication within the corridor context.
- Legally loaded vehicles that are close to the permissible maximum mass are delayed.
- Vehicles that are loaded close to the legal limit are statically weighed multiple times on the same journey.
- Overloaded vehicles have increased contact with potentially corrupt officials if they are weighed multiple times on the same journey.
- An overloaded vehicle can potentially skip a queue while other legally loaded vehicles are being weighed on the static scale.
- Some stations do not operate the entire day, allowing fly-by-night companies to overload during their hours of non-operation.
- At some TCCs, a specific quota of vehicles has to be weighed and processed as early in the morning as possible.

Inefficient operations not only impact freight vehicles and TCC operations, but have a ripple effect on the entire supply chain. The stakeholders are listed below, with some details of how they are impacted by inefficient operations:

- **Cargo owners:** Delayed activities mean slower delivery to the end client, which can delay the payment after the delivery of the goods. Some goods are perishable and delayed delivery may cause spoilage or total loss of the cargo.
- **Transport companies:** A transport company has a low profit margin and can transport more goods when turnaround times are shortened but an inefficient system causes increases in turnaround times.
- **Freight vehicles and drivers:** Inefficiencies cause multiple stop and start se-

quences in a trip that increase fuel consumption, tyre wear, and driver fatigue.

- **Road agencies:** Their sole purpose is to maintain the roads and, if overloaded vehicles damage the roads, the agencies have to increase the frequency of road maintenance.
- **Toll concessionaires:** Increased numbers of overloaded vehicles cause road pavement to deteriorate before their standard lifespan, which intensifies maintenance schedules and increases costs.
- **TCCs:** Inefficient operation can cause overloaded vehicles to slip through, nullifying the purpose of the TCC. There is unnecessary wear-and-tear on the scales because most of the vehicles weighed are weighed unnecessarily.
- **Cross border agencies, port authorities, and the country's revenue service:** Illegal activities and transportation of goods cause companies to be charged with fraud, and vehicles to be detained. If undeclared goods are not detected, the revenue from import taxes decreases. The mass of the declared goods will not match the mass of the goods delivered if goods are removed from the overloaded vehicle to correct the mass. This will result in charges of fraud that will ensure the vehicle is impounded.
- **The country's treasury:** The national Treasury department has to pay for road damages and so inefficiencies can, in turn, have a negative impact on the gross domestic product (GDP) of the country.
- **Cargo receivers:** Delayed delivery of goods can disrupt operations, which leads to potential overtime work by and payment to personnel who receive goods outside standard operational hours. Lost sales or production may be incurred by the cargo receiver.
- **Consumers:** Costs are ultimately passed on to the consumer, which, in extreme cases, causes a rise in consumer products by means of increased product costs.

1.4 Proposed improvements

The industry confirmed the importance of overload control for road infrastructure at the 35th annual Southern Africa Transport Conference (SATC) held in Pretoria, South Africa, in July 2016. This conference had multidisciplinary attendees and presenters and it became clear during the discussions and forums that more than one approach can be taken to address the issue of overload control. The suggestions varied from improving road pavement to finding additional finances for maintenance or improving law enforcement, from reducing bribery or self-enrichment to monitoring secondary roads.

These are all valid approaches to pursue but this study recommends improving the system, with minimal capital outlay for TCC redesign, while facilitating data-sharing between TCCs. This is complementary to the study's primary goal of data-sharing between TCCs to enable more intelligent joint decision-making.

Control theory has a fundamental principle of using feedback and feed forward loops to compare input with a desired output [33]. The adoption of big data and the implementation of artificial intelligence (AI) have increased the speed at which data can be processed while incorporating intelligent decision-making about the data processed [34–37]. This can be expanded for use in the context of the overload control corridor and adjusted to feed downstream information forward to improve the operational efficiency of the TCCs. The proposed improvements were achieved by following the steps:

1. Analyse the current status of the TCC system configuration to determine its efficiencies.
2. Focus on improving systems at the TCC, with minimal physical changes proposed.
3. Deploy a technology analysis.
4. Design a system for improved overload control by devising an intelligent weigh-in-motion (IWIM) algorithm.
5. Collect data from sites to use in an experimental system that represents real-world statistics.

6. Determine the data to be integrated to realise the IWIM algorithm.
7. Implement AI to facilitate the model development.
8. Verify and validate algorithm operation.
9. Analyse improvements for stakeholders.
10. Analyse economic benefits for stakeholders.

Successful implementation of these steps led to the development of a system to enable data-sharing between TCCs, as addressed in Chapter 3. The development of the IWIM algorithm to reduce the number of non-overloaded vehicles weighed at the TCCs is described in Chapter 4. Decreasing the number of legally loaded vehicles weighed will increase the effectiveness of TCCs in prosecuting the owners of overloaded vehicles, and will minimise the potential for overloaded vehicles to bypass the TCCs due to excessive queuing. Chapter 5 focuses on the financial benefits to the stakeholders due to the added efficiency of the system.

1.5 Problem statement

The system to control the passage of overloaded vehicles along South Africa's freight corridors is inefficient with around 78% of statically weighed vehicles not being overloaded. The operation of the overload control system can be improved by implementing an IWIM that makes use of data-sharing between TCCs on freight corridors. The improvement can be achieved by using an AI or artificial neural network (ANN) model to minimise the number of legally loaded vehicles being weighed statically, while also minimising the number of vehicles incorrectly directed away from the static scale.

1.6 Envisaged contributions of the study

The study makes three novel contributions.

1.6.1 Contribution 1

The first contribution lies in *applying an existing method to a new field or in a new way*. The study does this, firstly, by *implementing AI/ANN on multiple data sets from freight logistics operations to develop an IWIM (WO 2015/052662 A1 [30]) to improve freight corridor efficiency*; and, secondly, by *implementing the control theory principle of feeding data forward to improve the efficiency of TCC operations*.

1.6.2 Contribution 2

The second contribution lies in its *critical analyses of existing information in a new way*. The study does this by *developing a combined economic benefit model for the multiple stakeholders of freight corridors resulting from the IWIM implementation*. Quantifying the benefits for various stakeholders determines the improvement in operational efficiency of the TCCs.

1.6.3 Contribution 3

The third contribution lies in *combining existing methods/designs to achieve a new method*. The study does this by *proposing an alternate management method of controlling overloaded vehicles to improve operational efficiency at the TCCs in freight corridors*.

1.7 Chapter overview

This chapter discussed freight logistics in South Africa and the overload control measures implemented to protect the road infrastructure required by transporters. An overview of the current shortfalls and drawbacks was covered, as well as proposed improvements. The proposed improvements were discussed in terms of envisaged contributions.

The rest of the thesis is laid out as follows:

- **Chapter 2: Literature overview** covers an in-depth analysis of the existing body of knowledge in relation to the envisaged contributions.
- **Chapter 3: Status quo data analysis and proposed system** is used to explain the current deficiencies within the overload systems that were used as the baseline when proposing an improved system design. This chapter addresses Contribution 3, combining existing methods to achieve a new method.
- **Chapter 4: Intelligent Weigh-in-Motion algorithm design for integrated corridor optimisation** describes the IWIM model development by analysing the performance of multiple AI models on industry representation data sets. Improvements in the models are compared with the current rule-based system. Model validation and verification determine whether the algorithm is functional and the extent of the improvement it can provide to the stakeholders. This chapter addresses Contribution 1, applying an existing method in a new way.
- **Chapter 5: Economic benefit model development** specifies the financial gains for the stakeholders achieved by the new application described in Chapter 4. This chapter addresses Contribution 2.
- **Chapter 6: Conclusion** summarises the thesis, gives proof of contributions to the field, and recommends future work on the topic.

Chapter 2

Literature overview

An investment in knowledge pays the best interest - Benjamin Franklin

This chapter explains the nature of logistic operations, the importance of transport operations in supply chain management (SCM), and the use of overload controls in the South African context.

Chapter 1 gave a brief background for introductory purposes. This chapter reports the results of an in-depth literature review of the multiple aspects of logistics in SCM, transport operations and overload control in South Africa and abroad. It was necessary to understand the current process flow of overload control management and the technology required for intervention before an optimised system could be developed with the potential for implementation in logistic operations.

Logistics is the part of the supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet the customers' requirements [13].

2.1 Logistic operations

South African logistic operations declined after the recession experienced in 2008. The logistic cost in-country dropped from 14,7% of GDP in 2008 to 13,5% in 2009 [38]. The effects were still present in 2010, with a GDP share of 11,4%, and remained fairly stable between 11,0% and 11,8% from 2011 to 2016 [21,39], as can be seen in Figure 2.1.

The 2008 recession was also clearly indicated in the percentage drop in transportable GDP. Nevertheless, transportable GDP increased to 56,0% by 2016. This high percentage clearly indicates the importance of road transport and logistics to the country's economy. There has, however, also been a significant increase in the costs of logistics that will impact the bottom line because increased costs decrease profits.

Road infrastructure is a costly asset in a country, and it requires an effective system to manage, monitor, and plan road maintenance and rehabilitation. In South Africa, this is the responsibility of the parastatal, the South African National Roads Agency SOC Limited (SANRAL) [40–46].

The maintenance of the road infrastructure must be a recurrent annual budget item



Figure 2.1: Trends in South Africa's logistic costs [21]

to ensure road condition is kept to as high a standard as possible, as indicated in Figure 2.2. However, inefficient transport logistics inhibit trade operations, and road use by overloaded vehicles causes premature failure of road infrastructure [47]. Overloaded vehicles accelerate the onset of fatigue cracking, rutting, cracking, and corner-breaking on road pavements [48]. (Extensive studies have been conducted to quantify the damage caused by illegally loaded vehicles, and these studies are discussed in Section 2.2.4 below.)

Figure 2.3 indicates SANRAL's annual expenditure on road projects and maintenance on 22 214 km of national road networks that it is responsible for of the around 750 000 km roads in South Africa. Capital and maintenance spending was 74% on non-toll roads and 26% on toll roads in South Africa [46]. Table 2.1 compares SANRAL's reported statistics of vehicles weighed, overloaded vehicles, drivers charged and arrested, and fines issued between 2015 and 2019. The extremely low percentage, 18,86% to 25,54%, of fines paid compared to fines issued is a major operational concern.

Figure 2.4 gives an overview of the vehicles weighed and overloaded in the 2019 annual report from SANRAL.

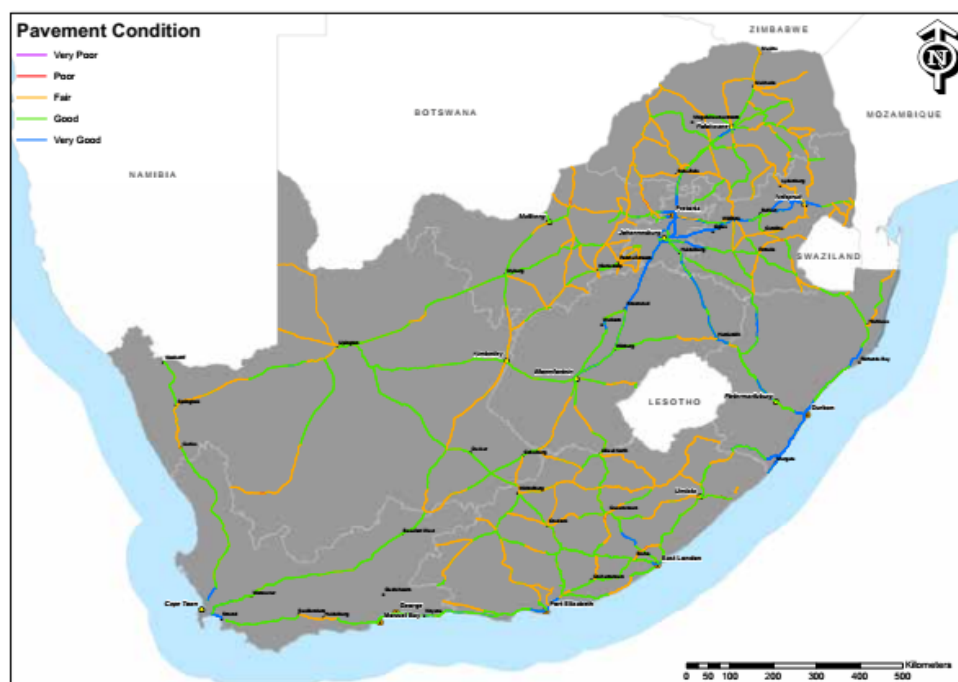


Figure 2.2: Pavement conditions on national roads 2018/19 [46]

Trend in spending on road projects and maintenance

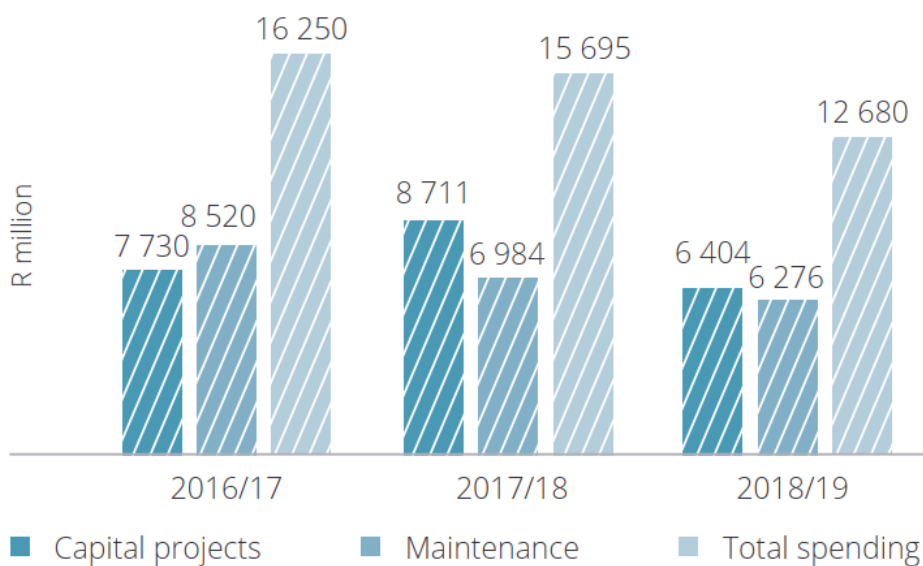


Figure 2.3: Trends in spending on road projects and maintenance by SANRAL, 2016/17 to 2018/19 [46]

Vehicles weighed at SANRAL weighbridges and number overloaded

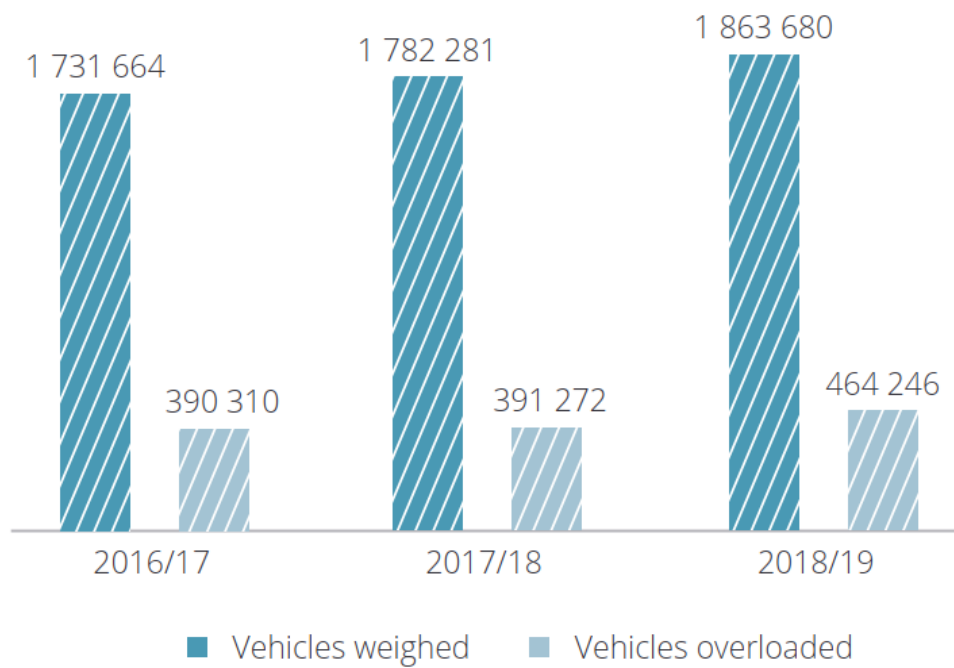


Figure 2.4: Total vehicles/overloaded vehicles weighed at SANRAL weighbridges, 2016/17 to 2018/19 [46]

Table 2.1: SANRAL overload statistics, 2015/16 to
2018/19 [43–46]

Year	2018/19	2017/18	2016/17	2015/16
Weigh stations count	19	19	19	13
Satellite weigh stations	16	16	16	16
Weighed vehicles	1 863 680	1 782 281	1 731 664	893 608
Overloaded vehicles	464 246	391 272	390 310	214 818
Overloaded percentage	24,91%	21,95%	22,54%	24,04%
Charged drivers	34 540	30 623	28 399	19 853
Charged percentage	1,85%	1,72%	1,64%	2,22%
Arrested drivers for gross overloading	986	1 044	1 836	1 601
Arrested percentage	0,05%	0,06%	0,11%	0,18%
Fines issued	R32 500 000	R33 400 000	R21 705 965	R19 049 580
Payment received of fines issued	R 8 300 000	R 6 300 000	R 4 096 670	R 4 547 162
Percentage of fines received	25,54%	18,86%	18,87%	23,87%

Efficient, timely delivery is a key factor in our modern era. A minor improvement or decrease in delivery efficiency can win or lose multiple clients for a business. This is a harsh reality in business that Alan Sugar aptly describes: *"My company was trying to do a very big deal on a property owned by the government. We were told we had to have the tender in by 5 o'clock, and what happened was that some motorbike rider decided to stop and have a cup of coffee in Starbucks and delivered the envelope at 5.15 – and we didn't get the deal"* [49, p. 99].

It is widely recognised that southern Africa has great growth potential in the global economy [50]. The fact that logistic costs make such a high contribution to the South African GDP indicates that, as previously stated, they cannot be neglected [21,51]. A macro-level quantification metric was proposed by Rossouw [52] for use as the Logistic Metric to define the performance of the South African logistics sector. The metric states [39]:

$$\frac{\text{Logistics cost}}{\text{GDP}} \quad (2.1)$$

This metric indicates the direct costs of the logistics sector to the transportable GDP and the figure is improved by either a decrease in logistic costs or an increase in GDP. Unfortunately, as can be seen in Figure 2.3, the GDP has remained fairly constant for the past several years but logistic costs have increased year on year, to the detriment of the country's standing and performance.

What can be changed to improve the Logistic Metric? Logic dictates that the simplest way would be to decrease logistic costs because that change would benefit business owners as well. A study was conducted to indicate the key challenges and cost drivers in the South African road freight sector [50]. The respondents indicated the following [50]:

- (Un)availability of return loads and the costs associated with empty runs (66%)
- Poor road conditions (64%)
- Theft (52%)
- The cost of fuel (52%)
- Congestion and its associated delays (52%)
- Lack of law enforcement and prevalent non-compliance (43%)

These factors are key to improving the road freight sector as a whole and are relevant to multiple stakeholders. They are therefore discussed in Section 2.1.1 as part of the supply chain. However, the entire supply chain needs to be understood before proposing possible improvements to its components.

2.1.1 Supply chain

The supply chain is an essential part of the logistics process. It is not limited to road transport, although road transport is one of its key components [53,54]. Understanding how the whole supply chain works allows a clear perception of where the smallest intrusive action can achieve the greatest impact.

The supply chain has multiple actions and can be viewed from multiple starting points. The starting point for this study's purposes is the collection of goods from the supplier by the transporter company. Two transporters were investigated: One was making cross-border deliveries from Johannesburg, South Africa, into the rest of southern Africa; and the other was receiving cold goods in Cape Town, South Africa, for delivery to Johannesburg. In this specific situation, the supplier and the transporter were on the same premises, reducing the collection time.

It is important to recognise all the supply chain stakeholders with investments in the freight corridor and therefore they are specified in the Section 2.1.1 below.

Stakeholders

Stakeholders are affected, directly or indirectly, by overload control activities and the inefficiencies of corridor operations. Their effect on the stakeholders is key to determining the economic impact that will be discussed in detail in Chapter 5.

Cargo owner – has an obligation to deliver goods successfully to the client and entrust the cargo to the transporter for this success. May incur severe financial losses if the

delivery is late, damaged, or lost in transit.

Cargo transporter or truck driver – spends much time on long-haul trips in a truck to deliver the goods to a client. Delays in cross-border trips force drivers to spend additional time away from home. The driver has to maintain a high level of focus on the road when travelling. Deterioration in the infrastructure increases the likelihood that other vehicles will have an crash that may involve them. Travelling speeds may be decreased, resulting in additional pressure from the vehicle owner in terms of turnaround times.

Transport owner – may, in some cases, run the transport business, and has a key interest in the truck and a profitable turnaround time. South African cross-border freight usually does not have trucks owned by their drivers, as seen in other parts of the world.

A **Client** – would like their order to be delivered intact and timeously. Delays along a route or loss/damage of a product can have severe implications for their deadlines.

Road agency – has a mandate to manage, monitor, and plan road maintenance and rehabilitation. Ensuring efficient use of the road infrastructure minimises crashes and road maintenance, thus minimising expenditure.

The **Internal Revenue Service** – is interested in monitoring products leaving and entering the country to ensure the relevant taxes are collected.

National Treasury – is usually the funder that pays for the road infrastructure. Effective use of finances makes funds available for other sectors.

Cross-border Operation – has to ensure the vehicles entering or exiting the country are legally loaded. Overloaded vehicles may contain additional stock entering or leaving a country for which taxes have not been collected. This impacts the bottom line of the country.

TCC – is the key point for identifying and prosecuting overloaded vehicles and is thus a primary point of investment for the apprehension of overloaded vehicles.

Toll concessionaire – has the mandate to manage, operate, and maintain a section of road infrastructure by agreement with SANRAL and the public-private partnership (PPP). Minimising overloaded vehicles protects the infrastructure, minimising maintenance costs on the section of road they manage.

Road users – travel on the roads for various reasons. A deteriorated road infrastructure increases their operating costs, just as it does for heavy vehicles.

Cross-border transport

The first scenario describes what happens during **cross-border** transport of goods from South Africa, specifically Johannesburg, into southern Africa. Destinations in southern Africa depend on distribution centres and store locations in Mozambique, Namibia, Zambia, and Zimbabwe. The stakeholders involved in the trip include the **cargo owner**, **road users**, the **transport owner**, the **client**, the **road agency**, the **National Treasury**, **cross border operations**, **TCCs**, **toll concessionaires**, and **law enforcement** officers. Gauteng province is an economic hub in South Africa. Goods need to be transported long distances to and from the province and minerals in the interior have to be transported over extended distances for export to other countries.

A vehicle is typically dispatched from a distribution centre (DC), as can be seen from the starting point at the top of Figure 2.5. Stock collection is then completed at the cargo owner's warehouse. The mass of the vehicle has to be confirmed before dispatch at the transport owner's local weigh bridge, while ensuring the vehicle is sealed for safekeeping. An efficient load that optimises the transporter's profit margins is generally just below the legal threshold. The corridor travelling can commence after all the paperwork has been finalised. A pile of paperwork must be taken along on the trip and may be requested by officials at any stage of the journey.

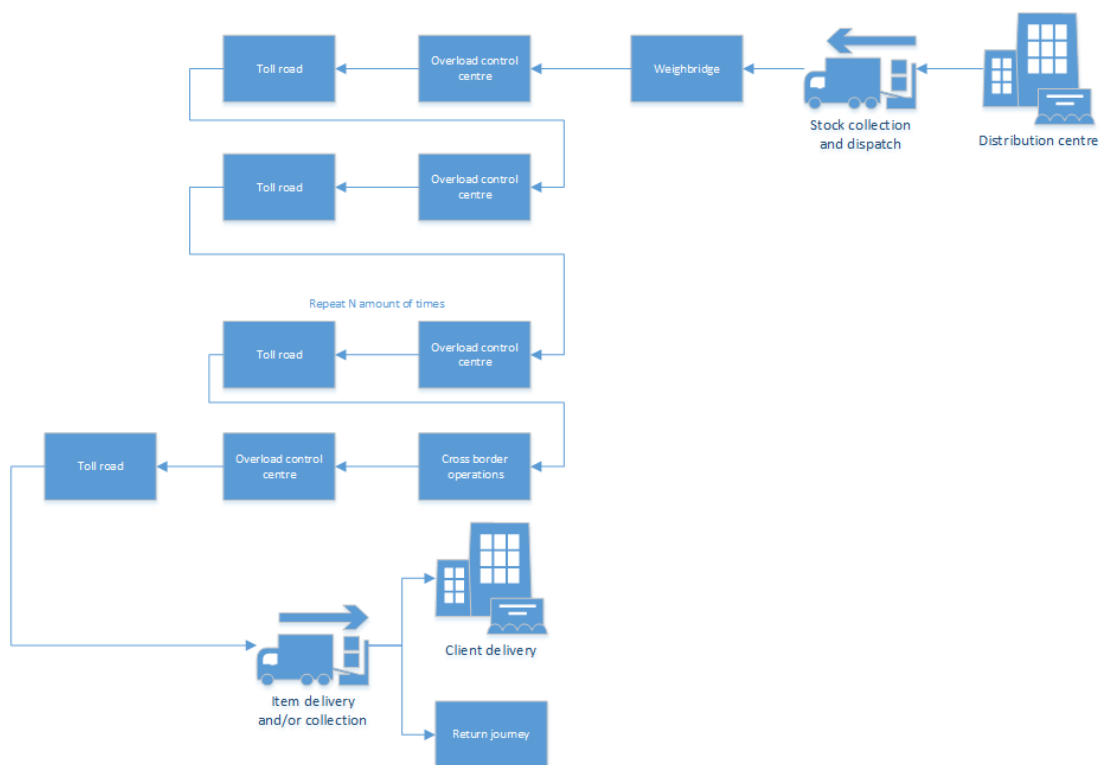


Figure 2.5: Typical cross border operation flow

When a driver delivers the cargo to a client (at the destination), they must ensure the best possible trip with minimum damage to the vehicle and the cargo. Corridor travelling generally constitutes the largest portion of the journey, and the quality of the journey is highly dependent on the quality of the road infrastructure. At the TCCs scattered along the corridor, the vehicle is first screened by a WIM scale. If its mass is found to be close to or over the legal threshold, the vehicle is directed to a static scale, where its mass is verified. A legal vehicle is directed back to the corridor to complete the journey. The prosecution process is started if the mass of the vehicle exceeds any of the permissible maximum masses.

Sections of the corridor are managed by different toll concessionaires, who ensure that the vehicle passes through a toll plaza. This can cause delays when volumes are high.

Typically, there are additional TCCs along the corridor and the mass verification process is repeated at each of them until a border post is reached. A weighing operation takes place on each side of the border post. The border post has multiple entities that have an interest in the border-crossing vehicle. Processing of the vehicle is duplicated on both sides of the border. The process at the Beitbridge border post is summarised in Figure 2.6.

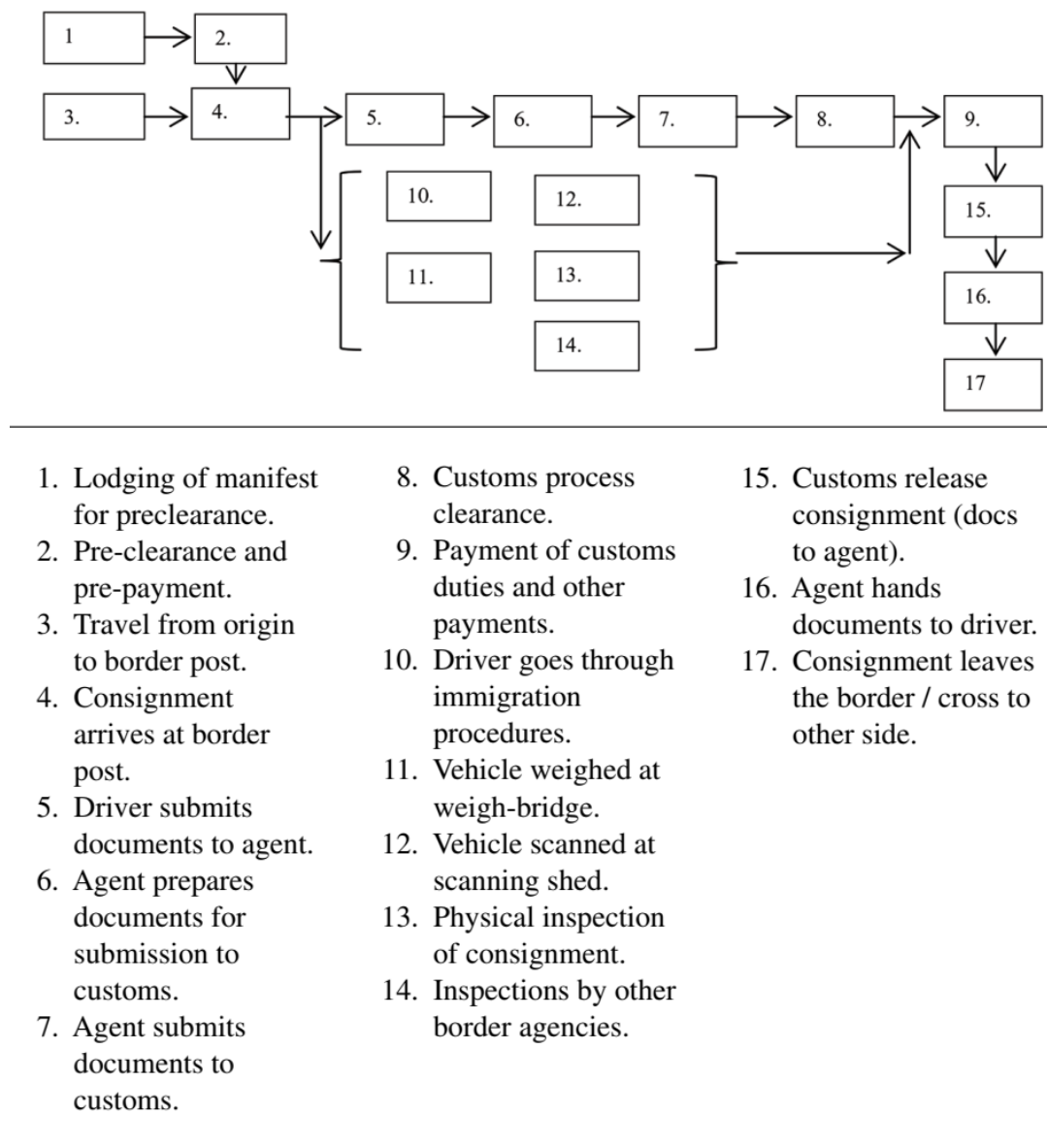


Figure 2.6: Typical cross border operation flow and operational steps [22]

Unified legislation in the SADC region has been the subject of numerous debates and has largely been successful. However, this means that the same operation for overload control management is implemented once a vehicle crosses the border. Likewise, it can be expected that toll roads and travelling continue in the same manner until the vehicle reaches its destination. If another load can be obtained for the return journey once the vehicle has been offloaded, the same scenario takes place in reverse as driver and vehicle make the journey back to the DC.

The second scenario, described below, is that of the **cold chain management (CCM)** of transporting goods from Johannesburg into southern Africa. The stakeholders overlap with those of the cross-border operations in the first scenario, with the key difference that perishable products place specific time constraints on the delivery. Freight that requires CCM have a greater potential for damage due to delays than other freight.

Cold Chain Management

Even though the journey covered is also from Johannesburg, the perishable cargo in this scenario generally originates from the coast and is forwarded for other producers there. This journey may be in excess of 1 000 km and is often not in cooled vehicles. This results in a large increase in product temperature, which decreases shelf life significantly before dispatch from Johannesburg. A typical load of apples delivered from Cape Town may require in excess of three days in a cold warehouse to be decreased to 5 °C before dispatch [55].

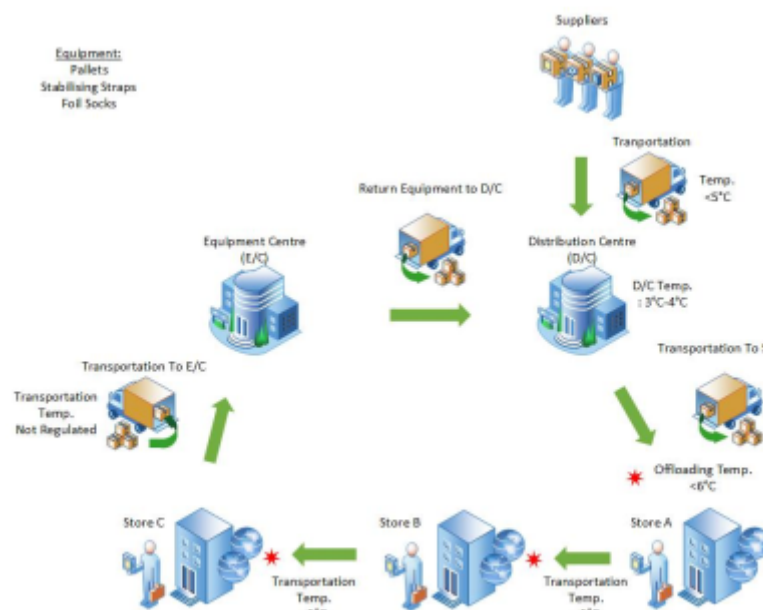


Figure 2.7: Overview of typical CCM flow [55]

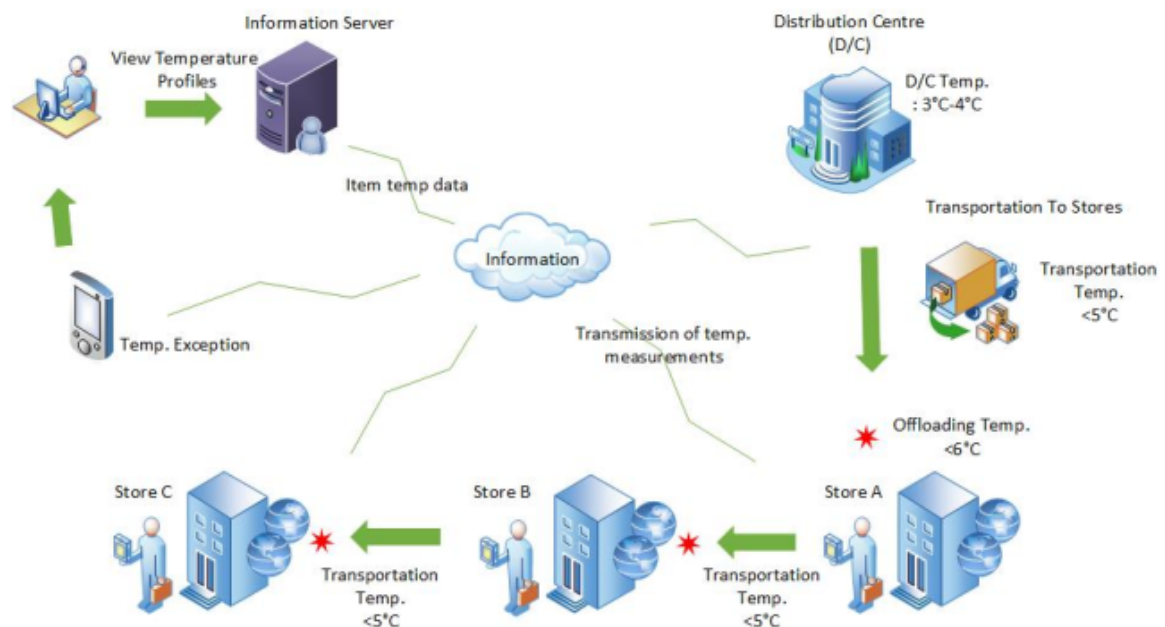


Figure 2.8: General information sharing proposed for CCM [55]

The vehicle is loaded with the perishable goods and dispatched to various possible locations, as indicated in Figure 2.9. It is important to deliver perishable goods as quickly as possible to ensure the longest possible shelf life at the client's store. The effect of temperature on shelf life can be seen in Table 2.2.

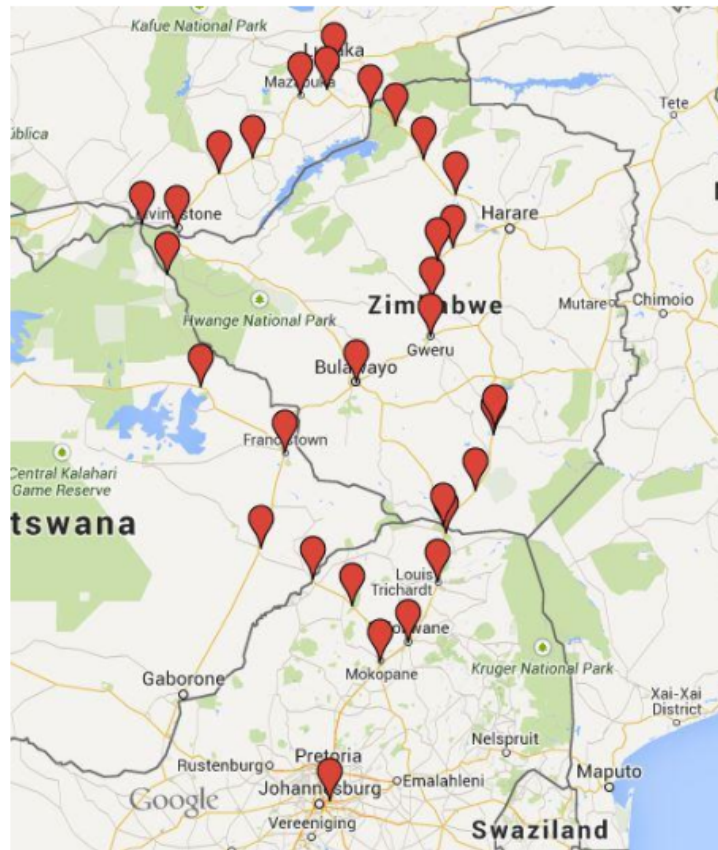


Figure 2.9: Typical cross-border destinations for CCM [55]

Table 2.2: Estimated shelf life of produce at different temperatures [55]

Item		Storage potential			
Types of goods		Optimal temp (OT)	OT + 10 °C	OT + 20 °C	OT + 30 °C
Fish	Temp	0 °C	10 °C	20 °C	30 °C
	Shelf life	10 days	4–5 days	1–2 days	Few hours
Mangoes	Temp	13 °C	23 °C	33 °C	43 °C
	Shelf life	2–3 weeks	1 week	4 days	2 days
Green vegetables	Temp	0 °C	10 °C	20 °C	30 °C
	Shelf life	1 month	2 weeks	1 week	<2 days
Apples	Temp	-1 °C	10 °C	20 °C	30 °C
	Shelf life	3–6 months	<2 months	<1 month	2 weeks

When the vehicle is ready for dispatch, it is weighed in the same fashion as the cross-border operation vehicles because only the cargo type has varied. The TCC and toll road operation functions in the same manner. The operation only varies slightly at the border post, where refrigerated goods have a considerably accelerated passage when compared to other cargo types, as indicated in Table 2.3. The faster processing has the potential to prolong the refrigerated cargo's shelf life. Another load can be obtained once offloading has occurred and the return journey to the DC can be started, as in the cross-border operations scenario.

Table 2.3: Average transit times for different cargo types based on data measured at Beitbridge border post [56]

Cargo type	Average transit time (hours)
Break bulk	30.2
Consolidated	60.9
Refrigerated	7.5
Tanker	8.9
Across all cargo types	26.9

2.1.2 Simulation implementation in supply chain management

The impact of a suggested change must always be validated by real-world trial studies. However, deployment of a new concept, such as the one developed in this thesis, would be costly to test in a real-world situation. It is much more cost-efficient to prove its functionality by implementing it in a simulation model to justify actually deploying the new concept.

Simulation models and packages improve the understanding of the operational impact of changes to supply chain processes without the expense of rolling out infrastructure to check their effect. Road infrastructure and traffic flows, and even internal business processes, can be modelled in the relevant packages. Operational efficiency for transportation stakeholders has been studied in a multi-agent approach in previous work [57]. Impact quantification has been conducted for work related to border crossings [56]. The impact of electronic screening at weigh stations has also been investigated [58].

This impact study looked at alterations to the entire supply chain, with an in-depth focus on specific subsections in the supply chain process. It was necessary to determine whether the alterations would benefit the supply chain's competitiveness.

2.1.3 Competitiveness in a logistic supply chain

First world countries such as the United States have indicated that a well developed transportation system is a key factor in economic competitiveness [15]. Logistic operations are a strategic resource for our South African economy too, and are essential to maximise in global competitiveness and ensure a trading presence abroad [51].

Previous frameworks designed to rate supply chain performance and logistic operations at a business level [59] had the drawback of having to analyse several business entities and not having a country-wide or regional view of the situation. Boosting economic competition should increase productivity while improving efficiency [60]. A decrease in markups would increase the economic competition metric used in Equation 2.1. However, ensuring the exposure of local markets to foreign entry that may force a decrease in markups [60] and improve regional integration is highly dependent on transport corridors [61].

Efficient logistics support a supply chain's competitiveness by satisfying a client's demand. This is done this by supplying the products that are needed, when they are needed, and at a competitive price [62]. The need to leverage cost/productivity advantages is met by maximising capacity utilisation, turnaround of assets, low inventory levels, and low wastage [54]. This can only be achieved by having an in-depth knowledge of the operations in the supply chain necessary to optimise the process. Leverage of just-in-time delivery can decrease operational costs if the corridor can be trusted, i.e., if it is reliable and optimised. A corridor should only be considered successful after taking into account its safety and environmental impact [63], which is why overload control management is so important.

Vehicles are overloaded intentionally to move more cargo at a similar cost [27]. Reducing the cost to the company per ton of goods transported forces other business operators to reduce profit margins to remain competitive and may, in extreme cases, cause law-abiding competitors to close their businesses [27]. Overload control management is there to protect law-abiding businesses [27].

2.1.4 The human factor and corruption

Human factors have a huge impact on logistics and supply chains. Humans tend to make errors and become fatigued, and have a drive for self-enrichment. An increase in corruption is the highest ranked risk for South Africa [64]. Transparency International intends to eradicate corruption and produces a yearly Corruption Perception Index. The index rates range from 100, meaning *clean of corruption*, down to 0, meaning *most corrupt*. The global corruption map is indicated in Figure 2.10 and a closer look is given to Sub-Saharan Africa in Figure 2.11 [65,66]. The latter indicates that the global 2017 average was 43 in the Corruption Perception Index, and Sub-Saharan Africa's average was 32. South Africa was on a par with the global average at 43 [65–67].

Regional surveys have shown that 40–50% of South Africans have paid bribes [68]. This is extremely concerning when combined with the perception that both police and government officials are corrupt (36% and 35% respectively) [69]. An African survey indicated that 58% of people perceived an increase in corruption and, in South Africa, an increase of 83% was perceived [70]. It is plausible to assume that overload controls and cross-border operations have the same level of corruption, and transport owners verify (off the record) that bribes are included as a standard item in the petty cash provided to drivers. In fact, SCM in the public sector is perceived as corrupt, inefficient, and unreliable [71].

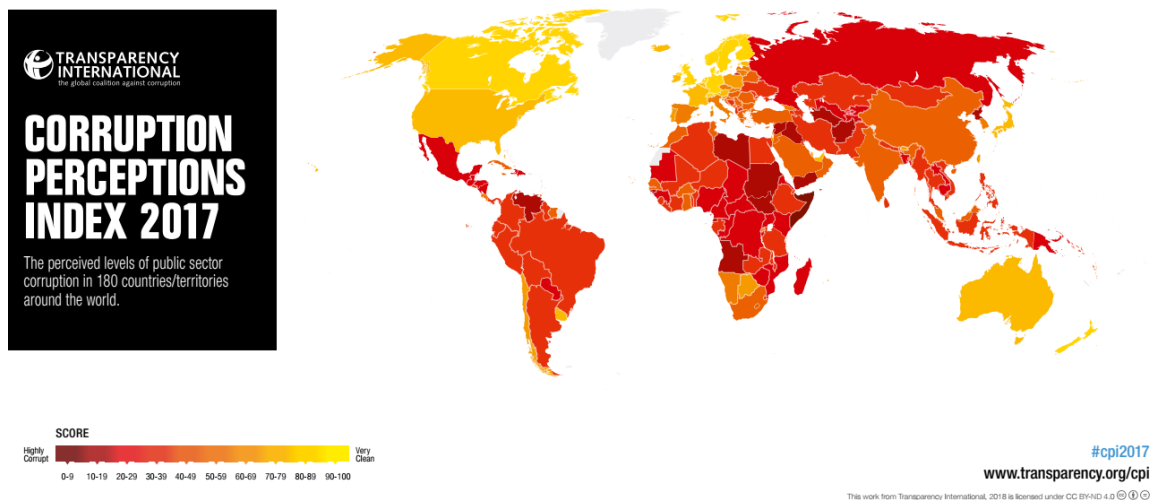


Figure 2.10: Global Corruption Perception Index [65]

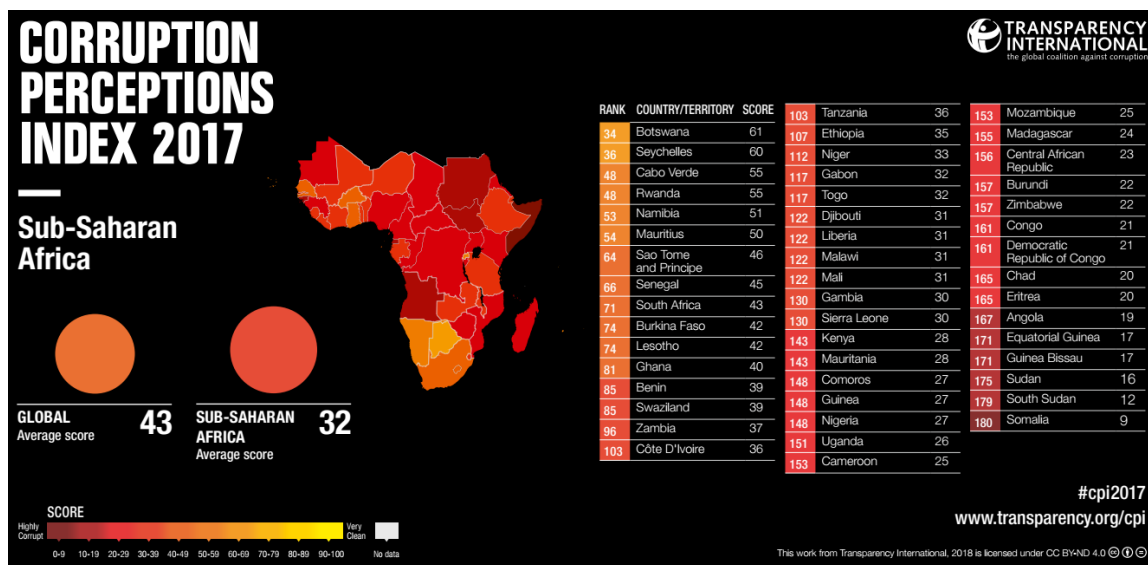


Figure 2.11: Sub-Saharan Africa Corruption Perception index [66]

Poor work ethics concern multiple stakeholders. For example, SANRAL reports indicate that TCCs operate 24 hours a day but industry investigation has indicated otherwise [41–43]. This is to be expected when considering that stations in the United States are not open 24 hours a day and some are not even open 40 hours a week [72]. Intentional avoidance of weigh stations occurs when drivers signal fellow drivers that a

station is closed [73–75]. Transporters have also witnessed a high volume of vehicles being statically weighed to fulfil daily quotas early in the day so that the weighbridge operators can slack for the rest of the work day. If drivers know about this trend, there is a high risk that overloaded vehicles will not be weighed. Overload control measures should thus be implemented to counteract this.

2.2 Overload control implementation

Overload control is simply the control of freight vehicles' axle- and axle unit loads, and the total vehicle mass as AVCM, and it is implemented to minimise damage to road infrastructure and ensure the safety of heavy vehicles. AVCM indicates the mass of the vehicle that should be below permissible limits and is often also used as gross vehicle mass (GVM). As mentioned previously, protecting the road infrastructure is important in a landlocked country such as South Africa and other countries in the SADC region. Since self-regulation has been successfully implemented in South Africa and abroad, as discussed in depth in Section 2.4, it is logical to investigate local overload control operations in the next section.

2.2.1 South African overload control

Overload control is intended to reduce the high costs of repairing the damage inflicted on the road infrastructure by overloaded vehicles [27, 40–43, 45, 46, 76, 77]. SANRAL received permission from the DOT and the National Treasury in 2000 to implement overload control as a primary function and to receive funds to spend on increasing the capacity of TCCs [41]. SANRAL indicated that overloaded vehicles caused damage to infrastructure amounting to ZAR 600 million in 1997, which escalated to ZAR 1 billion in 2011/12. Funds are not always available to repair the damage caused, so the road pavement sometimes remains damaged for long periods, and the effect ripples into other stakeholders' operations [27].

Although economic development is clearly linked to efficient transportation, it requires high financial expenditure to install and manage transportation infrastructure [78]. The large size of the infrastructure managed by SANRAL necessitated the appointment of toll concessionaires with PPP agreements. Under these agreements, companies install, manage, and maintain specific sections of road as toll concessionaires for up to 30 years [78]. Implementation of the agreements gave SANRAL 19 TCCs operated by the concessionaires, and 16 satellite stations that only operate if overloading incidents increase on the national road (N)1, N3, and N4 [43].

The concessionaires in PPPs with SANRAL are Bakwena, the N3 Toll Concession (N3TC), and the Trans African Concessions (TRACs). These partners have implemented traffic monitoring systems to analyse traffic patterns and speeds, and the monitoring systems incorporate WIM equipment to analyse axle loads [43,45,46,77]. The WIM information is used to manage and plan road networks [43,45,46,77]. Management of the overload control operations and prosecuting measures is specified in the *Road Traffic Act, 1996 (Act 93 of 1996)* [27,79].

Legislation

The overload legislation was developed by the South African government dictates how overload control is managed. The regulations covering the management relate to the *National Road Traffic Act, 1996* in conjunction with the *South African National Roads Agency Limited and National Roads Act, Act 7 of 1998* [79–81]. The permissible maximum masses are specified in the *National Road Traffic Act, 1996*, [79] Sections 234 to 243, the text of which is in Appendix A. The limitations of permissible loads are summarised in the National Department of Transport's *Guidelines for Law Enforcement in Respect of the Overloading of Goods Vehicles* [27].

The applicable legislation [27,79] is summarised below.

- **Regulation 234:** *Permissible maximum axle massload of vehicle* states that no person shall operate a vehicle on a public road if the permissible maximum axle load is exceeded. The maximum load is stipulated in Regulations 238, 239, 240, and 243.
- **Regulation 235:** *Permissible maximum axle massload of vehicle* states that no person shall operate a vehicle on a public road if the permissible maximum axle unit load is exceeded, where an axle unit load is a combination of axles. The maximum load is stipulated in Regulations 238, 239, 240, and 243.
- **Regulation 236:** *Permissible maximum vehicle mass* states that no person shall operate a vehicle on a public road if the permissible maximum vehicle mass is exceeded. The maximum load is stipulated in Regulations 239 and 241, provided the permissible maximum vehicle mass does not exceed 56 000 kg.
- **Regulation 237:** *Permissible maximum combination mass* states that no person shall operate a vehicle on a public road if the combination mass stated in Regulations 234 and 235 is exceeded. The maximum load is stipulated in Regulations 239 and 241, provided the permissible maximum vehicle mass does not exceed 56 000 kg.
- **Regulation 238:** *Load on tyres* states that no person shall operate a vehicle whose wheel massload exceeds the standard specification of SABS 1550: *Motor vehicle tyres and rims: Dimensions and Loads*, Part 1: *General*, Part 2: *Passenger car tyres*, and Part 3: *Commercial vehicle tyres*.
- **Regulation 239:** *Gross vehicle mass, gross axle massload, gross axle unit massload, gross combination mass, power to mass ratio, and axle massload of driving axle to total mass ratio not to be exceeded*. It states that no person shall operate a vehicle if it exceeds the gross vehicle mass, gross axle massload, or gross axle unit massload.
- **Regulation 240:** *Massload carrying capacity of road* is summarised in Figure 2.12 [27].

Item	Mass limit on Steering axles (kg)	Mass limit on axles with two or three wheels (kg)	Mass limit on axles with four wheels (kg)
Single wheel	3 850	4 000	4 000
Single axle	7 700	8 000	9 000
Two-axle unit	15 400	16 000	18 000
Three-axle unit	23 100	24 000	24 000

Figure 2.12: Mass limits as per Regulation 240 [27]

- **Regulation 241:** *Massload carrying capacity of bridges* states that no person shall operate a vehicle on the road if the mass exceeds the mass calculated according to the bridge formula (see the example in Figure 2.13).

$$\text{Permissible mass} = (L \times 2\,100) + 18\,000 \text{ kilogram}$$

where L = *the distance from the first axle of any axle or axle unit to the last axle of any consecutive axle or axle unit (in metres).*

See Figure below:

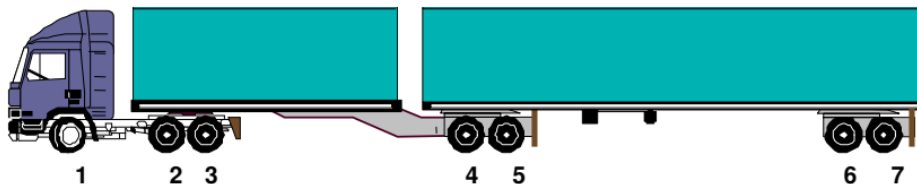


Figure 2.13: Bridge formula calculation [27]

- **Regulation 242:** *Distribution of axle massload and wheel massload on vehicle fitted with pneumatic tyres* states the limitations of pneumatic tyres and is summarised in Figure 2.14 [27].

Regulation	Description in regulation	Vehicle type as interpreted from descriptions in regulations	Load on steering axle or steering axle unit as a percentage of the sum of all axle massloads
242(b)	Combination of motor vehicles	Truck-tractor plus at least one semi-trailer with steering axle or steering axle unit.	11% (of truck-tractor and first semi-trailer)
242(c)	Motor vehicle, not being a combination of motor vehicles with a <u>steering axle unit</u>	Rigid vehicle with a <u>steering axle unit</u>	30%
242(d)	Any other vehicle	Rigid vehicle with a <u>steering axle</u>	20%
242(d)	Tractor	Tractor	12%

Figure 2.14: Extracted Regulation 242 – simplified overview [27]

- **Regulation 243:** *Axle massload of vehicles fitted with tyres other than pneumatic tyres* states that no person shall operate on the road if it is fitted with metal tyres, if any axle massload of such vehicle exceeds 2 700 kilogram (kg).

Vehicle classification is different for multiple end-users, even if they refer to the same vehicle type/configuration. Understanding the codes is important for data development and interpretation. The SANRAL classification scheme is summarised in Figure 2.15 [82].

SINGLE LOOP	DUAL LOOP	CODE	DUAL LOOP WITH AXLE SENSOR (RSA full)	DUAL LOOP WITH AXLE SENSOR (Toll)
None	None	1	Motorcycle *	Toll Class 1
Light	Light	2	Light Motor Vehicle	
		3	Light Motor Vehicle + Trailer	
Heavy	Short Truck	4	Two Axle Bus	Toll Class 2
		5	Two Axle Single Unit	Toll Class 3
		6	Three Axle Bus + Trailer	
		7	Two Axle Unit + Trailer (Max 4 Axles)	
		8	Three Axle Single Unit Incl Single axle Light Trailer	
		9	Four or Less Axle Single Trailer	Toll Class 4
	Medium Truck	10	Buses with 5 or more Axles	
		11	Three Axle Single Unit and Light Trailer (More than 4 Axles)	
		12	Five Axle Single Trailer	
		13	Six Axle Single Trailer	
	Long Truck	14	Five or Less Axle Multi-trailer	
		15	Six Axle Multi-trailer	
		16	Seven Axle Multi-trailer	
		17	Eight or more Axle Multi-trailer	

* Weigh in motion using capacitive sensors are not sensitive enough axle detection devices to be activated by motorcycles or very light trailers

Figure 2.15: Vehicle classification schemes [83]

Protection of the road infrastructure by means of legislation requires extensive law enforcement. The following section will discuss the law enforcement measure implemented towards protecting the road infrastructure.

Law enforcement

The Department of Transport's *Guidelines for Law Enforcement in Respect of the Overloading of Goods Vehicles* clearly indicate the powers and duties of traffic officers [27]. Uniformed traffic officers are permitted to determine the mass of a vehicle or vehicle combination, as stated in Section 2.2.1. They may direct the vehicle to mass-measuring devices to obtain the mass [27]. If the maximum allowed mass is exceeded, the traffic officer may prohibit the vehicle from public road access until the mass has been reduced.

Studies have indicated that axle overloading reduces during periods of strong law enforcement compared to periods of no enforcement [84]. The axle load distribution can be seen in Figure 2.16, where the area for vehicles between 8 and 16 tonnes was

23,01% when there was no law enforcement, and decreased to 12,62% when there was strong law enforcement.

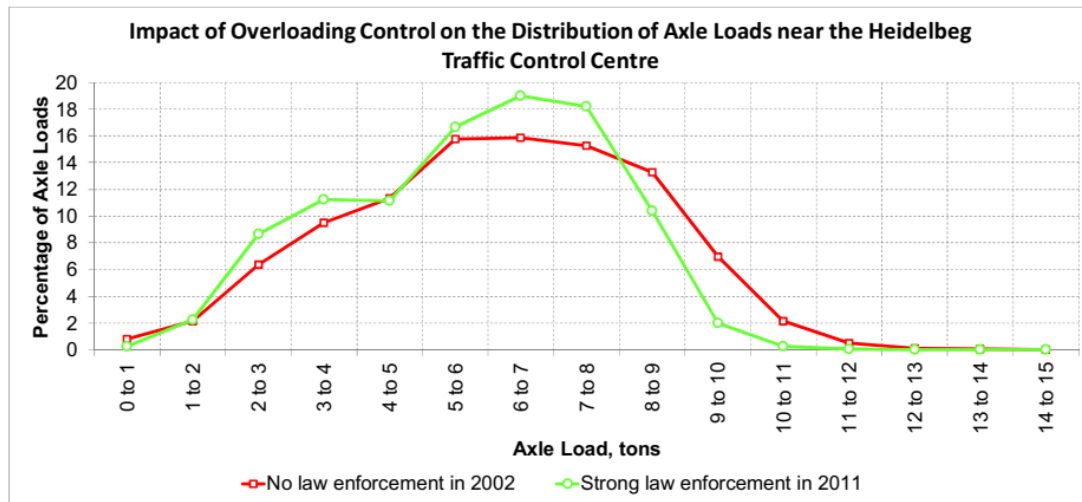


Figure 2.16: Distribution of axle loads with *no* enforcement and *strong* law enforcement [84]

Screening of vehicles

Screening is the process of identifying potentially overloaded vehicles and directing them to a weighbridge for verification. The screening process is implemented for the following reasons, as indicated in the *Guidelines for Law Enforcement in Respect of the Overloading of Goods Vehicles* [27]:

- To increase the productivity of weighing sites by wasting as little time as possible on legally loaded vehicles
- To prevent legally loaded vehicles from being unnecessarily delayed
- To control corruption and bribery effectively. Incidents of overloading are recorded and have to be accounted for
- To monitor traffic officers for effectiveness and productivity.

There are two main screening methods. The first method is **visual screening**, which occurs when traffic officers detect potential overloading based on thier experience [27].

They may do this by observing the appearance of the springs or tyres, by hearing the strain of the engine on inclines, or by the size of the load. This screening method is implemented when no WIM scale is available; and the officer may have to escort the vehicle to a weighbridge.

The second screening method is by means of a *WIM* or similar device. They can be high-speed weigh-in-motion (HSWIM), low-speed weigh-in-motion (LSWIM), or portable LSWIM scales. All these scales are inherently inaccurate due to the dynamics of the vehicle's movement [72]. These dynamic factors historically, (American standard of 2002), caused the inaccuracy to be so poor that the tolerance was as high as 20% between WIM and static scale measurements [85]. Later studies indicated that the WIM error was reduced to 10% [72,86]. Recent improvements have the industry now working on HSWIM scales with inaccuracies of only 2,5% [87].

An *HSWIM* scale is usually permanently installed in a road pavement where the vehicles are travelling at standard speeds. A sequence of HSWIM scales is installed on the North-South Corridor in the KwaZulu-Natal (KZN) and Free State (FS) provinces. This has the benefit of measurements without screening lanes as the weighbridge cannot be installed directly next to the corridor. Traffic officials redirect the vehicle if the HSWIM scale detects a vehicle that is potentially overloaded. A typical in-road installation is indicated in Figure 2.17. The HSWIM scale and the TCC in this configuration are often several kms apart, and the TCC is some distance from the corridor.

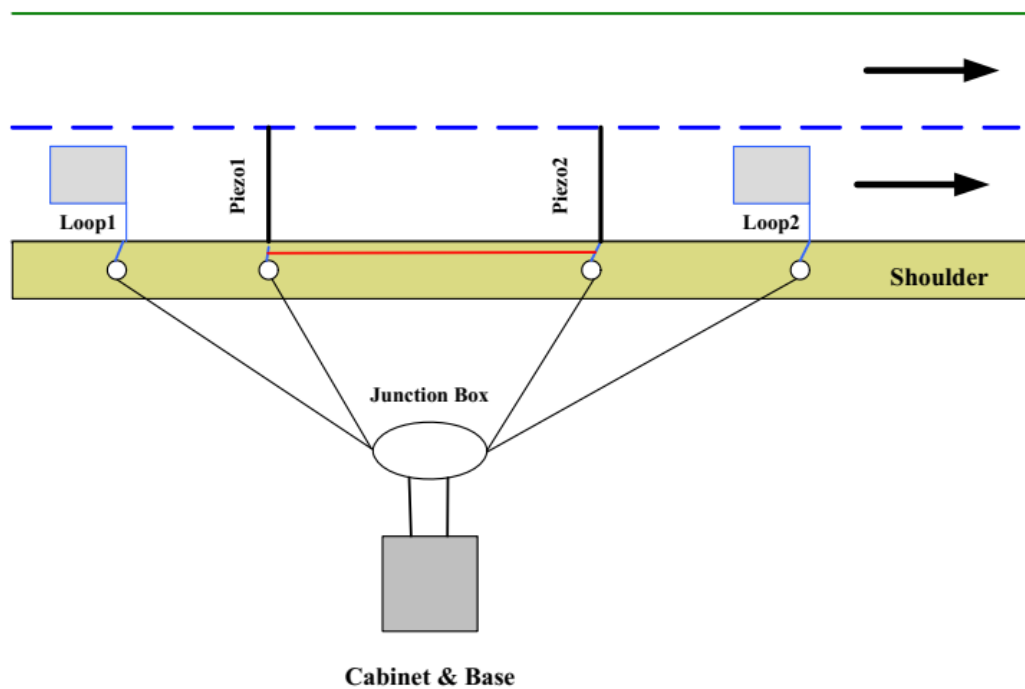


Figure 2.17: Typical in-road HSWIM installation [72]

An *LSWIM* scale is specifically implemented for a more accurate screening lane at a weighbridge and is what is commonly referred to simply as a WIM scale. The vehicles travel at lower speeds, which decreases the dynamic forces measured.

Multiple studies have been conducted on the accuracy, calibration, and placement of WIM scales at weighbridges in road networks [88,89].

Weighbridges

Weighbridge/TCC placement is ideally directly alongside the road it intends to serve. However, there are three typical weighbridge configurations. It sometimes happens that the weighbridge is not located next to the road, and vehicles need to be directed to the weigh station at the TCC for static scale weighing. This can be seen as the *first* configuration of a weighbridge. Typically it has a WIM scale in the road pavement with a traffic signal that indicates to the traffic officer whether the vehicle should be directed

to the static scale or not. The traffic officer may in some cases be unclear which vehicle has to be redirected if a large number of heavy vehicles are passing the WIM scale during the short space of time. Road traffic signs and clear instructions are required for vehicles to navigate to the TCC. The traffic officer radios through the license numbers of vehicles that are en route to the TCC [27].

The *second* configuration of a weighbridge is a TCC alongside the road, without a screening lane, so that all heavy vehicles have to be statically weighed. This can cause extreme delays on the route but, fortunately, this configuration is less common.

The *third* configuration is a TCC with a screening WIM lane. In some situations, a static scale cannot be constructed for both directions of the road it serves so a screening lane and traffic signs are used to direct vehicles to the single static scale.

The layout of a typical TCC can be seen in Figure 2.18.

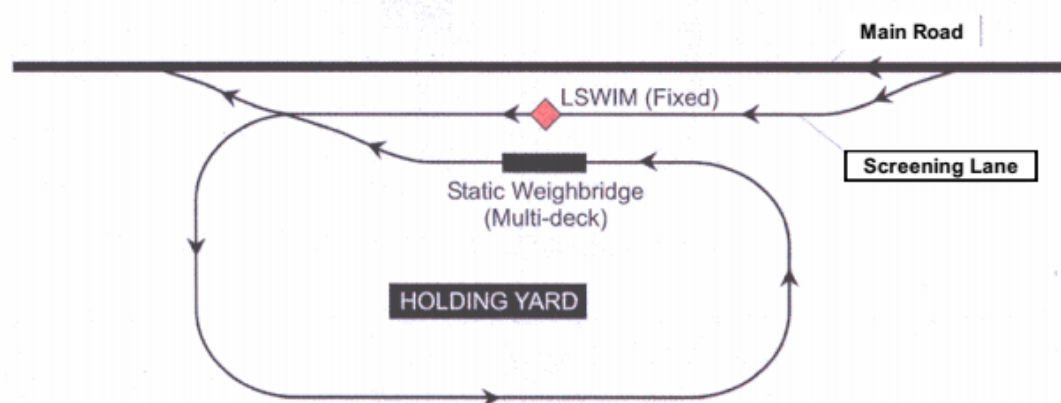


Figure 2.18: Typical layout of a TCC [90]

Mass verification process

The weighing process starts with the procedures stipulated by the static scale provider [27]. The overloading field sheet used in the overloading procedure covers all information required in court. An example of the field sheet can be viewed in Appendix D. The

procedure that is required to be followed by the officials is indicated in Figure 2.19.

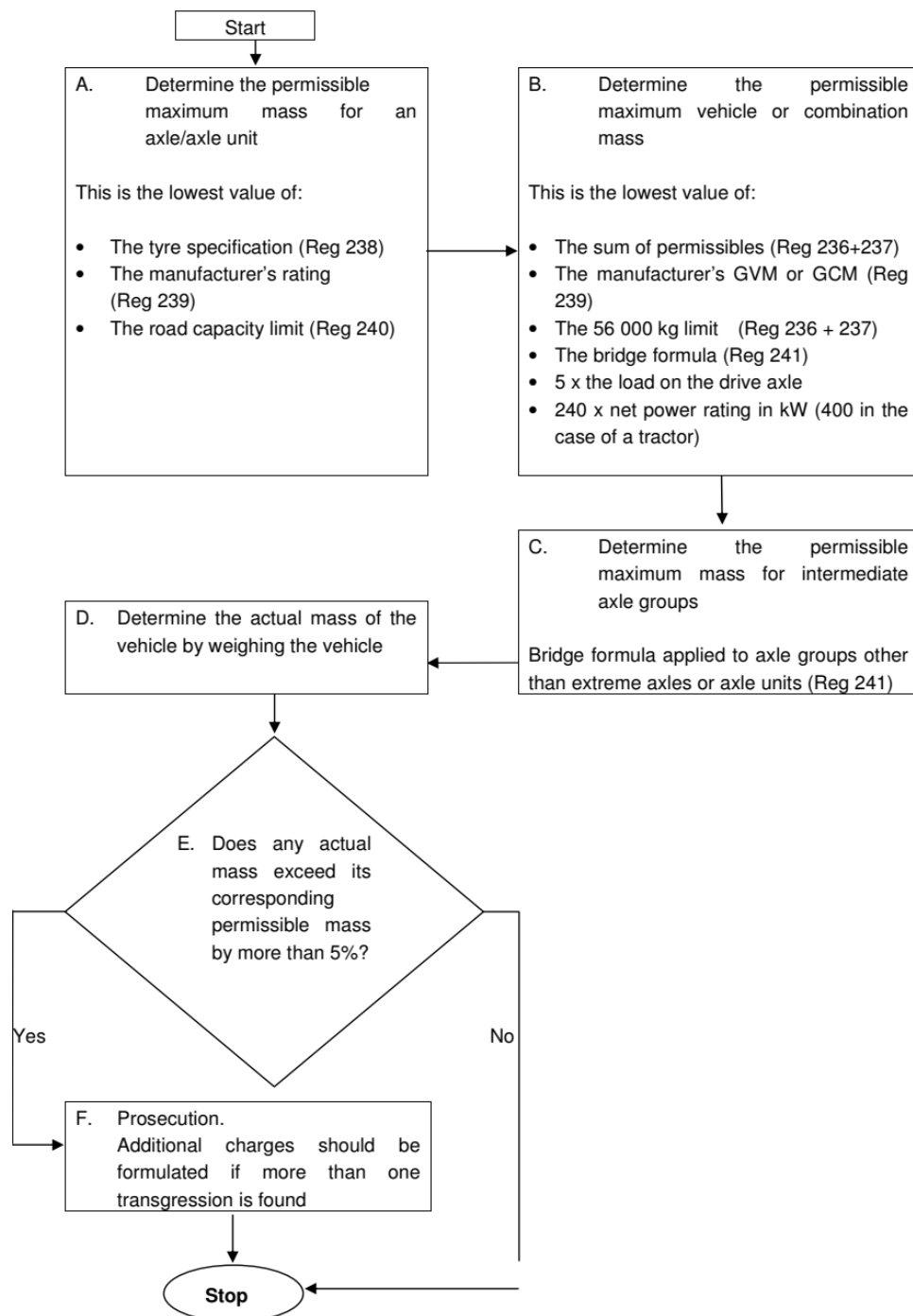


Figure 2.19: Flow diagram of the overloading control process [27]

Because small errors may occur in the weighing process, a 5% grace or tolerance above

the legal limit is permitted on axles and 2% on the AVCM [27]. If a vehicle is loaded 0% to 5% above the legal limit, the driver of the vehicle is issued a courtesy notice that the vehicle is overloaded but will not be prosecuted [27]. If the overloading is above the 5% grace/tolerance, the driver is *charged*, and possibly the business operator too [27]. *Seizure and arrest* occur if the vehicle is [27]:

- more than 50% overloaded on the AVCM – for a vehicle with a mass less than 3500 kg.
- more than 50% overloaded on an axle/axle unit and more than 5% overloaded on the AVCM – for a vehicle with a mass less than 3500 kg.
- more than 25% overloaded on the AVCM and/or groups of axle units – for a vehicle with a mass over 3500 kg.
- more than 35% overloaded on an axle or axle unit and 5% overloaded on the AVCM – for a vehicle with a mass over 3500 kg.

Vehicles that are overloaded should be forbidden to travel on the open road and should park at the TCC. Loads may be shifted or offloaded to get the vehicle down to the legal permissible mass [27].

Roadworthy inspections

Safe operation of heavy vehicles on the roads are highly dependent on correct mechanical functionality. An increased chance of an crash can be expected if a vehicle has mechanical defects. Vehicle inspections are often performed at TCCs to reduce this risk.

The first method of inspections are with a dedicated vehicle inspection pit at the TCC. The heavy vehicle is directed to the pit that is used to extensively assess the condition of the vehicle. Inspections typically include break inspection, tyre thread, and shocks functionality. This is ideally indicate that the vehicle is in correct operating condition and inform the driver if the vehicle is not up to standard. Fines may be issued in severe cases if the vehicle is not in correct functionality.

The second method of inspection is for stations that do not have a dedicated vehicle inspection pit. Visual inspection are performed often in the lanes that is dedicated for the normal TCC operation. The screener lane is often the easiest location for this inspection. This has the drawback of disrupting the flow as a vehicle will cause all traffic to be halted in the specific lane that will ensure delays for other vehicles using the same lane.

2.2.2 International overload control

International overload control measures are similar to South Africa's. This is not surprising because a third world country often observes international trends before implementing its own measures.

Because a vehicle that is overloaded by 10% increases road pavement damage by 40% [91,92], countries have introduced overload control interventions to protect the road pavement and other infrastructure [91,93]. Their overload control limitations and legislation are therefore directly linked to the road pavement design, as discussed in Section 2.2.3.

The United States of America (USA) is significantly different from other countries in that each state has its own specific mass limitations [93]. However, interstate highways are required to be compliant with national DOT regulations, similar to South Africa's national roads. A minor difference is that limitations are stipulated in pounds (lbs) rather than kg. Single-, dual-, and tandem axles' maximum mass constraints are indicated in the same manner as in South Africa. The formula for road bridges also dictates vehicle limitations because it is used in bridge and road pavement design.

The implementation of WIM in countries abroad has a similar focus on reducing the number of vehicles that are weighed statically at a TCC. Attempting to weigh all vehicles statically and quickly causes extreme congestion at the TCC, which allows vehicles to bypass static weighing [94]. This has sometimes happened only 10 minutes after the TCC has become operational when all vehicles needed to be weighed statically

without any prescreening WIM. Countries such as America, Brazil, Chile, Hungary and Poland have TCC layouts close to the static scale that are similar to the South African screener lane configuration, as indicated in Figure 2.20 [94,95]. The vehicle's mass with tolerance is determined by the WIM, which is combined with automatic number plate recognition (ANPR) for vehicle identification [96]. The vehicle is then directed to the static scale for more accurate mass verification.

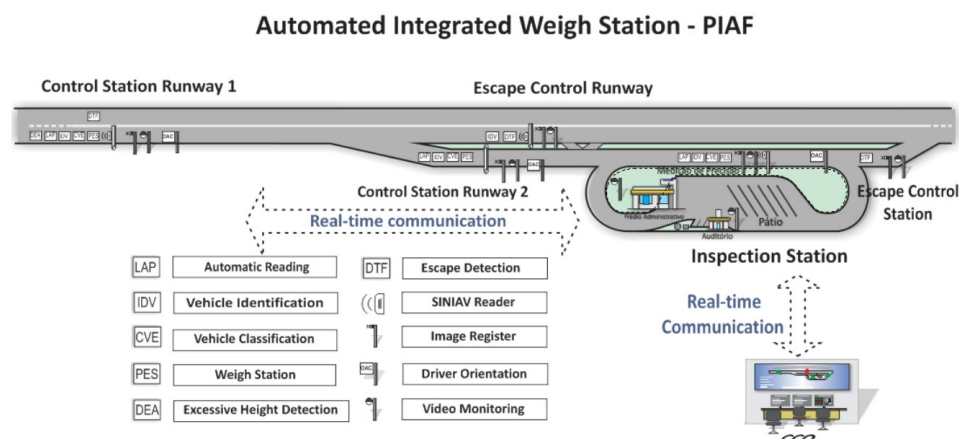


Figure 2.20: Flow diagram of the overloading control process for an Automated Integrated Weigh Station (PIAF) [94]

An alternative WIM configuration is often used to improve information-gathering along a route that does not have a fully constructed TCC [97,98]. This is often referred to as Virtual Weigh-in-Motion (VWIM) or a Virtual Weigh Station (VWS) internationally and the WIM is frequently conducted with vehicle identification in a corridor formed by law enforcement vehicles [97,98]. Vehicle mass information and identification are shared with local law enforcement so that they can take appropriate action if a vehicle is overloaded. Figure 2.21 indicates the implementation. This information is often gathered over a long period of time and linked to specific owners or companies to track how often overloading occurs for more direct intervention with the entity. Detection of overloading by the VWIM ensures that traffic officials can direct vehicles to a static scale on the corridor for a more accurate measurement. South Africa has similar implementation on corridors such as the N3 in KwaZulu-Natal, with several WIM installations on the corridor, and information is relayed to traffic officials for action.



Figure 2.21: Flow diagram of the overloading control process [95]

Several countries are in the process of implementing WIM for direct enforcement and prosecution. Chile was one of the first countries to do so successfully [95]. Belgium, the Czech Republic, France, Poland, and the USA have implemented legislation to make similar use of WIM stations for direct enforcement [99–105]. This is only possible if the scales are extremely accurate and extensive research is conducted to ensure calibration is exact. Iran has moved towards applying ANN models specifically for direct enforcement [106]. These models use WIM weights, axle configurations, axle loads, and AVCM for direct enforcement.

Auto calibration techniques have been successfully developed in countries such as Poland [107,108]. Research is still being conducted to improve the efficiency of the auto calibration further. Auto calibration research includes further testing, practical experiments, and modelling. These studies indicate that auto calibration algorithms should be tailored to the usage conditions [107,109]. The algorithms need to compensate for interfering factors such as traffic flow and temperature variations.

Any steps towards auto calibration must start with reliable calibration of the scales. Several studies have been directed towards testing and calibrating WIM scales and ensuring high data quality. Switzerland has implemented techniques to ensure performance assessment, testing, and certification norms [110]. Tests to evaluate differences

in industry norms are being conducted in climatic chambers and on road surfaces [110]. Work is being conducted each year to ensure calibration techniques are refined. Data-based WIM calibration and data quality are keys to further improving the reliability of WIM systems [111–113]. This extends to looking into the vehicle dynamics that need to be taken into account when they are travelling over the scales [114].

The weight of a vehicle with a mass sensor unit (MSU) on board can be measured while the vehicle is in transit [115,116]. Vehicles equipped with MSUs can be tracked while travelling and violations can be logged. There is still ongoing assessment of the technology capability, framework development, and integration into existing technology with new use cases [116].

It is possible for electronic screening (e-screening) to assist vehicles to legitimately bypass a TCC for static scale visits. Vehicle owners voluntarily join schemes such as *PrePass*, *Caltrans*, and *TxDOT* in the USA. An electronic tag is installed on their vehicles and scanned at WIM stations, and they are allowed to bypass a TCC if no mass violation is detected. The companies that use e-screening are tracked over the long term to determine whether their performance stays legal or violations occur.

Advanced data processing of screening and traffic flow can assist with traffic control and convoy detection to detect potential suspicious vehicles travelling on the corridor [117]. This is done by using HSWIM for electronic sensing on corridors. Successful sharing of the data requires a fixed methodology of data storage. The aggregation of heavy vehicle and WIM data into a formal data model is being investigated to improve the system's implementation [118]. This is an ongoing effort and buy-in from multiple parties is required to make it a success.

2.2.3 Road pavement construction and rehabilitation

Road infrastructure construction projects are similar to many other multi-disciplinary project. There are specific stages that must be followed to ensure success. Establishing the user's initial requirements is a key aspect that feeds through to the later stages [119]. It is essential to confirm the user requirement statement (URS) to minimise scope creep in later stages of the project [119].

A road pavement is designed in terms of traffic flow, heavy vehicle movement, and its expected lifespan. SANRAL has developed a *South African Pavement Engineering Manual* stipulating the design principles of the road infrastructure installation from start to finish [120].

A traffic estimation is an essential starting point for the design, with multiple variables to take into account. An extract of all the variables considered can be seen in Figure 2.22. The essentials for this study are the aspects relating to heavy vehicles [120].

- **E80**: standard axle load (80 kN per axle)
- **E80/HV**: E80, also known as the equivalent standard axle load (ESAL) per heavy vehicle, considering all axles
- **EVU**: equivalent vehicle units with respect to lane capacity (e.g., 1 heavy = 3 light)
- **HVV**: heavy vehicle volume
- **LEF**: load equivalency factor
- **n**: damage exponent in power damage law
- **sdp**: structural design period
- **SHV**: short heavy vehicle
- **WIM**: weigh-in-motion.

- **AADE:** annual average daily E80s
- **AADT:** annual average daily traffic
- **ADE:** average daily equivalent E80s
- **ADT:** average daily traffic
- **ADTT:** average daily truck traffic
- **B_E:** lane distribution factor
- **CTO:** Comprehensive Traffic Observations Stations
- **E80:** standard axle load (80 kN per axle)
- **E80/HV:** E80 per heavy vehicle, considering all axles
- **ES0.003 to ES100:** TRH4 design traffic classes
- **ET:** cumulative equivalent traffic
- **EVU:** equivalent vehicle units with respect to lane capacity (e.g., 1 heavy = 3 light)
- **F_{7/5}:** adjustment of 5 day to 7 day traffic count
- **F_E:** adjustment for exceptional periods
- **F_S:** adjustment for seasonal variation
- **HVV:** heavy vehicle volume
- **LEF:** load equivalency factor
- **MESA:** million equivalent standard axles
- **n:** damage exponent in power damage law
- **sdp:** structural design period
- **SHV:** short heavy vehicle
- **WIM:** weigh-in-motion

Figure 2.22: Variables extracted for the analysis phase from SANRAL [120]

Analysis of the standard 80kN axle load was developed in a first world country and third world countries greatly benefit from using the knowledge obtained [120–122]. The standard axle load concept was initially researched in 1961 after extensive road tests [120]. Even though the standard 80kN axle load has no direct link to permissible axle loads, it is used as a design standard [120]. The load equivalence factor (LEF), also known as the power damage law, is important for determining the relationship between the axle load and the damage an overloaded axle can do compared to a standard standard 80kN axle load axle load [120]. The fourth power law ($n = 4$) was also

determined in the study conducted in 1961 [120,121]. This equation can however vary with ($n = 2$) and in extreme cases increase to ($n = 10$). The equation for LEF can be seen in Figure 2.23.

$$\frac{\text{Structural capacity for reference load}}{\text{Structural capacity for load } P} = \text{LEF} = \left(\frac{P}{80}\right)^n$$

where	LEF	=	Load Equivalency Factor (E80)
	P	=	Any axle load for which the load equivalency is required (kN)
	80	=	Reference axle load, typically 80 kN (standard axle)
	n	=	damage exponent

Figure 2.23: The LEF or power damage law equation [120]

The design of road pavement has been conducted by means of the standard 80kN axle load since the 1960 but research and industry effort has ensured that a road pavement design has changed towards the Mechanistic-Empirical Design method [123]. The design practice ensures that several conditions are taken into account to ensure proper road pavement design for a specific region. These include traffic data input, climatic data input, performance criteria, and others [123]. The design practices are intended to improve design reliability, predict specific failure modes (which can minimise premature failures), better characterise seasonal/drainage effects and reduce overall life cycle costs [123,124]. Studies have been conducted on various axle configurations and the damage they impose on the road pavement, which is indicated in Figure 2.24 [120]. It can be seen that some axle configurations when overloaded cause as much as 100 times the damage of a standard 80kN axle load. Grouped axles are often used in heavy vehicles and therefore the LEF of the groups should also be calculated, as is shown in Figure 2.25 [120].

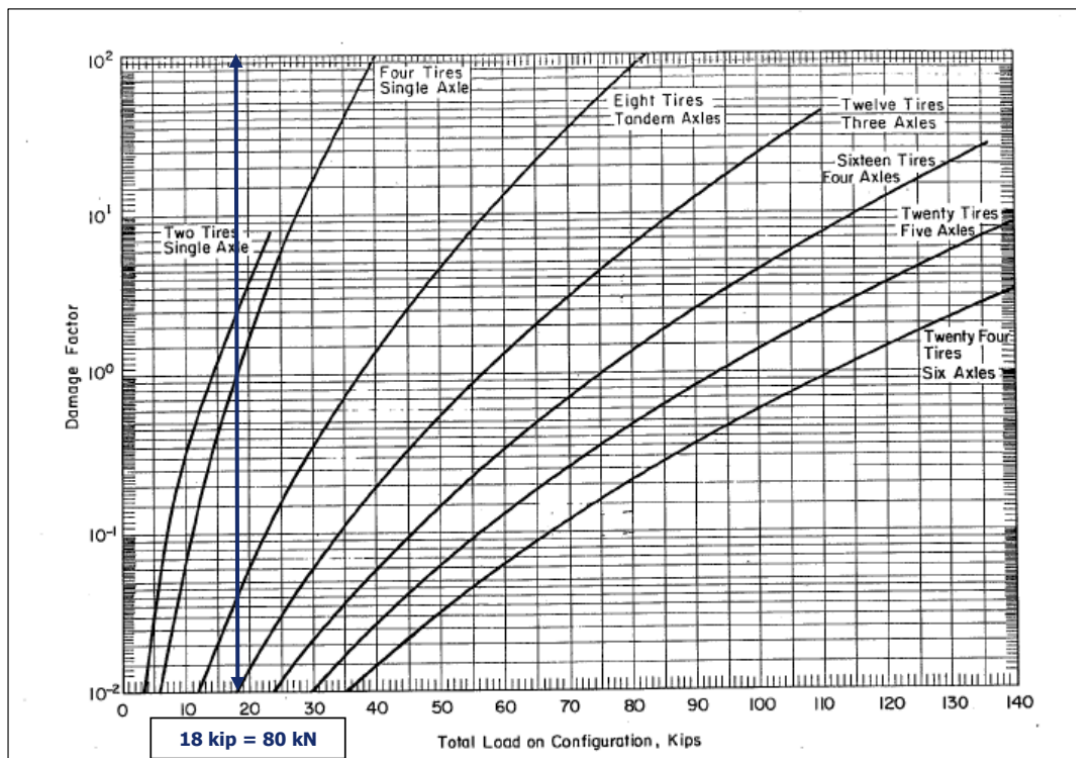


Figure 2.24: Damage factors for various axle configurations as a function of total load [120]

$$LEF_i = \frac{\left(\frac{P_l}{80}\right)^n + \left(\frac{P_u}{80}\right)^n}{2}$$

where LEF_i = Load Equivalency Factor (E80) for the load interval i
 P_l = Lower limit of the axle load interval (kN)
 P_u = Upper limit of the axle load interval (kN)
 80 = Reference axle load (80 kN)
 n = Damage exponent

Figure 2.25: Load equivalency of grouped axle load data [120]

Designing for the lifetime of road infrastructure requires a calculation of its lifetime, taking into account the full traffic spectrum [120]. The calculation has to establish, firstly, *the number of ultimate load repetitions of each axle group* to determine the fatigue of a layer in the road [120] and, secondly, *the proportion of damage* caused by the loads [120]. These

figures *add the damage for each axle load and axle load group* to the equation in Figure 2.26, which is used to determine the end of life of a layer in the road [120].

$$\text{Damage} = \sum \frac{n_{j,i}}{N_{j,\max}} \leq 1$$

where $n_{j,i}$ = Number of load applications of load j
 $N_{j,\max}$ = Repetitions to failure of load j , as determined by transfer function

Figure 2.26: Lifespan calculations due to damage by axle and axle group loads [120]

The traffic volume monitoring that toll concessionaires conduct in conjunction with their load calculations ensures correct maintenance intervals. These parameters are monitored by means of traffic counting, WIM records, and/or traffic surveys. The parameters are indicated in Figure 2.27 [120]. Incorporation of the information gathered in this phase ensures that accurate lifespan calculations can be done with the design choices of the engineer. The lifespan factor is the final requirement for calculating the number of standard 80kN axle loads the road pavement will be able to handle [120]. Typically, a structural design period is for a 20-year lifespan.

- **ADT** is the average daily traffic, and includes all vehicles (light and heavy) travelling in all directions.
- **AADT** is the average annual daily traffic and includes all vehicles and all directions. The total year's traffic is divided by 365 days. Heavy vehicles are often given as a percentage of the AADT or ADT.
- **ADE** is the average E80s per lane per day over the duration of the survey period, calculated using Equation (4).
- **AADE** is the total E80s per lane for one year, divided by 365 days. ADE is extrapolated over the year to get AADE. Care must be taken to ensure the ADE survey period is representative of the full year's traffic.

Figure 2.27: Traffic count parameters [120]

2.2.4 Impact of overloading

The previous section indicated that extensive work is done in the design phase to establish the number of standard 80kN axle loads that the road pavement can handle before it requires maintenance. It is easy to show the impact of overloading on the road pavement by making use of this variable. Historic studies have indicated that, if 15–20% of vehicles are overloaded, they will cause 60% of the damage to the road, as indicated in Figure 2.28 [28]. A vehicle overloaded by 10% can cause 40% additional damage when compared to ESALs [32]. The damage is however can be significantly lower and is highly dependent on the road pavement design that will increase or reduce the damage exponent n . National highways design are in most cases designed for larger volumes of heavy vehicle travelling and thus higher standard 80kN axle loads traffic before deterioration is expected. Primary roads are often designed for 100 million standard 80kN axle loads and secondary roads around 10 to 30 million standard axle loads. Further improvement to the design process is conducted by making use of Heavy Vehicle Simulator to have accelerated road pavement design testing [125]. This method ensures that better estimates are developed for different road pavement designs and serve as input with the Mechanistic-Empirical Design for a reliable road infrastructure.

Cost estimates have established the marginal cost per square km as 0,066 Swedish krona (SEK) or ZAR 0,096 per ESAL [126]. SANRAL has indicated that periodic maintenance costs are ZAR 2–3 million per km, with improvements to roads of unacceptable quality going as high as ZAR 12–18 million per km [46].

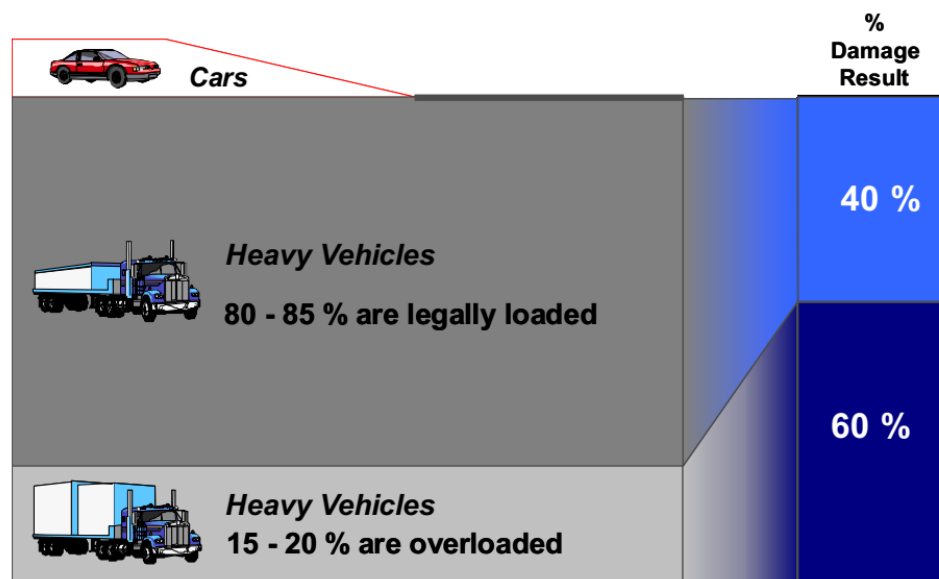


Figure 2.28: Estimated road damage due to overloading [28]

Road pavement damage is not the only impact of overloaded vehicles but it is the easiest to see. Operating costs of heavy vehicles increase by up to 12,8% when they operate on deteriorated road infrastructure [127]. Overloaded vehicles operate outside their manufacturers' design specifications, therefore they have an increased likelihood of being involved in crashes [27]. Overloaded vehicles tend to travel the roads less travelled – secondary roads, which are not designed for large amounts of heavy vehicles and do not have maintenance operation on them as regularly as primary and concessionaires maintained road infrastructure.

The costs due to road crashes have been estimated at ZAR 142,95 billion, which equates to 3,4% of South Africa's GDP [128]. The facts indicate that only 4,8% of crashes involve heavy vehicles but there are usually many fatalities when they do occur [129, 130]. The extensive impact on the economy includes police time in clearing the crash scene, lost working hours of workers stuck in traffic, and delayed delivery of goods [130].

2.3 Vehicle identification

Accurate identification of vehicles is essential for the prosecution process because prosecution of an overloaded vehicle must be dropped if doubt can be shed on something as minor as its identification. The multiple identification methods that are available include automatic number plate recognition, radio frequency identification and manual records.

2.3.1 Automatic number plate recognition

A camera is required for ANPR, also known as automatic license plate recognition (ALPR) or simply license plate recognition (LPR), as well as optical character recognition (OCR) to determine the text on the license plate of the vehicle. The system typically makes use of a high-speed camera with an infrared (IR) filter to capture the image [131]. The accuracy of the camera changes according to the time of day, as illustrated in Figure 2.29. The system's accuracy is highly dependent on limitations that are addressed by adopting a set of good practices [132].

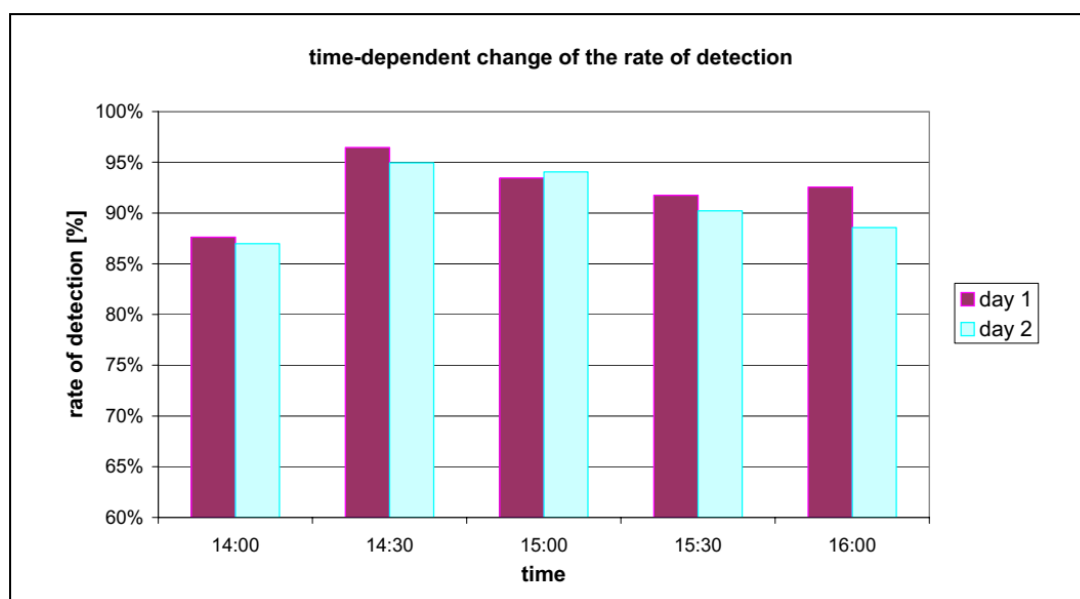


Figure 2.29: Detection rates at different times for two days [133]

Accuracy is in the range of 70% and implementation of good practices can increase the detection rate from around 85% to 100%, as indicated in Figure 2.30 [96, 133, 134]. The image quality is improved by considering the positioning of the camera – its placement height and angle, and its range of view – the IR illumination, and the type and size of the lens [132, 135]. These cameras are installed at WIM and static scales in TCCs.

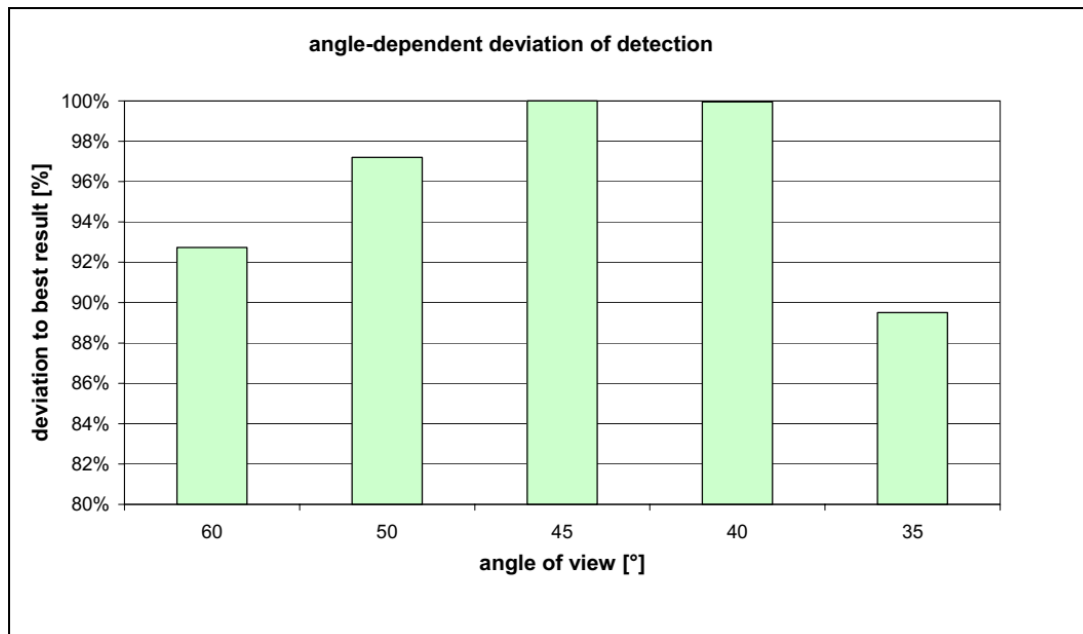


Figure 2.30: Angle-dependent detection rates [133]

2.3.2 Radio frequency identification

Implementation of acRFID has been assimilated into various industries besides logistics and SCM [6, 56]. Governments have adopted e-screening of vehicles to enforce regulations [136]. Studies have shown that e-screening of legally loaded vehicles has decreased travel times and emissions [136]. This reduction is due to vehicles being allowed to bypass specific weigh station where they are implemented and thus not being required to queue at the stations to be statically weighed [136].

South Africa has implemented radio frequency identification (RFID) tagging of vehicles in open road tolling and operations at TCCs. It has limited implementation at the TCCs,

except on the N4, where the internal process is managed by vehicle identification at specific points in the weigh station. Vehicles are tagged and registered the first time they enter a TCC. For heavy vehicles, it is important to place RFID tags on the lower part of the windscreen [137, 138].

The accuracy of RFID has been shown to be close to 100% for speeds in excess of 120 kilometres per hour (km/h) [137, 138]. The accuracy has been shown to be reduced in some cases when speeds are over 200 km/h [137, 138].

2.3.3 Manual entry of registration numbers

Situations may arise when the ANPR is inaccurate, even after implementing best practices in camera placement. This inaccuracy means that the weighbridge operators need to manually verify the ANPR with what can be seen on the vehicle's license plate. Additional human errors may occur in this step (or license plate details may purposefully not be input).

2.4 Self-regulation

The industry has realised the need for improvements in overload control and has implemented self-regulation measures that have protected infrastructure, improved operations, and enhanced safety. Successful implementation and debates could lead to regulatory changes for the entire industry [139].

2.4.1 Road traffic management systems

A Road Transport Management System (RTMS) was started in 2003 after the realisation that heavy vehicle overloading and road safety were major issues in South Africa [140]. Initial projects were launched in the KZN and Mpumalanga provinces with a heavy

vehicle accreditation scheme in the forestry industry [140]. A 40% reduction in overloading was experienced within two years of the implementation [140]. This astonishing result led to the establishment of a steering committee to expand implementation to additional sectors. Key aspects of the scheme address [140]:

- Load optimisation
- Driver wellness
- Vehicle maintenance
- Productivity

Results have clearly indicated the success of the RTMS, with SANRAL indicating that fleet owners report a reduction of 90% in prosecutable overloading offences, a 75% decrease in speeding offences, a 40% improvement in fuel consumption, and a 44% decrease in crashes [41–43]. The South African National Standard (SANS) 1395-1:2014 has been constructed as the industry standard for RTMSs [141]. Accreditation by the scheme has improved operational processes, which are audited annually by an independent company, and may lose their accreditation if consistent compliance to the standards are not met by the company [142].

2.4.2 National Heavy Vehicle Accreditation Scheme

Australia has initiated a National Heavy Vehicle Accreditation Scheme (NHVAS) for self-regulation. Similar to the success of RTMSs, crash rates of non-accredited vehicles were 2,5 times higher than the crash rates of accredited vehicles [139]. The key factors of the scheme can be applied to address specific business goals. Implementation of the scheme is also designed to improve safety and productivity in the sector [143]. It entails managing mass, maintenance and fatigue as follows:

- **Mass Management:** This management module is intended to implement good practices in the loading and documentation procedure, with the key benefit of being allowed to load additional tonnage on a trip [144]. It also results in improved productivity, correct loading at the first attempt, minimised maintenance,

improved relationships with enforcement agencies, and it reduces the impact of law enforcement [144].

- **Maintenance Management:** This management module is intended to ensure the vehicle is maintained at a high standard at all times [145]. Benefits include improved efficiency, increased lifespan of vehicle assets, more confidence in vehicles, and improved relationships with enforcement agencies [145].
- **Basic Fatigue Management:** This part of the NHVAS addresses the road safety aspects of managing the fitness of the driver to operate the vehicle [146]. Aspects that are reviewed include medical assessment, use of alcohol/drugs, medical conditions, and the driver's current state of fatigue.

Self-regulation has been extended to altering vehicles to optimise loading capacity while improving vehicle safety by means of performance-based standards (PBSs).

2.4.3 Performance-based standards

PBSs have their origin in Canada and New Zealand in the 1980's with expansion to Australia in the 1990's. PBSs started to gaining traction in South Africa in the 2000's with the first pilot project being conducted in 2007 [147]. The PBSs scheme specifically assesses vehicle performance on the road to grant dimensional and mass exemptions so that vehicles with higher productivity can continue to make use of the road infrastructure legally [148].

Case studies in South Africa indicate a large productivity improvement [149]. Payloads of test case vehicles increased as much as 19,9%, and fuel consumption decreased by as much as 13,2% per tonne hauled [149]. A dual tyre axle configuration can cause a 61% decrease in road wear per ton of payload compared to non-PBS vehicles [150]. This is an improvement on prior generation PBS designs, which increased road wear by 9% [150].

The safety of the vehicle is so important that several simulations are conducted on the design to determine the vehicle's performance before alterations are made to a South African vehicle [151]. The tests include high-speed lane-changes, low-speed turns,

tracking ability on an uneven surface, and a rollover test [151]. This process is directly related to that of its Australian counterpart [152].

Simulation within any industry requires appropriate data collection as well as data processing to gain insight. Data processing implementation is discussed in the following section.

2.5 Data processing

Data collection is an essential part of any operation because knowledge developed from the data can facilitate a deeper understanding of the operation. This is also true for the intended data sharing required for the algorithm proposed in this thesis.

Recently, data collection in multiple sectors has been scaled up by big data management, cloud computing, and AI. The introduction of big data and the internet of things (IOT) has ensured that larger quantities of data are available for processing. The question is What is the most efficient way to process the data to obtain relevant information and knowledge to fuel an optimised system decision-making process? The system optimisation has to be able to process inputs from several data sources with a high probability of noise.

The human brain has the capacity to find patterns in data if it spends enough time on it. Historically, statistical analysis of data was a key factor in gaining some form of knowledge from a data set. However, the speed at which decisions have to be taken means that large data sets cannot be processed manually. A mechanism is required to convert data to knowledge as fast as possible to assist business operations.

Technology has allowed multiple mechanisms to be developed to take large volumes of data and process them, and to provide some form of decision-making support. These mechanisms include analytic tools or business intelligence (BI) tools, and AI, each of which has benefits and constraints when implemented.

BI tools are essentially tools that are available for data analysts to use or develop to interpret data quickly. They can be developed as needs arise in a business environment. However, the analyst requires insight into the relevant field to extract the information required to construct the tools, and acquiring that insight can take considerable time. Nevertheless, using BI tools is much faster than historical data processing on platforms such as Excel.

The trend has recently changed to making use of *AI techniques*. AI is implemented to make a machine think and behave intelligently [153,154]. It is a mechanism to collect large amounts of data efficiently, in ways that a human cannot process, and to extract some knowledge to improve real-world and real-time decision-making [153–155]. AI development has improved over the last few decades and AI is now in common use, without being obvious to the general public [156].

There are various AI methods that can be implemented with specific outcomes in mind. Natural language processing is an example of AI, where a mobile phone can react to voice commands such as “Hey Siri” or “Hey Google” and understand the instructions to start phone calls, set reminders, or start navigation tools [36,157]. Back end analytics are used in large corporations such as Facebook and Google to predict market trends or understand their users so as to target advertising [36]. AI is being used to improve cities and evolve them into smart cities and to develop self-driving cars [37,158]. Improving business operations is another typical application of AI. Applications range from detecting water leaks to optimising warehouse flows [34,159]. In the field of overload control, AI is used for predicting static scale masses from WIM measurements [35].

All these applications indicate that the implementation of AI has significant benefits for freight corridor and TCC operations. The overload control process has multiple inputs for which the key outcome is to determine whether a vehicle is overloaded or not. The focus of the next few paragraphs is therefore on brief overviews of the extensive literature about the AI methods that can be used to do this [160]. The method selected is discussed in Chapter 4.

Fuzzy logic is based on the mathematical theory of fuzzy sets created by Lotfi Zadeh in 1965, which is an extension set of Boolean logic [161, 162]. The advantage of using fuzzy logic is that it takes a human reasoning process and puts it into a natural language or pseudo code [161, 163]. Logical reasoning functions on a true or false basis and fuzzy logic addresses the proportion that can be true [163] to choose an outcome based on the probability in a logical process. Such processes are used to create intelligent systems [164].

The **laws of thought** approach in AI uses *intelligent agents* or rational agents to determine the best possible outcome when uncertainty is present in the decision process [164]. An agent is defined as anything that perceives the environment through sensors and make changes through actuators [164]. The behaviour of agents is mathematically described by mapping sequences to actions through agent functions [164]. These agents are as good as the function they are constructed on.

The input-output relationship between data is often of interest in data analysis [165]. This aspect is no different in the overload control scenario. Several classifiers can be used to determine a discrete outcome variable [166]. These include [36, 153, 167]:

- Logistic regression
- naïve Bayes
- Random forest

Logistic regression is one of the techniques used to explain the relationship between assumed input independent variables with a dependent variable as output [153]. The function takes an input vector multiplied by a set of mass to determine the output vector [167]. A mathematical representation of this can be seen in Figure 2.31. This can be simplified to determine y_pred_i and the final probability equation of the outcome is a binary output of true or false.

$$\begin{bmatrix} X(0) \\ X(1) \\ \vdots \\ X(n) \end{bmatrix} * W = \begin{bmatrix} Y(0) \\ Y(1) \\ \vdots \\ Y(n) \end{bmatrix}$$

$$y\_pred_i = sign(X_i * W)$$

$$Prob(y_i = +1 | X_i) = logistic(X_i \cdot W)$$

Figure 2.31: Simplified logistic regression mathematical equations [167]

The **naïve Bayes** classifier is based on the probabilistic binary outcome or multi-class output [167]. This technique considers each input variable's contribution to the outcome, assuming that the input variables are independent [153]. Subsets of naïve Bayes techniques can be implemented, such as the Gaussian and Bernoulli, where the function assumes that the variables are generated on a Gaussian or Bernoulli distribution [167]. Like the logistic regression technique, the probability of the outcome is determined by the simplified mathematical equation in Figure 2.32.

$$Prob(Ck, X(i,0), \dots, X(i,n)) = Prob(X(i,0), \dots, X(i,n) | Ck)$$

Figure 2.32: Simplified naïve Bayes equations [167, p. 206]

Random forest is a technique that makes use of several decision trees during construction [153]. Decision trees have branches with simple decisions, where each decision is basically a rule that is constructed, based on the input variables and the target output variable [153]. Once the rule has been constructed, it steps through all the decision

trees and finally determines the outcome based on the input [153]. A benefit of the random forest is that it incorporates a form of dropout to ensure it does not overfit on the training data by only making use of a subset of the input variables [153]. A simple tree example can be seen in Figure 2.33, where input variables are used to determine the potential rainfall. A random forest tree example is indicated in Figure 2.34, where multiple decision trees are combined to assist in an ensemble of decision trees.

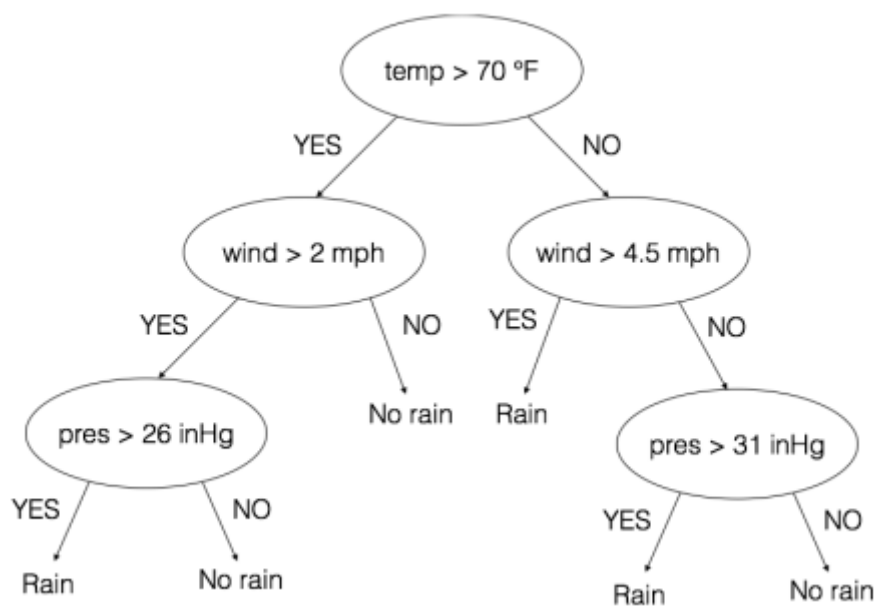


Figure 2.33: Simplified decision tree example [168]

Implementation of these classifiers has the ability to take multiple, seemingly independent data inputs to produce a discreet output [153,167]. The methods have recently been improved by making use of machine learning or ANN.

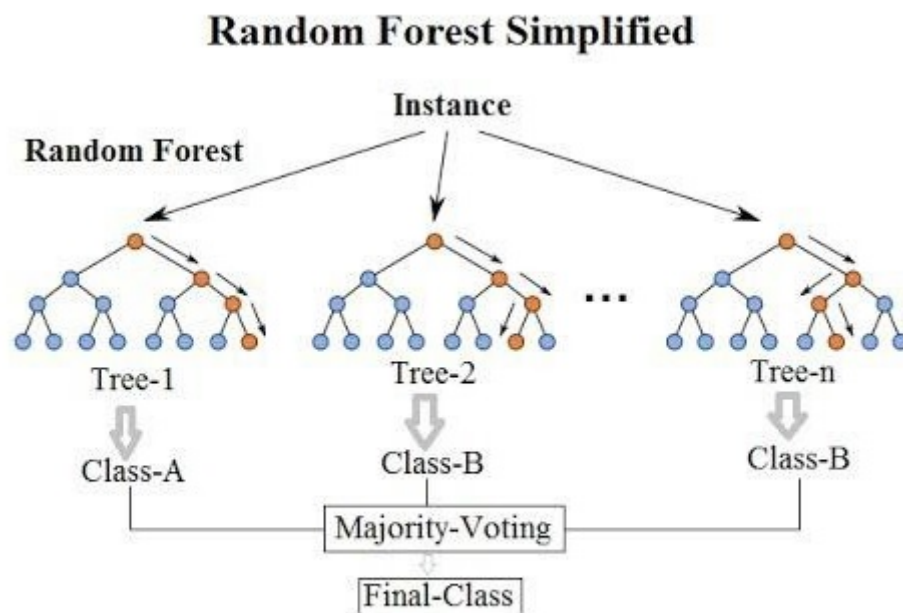


Figure 2.34: Random Forrest Simplified example [169]

Machine learning has its origins in work published in 1957 regarding the *concept of the perceptron learning rule based on the McCulloch-Pitts (MCP) neuron model* [155]. This was the first concept that proposed that an algorithm would automatically be able to learn mass coefficients in an input to make an output decision [155]. Machine learning algorithms are dependent on numerical data that can be analysed to extract meaningful information [153], therefore data must be processed before implementing machine learning algorithms [167]. Algorithms that can typically be implemented with classifiers include the following [155, 167]:

- k-nearest neighbours (kNN) algorithms
- support vector machine (SVM)
- Deep learning algorithms
- Ensemble learning

Each algorithm has its own purpose and commonly requires a 80/20 split in training data and test data. An algorithm such as the **kNN** is known as a lazy classifier because it makes a decision based on the nearest training set of data to conclude an output [155, 167]. The classifier looks at the closest example of the training data set and determines what classification to give the input data set [167]. This method can, unfortunately, take an extremely long time to train and to predict, depending on the size of the training data set, and it may decrease in speed once a large enough data set threshold is passed [167].

A **SVM** is regarded as a powerful supervised learning technique and is stable enough to deal with noisy data. However, the output provided is only an estimation if probability calibrations are not incorporated [155]. The SVM will attempt to determine the best hyperplane to separate the classification outputs based on the input data [153]. An example of a hyperplane can be seen in Figure 2.35, with a binary output or a true-or-false output, depending on the input variables.

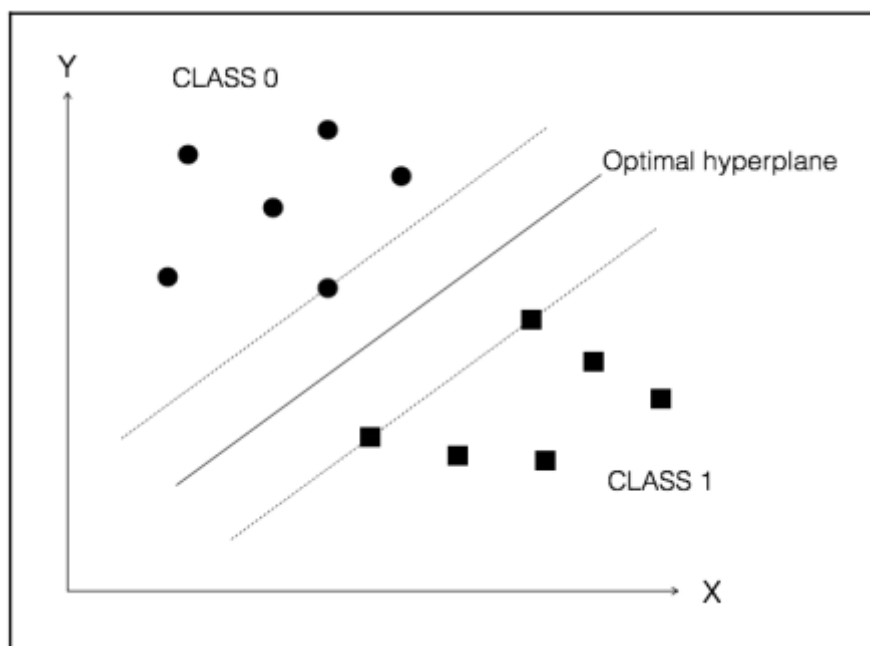


Figure 2.35: SVM hyperplane example [153]

Neural networks and deep learning are extensions of machine learning to solve problems [153,155,167]. They are based on the human learning principle, where the neural network is constructed on layers of neurons [155,167]. These neurons have an input layer, a hidden layer, and an output layer, to which neurons with a weighted value are connected during the learning phase [153,155,167]. A visual representation can be seen in Figure 2.36, where the blue is the input layer, orange the hidden layer, and purple the output layer. Training by this method can be extensive due to the large number of weights that must be calculated if the input data sets are complex.

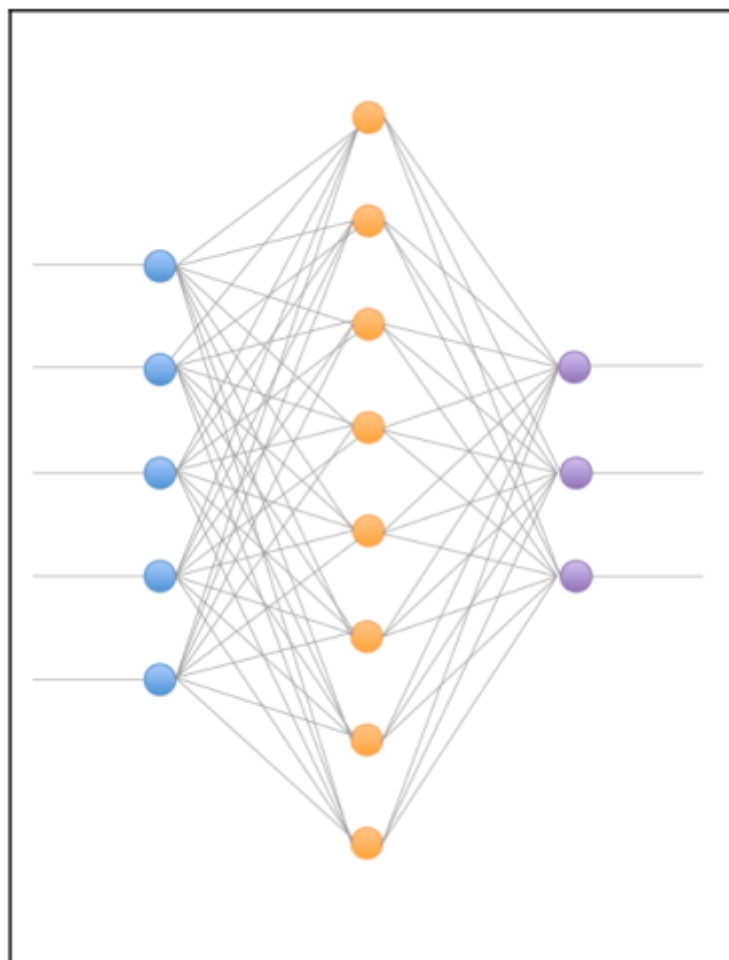


Figure 2.36: Visual representation of neurons in a neural network [167]

Ensemble learning is the use of multiple models in combination to produce better results than can be produced by a single model [153]. The combination of multiple models can use the strengths of all, while minimising or eliminating the weakness of some of the models. However, this method has the drawback that it increases the complexity and computational requirements to implement AI [155]. Ensemble learning is used for predictive modelling and anomaly detection, which require a time series or sequential data set to be constructed before implementation [167, 170].

Anomaly detection is one of the methods to determine the condition of a system by detecting unusual or unexpected events, that is, events whose occurrence is statistically improbable [170]. Anomaly detection can be used without calibrating or recalibrating a threshold that needs to be set up [170]. It assists human intuition and judgement in a business environment [170].

2.6 Conclusion

Transportation plays an essential part in the economic development of a region. Since overloaded vehicles clearly increase the damage to road pavement, inefficiencies in the overload control system can have significant effects on the road infrastructure. The impact of deteriorated road infrastructure ripples to multiple stakeholders.

Information sharing has been considered for implementation abroad for more than a decade [171]. However, investigating the local systems of overload control showed that this is not the case in South Africa. Legal vehicles are reweighed several times on a journey.

Investigations into the status quo are reported in Chapter 3 to show the full extent of current operations because improvements can only be proposed once the status quo is understood. Thus, it will be possible to find a better compromise between effective law enforcement and the impact on legal road users.

Chapter 3

The status quo and the proposed system

There are secrets in the chaos - Anonymous

This chapter presents the status quo and proposes a system to improve the efficiency of overload control at TCCs. The proposal concerns the hardware required to implement the IWIM algorithm that is developed in Chapter 4.

The work in this chapter is directed towards **Contribution 3**.

Understanding the current operational status quo is necessary for re-imagination, innovation, and process disruption towards improvement. The TCC process, the statistics of the current state of operations, and time analysis are some of the information that must be understood.

A pilot project was initiated with SANRAL to collect this information. The route that was used to establish the status quo forms part of the North-South Corridor. This corridor can be seen in Figure 1.2 on page 4 and covers the route from Durban to Beitbridge inside the borders of South Africa. Two large TCCs on the corridor were selected for analysis because they were the easiest sites to access.

3.1 Site selection for the study

The sites selected for this study were the Mantsole TCC on the N1 and the Heidelberg TCC on the N3. These stations are in sequence on the North-South Corridor.

The selected sites were used to gather current data on the operation. Some hardware had to be installed to gather information that was not previously available. The first installation was of cameras for ANPR. Another installation was of RFID readers to verify the accuracy of detecting vehicles with RFID tags installed against the camera system or the manual entry system. Transporters were contacted to tag vehicles with RFID tags and their details were captured so they could be identified throughout the study.

The data subsequently captured is described in Section 3.3. The status quo operational analysis is presented in Section 3.4 and was used as the baseline from which improvement operations were measured.

Site inspections of the Mantsole and Heidelberg TCCs were conducted after RFID readers were installed in their WIM screening lanes and static scales. Mantsole's operational flow is discussed in Section 3.1.1 below, and Heidelberg's operational flow is discussed

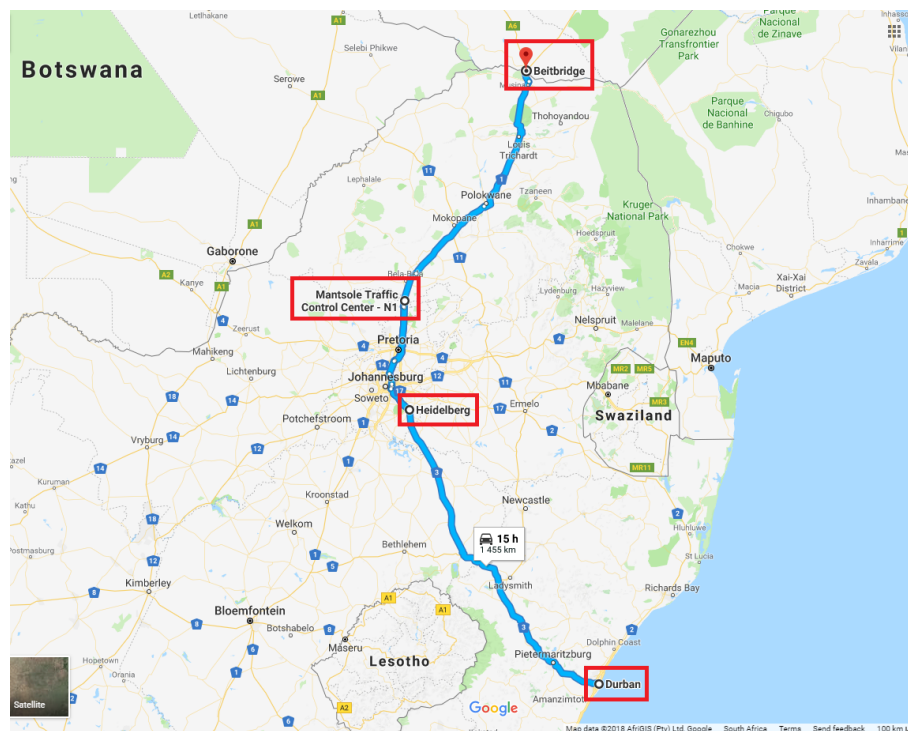


Figure 3.1: Google Earth location of the sites selected

in Section 3.1.2 thereafter. These layouts do not represent all TCC layouts in South Africa but give an overview of stations with WIM screener lanes at the TCC. Both the TCCs in the case study do in some form represents stations that have a WIM a distance away and vehicles need to be directed by traffic officials to the static scale if overloaded for static scale mass confirmation.

3.1.1 Case study - the Mantsole Traffic Control Centre

The Mantsole site has a screening lane with a WIM scale, ANPR, and an RFID reader installed in both directions of the corridor (see Figure 3.2). The site services to northbound (NB) and southbound (SB) traffic are almost mirror images of one another, except that the part of the site on the NB side has access to the R101 and the TCC also services the R101, which has a two WIMs installed. The site is managed according to a PPP agreement between SANRAL and Bakwena.

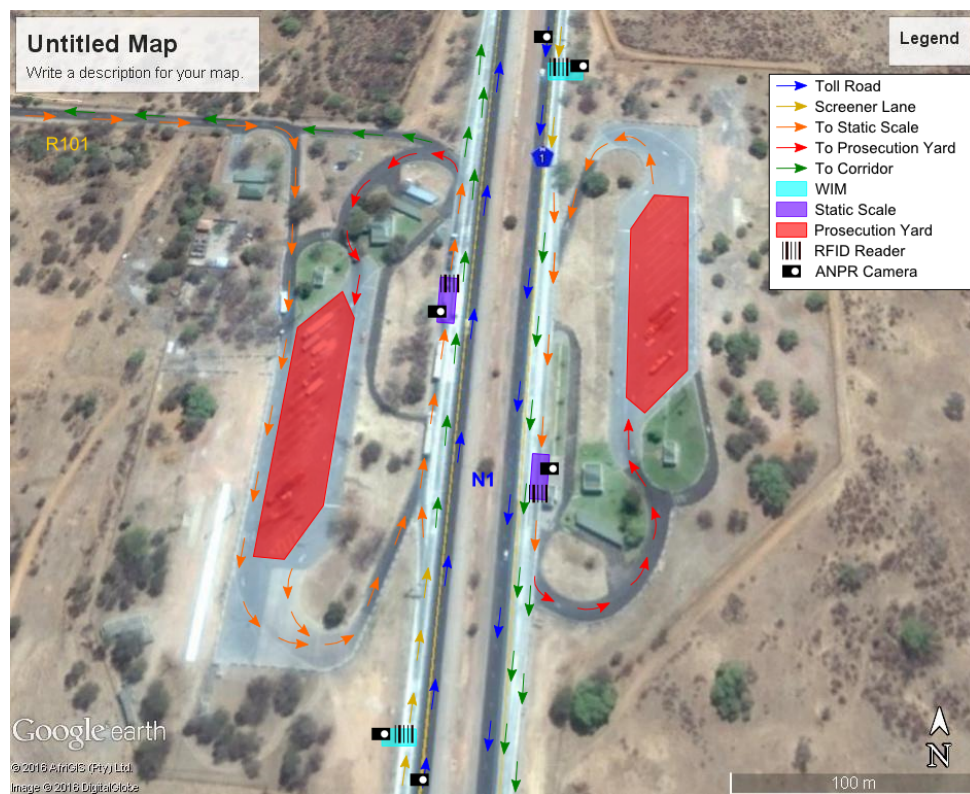


Figure 3.2: Aerial view of the Mantsole TCC – Google Earth image with arrows indicating the direction of the flow

The process flow at Mantsole is indicated in Figure 3.3, with the accompanying R101 flow in Figure 3.4. The steps in the process itemised below correspond with the enumerated values in the figure's process flow diagram.

1. The vehicle *enters the screening lane* of the TCC.
2. A *magnetic loop* is triggered in front of the WIM scale and indicates the vehicle is going to cross the WIM scale.
3. The *WIM scale is triggered* to determine the mass of the vehicle. This mass is used to decide whether the vehicle should be statically weighed.
4. A *magnetic loop* is triggered after the WIM scale to indicate the vehicle has passed across the scale.
5. *Classification of the vehicle* is determined with the WIM information (for a visual presentation of vehicle classification, see Figure 3.24 on page 118).
6. In a parallel process, an *ANPR* image is taken and processed to determine the

- license details of the vehicle and link it to the WIM record.
7. Legislation is used to determine whether the *vehicle has triggered the threshold* for being statically weighed.
 8. A vehicle that has not triggered the threshold is directed back to the corridor by a *a signal directing between static scale and the corridor*. This is the first signal the vehicle will come across when entering the TCC.
 9. A magnetic loop is *triggered at split* between static scale and the corridor.
 10. This loop trigger is used to *deactivate the first signal*.
 11. A *second signal is activated to the corridor*. It directs the vehicle to proceed on its journey when the vehicle is below the WIM threshold.
 12. A magnetic loop is *triggered after the corridor split*.
 13. This loop deactivates the *second signal*.
 14. *Alarm activation* occurs if the vehicle is overloaded according to the WIM scale.
 15. The vehicle is directed to the static scale by the *first signal but now directs the vehicle to the static scale*.
 16. The *loop* between the corridor split and the static scale is activated to detect the vehicle's movement.
 17. *Loop triggered* will determine which way the vehicle travelled.
 18. Triggering of the loop on the way to the corridor instead of the static scale will indicate a bypass and a *bypass detection alarm* is activated.
 19. The loop *deactivates the signals* and resets for the next vehicle.
 20. The vehicle is now in the queue to be statically weighed.
 21. A *loop is triggered before the static scale boom* once the vehicle reaches the front of the queue.
 22. The *boom opens* to allow the vehicle to proceed onto the static scale.
 23. The *truck parks on the static scale decks* to be weighed.
 24. The *first boom closes* behind the vehicle, ensuring another vehicle does not drive too close to the truck being weighed.
 25. *Static scale weighing of the vehicle* commences.
 26. *Linking of the mass to the registration* is conducted by means of the ANPR image or the weigh master's visual confirmation if there a mismatch.

27. *Overloaded state* of the vehicle is confirmed or rejected.
28. *The boom opens after the static scale.*
29. *Activation of the signal to holding yard* directs the vehicle to be prosecuted according to relevant legislation if it is overloaded.
30. *Loop triggers after the static scale* once the vehicle crosses.
31. *The loop trigger closes the boom after the static scale.*
32. *Opening of the boom after the static scale and the corridor boom* occurs if the vehicle is within legal limits.
33. *Signal activation* directs the vehicle back to its journey along the corridor in the same manner as the WIM signal.
34. *Loop trigger at the corridor boom* detect that vehicle has continued on its journey.
35. *Closure of the boom after the static scale and the corridor boom* completes the weighing process.
36. In the R101 process, the *vehicle travels towards the R101 WIM* scale and enters it to be weighed.
37. *A loop event triggers* when the vehicle passes over loop before the WIM scale, in the same manner as at the Mantsole TCC.
38. The WIM is triggered and the mass determined.
39. *The loop event after WIM* determines that the vehicle has crossed the scale.
40. *Vehicle classification* is conducted as in process step 5.
41. The ANPR is captured and processed for license identification, as in the process step 6.
42. *Vehicle overloaded within threshold* is processed as in step 8.
43. *A signal* directs the vehicle to the corridor if its mass is below the threshold.
44. *Loop triggers* to determine whether the vehicle is travelling in the right direction.
45. *Deactivation of the signal* occurs after the loop triggers.
46. *The signal is activated* to direct the vehicle to the corridor if the vehicle is not overloaded.
47. *Loop triggers* to determine whether the vehicle is travelling in the right direction.
48. *Signal* is deactivated after the loop triggers.
49. The TCC WIM *overloaded* procedure is followed from step 14 to 35.

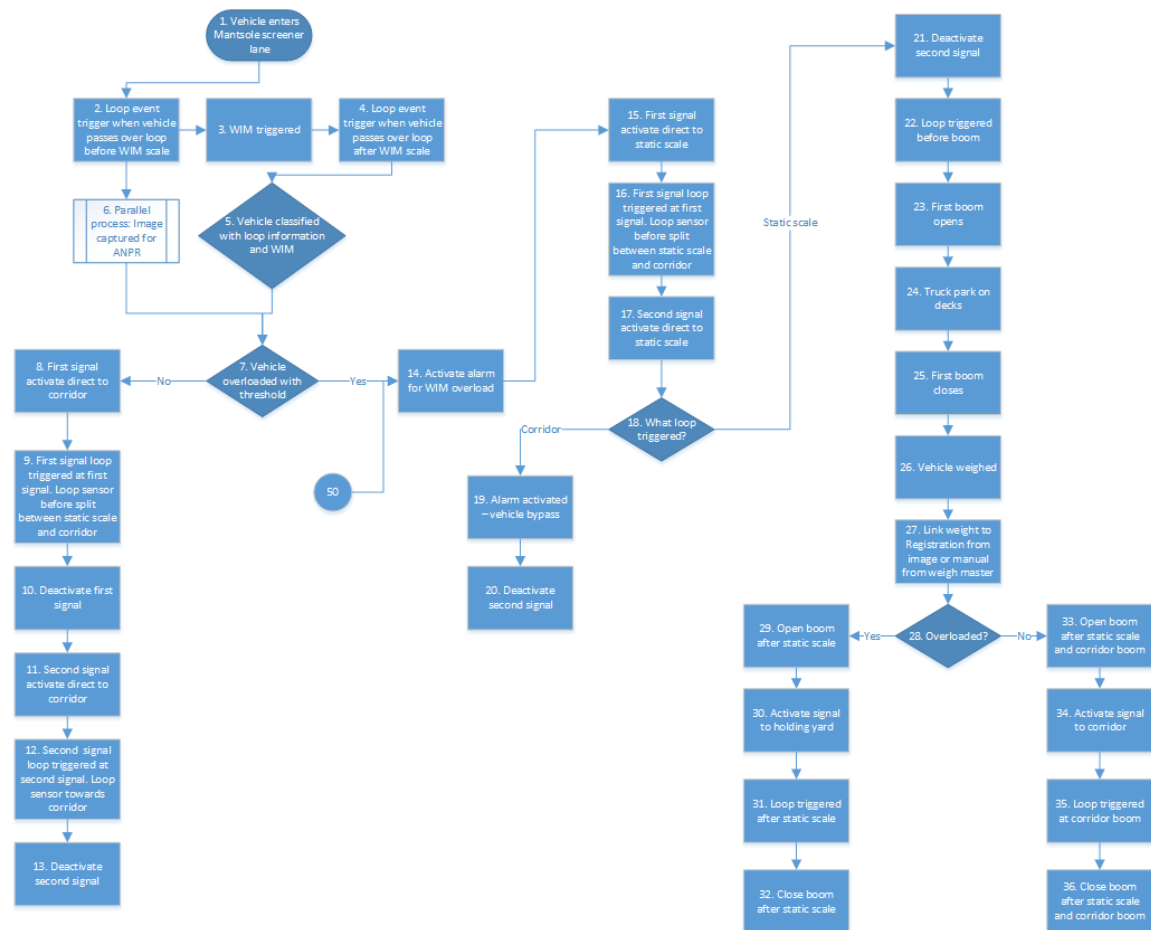


Figure 3.3: Mantsole process flow on the N1

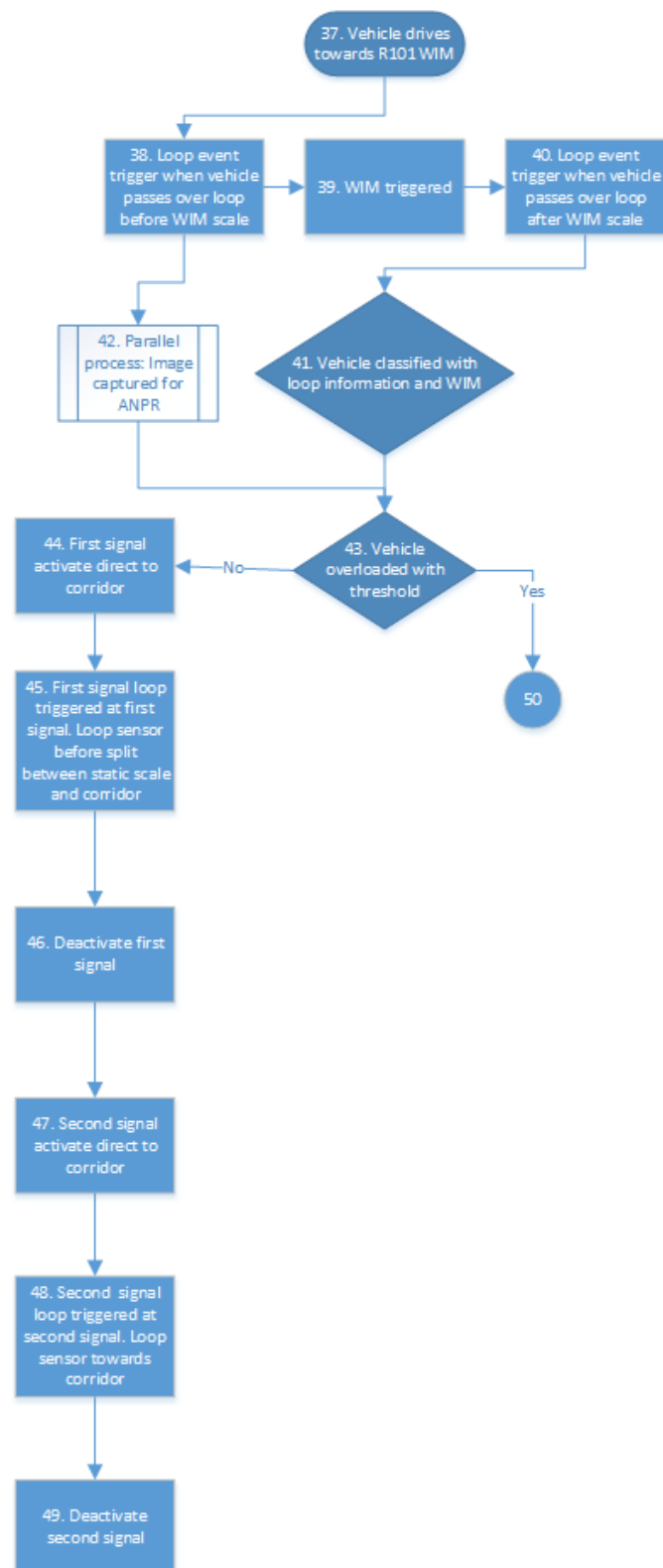


Figure 3.4: R101 process flow to Mantsole on the N1

3.1.2 Case study - the Heidelberg Traffic Control Centre

Heidelberg site configuration (Figure 3.5) has a screening lane with a WIM, ANPR, and RFID reader installed in both directions of the corridor, similar to the Mantsole configuration. The site's NB and SB sides are almost mirrored except that the NB side has access to the R103 and the SB side accesses the R23. The site services both these secondary routes and has WIM scales on each of them. The site is managed according to a PPP agreement between SANRAL and the N3TC.

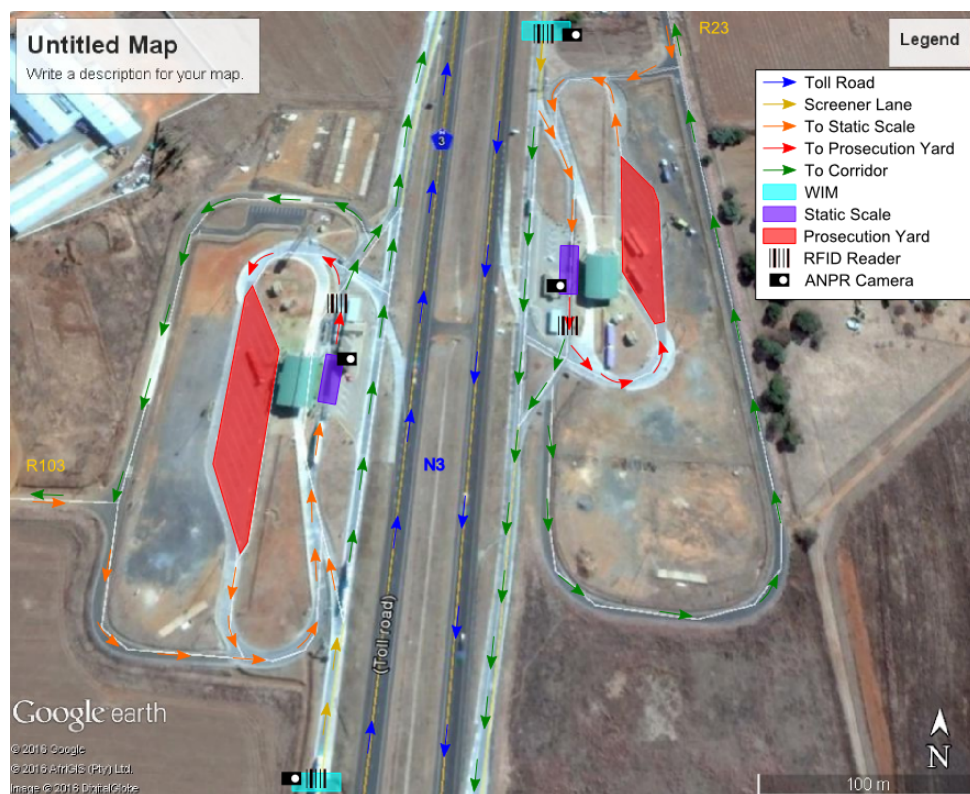


Figure 3.5: Aerial view of the Heidelberg TCC - Google earth image with arrows indicating the direction of the flow

The operational flow is the same on the NB and SB sides of the TCC and, for this reason, only one is discussed and displayed in Figure 3.6. Heidelberg SB also controls the R23 WIM and the process flows are indicated in Figure 3.7. Several steps in the process flow are exactly the same for Heidelberg as for Mantsole. A minor difference in the layout at Heidelberg can be seen where vehicles queue for the static scale. There is space for

roughly three heavy vehicles between the screening lane and the static scale. A fourth vehicle stops all flow in the screening lane. The traffic from the R103 and R23 also feeds into their respective static lane queues. This means that traffic is managed at a convergence point between two queues into one static scale. Large numbers of vehicles are directed to the static scale to verify the drivers licenses of heavy vehicle drivers, and the roadworthy tests of a roadworthy test centre are also conducted at the TCC. This causes severe delays that make it possible for vehicles to bypass the weighing process.

The steps in the process itemised below correspond with the enumerated values in Figure 3.7's process flow diagram.

1. to 17 are the same as in Mantsole's process flow.
18. The *loop detects* vehicle movement after the static scale's directing boom.
19. This ensures the *vehicle queues* for the static scale.
20. The *static scale boom* is opened by the weigh master to allow the vehicle onto the static scale.
21. The *vehicle axle, tyre details, and registration* data are captured onto the system manually by the weigh master.
22. The *static mass* is linked to the record.
23. The *boom is opened after the static scale*.
24. The *loop detects that the vehicle travelled* past the static scale.
25. The *booms are closed*.
26. The vehicle's *overloaded* status is confirmed or rejected.
27. The *prosecution directing boom is opened* if the vehicle is overloaded.
28. The *loop detects movement towards the yard*.
29. The *boom is closed* after the movement is detected.
30. The *corridor boom is opened* if the vehicle is not overloaded.
31. The *loop detects movement towards the corridor*.
32. The *boom is closed* after the movement is detected.
33. to 40 – steps are similar to Mantsole's R101 process from steps 37 to 43.
34. The *signal to corridor* is activated if the WIM threshold is not triggered.
35. The *signal to static scale* is activated if the WIM threshold is triggered.

36. The *loop detects* the movement of the vehicle towards the corridor or the static scale.
37. *Another signal is activated* to direct the vehicle to the static scale.
38. The vehicle follows the N3 TCC procedure as indicated in Figure 3.6.

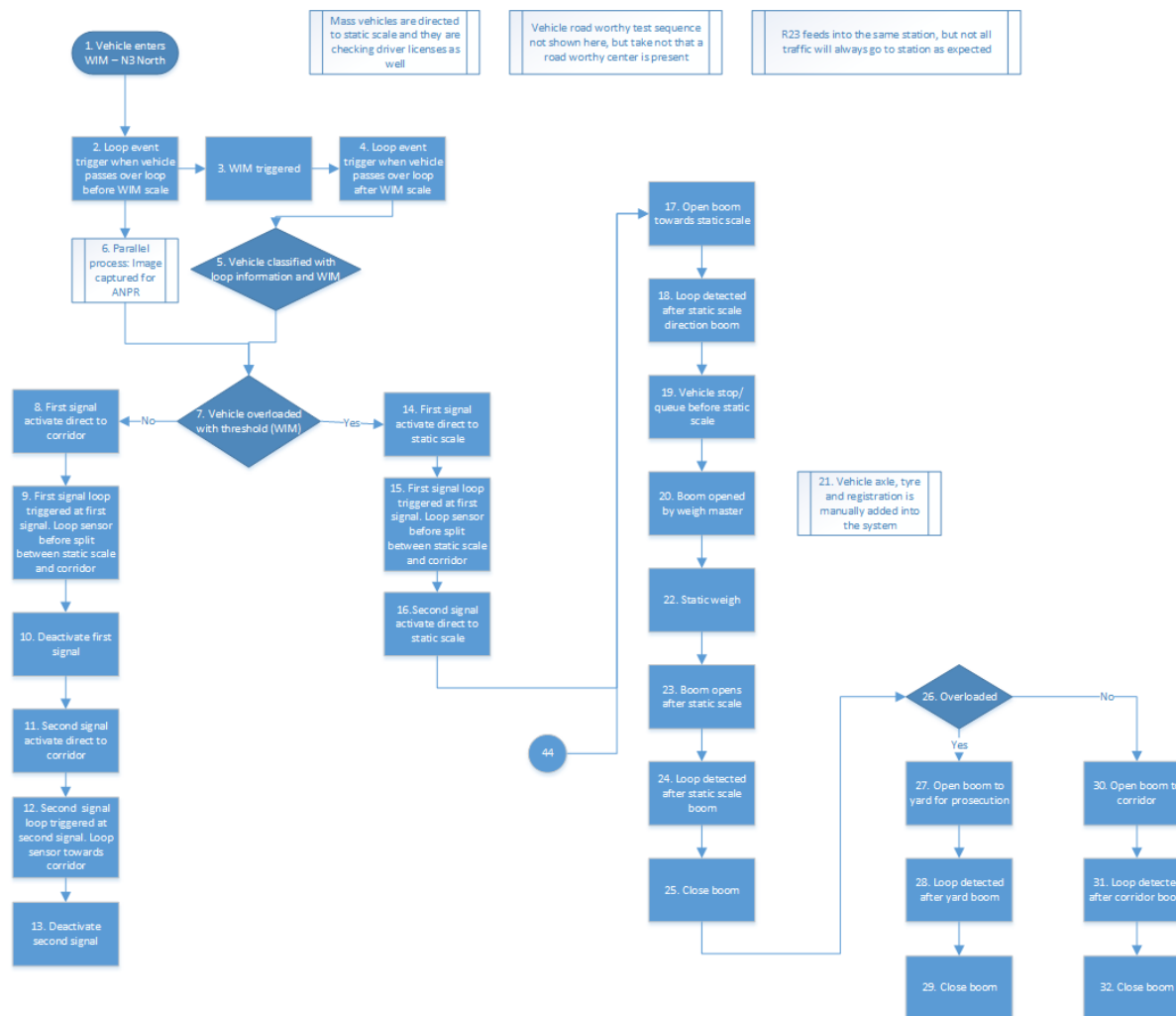


Figure 3.6: Heidelberg TCC process flow on the N3, southbound

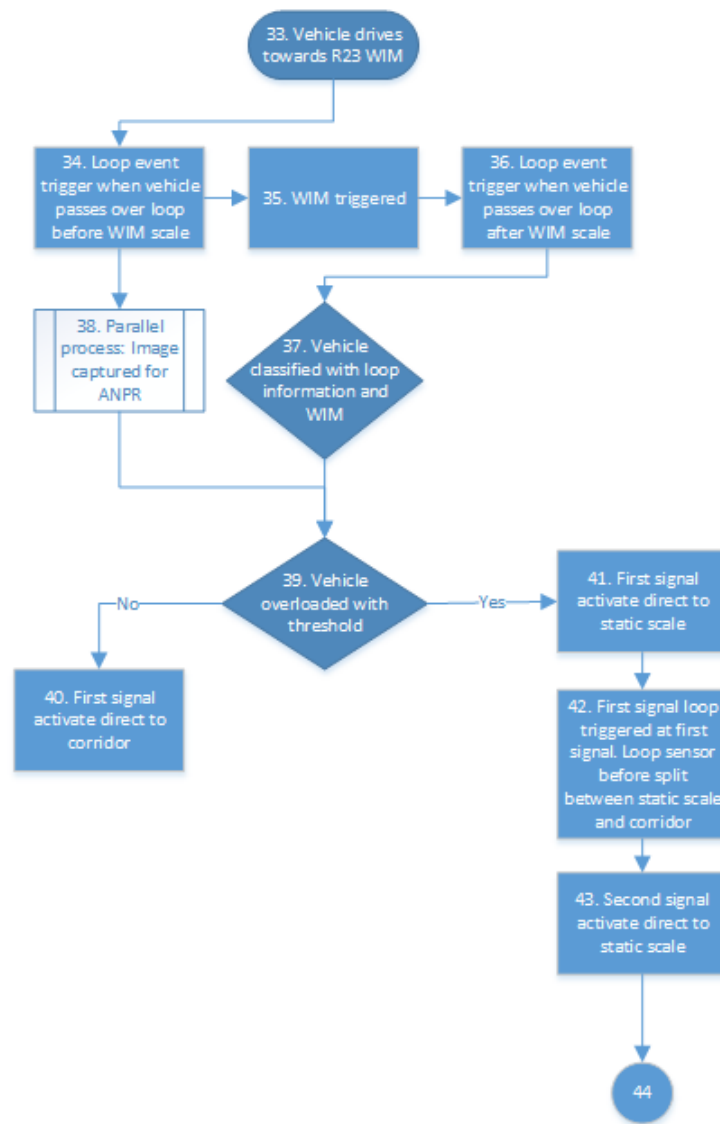


Figure 3.7: R23 process flow to Heidelberg TCC on the N3

3.2 Status quo procedures

The investigations described in Chapter 2 indicated the technology that is typically implemented in the TCC process in other countries. The status quo procedures, specific system components, and hardware implemented at South African TCCs had to be investigated in more detail. The test site configurations at Mantsole and Heidelberg TCCs are indicated in Figures 3.2 and 3.5, respectively; the specific hardware installed is listed below:

- Static scale
- WIM scale
- LSWIM scale
- Screening lane
- Traffic counting by implementing the ANPR installation
- ANPR
- RFID reader

3.2.1 Overview of the current system

The current system has key components that are included with the weighing equipment. They interface with numerous systems but have not been explicitly mentioned in previous sections although they form an essential backbone to the operations. These components of the current system are displayed in Figure 3.8. Systems engineering practices categorise such a component as either a functional unit (F/U) or an interface (I/F) unit.

A simplified high-level image of the corridor is given in Figure 3.8. It was clear after site inspections and data collection that each station functioned independently when considering the data from the weighing operations. The image indicates two TCCs beside one another but there is actually an extensive portion of the corridor between them.

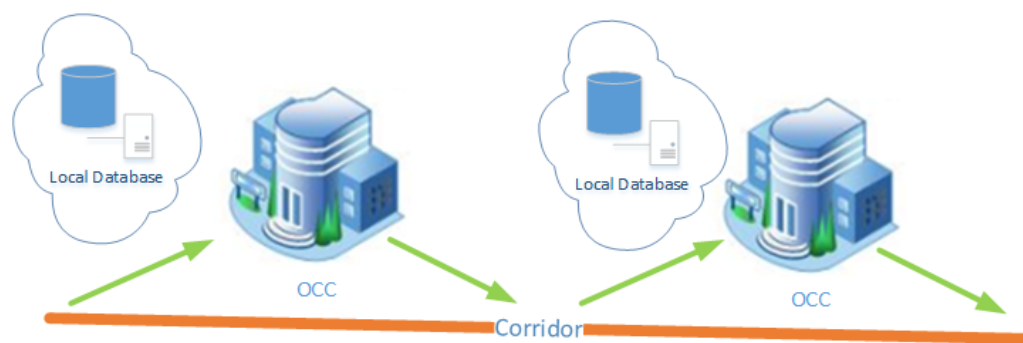


Figure 3.8: Current high level data isolation overview

The F/U and I/F unit are indicated in Figure 3.9 on page 87. This is a generic set of the F/Us and I/F units observed during the site inspections. The F/U and I/F unit are incorporated in the process flow described in Section 3.2.2. The communication protocols may vary between sites because different operators manage the sites and different system integrators have been awarded the site implementation tenders. An F/U and I/F unit are used in conjunction with the process flows.

The functional components are listed first.

- F/U1: *Corridor* is the physical road pavement that is travelled on.
- F/U2: *Heavy vehicles* are the main factors to be monitored and observed throughout the process at the TCC and they interact with several other F/Us.
- F/U3: *WIM scale* is used to determine the mass of the heavy vehicle while in motion.
- F/U4: *ANPR camera* captures an image of the license plate and identifies the vehicle's registration number.
- F/U5: *Data processing in the database* stores the information from the WIM scale but currently does not link the ANPR data to the record.
- F/U6: *WIM rule set* determines whether the heavy vehicle should be directed to the static scale or to the corridor.
- F/U7: *WIM routing system* indicates what direction the heavy vehicle should take after passing over the WIM scale.

- F/U8: *Bypass detection* is activated to determine whether the vehicle is following the correct instructions from the routing system.
- F/U9: *Static scale* is used to determine the mass of the heavy vehicle while static (stationary).
- F/U10: *mass capture* unit stores the mass of the vehicle when it is statically weighed.
- F/U11: *Static scale rule set* determines whether the heavy vehicle is legally loaded (according to legislation).
- F/U12: *Static scale routing system* indicates what direction the heavy vehicle should take after the static scale.
- F/U13: *Holding yard* is where the heavy vehicle parks to be processed by traffic officials.
- F/U14: *Prosecution* is the process undergone by the heavy vehicle and driver if the legislation dictates a breach of the permissible vehicle mass.
- F/U15: *Data capture to database* stores the information from the prosecution in the database.
- F/U16: *Data processing to database* stores the information about the static mass in the database.

The interface components are described below.

- I/F1: Is between F/U1 and F/U2, where the vehicle interacts with the road pavement of the corridor.
- I/F2: Is between F/U2 and F/U3, where the vehicle travels over the WIM.
- I/F3: Is between F/U2 and F/U4, where the vehicle registration is detected by means of the ANPR camera.
- I/F4: Is between F/U3, F/U4 and F/U5, and sends data to a database for processing.
- I/F5: Is between F/U5 and F/U6, and compares the captured information with the WIM rule set.
- I/F6: Is between F/U6 and F/U7, and determines in which direction the vehicle should be routed.

- I/F7: Is between F/U2 and F/U7, and directs the vehicle either to the static scale or to the corridor.
- I/F8: Is between F/U7 and F/U8, and detects any bypass of the intended routing location.
- I/F9: Is between F/U2 and F/U9, and directs the vehicle to travel and stop to be weighed on the static scale.
- I/F10: Is between F/U9 and F/U16, and sends data to a database for processing.
- I/F11: Is between F/U10 and F/U16, and stores the static mass data.
- I/F12: Is between F/U10 and the weigh master, and allows the acceptance and finalisation of the static mass procedure.
- I/F13: Is between F/U10 and F/U11, and compares the static mass with the static mass rule set to determine the next action.
- I/F14: Is between F/U11 and F/U12, and uses the rule set to direct the vehicle accordingly.
- I/F15: Is between F/U9 and F/U12, and directs the vehicle from the static scale either to the corridor or for prosecution.
- I/F16: Is between F/U13 and F/U14, where prosecution occurs in the holding yard.
- I/F17: Is between the traffic official and F/U14, and is the interface to the prosecution system.
- I/F18: Is between F/U15 and the traffic official, to capture data into the applicable database.

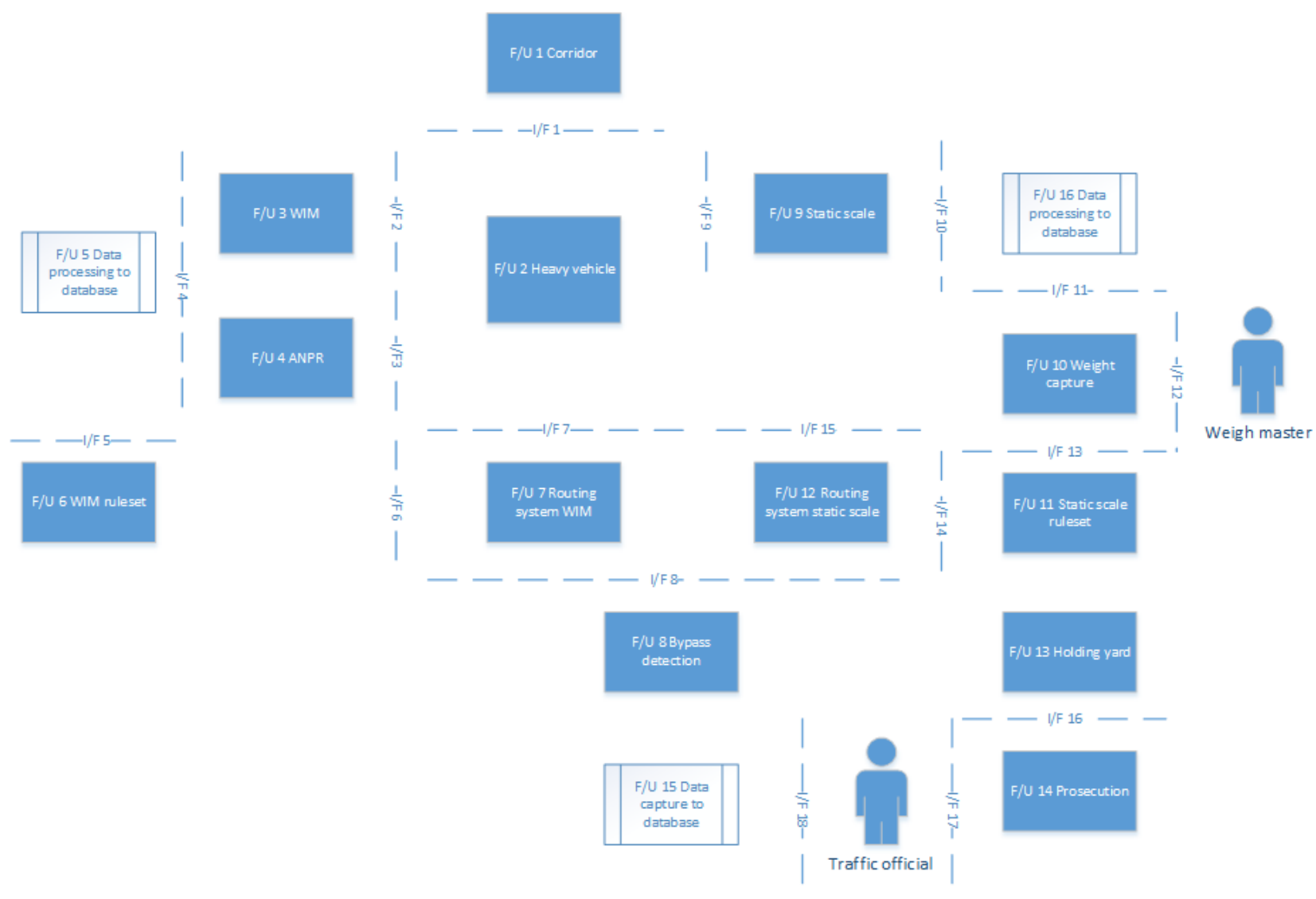


Figure 3.9: Overview of the current system at TCC level

3.2.2 Process flows in the status quo

The process flows applicable during the operation of the TCCs will now be further discussed. These elements in the process ensure the current operation is functional. Any proposal for an improved system will logically include some or all of the following elements:

1. Heavy vehicle
2. Officials
3. Weigh master
4. WIM
5. Static scale
6. Bypass detection
7. Prosecutor
8. ANPR
9. Routing system

Heavy vehicles

Heavy vehicles, in conjunction with their drivers, are the main components that are circulated through the TCC. The state flow depicting the processing of heavy vehicles is shown in Figure 3.10 on page 90. The state flow starts by assuming the vehicle is already travelling along the corridor (*step 1*). The approach of the vehicle to the TCC constitutes the first decision or state of the heavy vehicle. The driver has to choose whether to bypass the station or enter the screening lane at the WIM (*step 1.1*). Bypass detection identifies the vehicle if the driver attempts to bypass the station, as described in *Bypass detection (step 1.2)* of the state flow.

The WIM scale is crossed after entering the screening lane (*step 1.3*). The mass of the vehicle determines whether the vehicle has to proceed to the static scale or return to the corridor (*step 1.4*). The directing system will be followed or disobeyed by the driver (*step*

1.5). An attempted bypass has to be detected by the *Bypass detection*. Mass determined by the WIM scale is used to direct the vehicle's next state (*step 1.6*). A potentially illegal mass that triggers the threshold results in the vehicle being directed to the static scale (*step 1.7*). A threshold that is not triggered results in the vehicle being directed to the corridor (*step 1.8*).

If the vehicle triggers the WIM scale, the driver of the vehicle once again has the choice to bypass a system, in this case, the static scale (*steps 1.9 and 1.11*). Queuing at the static scale is dependent on the number of vehicles that are directed to it (*step 1.10*). If a queue forms, there will be delays, and additional fuel usage due to long periods of idling. Tyre wear-and-tear will not be much affected by queues but by unnecessary stops. The vehicle can drive towards the static scale once the boom opens (*step 1.12 and 1.13*). The static weighing procedure commences according to legislation and determines where the vehicle will be directed next (*step 1.14*). The corridor is reaccessed if the vehicle's mass is legal (*step 1.8*) or if the driver attempts to bypass prosecution (*step 1.15*). An overloaded vehicle is directed to prosecution procedures (*step 1.16*). The prosecution procedures commence when the vehicle is processed in the TCC's holding yard (*steps 1.17 and 1.18*).

The driver of the vehicle may choose to bribe the officials to ignore its overloaded state and, if successful, regain access to the corridor and continue the journey (*step 1.19*). Sometimes the load has just moved in transit so that there are high loads on specific axles. If this happens, the driver can attempt to redistribute the load and be reweighed (*step 1.20 to 1.10*).

A vehicle that is overloaded may not continue on its journey while overloaded so part of the load has to be transferred to another vehicle to remove some of the load from the vehicle, which needs to be arranged (*step 1.21*). Cargo must be transferred to the new vehicle (*step 1.22*), and both vehicles have to be weighed again, so they are directed to the queue (*step 1.10*).

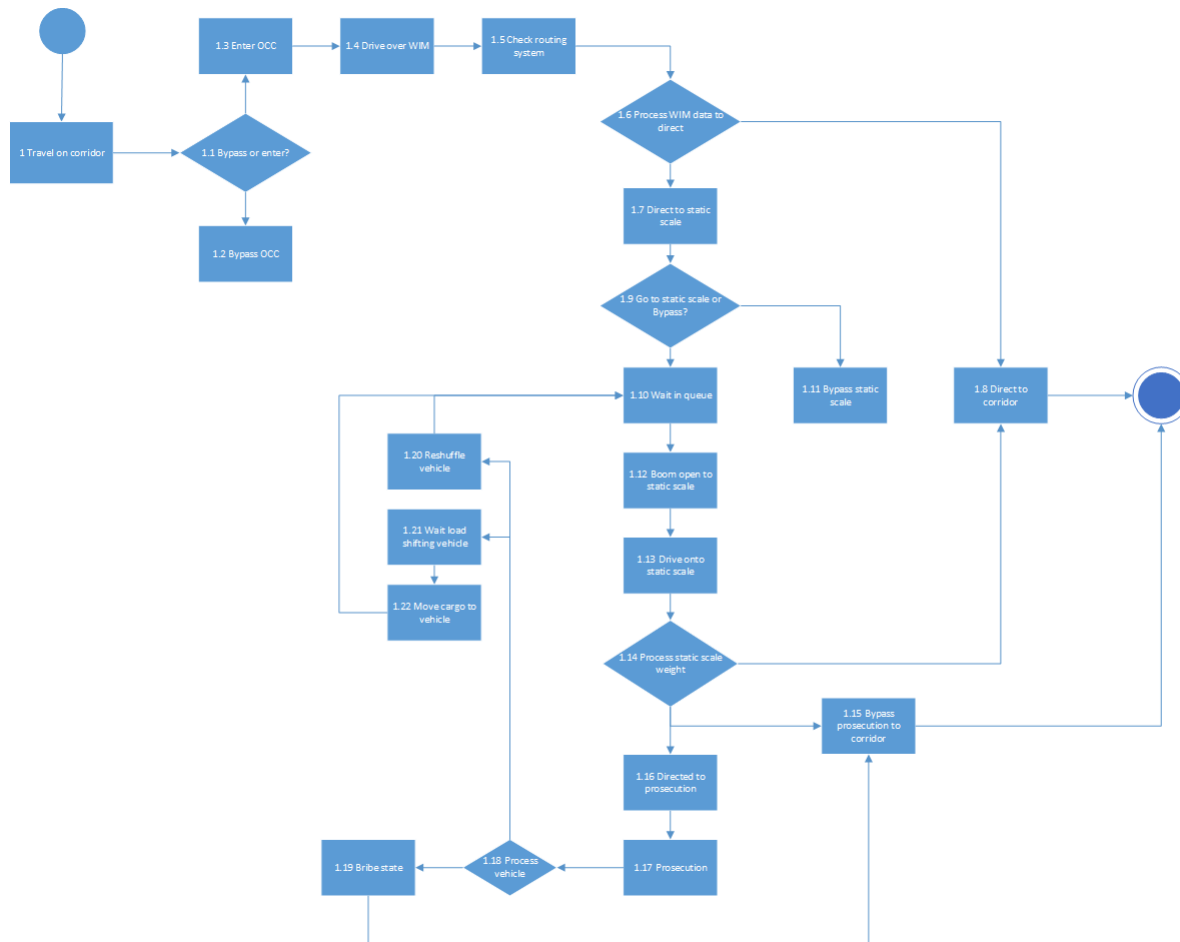


Figure 3.10: State flow of a heavy vehicle at the TCC

Officials

Traffic **officials** at the TCC are responsible for the operations at the station and for prosecuting vehicles that bypass the TCC. The state flow of the officials is shown in Figure 3.11. Officers can be on duty but not in a working state as they are known to have extended rest periods when they do not perform their tasks (*step 2.1*). An officer who is on duty watches out for vehicles that bypass the WIM scale or the TCC (*step 2.2*). A vehicle that bypasses the station should be stopped by the officer (*step 2.3*) but, if the officer is too slow to stop the vehicle, there is a choice to report it to a downstream station (*step 2.4*). The bypassing offence can be reported to a downstream station (*step 2.5*) or ignored and no action is taken (*step 2.6*). The bypassing offence can be reported to a downstream station (*step 2.5*) or ignored and no action is taken (*step 2.6*).

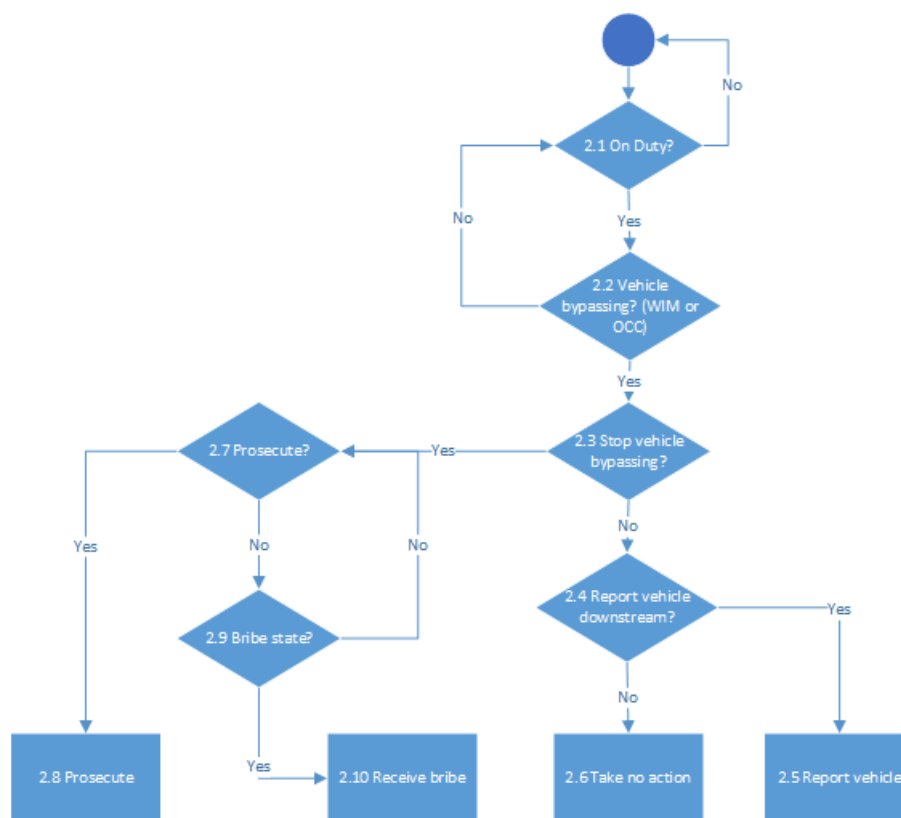


Figure 3.11: State flow of a traffic official at the TCC

Stopping of the vehicle has two potential outcomes. The first is to choose to prosecute the driver (*step 2.7*), which will lead to prosecution (*step 2.8*). Secondly, an official may

choose to engage with the driver of the vehicle with the hope of eliciting a bribe (*step 2.9*). This can lead either to acceptance of the bribe (*step 2.10*) or to forced prosecution of the vehicle to proceed as normal (*step 2.7*).

Weigh master

The **weigh master** is stationed where the system gives the feedback from the static scale weigh output. The state flow is indicated in Figure 3.12 on page 93. The weigh master can be on duty or not, similar the traffic officer (*step 3.1*). The weigh master instructs the driver to move the vehicle onto the static scale (*step 3.2*). The driver is directed until the vehicle is correctly positioned on the static scale (*step 3.3*). The ANPR information from the WIM reading is visually verified (*step 3.4*). A mismatch with the visual verification requires manual entry by the weigh master and may have a chance to incorrectly type in the details (*step 3.5*). The ANPR details can be accepted if the details are correct (*step 3.6*).

Axle configuration is matched with the loop information by a distant visual verification of the axle counts (*step 3.7*). The mass on the axles are captured and stored (*step 3.8*) and finalisation of the mass will then be captured (*step 3.9*). It is determined whether the vehicle is overloaded (*step 3.9*) and a legally loaded vehicle is directed to the corridor (*step 3.11*). The weigh master has the decision (not a definite step in the process) to go into a bribe state to request a bribe or to accept/reject one offered (*step 3.12*). An overloaded vehicle is directed to prosecution (*step 3.13*). The bribe state acceptance entails an attempt to adjust the mass value(s) on the system (*step 3.14*), the bribe is received (*step 3.15*), and the vehicle is directed to the corridor (*step 3.11*).

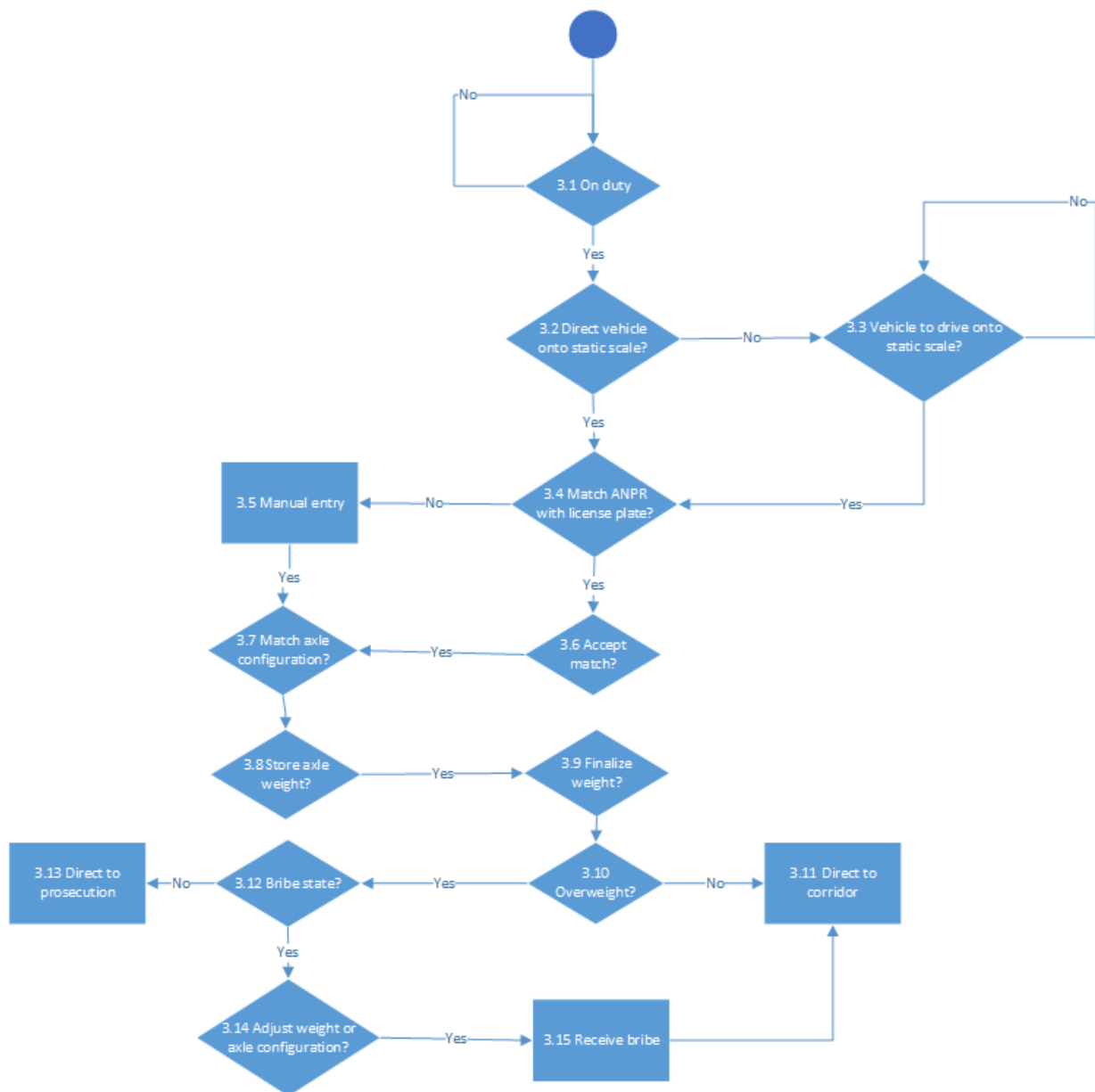


Figure 3.12: State flow of the weigh master at the TCC

Prosecuting officer

The **prosecuting officer** ensures an overloaded vehicle is taken through the legal prosecution process. The state flow of the process is shown in Figure 3.13. The initial step in the process again considers whether the prosecutor is on duty or not (*step 4.1*). The prosecution process commences once a vehicle is in the holding yard (*step 4.2*). Again, a bribe state can commence if the prosecutor is offered a bribe (*step 4.3*). If no bribe state is present or if the bribe is not accepted, the legal prosecution commences (*step 4.4*). After the prosecution, corrective measures to the load of the vehicle may commence (*step 4.5*). A bribe accepted is received (*step 4.6*) and the vehicle is directed to the corridor (*step 4.7*).

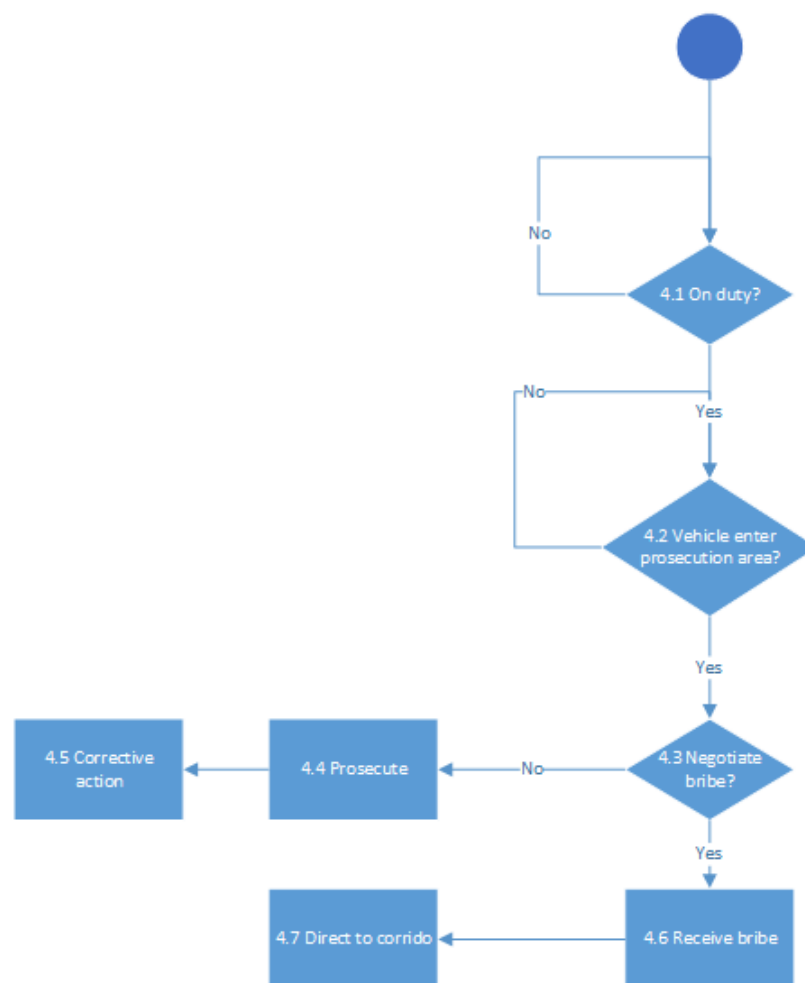


Figure 3.13: State flow of the prosecutor at the TCC

Weigh-in-motion scale

The **WIM** scale has a short process flow, as can be seen in Figure 3.14. First, the magnetic loop detects a vehicle approaching (*step 5.1*). The axle configuration is determined by the equipment (*step 5.2*), followed by the axle loads' being compared to the legal thresholds (*step 5.3*). AVCM is measured (*step 5.4*) and the measurement is sent to the routing system (*step 5.5*) so that it either directs the vehicle to the corridor or to the static scale. The vehicle is identified by means of ANPR, as discussed in Section 3.2.2 while travelling over the WIM.

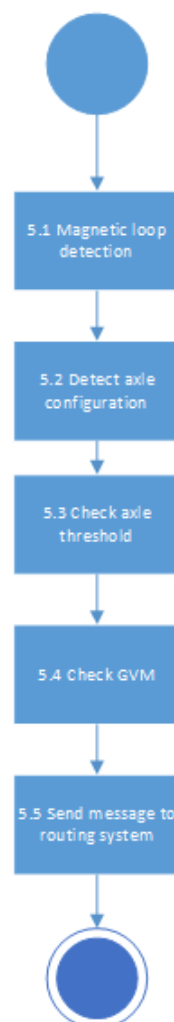


Figure 3.14: State flow of the WIM at the TCC

Static scale

The **static scale** has a short process flow similar to that of the WIM, as shown in Figure 3.15. The vehicle is detected at the static scale (*step 6.1*). The static scale has separate sections that weigh the different axle groups (*step 6.2 to 6.5*). These details are sent to the system to be processed to determine overload status (*step 6.6*).

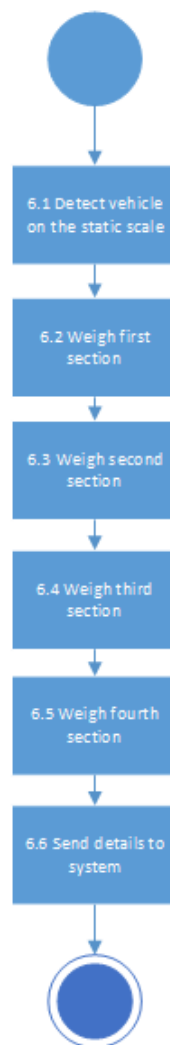


Figure 3.15: State flow of the static scale at the TCC

Bypass detection

The **bypass detection** device has multiple inputs for the different stages in the TCC process. The WIM process is indicated in Figure 3.16 below and the static scale process is indicated in 3.17. Firstly, the system receives a message if a vehicle should be directed to the corridor (*steps 7.1 and 8.1*). If the vehicle should not be directed to the corridor, the device directs the vehicle to the static scale from the WIM scale (*step 7.2*) and to prosecution from the static scale (*step 8.2*). In both of these instances, the bypass detection device activates an alarm if the vehicle does not follow the correct path (*steps 7.3 and 8.3*).

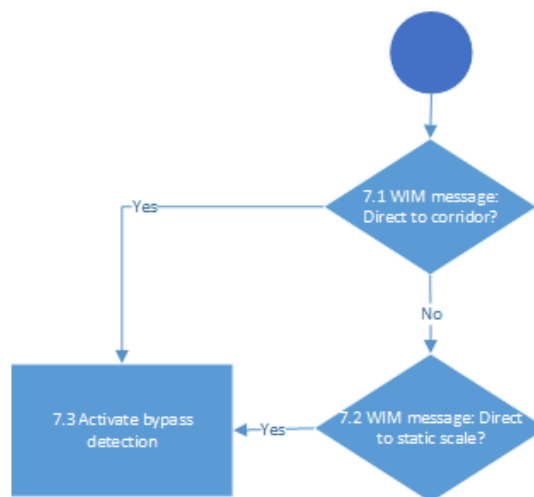


Figure 3.16: State flow of the bypass detection for the WIM at the TCC

The **bypass detection** process is indicated in Figure 3.18 on page 98. The system initially reads the routing system (*step 9.1*). The direction of the vehicle is determined on the system (*step 9.2*). A static scale direction (*step 9.3*) that is detected by the magnetic loop to the corridor (*step 9.5*) alerts the traffic officer by means of an alarm (*step 9.7*). A vehicle directed to the corridor (*step 9.1*) that is detected by the static scale loop (*step 9.6*) has to be flagged as a discrepancy (*step 9.8*).

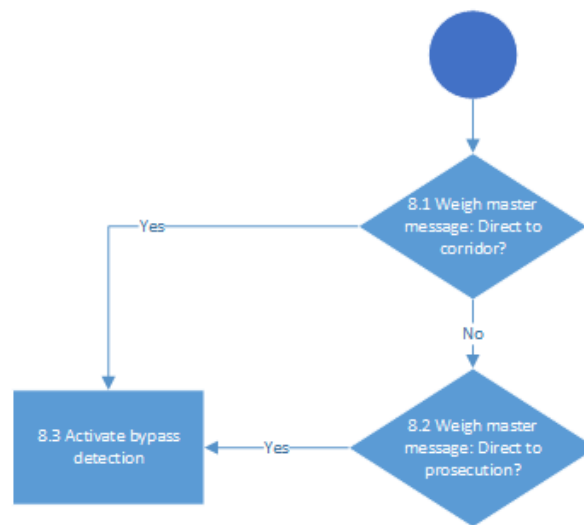


Figure 3.17: State flow of the bypass detection for the static scale at the TCC

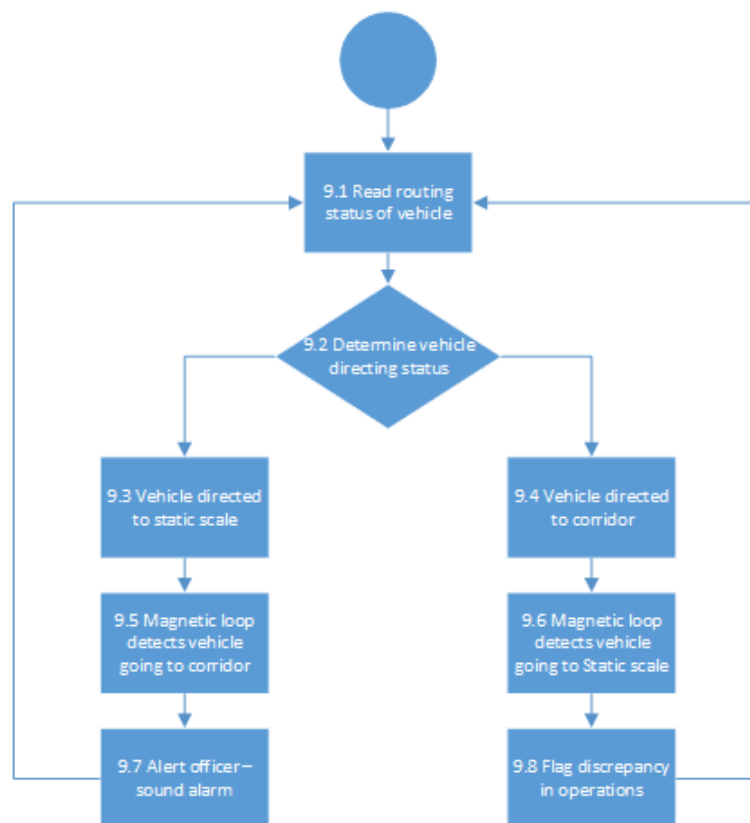


Figure 3.18: State flow of the bypass detection for the TCC

Automatic number plate recognition

The **ANPR** camera system is used to identify the registration number of the vehicle from its licence plate, as previously mentioned, and its process flow is shown in Figure 3.19. Initially, the vehicle is detected (*step 10.1*) and the image of the licence plate is captured (*step 10.2*). Text recognition is then required (*step 10.3*) with a stamp on the captured information (*step 10.4*) that is sent to the system (*step 10.5*). This system can be used to link information of the WIM and the static scale.



Figure 3.19: State flow of the ANPR cameras at the TCC

Routing system

The **routing system** is a combination of boom gates and traffic signals to direct vehicles to the correct location in the TCC process. Figure 3.20 on page 101 indicates the process flow of a statically weighed vehicle. The initial boom is opened to allow the vehicle onto the static scale (*steps 11.1 and 11.2*). The boom is closed once the vehicle is on the static scale (*step 11.3*) for the weighing operation (*step 11.4*). Then the boom after the static scale is opened (*step 11.5*) and the vehicle exits the weigh station area (*step 11.6*). The results of the weighing operation determine where the vehicle is directed next. A prosecution direction causes that specific boom to open (*step 11.8*) or a corridor direction causes the corridor boom to open for a legally loaded vehicle (*step 11.9*). The final steps are to close all the relevant booms (*steps 11.10 to 11.12*). Vehicles often drive through the booms and ignore the direction advised by the system.

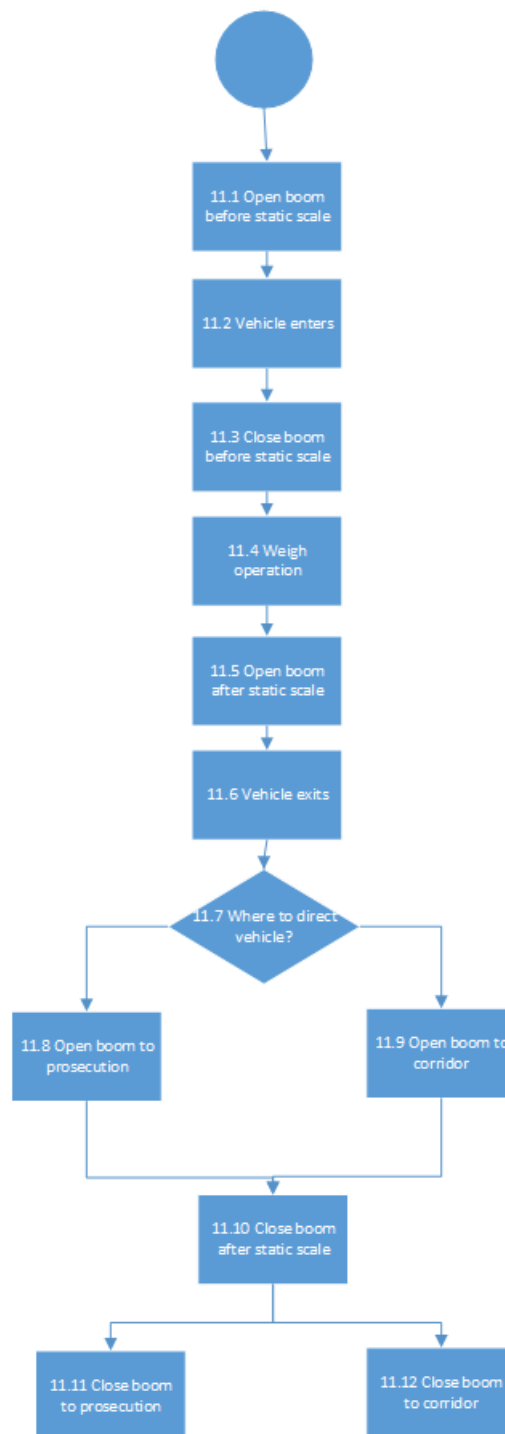


Figure 3.20: State flow of the boom directing process in the routing system at the TCC

3.3 Data capture

The preliminary databases ensured that the data from multiple sources were stored in a relevant and usable format. The raw data from the multiple sources were analysed to understand the status quo. These data were used in the implementation, optimisation, and testing of the algorithm, as discussed in Chapter 4. The data collected included historic mass data from WIM, HSWIM, and static scales, as well as traffic flow data, which were required for a real-time solution, as discussed in Sections 3.6.2 to 3.6.3.

The databases identified vehicles using either ANPR cameras or RFID. The database contents can be seen in Figure 3.21 on page 104. Data were provided in strings based on extended markup language (XML) and had to be parsed into a usable format. The parsing output was stored in *StaticXMLParse*, *WIMxmlParse*, and *WIMRFID* in a usable format for the data analysis described in Section 3.4.

The data labels were fairly descriptive and the WIM data set had specific inputs that were of importance to the algorithm.

- Vehicle classification
- Date and time of weighing
- AVCM or commonly used as GVM
- Axle loads
- ANPR image date and time
- Vehicle registration number
- Axle count
- Axle configuration
- WIM identifier

The static scale information was also valuable for the algorithm input.

- Date and time of weighing
- TCC identifier
- Axle count
- Axle configuration
- Axle loads
- Axle legal road capacity
- Vehicle registration number
- Linked WIM details

RFID linking was included in the pilot study to determine accurate linking of vehicle identification and the ANPR on site.

- Reader location
- RFID tag identifier
- Date and time of tag read

StaticXMLParse	WIM_distinct_req	WIMxmlParse	avg_axle_calc_RSAClass	avg_axle_calc
ID	id	ParseID	id	id
XMLID		XMLID	Axle1	Axle1
AuthCd	veh_req	RAWXML	Axle2	Axle2
WeightNo		Controller	Axle3	Axle3
DateTimeFix		ID	Axle4	Axle4
DateTime		ReaderId	Axle5	Axle5
WeightDate		TagID	Axle6	Axle6
WeightTime		DigitalID	Axle7	Axle7
WeightType		ScreenName	Axle8	Axle8
WeightSeqNo		DeviceName	Axle9	Axle9
ScaleOperator		LaneNo	Axle10	Axle10
WeightEndgeID		ClassificationScheme	Axle11	Axle11
AxleCount		WtClass	Axle12	Axle12
AxleConfig		dateTime	Axle13	Axle13
Axle1		GVM	Axle14	Axle14
RoadCapacity1		Headway	Axle15	Axle15
Axle2		Speed	Axle1_stddev	Axle1_stddev
RoadCapacity2		Length	Axle2_stddev	Axle2_stddev
Axle3		AxleUnitLoad1	Axle3_stddev	Axle3_stddev
RoadCapacity3		AxleUnitLoad2	Axle4_stddev	Axle4_stddev
Axle4		AxleUnitLoad3	Axle5_stddev	Axle5_stddev
RoadCapacity4		AxleUnitLoad4	Axle6_stddev	Axle6_stddev
Axle5		AxleUnitLoad5	Axle7_stddev	Axle7_stddev
RoadCapacity5		AxleUnitLoad6	Axle8_stddev	Axle8_stddev
Axle6		AxleUnitLoad7	Axle9_stddev	Axle9_stddev
RoadCapacity6		AxleUnitLoad8	Axle10_stddev	Axle10_stddev
Axle7		AxleUnitDistance1	Axle11_stddev	Axle11_stddev
RoadCapacity7		AxleUnitDistance2	Axle12_stddev	Axle12_stddev
Axle8		AxleUnitDistance3	Axle13_stddev	Axle13_stddev
RoadCapacity8		AxleUnitDistance4	Axle14_stddev	Axle14_stddev
Axle9		AxleUnitDistance5	Axle15_stddev	Axle15_stddev
RoadCapacity9		AxleUnitDistance6	Avg_GVM	Avg_GVM
Axle10		AxleUnitDistance7	Avg_GVM_stddev	Avg_GVM_stddev
RoadCapacity10		AxleUnitDistance8	Start_Time	Start_Time
Axle11		AxleUnitWidth1	End_Time	End_Time
RoadCapacity11		AxleUnitWidth2	Count_forTime	Count_forTime
Axle12		AxleUnitWidth3	RSA_Class	Axle_Count
RoadCapacity12		AxleUnitWidth4	Axle1_Mean	Axle1_Mean
Axle13		AxleUnitWidth5	Axle2_Mean	Axle2_Mean
RoadCapacity13		AxleUnitWidth6	Axle3_Mean	Axle3_Mean
Axle14		AxleUnitWidth7	Axle4_Mean	Axle4_Mean
RoadCapacity14		AxleUnitWidth8	Axle5_Mean	Axle5_Mean
Axle15		AxleLoad1	Axle6_Mean	Axle6_Mean
RoadCapacity15		AxleLoad2	Axle7_Mean	Axle7_Mean
VehicleNo		AxleLoad3	Axle8_Mean	Axle8_Mean
TrailerNo1		AxleLoad4	Axle9_Mean	Axle9_Mean
TrailerNo2		AxleLoad5	Axle10_Mean	Axle10_Mean
WIMDate		AxleLoad6	Axle11_Mean	Axle11_Mean
WIMTime		AxleLoad7	Axle12_Mean	Axle12_Mean
WIMSpeed		AxleLoad8	Axle13_Mean	Axle13_Mean
WIMAxleCount		AxleLoad9	Axle14_Mean	Axle14_Mean
WIMDeviceID		AxleLoad10	Axle15_Mean	Axle15_Mean
WIMVehRegNo		AxleLoad11		
WIMAxleConfig		AxleLoad12		
WIMMess1		AxleLoad13		
WIMMess2		AxleLoad14		
WIMMess3		AxleLoad15		
WIMMess4		Violation		
WIMMess5		ImageDateTime		
WIMMess6		ConfidenceFactor		
WIMMess7		VehRegNo		
WIMMess8		AxleCount		
WIMMess9		AxleConfig		
WIMMess10				
WIMMess11				
WIMMess12				
WIMMess13				
WIMMess14				
WIMMess15				

Figure 3.21: Database content view

3.4 Data analysis

Data showing the status quo were analysed, as previously stated, to gain a better appreciation of the delays and efficiencies of the current operations. This section covers the specific questions that were asked in order to understand the operations. The outputs of the analysis were used for algorithm inputs, and to quantify the delays and economic impact, as explained in Chapters 4 and 5.

It was clear from the data acquisition that several methods of data storage were used by the different stakeholders. This caused format discrepancies in the data that were stored in the process. The variations in storage methods were because the companies to whom tenders were awarded implemented systems based on proprietary designs. The proprietary nature of the resulting systems ensured that the same company was often awarded a contract extension. Matching data from the different sources (e.g., static scales and WIM scales) was therefore problematic.

The trends in the available data are described below.

Unique sites in the analysis

Site selection of Mantsole, Heidelberg, and Beitbridge was completed and the data sets identified the following unique sites from the WIM data set:

- HeidelbergNb - Heidelberg NB on the N3
- HeidelbergSb - Heidelberg SB on the N3
- MantsoleN1NB - Mantsole NB on the N1
- MantsoleN1SB - Mantsole SB on the N1
- BeitbridgeN1NB - Beitbridge NB on the N1
- BeitbridgeN1SB - Beitbridge SB on the N1

The data sets indicated that static scale data were collected from the following unique sites:

- N3 Nor - Heidelberg NB on the N3
- N3 Sou - Heidelberg SB on the N3
- 200 - Mantsole NB on the N1
- 201 - Mantsole SB on the N1

The date ranges within these data sets were as follows:

- Heidelberg WIM date range: 2016-09-07 17:02:10 to 2017-02-14 20:29:24
- Mantsole WIM date range: 2015-02-17 10:32:02 to 2017-01-21 00:05:14
- Heidelberg static scale date range: 2016-09-01 00:02:00 to 2016-12-31 10:11:00
- Mantsole static scale date range: 2016-11-17 04:25:00 to 2017-01-20 23:46:00
- Beitbridge WIM date range: 2017-07-19 08:52:00 to 2017-11-13 09:03:00

What percentage of vehicles registered in static scale records matches the WIM details that are linked on the system?

The accurate linking of vehicle identities between the WIM and static scales was an essential requirement for the algorithm design. Previously, comparison of the static scale data set with the WIM vehicle identity showed a linking accuracy of 72%, with 4,59% being empty of details. The WIM data set could be compared with ANPR data to measure the level of confidence that could be placed in its accuracy, since the system accepted the identity observed by the ANPR as correct.

The ANPR level of confidence in the accuracy of the vehicle identification was indicated with measurements ranging from 0–100. The data set indicated 7.83% of entries with zero confidence that the identity was correct. The average ANPR confidence level was that 63% of the identifications were correct and the figure increased to 69% after removing the zero entries. This indicated that there were environmental aspects that decreased the accuracy of the ANPR for vehicle identification at both the WIM and the static scale.

Static and WIM matching

- Mantsole total: 25 519
- Mantsole total of matching static scale and WIM registration numbers: 18 400 (72%)
- Mantsole empty WIM details: 1173 (4.59%)

ANPR confidence level on all records

- Total count of records: 436 125
- Total count of ANPR zero confidence records: 34 130 (7.83%)
- Average confidence: 63%
- Average when excluding zero confidence records: 69%

Unique vehicle counts

A real-world representation requires sufficient diversity in the number of unique vehicles recorded to accurately represent the real diversity. The real diversity at these sites was as follows:

- Heidelberg WIM scale total vehicle count: 285 764
- Heidelberg WIM scale unique vehicle count: 80 610
- Mantsole WIM scale total vehicle count: 150 361
- Mantsole WIM scale unique vehicle count: 59 317
- Heidelberg static scale total vehicle count: 43 867
- Heidelberg static scale unique vehicle count: 18 795
- Mantsole static scale total vehicle count: 25 519
- Mantsole static scale unique vehicle count: 13 747

What percentage of vehicles statically weighed are prosecuted?

The number of vehicles statically weighed and not prosecuted is a reality in the TCC process. This was initially seen in the SANRAL annual reports, which indicated that between 21,95% and 24,91% of vehicles were overloaded between 2015/16 and 2018/19. However, only 1,64% to 2,22% were charged for overloading, with less than 0,18% arrested for gross overloading. It has been indicated in previous studies that 75% to 80% of vehicles are loaded close enough to the legal threshold to trigger the WIM threshold [31].

What percentage of vehicles triggered WIM scale thresholds?

The data were analysed to determine how many vehicles would have logically triggered the WIM threshold. The first analysis was conducted on the static scale data set. The vehicles that were checked at the static scale should have triggered the WIM and been directed to the static scale. Table 3.1 below lists the statically weighed vehicles with axle unit counts of 2–5 axles. The result is indicated in Table 3.2, which lists the WIM data set per axle mass for vehicles that should have been directed because their mass was within 10% of the allowed mass. The data set indicated a maximum of 15 individual axle unit types observed and these are indicated as WIM Mass 1 to 15. Additional assessments were conducted on vehicles within 5% and 0% of the threshold in Figures 3.3 and 3.4, respectively.

Table 3.1: Mass above threshold per axle unit count

Axle unit count	2	3	4	5
Axle unit 1	206	485	486	0
Axle unit 2	647	2801	474	0
Axle unit 3	0	2441	605	2
Axle unit 4	0	0	352	1
Axle unit 5	0	0	0	0

Axle unit count	2	3	4	5
AVCM	126	0	0	0
Total vehicles	2826	9640	13 044	9
Grand Total				25 519

Table 3.2: Static scale data set – WIM axles within 10% of the permissible mass per axle unit count

Axle unit count	2	3	4	5
WIM Mass 1	1267	4095	4769	4
WIM Mass 2	2435	8285	11 269	6
WIM Mass 3	383	8436	11 063	8
WIM Mass 4	19	6710	10 088	5
WIM Mass 5	7	6877	10 581	6
WIM Mass 6	6	6722	9682	2
WIM Mass 7	5	30	8778	1
WIM Mass 8	4	9	89	1
WIM Mass 9	3	4	11	0
WIM Mass 10	1	1	4	0
WIM Mass 11	0	2	4	0
WIM Mass 12	0	3	3	0
WIM Mass 13	0	2	2	0
WIM Mass 14	0	0	2	0
WIM Mass 15	0	0	1	0
WIM axles within 10%				Total 25 519

Table 3.3: Static scale data set – WIM axles within 5% of the permissible mass per axle unit count

Axle unit count	2	3	4	5
WIM Mass 1	706	2044	2230	0
WIM Mass 2	2335	8160	9904	6
WIM Mass 3	350	8263	9507	8
WIM Mass 4	18	5575	8539	5
WIM Mass 5	7	5374	9287	0
WIM Mass 6	5	5640	8053	2
WIM Mass 7	3	19	7024	1
WIM Mass 8	3	8	45	1
WIM Mass 9	3	4	10	0
WIM Mass 10	0	1	4	0
WIM Mass 11	0	1	1	0
WIM Mass 12	0	3	3	0
WIM Mass 13	0	1	1	0
WIM Mass 14	0	0	1	0
WIM Mass 15	0	0	1	0
WIM axles within 5%	Total			25 519

Table 3.4: Static scale data set – WIM axles within 0% of the permissible mass per axle unit count

Axle unit count	2	3	4	5
WIM Mass 1	206	485	486	0
WIM Mass 2	2238	7896	7247	0
WIM Mass 3	300	7946	7063	7
WIM axles within 0%	Total			25 519

Static scale data set				
Maximum load based on axle unit count				
Axle unit count	2	3	4	5
WIM Mass 4	15	3591	6277	5
WIM Mass 5	5	2968	7243	0
WIM Mass 6	4	3695	5667	1
WIM Mass 7	2	14	4874	1
WIM Mass 8	3	7	18	0
WIM Mass 9	3	3	10	0
WIM Mass 10	0	1	4	0
WIM Mass 11	0	1	1	0
WIM Mass 12	0	2	2	0
WIM Mass 13	0	0	1	0
WIM Mass 14	0	0	0	0
WIM Mass 15	0	0	1	0
WIM axles within 0%	Total			25 519

The WIM data set was analysed next. The analysis was conducted on the vehicle classification's different axle configurations. Table 3.5 indicates the vehicles that were within 10% and 5% of the threshold in Table 3.6 of the AVCM. An additional analysis is conducted by considering the axle loads with 10% threshold in Table 3.7 and 5% threshold in Table 3.8.

Table 3.5: WIM scale data set – axles within 10% of permissible mass based on vehicle classification

Vehicle class	0	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Axle 1	5	946	269	5660	0	2249	448	1325	50	3194	26 061	43	369	40 995	689
Axle 2	0	4296	7455	13 520	18	4651	5988	1876	57	6610	60 797	379	791	93 757	1860
Axle 3	0	0	0	2403	4	2954	2234	183	31	1750	56 412	76	467	86 221	2053
Axle 4	0	0	0	41	1	0	1819	161	7	2695	38 150	76	440	89 843	1806
Axle 5	0	0	0	0	0	0	0	170	18	2852	33 683	177	420	90 012	1349
Axle 6	0	0	0	0	0	0	0	6	0	0	36 288	0	460	79 595	799
Axle 7	0	0	0	0	0	0	0	0	0	0	0	0	0	64227	353
Axle 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	313
Axle 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
Axle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axles within 10% Total:	436 125														

Table 3.6: WIM data set – axles within 5% of permissible mass based on vehicle classification

Vehicle classification	0	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Axle 1	4	412	100	2873	0	1169	243	737	27	1803	11 745	27	233	15774	260
Axle 2	0	3778	5850	12 211	15	3939	4535	1839	54	5780	53 219	260	668	76 089	1389
Axle 3	0	0	0	2074	3	2315	1565	165	28	1265	48 628	45	398	65 136	1593
Axle 4	0	0	0	34	0	0	1153	116	3	1930	29 043	46	350	74 008	1241
Axle 5	0	0	0	0	0	0	0	92	14	1988	22 290	117	335	74 253	800
Axle 6	0	0	0	0	0	0	0	6	0	0	26 427	0	367	63 405	425
Axle 7	0	0	0	0	0	0	0	0	0	0	0	0	0	46 795	185
Axle 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	179
Axle 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
Axle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Axle 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axles Within 5%	Total: 436 125														

Table 3.7: WIM data set – axles within 10% of permissible mass based on axle count

Axle count	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Axle 1	320	2298	321	1273	8820	13 820	181	10	0	1	0	1	2	0
Axle 2	3781	5523	2170	2782	19 464	29 676	547	16	0	5	2	0	3	0
Axle 3	0	1958	586	633	17 903	27 192	566	14	0	4	1	0	4	0
Axle 4	0	0	636	1054	12 060	28 404	587	4	0	4	2	0	2	0
Axle 5	0	0	0	1147	10 427	28 197	413	6	0	6	2	1	1	0
Axle 6	0	0	0	0	11 246	24 941	229	4	0	4	1	1	2	0
Axle 7	0	0	0	0	0	19 628	85	3	0	4	1	0	1	0
Axle 8	0	0	0	0	0	0	91	2	0	0	0	0	0	0
Axle 9	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Axle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Within 10% of maximum	Total: 436 125													

Table 3.8: WIM data set – axles within 5% of permissible
mass based on axle count

Axle count	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Axle 1	128	1108	155	677	3918	5429	65	5	0	0	0	0	1	0
Axle 2	3065	4887	1706	2465	16 960	24 371	424	15	0	5	1	0	3	0
Axle 3	0	1577	392	470	15 237	20 623	442	13	0	3	1	0	3	0
Axle 4	0	0	409	760	9287	23 480	414	3	0	4	1	0	1	0
Axle 5	0	0	0	791	6871	23 225	221	4	0	5	2	1	1	0
Axle 6	0	0	0	0	8103	19 953	130	3	0	3	0	1	2	0
Axle 7	0	0	0	0	0	14 120	44	3	0	3	1	0	1	0
Axle 8	0	0	0	0	0	0	60	2	0	0	0	0	0	0
Axle 9	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Axle 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axle 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Within 5% of maximum		Total: 436 125												

Heavy vehicle movement patterns as a function of time

Data about vehicle movement trends are essential for knowing whether additional staff are required on specific days and at certain times of day. The data set with this information is for 2009 to 2012 and was used for static scale information. An analysis of the days of the week was conducted first and the results are shown in Figure 3.23. The trends over the four years remained the same but the traffic volumes increased each year. This indicates a year-on-year increase in the number of heavy vehicles weighed. The weekends tend to have lower volumes but cannot be ignored.

The second analysis was of traffic at different times of the day. This is indicated in Figure 3.26, where the annual increase in vehicles statically weighed nevertheless indicates the same trend in vehicle movement patterns. The largest and most constant volumes occur from 07:00 to 19:00. Traffic volumes are lower at night but also cannot be ignored.

What is the split between vehicle classifications?

The split of vehicles between the different classes and axle configurations was indicated briefly in previous analyses. Vehicles are classified according to the RSA toll road specifications, which are indicated in Figures 3.24 and 3.25 on pages 118 and 119. The classification split is indicated in Figure 3.26 on page 120. Almost 40% of the total traffic is vehicle class 16, which is a seven-axle B-double/interlink. The second most common vehicles are six-axle single truck tractor semi-trailers.

Waiting time between the WIM scale and the static scale

The time waiting between the WIM scale and static scale is a key time wastage point in the process. The stopping and starting in the queue also increases fuel consumption. The histogram of time in minutes is indicated in Figure 3.27. The analysis shows the average time between the data sets is 15 minutes, with several measurements over

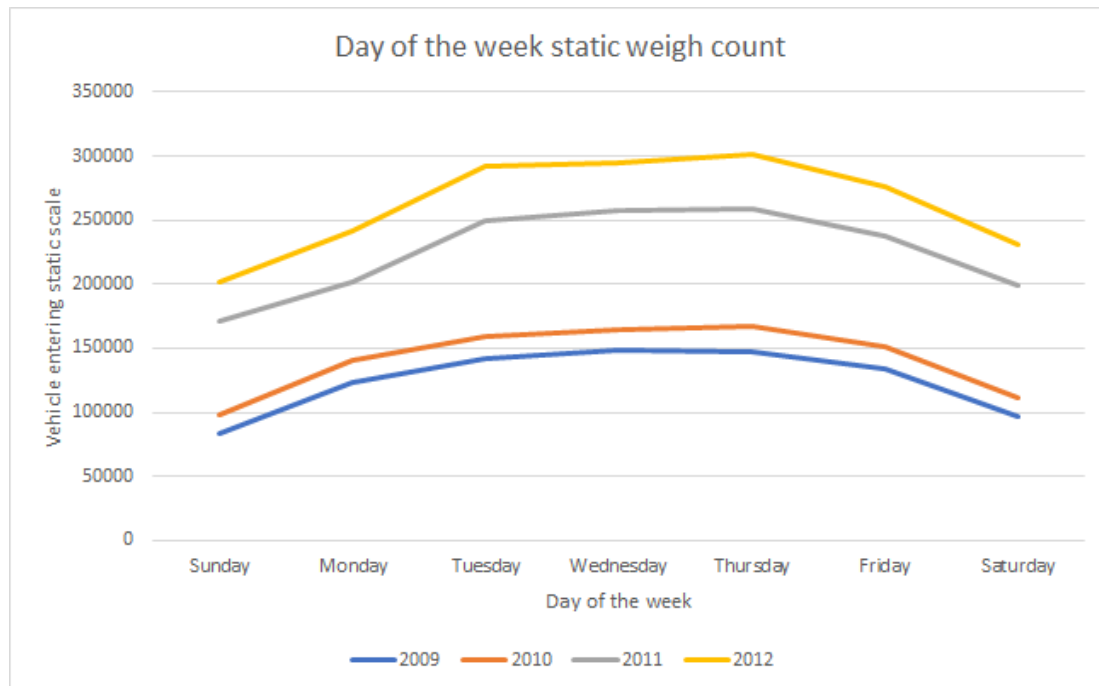


Figure 3.22: Traffic volumes by the day of the week at the static scale

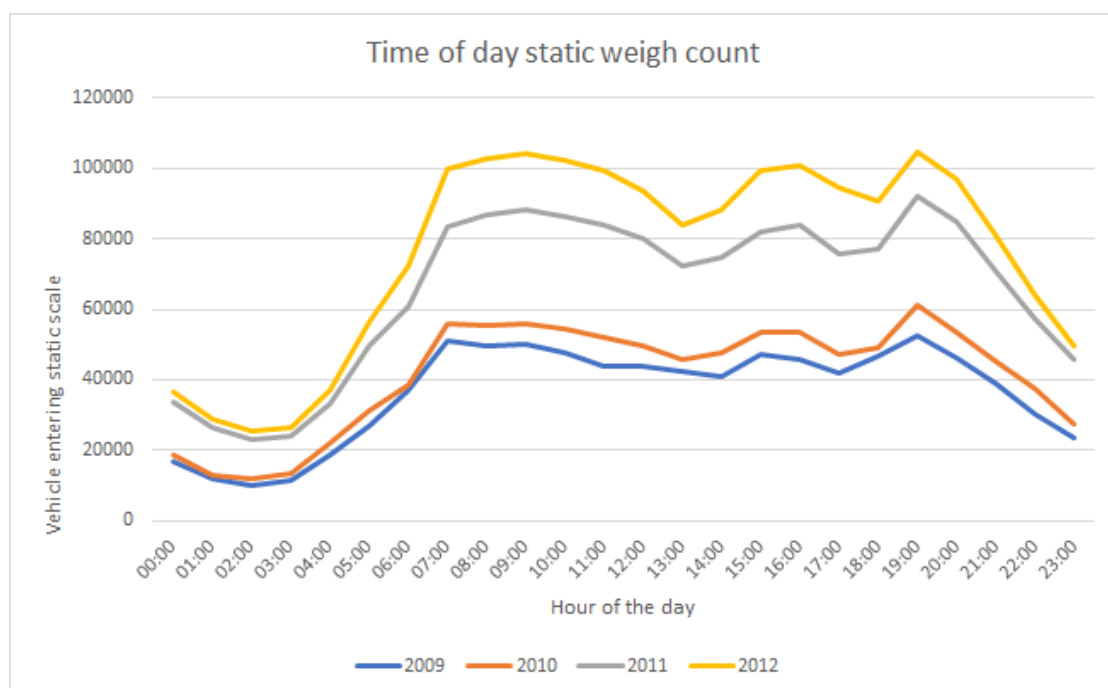


Figure 3.23: Traffic volumes by the time of day at the static scale

SANRAL VEHICLE CLASSIFICATION SCHEME			
Code	Description	Illustration (NB Not all the permutations are shown)	Toll
1	Motorcycles		1 (Light Vehicles)
2	Light Motor Vehicles		
3	Light Motor Vehicles Towing		
4	Two Axle Buses		2 (2-axle Heavy Vehicles)
5	Two Axle 6 Tyre Single Unit		
6	Buses with 3 or 4 Axle		3 (3 or 4-axle Heavy Vehicles)
7	Two Axle 6 Tyre Single Unit and Light Trailer (Max 4 Axles)		
8	Three Axle Single Unit including Single Axle Light Trailer		
9	Four or Less Axle-Single Trailer		
10	Buses with 5 or more Axles		4 (5-axle or more Heavy Vehicles)
11	Three Axle Single Unit and Light Trailer (more than 4 Axles)		
12	Five Axle Single Trailer		
13	Six Axle Single Trailer		
14	Five Axle Multi-Trailer		
15	Six Axle Multi-Trailer		
16	Seven Axle Multi-Trailer		
17	Eight or More Axle Multi-Trailer		

Figure 3.24: Visual presentation of RSA vehicle classification scheme and tolls [82]

Scheme 08 Vehicle Classes (RSA Vehicle)

	Class	Order	Vehicle
	00	0	Unknown Vehicle
Light			
Toll Group 1			
	01	1	Motorcycle
	02	2	Light Motor Vehicles
	03	3	Light Motor Vehicles Towing
Heavy			
Toll Group 2			
	04	4	Two axle Busses
	05	5	Two axle, 6 tyre single units
Toll Group 3			
	06	6	Busses with 3 or 4 axles
	07	7	Two axle 6 tyre single unit with light trailer (4 axles max)
	08	8	Three axle single unit including single axle light trailer
	09	9	Four or Less axle including a single trailer
Toll Group 4			
	10	10	Busses with 5 or more axles
	11	11	Three axle single unit and light trailer (more than 4 axles)
	12	12	Five axle single trailer
	13	13	Six axle single trailer
	14	14	Five or less axle multi-trailer
	15	15	Six axle multi-trailer
	16	16	Seven axle multi-trailer
	17	17	Eight or more axle multi-trailer

Scheme 09 Vehicle Classes (RSA Toll)

	Class	Order	Vehicle
	00	0	Error Class (added to specifications)
Light			
	01	1	All light vehicles
Heavy			
	02	2	2 axle heavy vehicles
	03	3	3 or 4 axle heavy vehicles
	04	4	5 or more axle heavy vehicles

Figure 3.25: RSA vehicle classification schemes and toll groups [82]

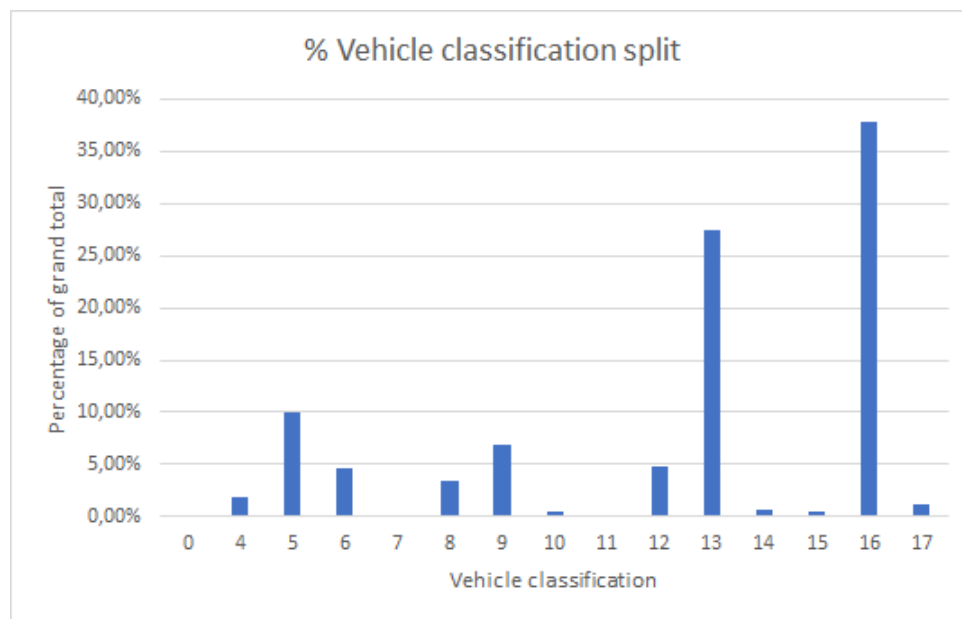


Figure 3.26: Vehicle classification split

40 minutes. There are also several entries of between 0 and 6 minutes, which seems reasonable. However, it needs to be taken into account that, even if there are short waiting periods, queues may be long during busy periods, allowing possibly overloaded vehicles to bypass the TCC.

Normalised mass analysis

Analysing the normalised mass with regard to permissible mass indicates the number of vehicles close to the thresholds. Figure 3.28 shows the normalised AVCM histogram. Many vehicle loads are in the 10% threshold, which supports the WIM trigger amounts. The axle unit load histogram is shown in Figure 3.29. It indicates that several axle units are above the threshold and also classified as overloaded.

The use of normalised mass will greatly assist if legislation changes: The trends should still look fairly similar.

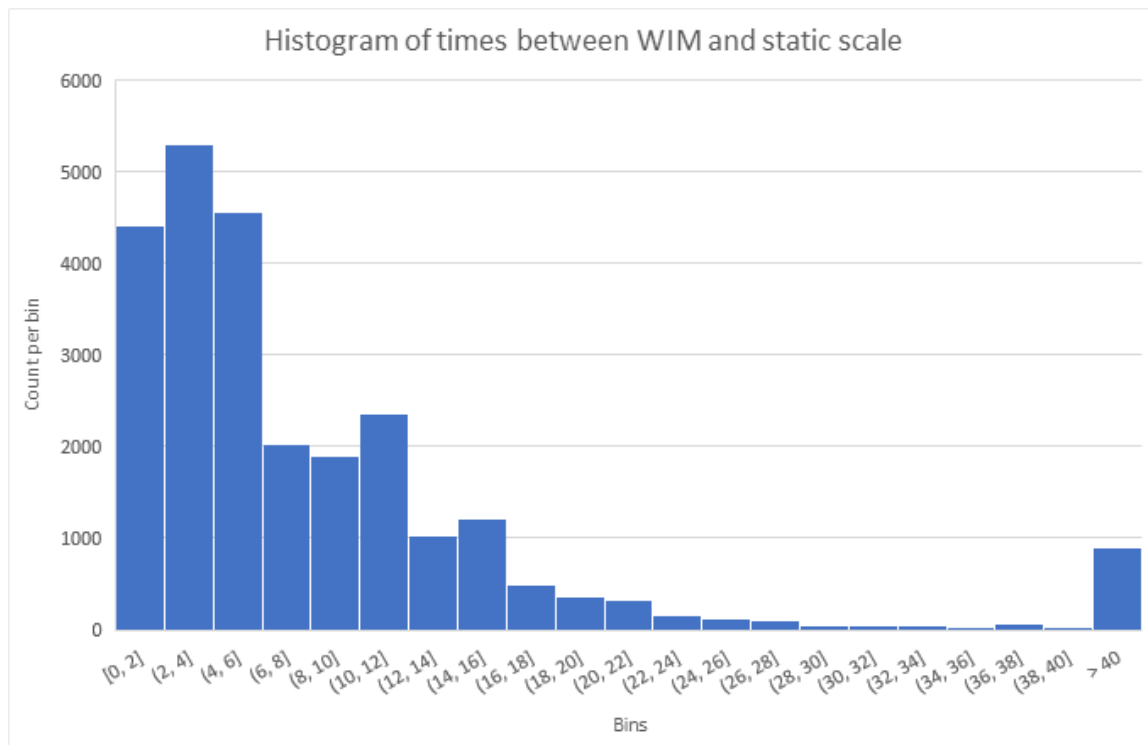


Figure 3.27: Histogram of time spent in minutes between WIM and static scale

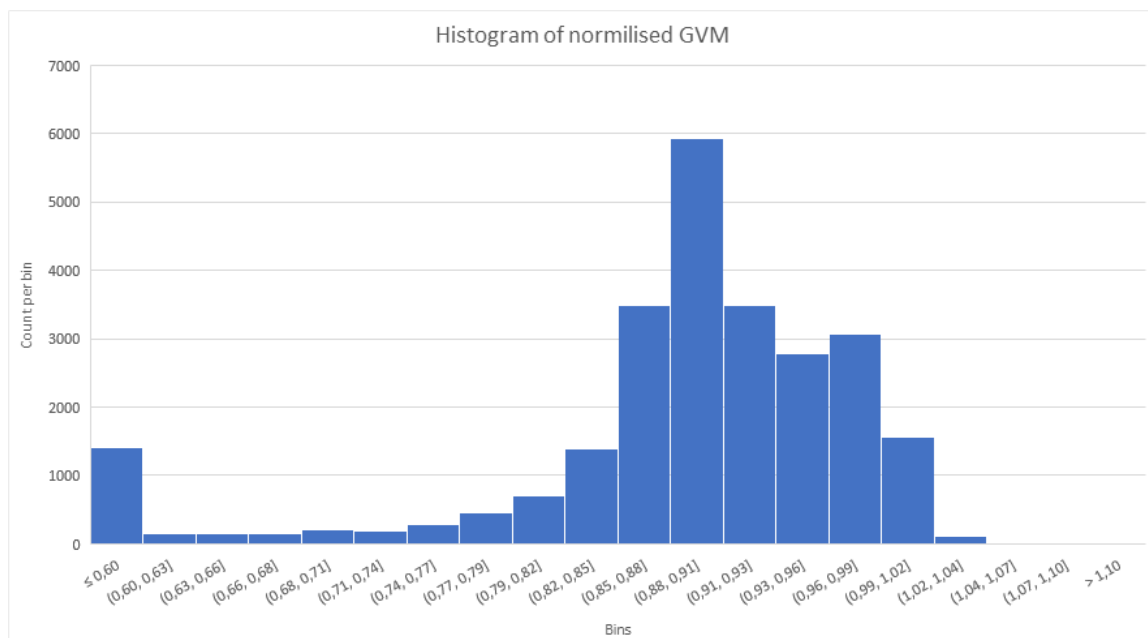


Figure 3.28: Histogram of normalised AVCM mass against permissible mass

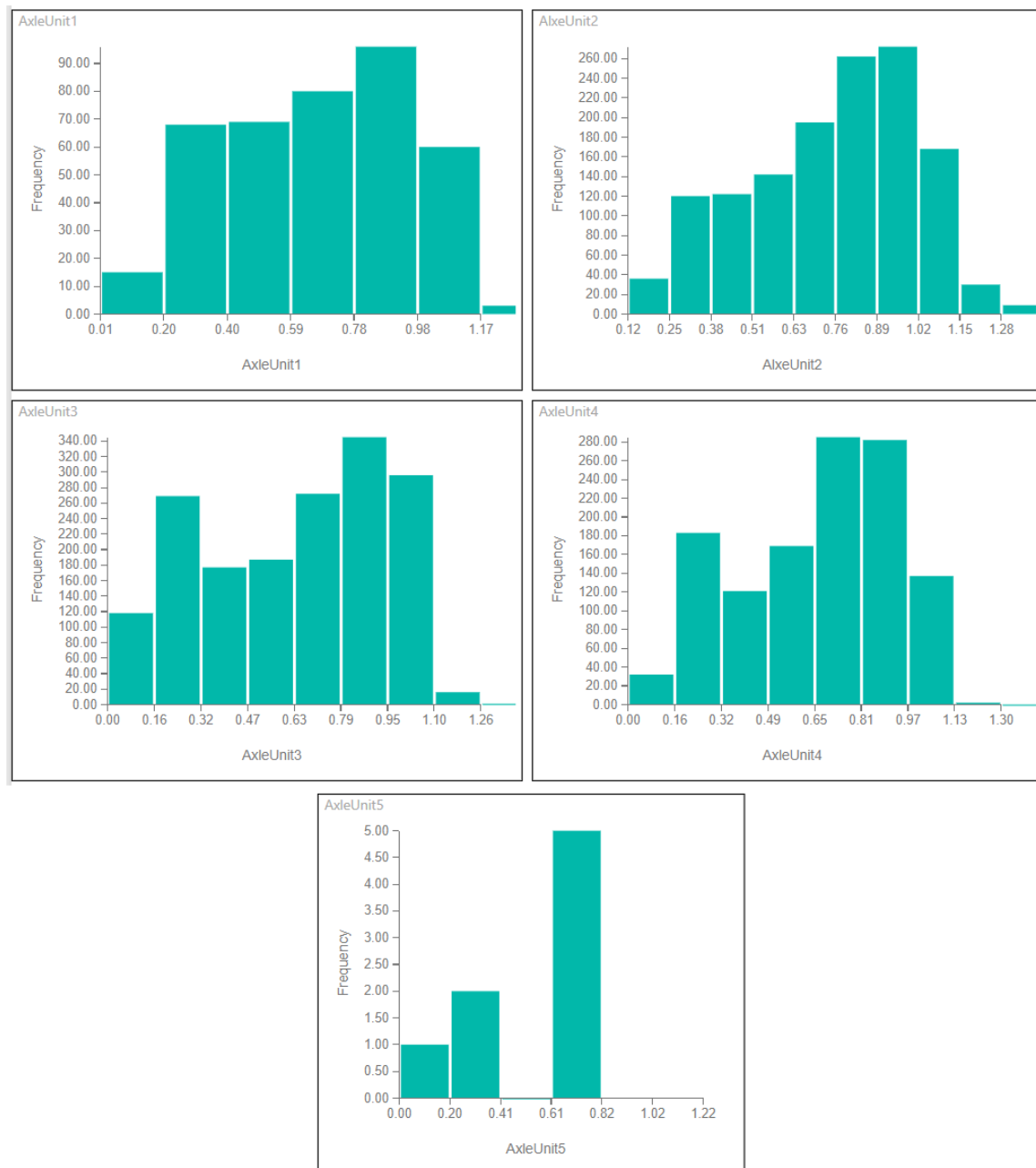


Figure 3.29: Histogram of normalised axle unit mass against permissible mass

3.5 Drawbacks

There were several drawbacks/inefficiencies within current operations when the system status quo and its statistics were analysed.

- The inherent inaccuracy of the WIM scale currently installed caused large numbers of vehicles to be statically weighed although they were not overloaded. This caused *time delays* for heavy vehicles, which had a domino effect on other stakeholders.
- There was too much *contact time* between potentially corrupt weighbridge officials and truck drivers.
- The layout of some TCCs caused *queuing* that disrupted WIM lane traffic and enabled possibly overloaded vehicles to *bypass* the TCC without being weighed by the WIM scale. Severe cases may have vehicles queuing to enter the TCC and in turn disrupt normal vehicle traffic flow while increasing the chances of an accident.
- Average time wasted between the WIM and static scale weighing was calculated at 15 minutes. This caused increased *fuel consumption* and vehicle *maintenance costs*.
- The time spent in repeated *reweighs* results in *increased travel time* that may have caused the vehicle to arrive at the border too late to cross it. This would automatically add several more hours to the trip.
- The abysmally *low number* of statically weighed vehicles that were *prosecuted* also indicates time wastage. Unfortunately, the collection of fines on overloaded vehicles was as low as 18,97% and 24,04% between 2015/16 and 2018/19 [42–46]. This translates to a total of ZAR 23 243 832 that was collected over the four years from fines, while constructing a TCC cost around ZAR 50 000 000. Therefore the fines could not fund the expansion of the TCC across the corridors and the toll concessionaires probably had to use toll fees to maintain the road infrastructure.
- *Data isolation* between stations limited information to specific TCC silos. Since intelligence within an industry is of utmost importance, this isolation hampered

intelligent use of the current information gathered. Data was not sent to a *central storage* facility and was only backed up by each TCC operator. An arrangement was made to send data to CSIR on a monthly bases but this often did not occur. The *format* discrepancies between sites also made additional data necessary in some data sets.

- Annual reports claimed 24/7 operation of the TCC but practical experience indicated that this was not the case, due to safety concerns at night. However, some vehicles still travel on the roads at night and overloading can easily occur then if the trend is spotted. The focus of most of the TCCs and *secondary roads* are neglected.

These drawbacks have significant impact when considering the traffic volumes of roughly 1 700 000 vehicles that are statically weighed annually. Reports have indicated that only around 22% of these weighed vehicles are overloaded and most are within the 2% grace limit, as a much lower percentage is fined. This has significant financial impact for several stakeholders, which is discussed in Chapter 5.

3.6 Proposed improvements

The thesis is focused on improving the efficiency of freight corridors. The proposed improvements can be achieved only by intervening in specific processes and installing hardware to achieve the stated goals.

This section discusses the proposed system to address these factors. The first proposal is a system design of hardware required to optimise the process. The second proposal entails slight changes in the state flows of systems. The alterations should be implemented on the status quo processes previously discussed as the base. The improvement proposed is based on the patent WO 2015/052662 A1 [30] entitled *Vehicle Overload Management System*, with the algorithm implementation discussed in this thesis as the IWIM algorithm. The patent is included in Appendix C, starting on page 366.

3.6.1 Optimisation goals

Freight corridor efficiency can only be improved by intervening in certain processes and installing hardware designed to achieve optimisation. *Firstly*, the system must be altered; and *secondly*, the status quo processes must be adapted.

The question remains, How and how much would these changes optimise the system? Since optimisation is the main objective of the thesis, the question is fundamentally answered below.

- How?
 - Decrease delay times for legally loaded vehicles that are reweighed multiple times with current operations.
 - Achieve this objective by integrating data between stations.
 - Use the integrated data as input to an AI-based algorithm, to be used as the IWIM algorithm, as indicated in Chapter 4.
- How much?
 - The benefits to stakeholders of the optimised system will be quantified in an economic model , as indicated in Chapter 5.

3.6.2 System design

The system design should require minimal additional hardware to minimise the financial requirements of the IWIM implementation. The previous section described the current flow of the system and the TCC operations but did not indicate the proposed functional systems. This section provides a holistic view of the proposed system alterations.

Proposed system overview

The first step in the proposal is to remove the data isolation between stations. This principle is indicated at a high level in Figure 3.30. It entails the addition of central database storage to send and receive data between the sites, as required in the algorithm designed in Chapter 4, which will facilitate implementation in the future.

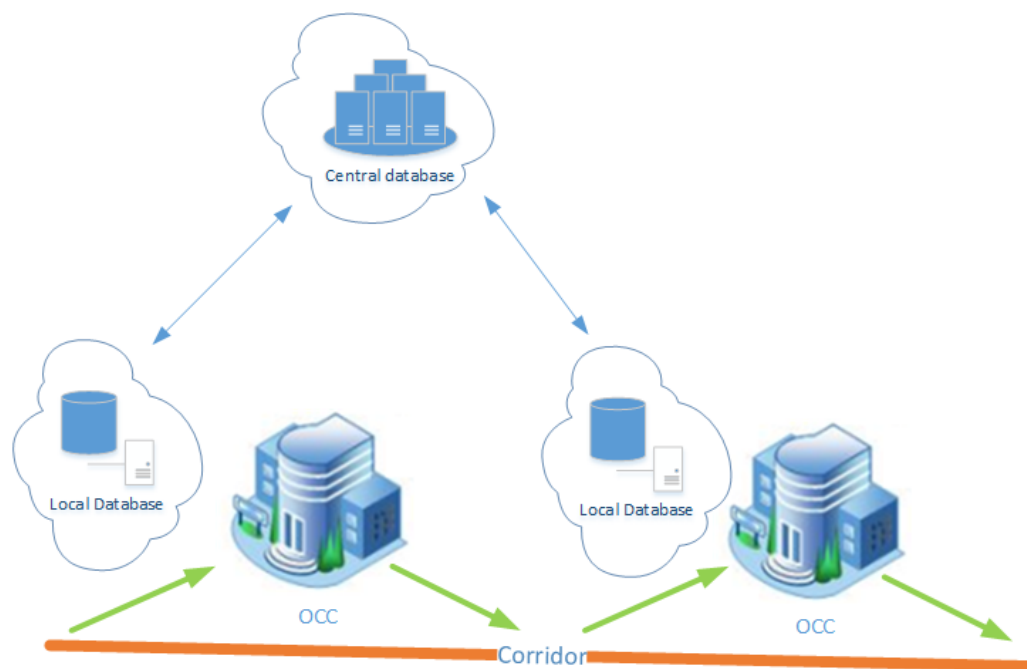


Figure 3.30: Proposed high level design without data isolation overview

The proposed system has several units that overlap the status quo system, which are indicated by blue arrows. Additions required for improvement in F/U and I/F are indicated by green arrows. This section describes the additions proposed, taking into account the current procedure portrayed in Figure 3.9 on page 87.

Functional operations are proposed as follows:

- F/U1: *Corridor* is the physical road pavement that is travelled on
- F/U2: *Heavy vehicle* is the main factor to be monitored and policed throughout the process at the TCC and interacts with several other F/Us.

- F/U3: *WIM scale* is used to determine the mass of the heavy vehicle while moving.
- F/U4: *ANPR camera* captures the image of the license plate and identifies the vehicle's registration number.
- F/U4.1: *RFID reader* is added for supplementary identification at the WIM, to be matched with ANPR data.
- F/U5: *Data processing* stores the information from WIM and ANPR data captured.
- F/U6: *IWIM algorithm rule set* uses the algorithm designed in Chapter 4 to route the vehicle accordingly.
- F/U7: *Routing system - WIM scale* indicates the direction the heavy vehicle should take after the WIM scale.
- F/U8: *Bypass detection* at the WIM scale incorporates additional systems as input for improved accuracy in detecting bypasses.
- F/U9: *Static scale* determines the mass of the heavy vehicle while it is stationary.
- F/U9.1: *RFID reader* is added for supplementary identification at the static scale, to be matched with ANPR data.
- F/U10: *Mass capture* stores the mass of the vehicle when statically weighed.
- F/U11: *IWIM algorithm rule set* uses the algorithm designed in Chapter 4 to route the vehicle accordingly.
- F/U12: *Routing system - static scale* indicates what direction the heavy vehicle should take after the static scale.
- F/U13: *Holding yard* is the parking location of the heavy vehicle to be processed by traffic officials.
- F/U14: *Prosecution* is the process of prosecuting the heavy vehicle and driver if the legislation dictates a breach of vehicle mass allowances.
- F/U15: *Data capture to database* stores the information from the prosecution to the database.
- F/U16: *Auto tag registration* is used to register vehicles with open road tolling tags to further optimise the system without the need to register on the system.
- F/U17: *Prosecution verification* is used to check whether a vehicle has been prosecuted before it is dispatched to the corridor.
- F/U18: *Central database* stores the data from all sites for use in the corridor optimi-

sation scheme.

- F/U19: *Time server syncing* is essential for travel time analysis and is used to synchronise equipment to one time server.
- F/U20: *Data sharing to central database* sends and receives site data to and from the central database.
- F/U21: *Maintenance monitoring* enables early detection if equipment is offline on a site.
- F/U22: *Alert maintenance staff* system alerts maintenance staff to attend to equipment downtime as soon as possible.
- F/U23: *Processing data to database* stores the information from static weighing to the database.

Interface operations are proposed as follows:

- I/F1: Is between F/U1 and F/U2, where the vehicle interacts with the road pavement of the corridor.
- I/F2: Is between F/U2 and F/U3, where the vehicle should be travelling over the WIM scale.
- I/F3: Is between F/U2 and F/U4, where the vehicle registration number is detected by means of the ANPR camera.
- I/F4: Is between F/U3, F/U4, F/U4.1 and F/U5 to send data to a database for information processing.
- I/F5: Is between F/U5 and F/U6 to ensure the captured information is used in the IWIM rule set.
- F/U6: *IWIM algorithm rule set* uses the algorithm designed in Chapter 4 to route the vehicle accordingly.
- I/F7: Is between F/U2 and F/U7 to direct the vehicle either to the static scale or to the corridor.
- I/F8: Is between F/U7 and F/U8 to detect any bypass of the intended routing location.
- I/F9: Is between F/U2 and F/U9 to stop the vehicle so it can be weighed on the static scale.

- I/F10: Is between F/U9 and F/U16 to send data to a database for information processing.
- I/F11: Is between F/U10 and F/U23 to store the static mass data.
- I/F12: Is between F/U10 and the weigh master to allow acceptance and finalisation of the static mass procedure.
- I/F13: Is between F/U10 and F/U11 to compare the WIM mass to the previous static mass, as part of the IWIM rule set.
- I/F14: Is between F/U11 and F/U12 to make use of the rule set to direct the vehicle accordingly.
- I/F15: Is between the F/U9 and F/U12 to direct the vehicle from the static scale either to the corridor or to the holding yard for prosecution.
- I/F16: Is between F/U13 and F/U14, where prosecution occurs in the holding yard.
- I/F17: Is between the traffic official and F/U14 to interface with the prosecution system.
- I/F18: Is between F/U15 and the traffic official to capture data to the applicable database.
- I/F19: Is between F/U18, F/U19, and F/U20 to send and receive relevant information between the databases.
- I/F20: Is between F/U15 and F/U20 to send data from the local site to the central database sharing module.
- I/F21: Is between all equipment on site and F/U21 to monitor uptime.
- I/F22: Is between F/U21 and F/U22 to alert maintenance staff to attend to an issue on site.
- I/F23: Is between F/U16 and the weigh master to confirm the registration number that is linked to the tag on the vehicle.
- I/F24: Is the interface between F/U14 and F/U17 to send and receive information between the systems to confirm that prosecution occurred.
- I/F25: Is between F/U22 and maintenance staff to interact with the maintenance alerting application.

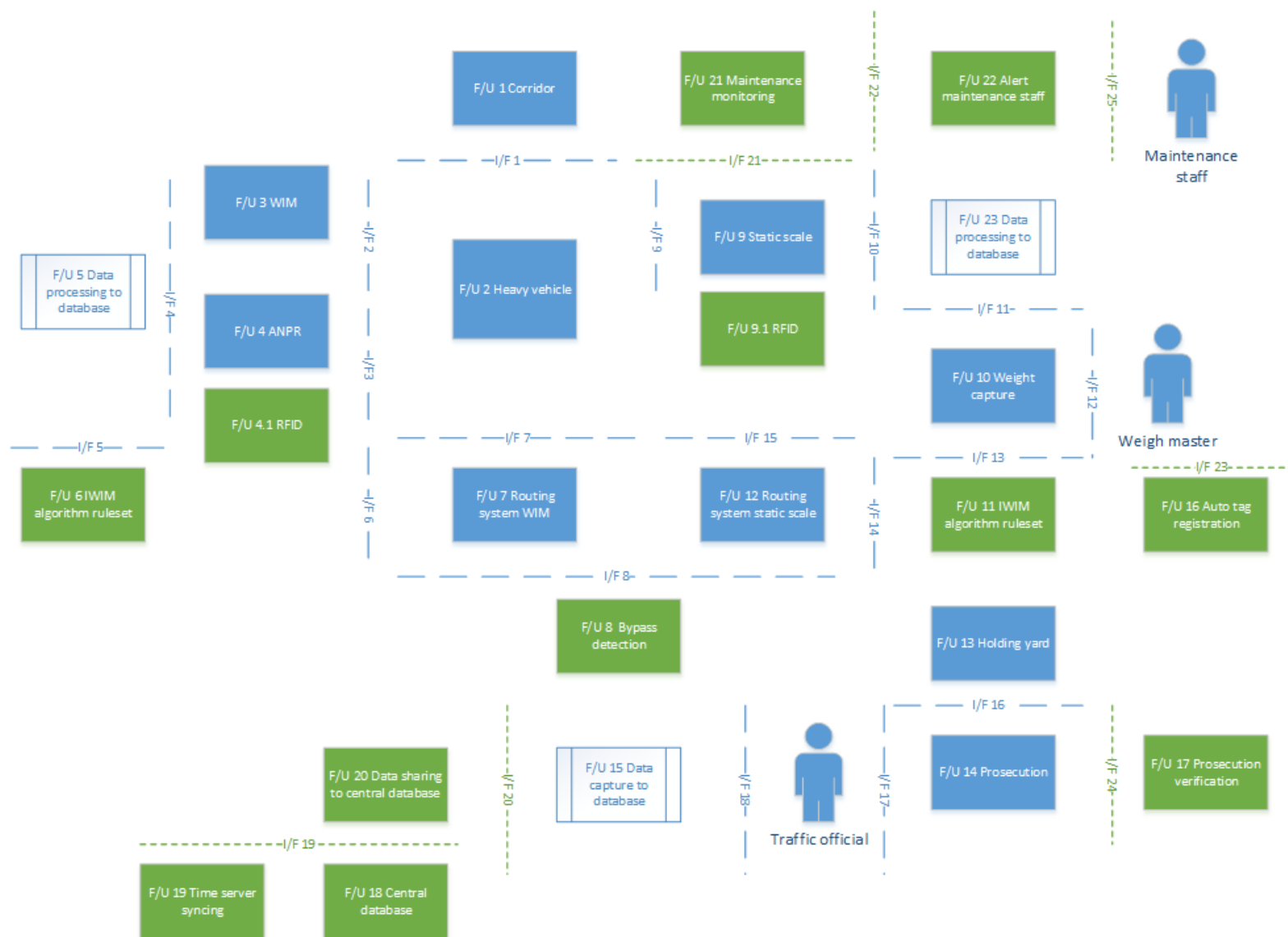


Figure 3.31: Overview of the proposed system at TCC level (blue indicates the current system; green indicates proposed changes)

3.6.3 Process flows for the proposed system

The first proposed change to the system is to add hardware to the current operations. the hardware would have to be accompanied by alterations to the process flows, as has been previously explained. The process flow is indicated as the IWIM state flow diagrams.

Intelligent weigh-in-motion algorithm

The intervention of the *IWIM* algorithm is the first process to be discussed and is indicated in Figure 3.32 on page 133.

The system is integrated and requires inputs from subsystems (*step 1.1*). A parallel process of the RFID reader will poll to see whether RFID tags pass the WIM scale (*step 1.2*). Detection of an RFID tag at the WIM scale will determine the following step (*step 1.3*). Standard status quo (SQ) procedure will commence if the vehicle has no detectable tag (*step 1.14*). The IWIM principle is based on self-regulation, as previously mentioned. RFID tags are used for several other applications and the tags' self-regulated registration status has to be confirmed (*step 1.4*).

If a registered tag is identified, it will mean that a previous sighting occurred at the upstream station (*step 1.5*). If there was no previous sighting, a threshold check (*step 1.13*) must be completed and the vehicle is directed to the corridor (*step 1.12*). In case of a previous sighting, it will have to be checked whether the travel time between stations is within the allowed limits (*step 1.6*), which will be discussed in more detail in the algorithm chapter (Chapter 4). An inappropriate travel time will ensure that the SQ procedure commences once again (*step 1.4*).

If the travel time is appropriate, the vehicle's WIM mass at the previous station will be considered (*step 1.7*). If the previous WIM mass was not overloaded/did not trigger a threshold, there will be another check of whether the current mass is below the threshold (*step 1.11*) and, if so, the vehicle will be directed back to the corridor (*step 1.12*). If the

current mass is higher than the threshold, the vehicle will be directed to the static scale (*step 1.10*).

If the vehicle was overloaded at the previous WIM scale (*step 1.7*), the system will have to consider the previous static mass (*step 1.8*), and the IWIM algorithm will include the current WIM mass. If no previous static mass was recorded, the vehicle will be directed to the static scale (*step 1.10*). The captured static mass will have to be checked to see whether it was legal (*step 1.9*). If the captured static mass was above the legal threshold at the previous station, the vehicle will be directed to the static scale (*step 1.10*). If the vehicle is below the upper threshold, other considerations apply (*step 1.11*).

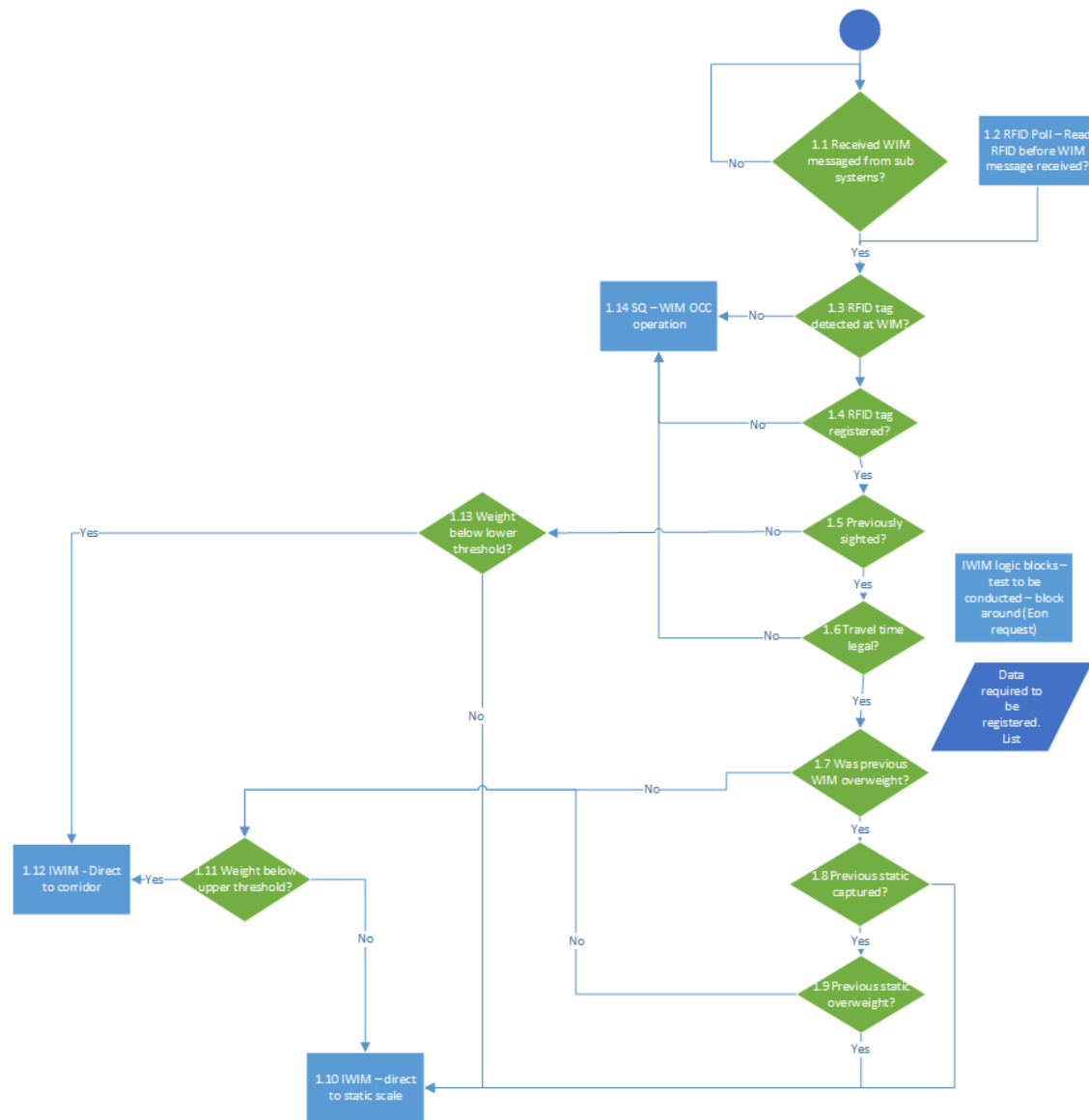


Figure 3.32: State flow of the IWIM concept for TCC

Radio frequency identification

The *WIM RFID* state flow is indicated in Figure 3.33 on page 135. RFID packets are linked to the registration details of the vehicles and to a magnetic loop before the WIM scale (*step 2.1*). Once the loop is triggered, a WIM information packet should be received (*step 2.2*). The loop will restart if no RFID packet is received (*step 2.3*) and the magnetic loop after the WIM scale is triggered (*step 2.4*). A received packet from the reader (*step 2.3*) will start the check against the registered vehicles (*step 2.5*). A non-registered vehicle (*step 2.6*) will continue according to the SQ WIM procedure (*step 2.7*). If a registered vehicle is detected (*step 2.6*), the link between the RFID and WIM information will commence (*step 2.8*). A message will be dispatched to the auto adjusting system (*step 2.9*).

The state flow of the *static scale RFID* device is indicated in Figure 3.34 on page 136. There is some additional intervention in the process. The boom will initially be opened only if a packet is received from the routing system (*step 3.1*). A reader will attempt to read an RFID tag (*step 3.2*) and, if no static scale packet is received (*step 3.3*), will mark the vehicle as untagged (*step 3.4*). The registration status is again confirmed by the RFID (*step 3.5 and 3.6*). A non-registered vehicle may be used in an auto vehicle registration process (*step 3.7*) to further optimise the system. Vehicles registered on the system will require the static scale mass captured at the previous station as verification of overload status (*step 3.8*). A link is of the static scale packet and RFID information is obtained to complete the RFID static scale process (*step 3.9*).

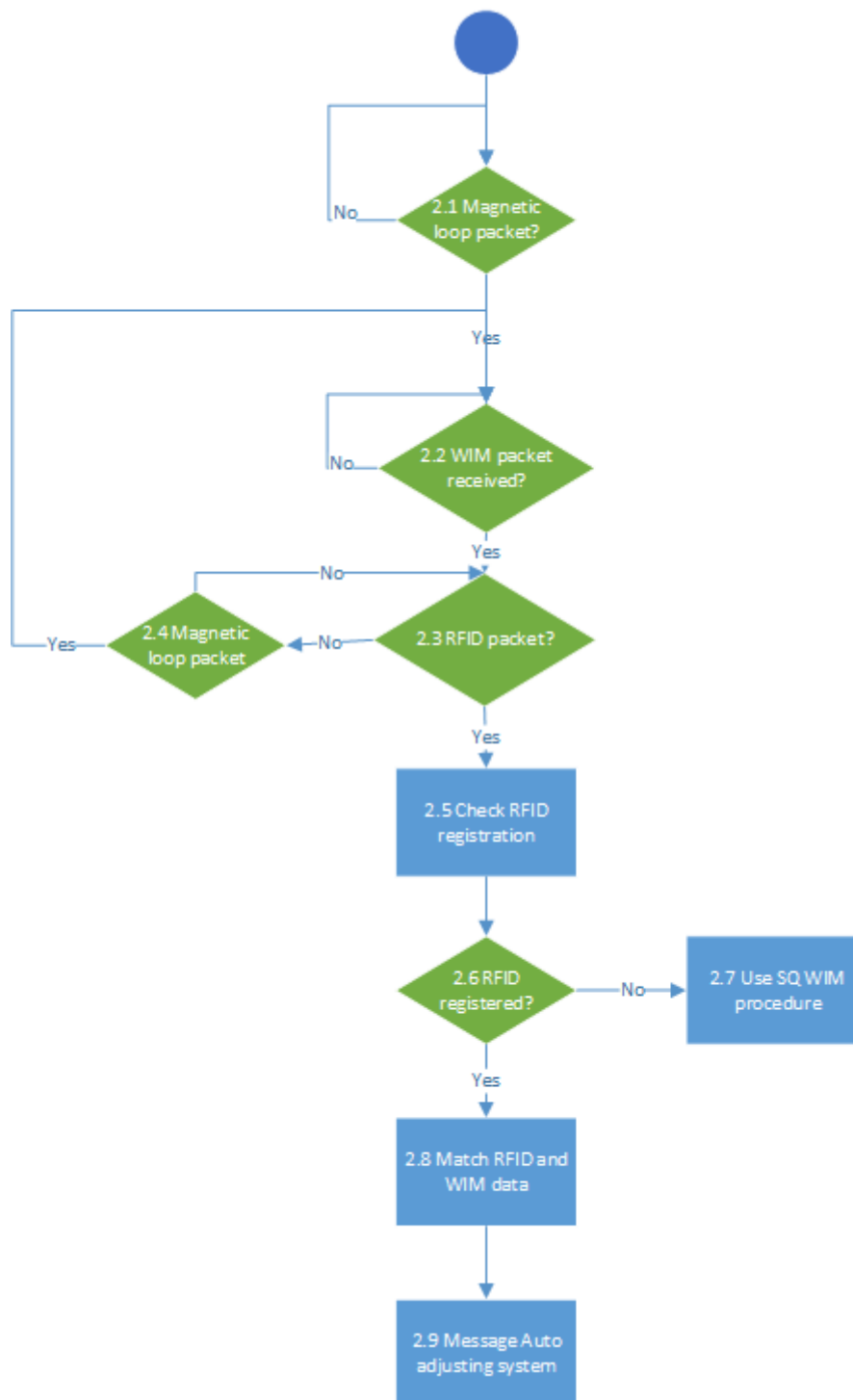


Figure 3.33: State flow of the IWIM and RFID usage at the WIM scale for the TCC

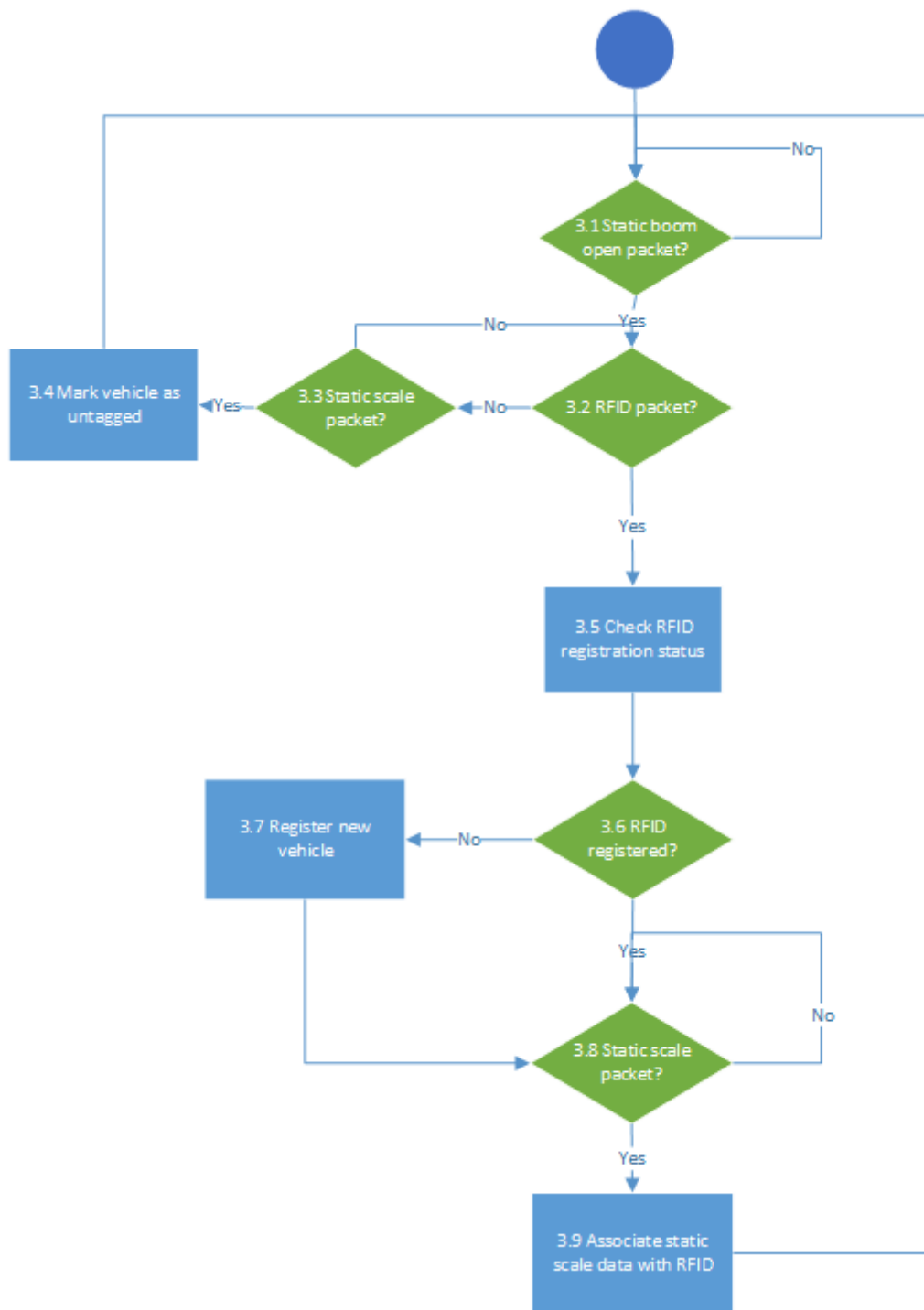


Figure 3.34: State flow of the IWIM and RFID usage at the static scale for the TCC

Bypass detection

It is important to detect vehicles bypassing the overload control process as it can be assumed that, in most cases, the bypass is done to evade law enforcement. The *bypass detection* part of the flow will have multiple inputs from different stages in the TCC process. The WIM process is indicated in Figure 3.35 on page 138. Bypass detection will first determine whether routing has instructed the vehicle to go to the corridor (*step 4.1*). (A vehicle directed to the corridor has not triggered the WIM and will most likely not be willing to go to the static scale.) The RFID packet received is checked (*step 4.2*) and, if no tag is included, will restart the process. The bypass detection will be activated (*step 4.4*). If no tag is detected at the static scale (*step 4.6*), a check will be triggered at the WIM scale (*step 4.8*). The process will repeat if no tag is detected at the WIM scale. A detection at the corridor RFID reader will record a correct routing to the corridor (*step 4.12*). A tag that is detected at the static scale (*step 4.6*) will flag incorrect routing to the static scale (*step 4.10*).

Where routing is not to the corridor (*step 4.1*), the signs will indicate the route to the static scale. This is essential to detect a potentially overloaded vehicle bypassing the static scale. The detection of an RFID packet will be the following step (*step 4.3*) and the process will restart if no tag is detected. Detection of a tag will activate the direction to the corridor (*step 4.5*). A tag detected at the static scale (*step 4.7*) will be recorded as correct routing (*step 4.11*). If no tag is detected at the static scale, a detection check at the corridor will be triggered (*step 4.9*). A tag detected at the corridor will be flagged as incorrect routing (*step 4.13*).

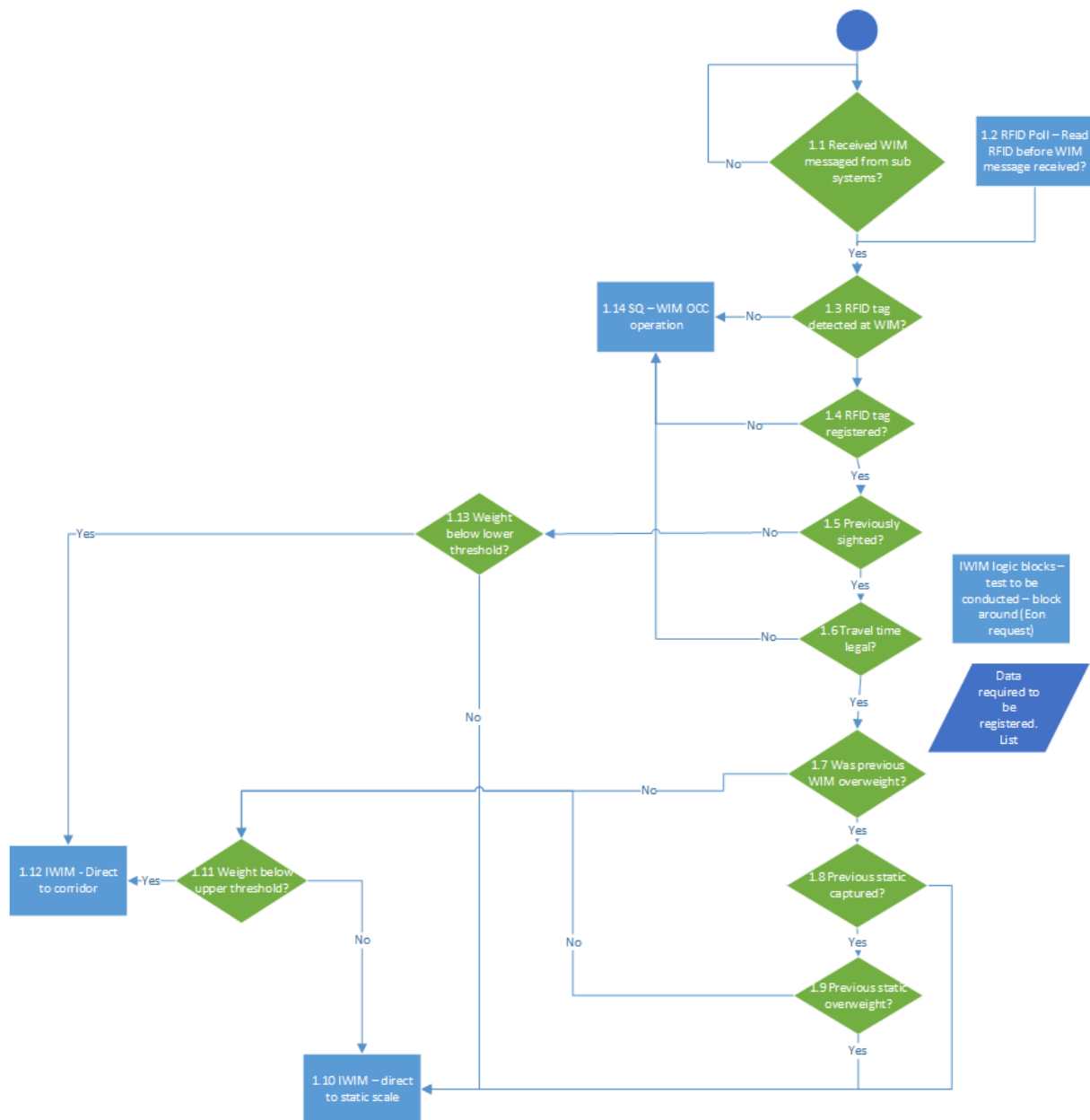


Figure 3.35: State flow of the IWIM bypass detection at the TCC

Automatic tag registration

Additional optimisation and registration of vehicles will be completed by an *IWIM auto tag registration* process. The process is indicated in Figure 3.36 on page 140. This process will be integrated with the static scale process to add a fair amount of certainty about the registration of the vehicle because registration verification forms part of the weigh master's process. The process will start when a static scale sequence is received (*step 5.1*). A static mass should be received from the weigh master (*step 5.2*) with an RFID packet (*step 5.3*). The registration process will continue if no tag has been registered (*step 5.4*). A link will be attempted with an ANPR packet (*step 5.5*) and confirmed by the weigh master (*step 5.6*). Manual entry can be done by the weigh master if the ANPR does not match (*step 5.7*) followed by the addition to the database for further incorporation in the IWIM implementation (*step 5.8*).

Data sharing

Integration of the data is an essential part of the algorithm input. The process is indicated in Figure 3.37 on page 141. The *data sharing* between stations does not need to be extremely fast because a vehicle will typically take an hour or two to travel between stations. The interval is therefore set to 5-minutes (*step 6.1*). New data at the current site will be compared to the central database (*step 6.2*) and new data will be copied to the central database (*step 6.4*). Data will be copied to the local database (*step 6.5*) when new entries are available on the central database (*step 6.3*) that are not in the local database. The central database can be hosted with SANRAL or a PPP agreement can be made to a company to ensure proper management of data with the relevant service level agreement (SLA). This centralised management of the data will ensure easy management of data and report construction to further increase effective use of overload control information.

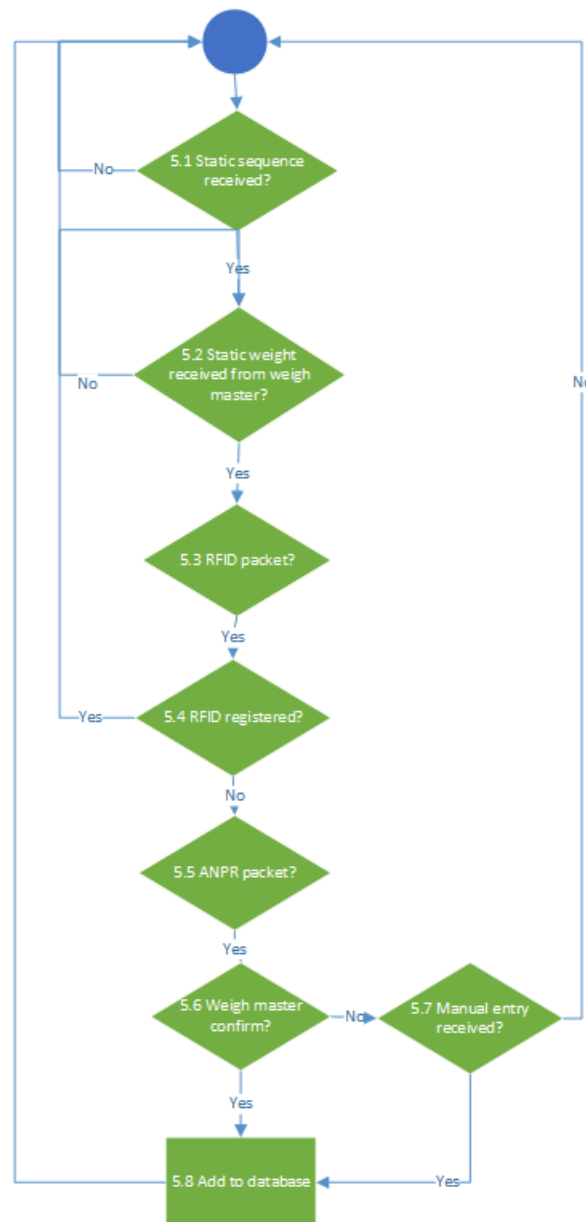


Figure 3.36: State flow of the IWIM automatic tag registration at the TCC

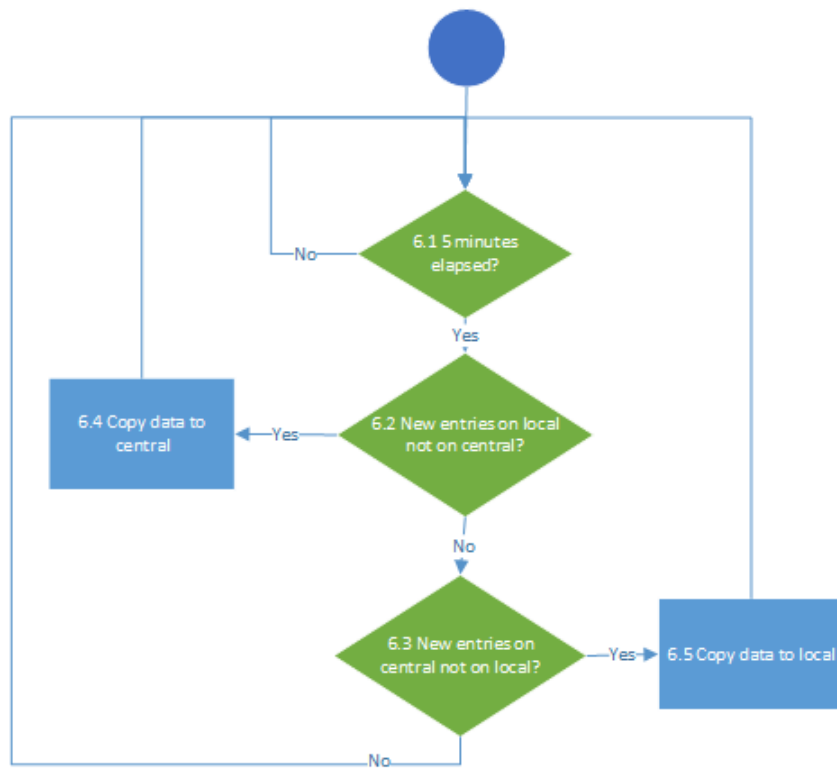


Figure 3.37: State flow of the IWIM data sharing between TCCs

Maintenance module

The *Maintenance module* is to ensure that the subsystems are all functional, and that maintenance staff are contacted to repair the system as soon as possible. The first step is to contact the subsystems (*step 7.1*) and request an uptime status feedback. Once feedback is received (*step 7.2*), the process will restart (*step 7.3*) to continue checking the subsystems. If there is no feedback, a 5-minute timer will start (*step 7.4*) to ensure a small communication drop does not cause a false alarm to the maintenance staff. A timer that has not yet been exceeded (*step 7.5*) will determine once again whether feedback has been received (*step 7.6*). If there is no feedback, the module will continue to recheck whether the time has been exceeded (*step 7.5*) and, if feedback has still not been received (*step 7.7*), an alert will be issued to the maintenance staff (*step 7.8*).

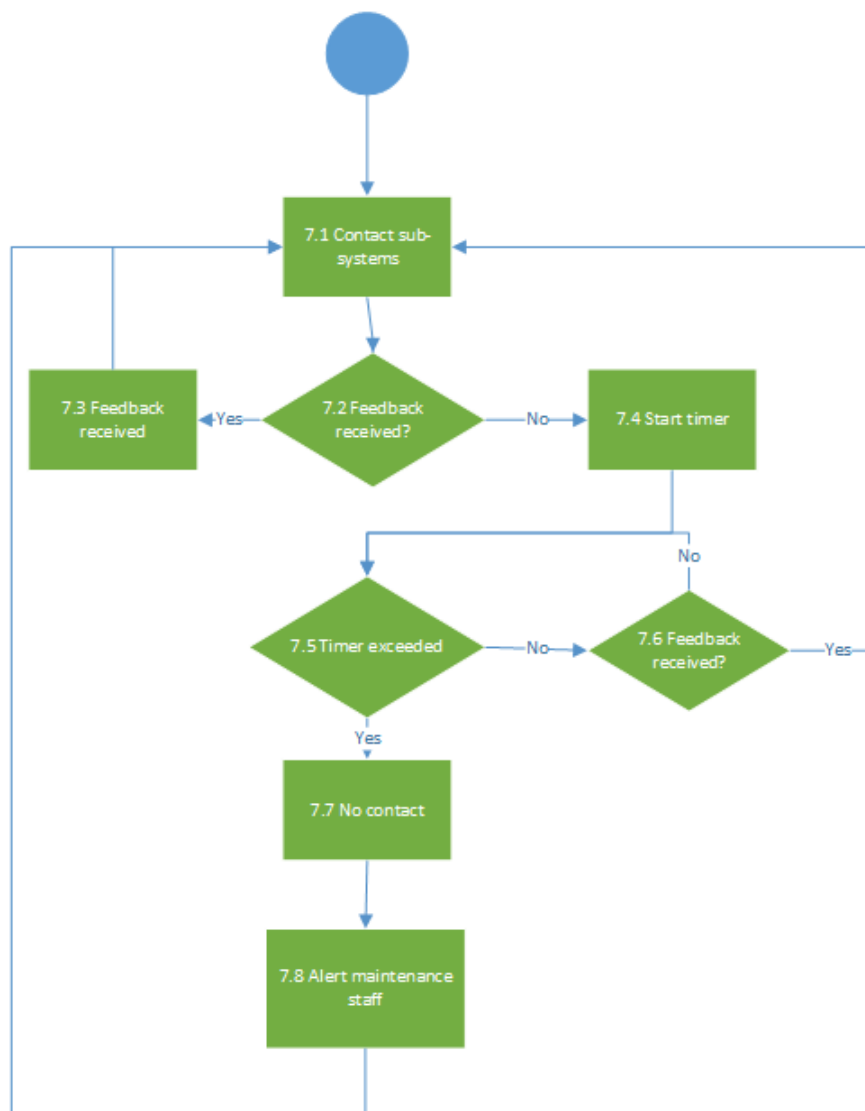


Figure 3.38: State flow of the IWIM subsystem maintenance checks

Threshold adjustment

Automatic threshold adjustment forms part of the algorithm design that will be discussed in Chapter 4. It will be incorporated with self-regulation registered vehicles to adjust the threshold at which the WIM will trigger higher than normal. An RFID packet must be received (*step 8.1*). If no packet is received, the standard threshold will be used (*step 8.2*) where "lower" indicates a 10% threshold at the WIM scale.

A registered vehicle will be compared to a previous sighting (*step 8.3*), followed by its status, if the mass was legal (*step 8.4*). In both these cases, the system will be directed to use a lower threshold if the previous mass was not legal (*step 8.2*). A previous legal static mass will check whether the travel time was legal between stations (*step 8.5*). If the travel time was legal, the system will use the upper threshold for the WIM scale (*step 8.6*).

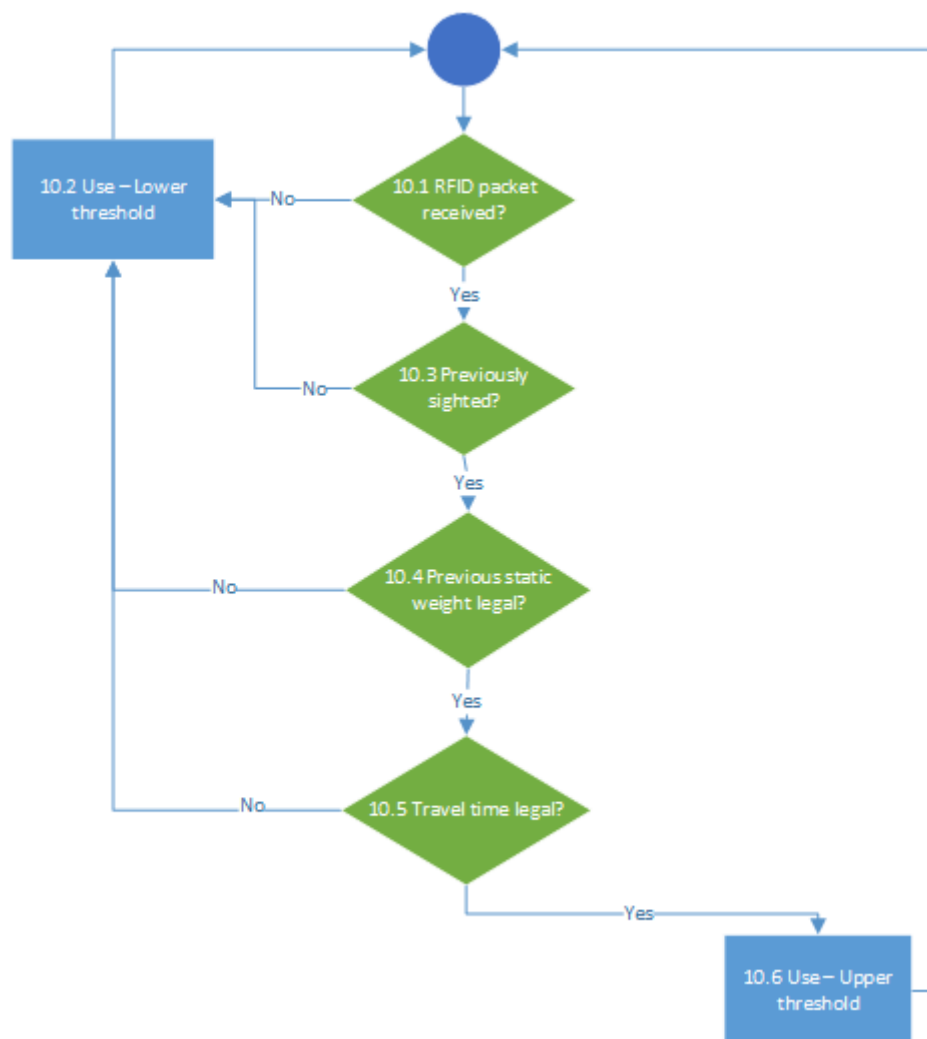


Figure 3.39: State flow of the IWIM automatic threshold adjustment for the WIM at TCC

Prosecution verification

Prosecution verification is intended to add vehicles to or remove them from a list of repeat offenders regarding an overloaded state when reweighing occurs. The process is indicated in Figure 3.40 on page 146. The process will require the static mass package (*step 9.1*). The vehicle will be identified by means of RFID (*step 9.2*) or ANPR (*step 9.3*). Failing to identify the vehicle will ensure no action is taken by the prosecution verification and will require manual verification by the TCC operator (*step 9.4*). The identified vehicle will be queried against the current verification list (*step 9.5*). A vehicle that is not on the list will be confirmed if it is currently overloaded (*step 9.6*). No action will be taken if the vehicle is not overloaded (*step 9.4*); and the vehicle will be marked as illegal if it is overloaded (*step 9.7*).

A vehicle that is already on the verification list (*step 9.5*) will receive an overload check (*step 9.8*). The vehicle is marked as "verified legal" if it is not overloaded (*step 9.9*) and marked as "repeat offender" if overloaded (*step 9.10*).

3.6.4 Hardware infrastructure

The hardware required to support the proposed system is shown in Figure 3.41 on page 148. There are two clear sections in the proposed system. The first incorporates the systems on site at the TCC and the second the central data storage system. This hardware will be used in Chapter 5 in the comparison of the implementation costs with the benefits the system offers to stakeholders.

The **central data storage** will have several components to address specific functions in the system. There will be a central database in the central data storage area for all the sites included in the corridor optimisation. The *web server* will be used as the interface for data sharing between the sites and central data storage. The *application server* will include algorithm updating as and when required so that the site hardware is not required to be too powerful and to reduce costs. The server costs can be minimised

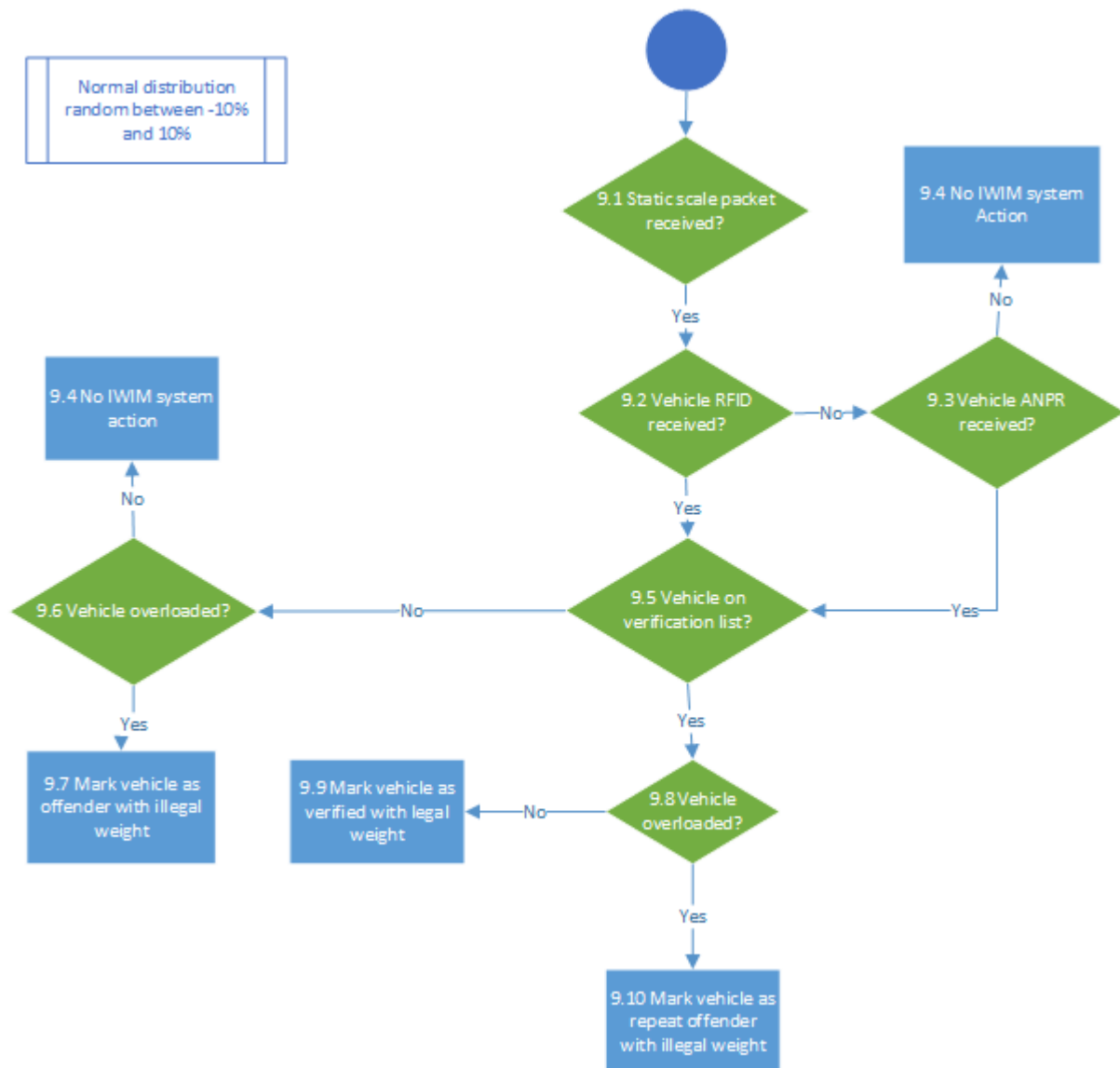


Figure 3.40: State flow of the IWIM prosecution verification at TCC

by services that include scalable hardware requirements only when the algorithm has been rerun. Implementation of good practices will include *data encryption*, a *firewall*, a geographical redundancy server location, and database backups.

The *mobility application* will be used to report and indicate system downtime from the maintenance services. This will alert the applicable technicians to be dispatched to ensure minimal downtime. The *reporting service* will assist in automated reporting of vehicle movements, traffic statistics, and the downtime of equipment on site.

Site systems will also include several components. The first addition will be RFID readers at the WIM and static scales. The TCC server may need an upgrade to function as an application and database server. This will ensure all inputs are received and processed against the algorithm to send details to the subsystems to be controlled. All details will be stored on the database server. *Equipment monitoring* will include *information collection* for the algorithm inputs. This monitoring will be used in the monitoring and alerting of maintenance staff. Good practices will also be implemented at the site and will include data encryption, firewall, cyber security considerations, a potential secondary server for redundancy, and database backups.

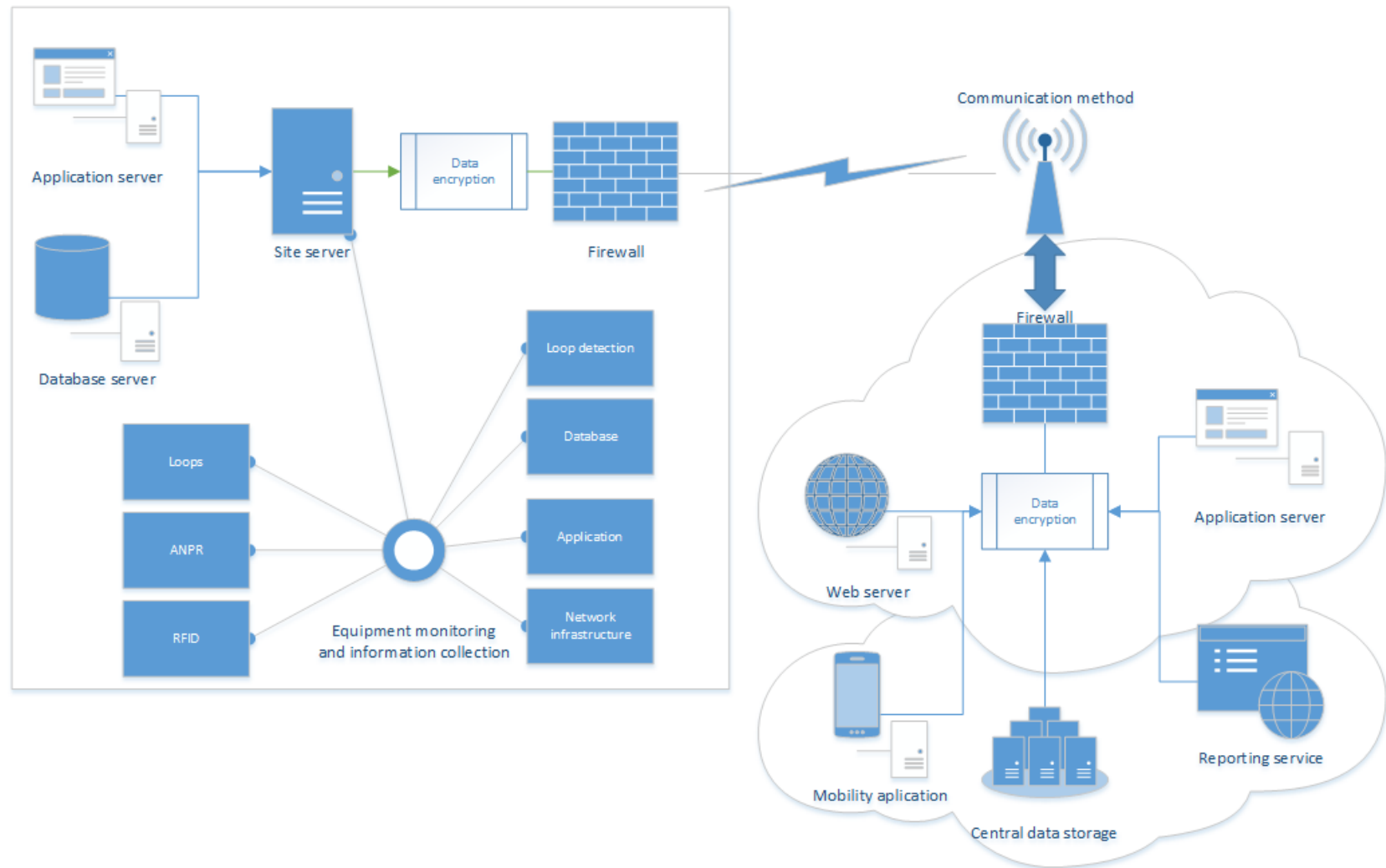


Figure 3.41: Proposed hardware required for system implementation

3.6.5 Master data management

The hardware required to support the proposed system will require a standardised database back end at both the TCC and the central data storage. This section proposes a preliminary high-level view of the database structure that may support industry implementation. The current design is proposed for a Microsoft SQL server but may be used in any other database platform when implementation occurs. The selection will have to take several aspects into consideration to have the optimal solution. The master data management will ensure that statistics can be obtained much more often to gain insight into the industry. The database structure is designed to support the algorithm implementation as designed in Chapter 4. Review of the algorithm design will assist in clarifying the database structure proposed in this section.

The **central data storage** will contain the entire data set from all the sites. The process of data sharing has been indicated in Section 3.6.3. Several database tables are proposed, which have taken the positive attributes from current data structures to minimise discrepancies and increase data availability in the data sets. This proposal will have to be debated prior to implementation and SANRAL as the client will have to integrate it into the service agreement with the PPPs.

The first database view proposed is to support the IWIM algorithm implementation as seen in Figure 3.42. This structure can be expanded to include additional aspects for future algorithm expansion. The *IWIMeventMaster* will have links between WIM readings, static scale readings, and algorithm outputs. This will allow analysis of operations and an overview of the impact of the system.

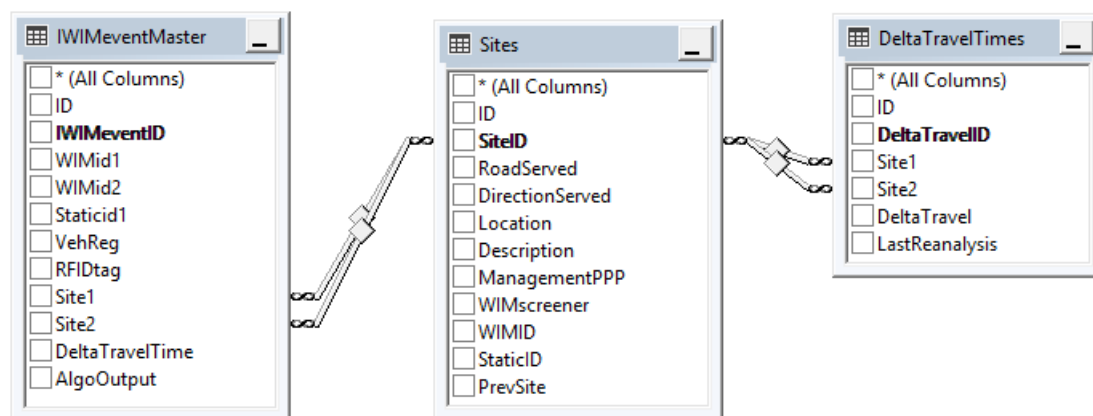


Figure 3.42: IWIM master proposed database structure

The second database view in Figure 3.43 on page 151 is an overview of the installation and information required for a SANRAL overview. This may be used as a overview of legislation changes, PPP management of sites, vehicle classification, site descriptions, static scale installations, and WIM installations.

The third database view in Figure 3.44 on page 152 is of the master data storage of static scale and WIM events. This will be used to receive data from sites and send data to the relevant sites to be used for algorithm optimisation on the sites. Data stored in this database will be used in the algorithm as designed in Chapter 4.

The **site data storage** will ensure site operations will support the proposed improvement to optimise the efficiency of the TCC. The database view in Figure 3.45 on page 153 supports the operations at site level and will capture the static scale and WIM events. Data transfer of records will be to and from these tables. Bypass detection and site prosecution verification will be included to support the proposed improvement.

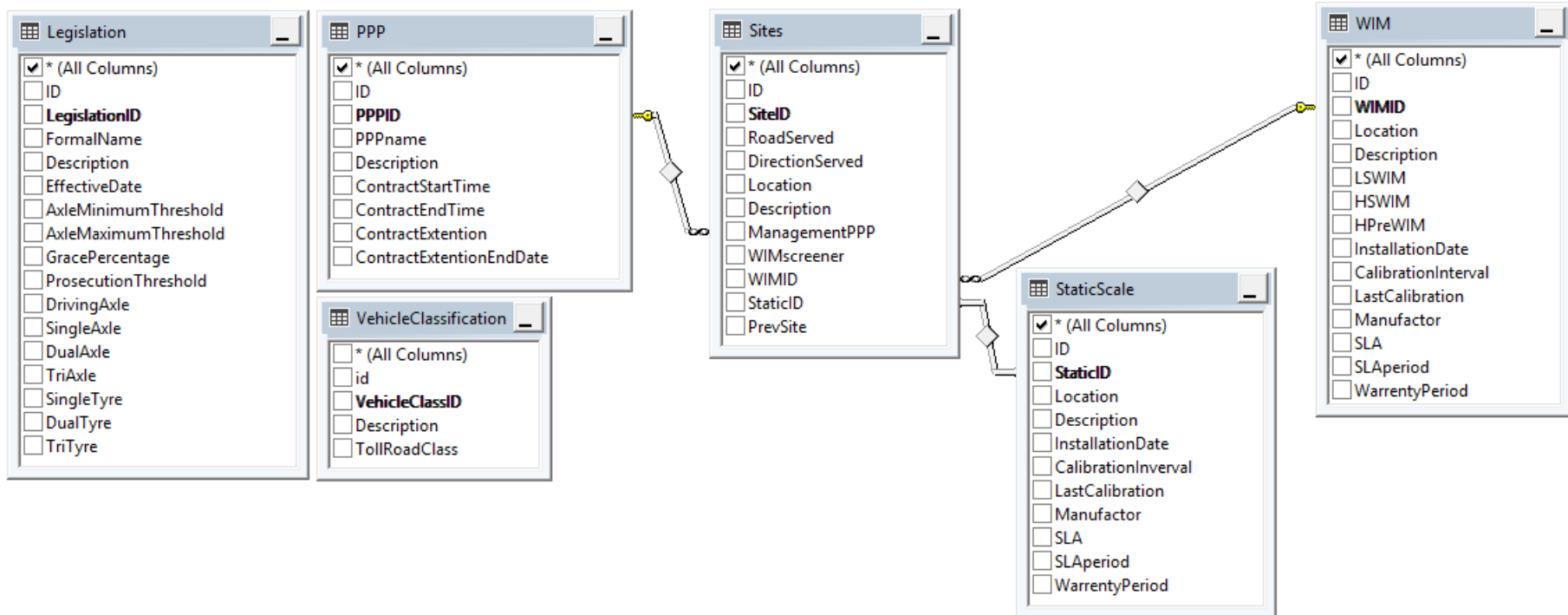


Figure 3.43: Static and WIM installation overview proposed database

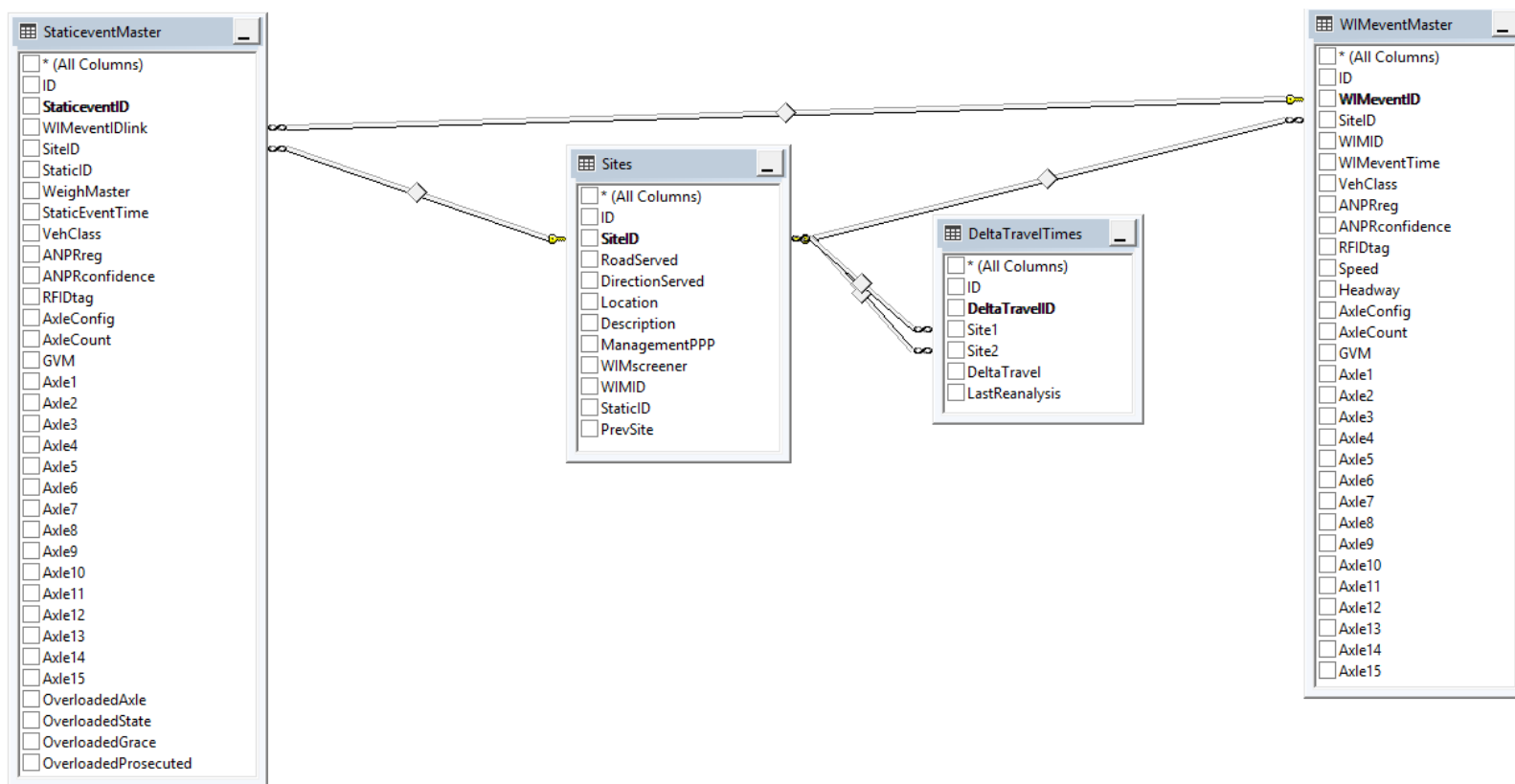


Figure 3.44: Master event proposed database structure

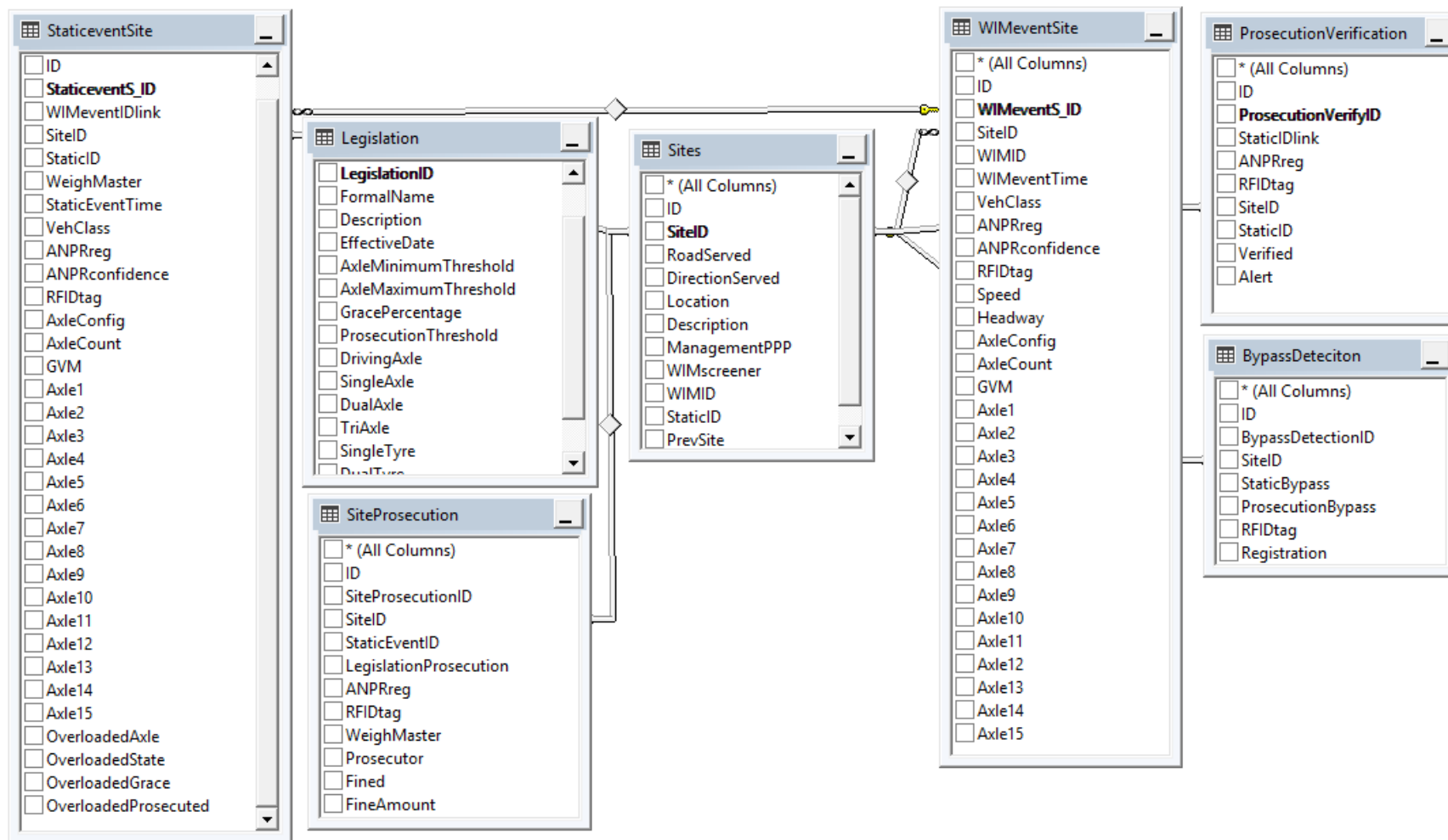


Figure 3.45: Site database proposal

3.7 Conclusion

This chapter has explained the site selection for the case study, as well as the layout and operational flow of the stations. An SQ analysis ensured a deeper understanding of the functional units that are currently involved in the TCC operations. Data captured at the sites was required to gain additional insights into the operations by means of data analysis.

The analysis indicated that there are several drawbacks in the current operations. There are significant delays between WIM scale and static scale mass checks. The delays are compounded by the fact that, of the roughly 1 800 000 statically weighed vehicles, only around 22% are overloaded. One key aspect that causes unnecessary reweighing is the lack of data sharing between the stations. Also, an unacceptable low percentage of the fines issued for overloaded vehicles are collected.

These drawbacks have given rise to a proposal that will improve the current operations. The proposal is to implement an IWIM algorithm that will alter some of the process flows in the current operations. This algorithm requires data sharing between stations to ensure optimisation. Hardware and database solutions are proposed to ensure that the algorithm can be implemented on site. This solution is however dependent on several technological components to be installed to ensure successful implementation of the proposed system. The cost needs to be considered against the benefit as additional motivation for implementation.

The next chapter will discuss the development and testing of the algorithm design.

Chapter 4

Intelligent Weigh-in-Motion algorithm design for integrated corridor optimisation

Algorithms aren't biased, humans are – Charles-Edouard Bouée

The work described in this chapter was aimed at developing AI techniques that implement the IWIM algorithm. These techniques were applied to several data sets, which included collected industry data as well as simulated data sets derived from measured data. We then quantified the potential future benefits that should result from implementing the optimised TCC process. It will only be possible to verify whether such benefits can be realised in practice once the proposed system is implemented, which will allow us to gather additional relevant data that is similar to the current industry data.

The **purpose** of applying AI to the problem of corridor optimisation was summarised in Chapter 1 as: *Improve overload control system operation by implementing IWIM measurements that make use of data sharing between TCCs on the freight corridors.* This could be achieved by making use of an AI or ANN model to minimise the number of legally loaded vehicles being statically weighed, while also minimising the number of vehicles being incorrectly directed away from the static scale. The **objective** was to improve the efficiency of the overload controls on the corridor for the benefit of multiple stakeholders within the industry.

The objective was achievable by using available data within the overload control process as inputs to an AI-based algorithm. Design of such an algorithm required specific steps to be taken before it could be implemented. Some steps may seem trivial, but they are essential to the accurate implementation of the selected AI technique. The steps that needed to be implemented are as follows:

1. Consolidate all the data sets required to generate inputs for the IWIM algorithm.
2. Conduct Rule-based model performance tests on the data sets constructed and use the tests as the baseline for measuring performance against the AI models.
3. Investigate the effect of adjusted WIM thresholds with data sharing between stations that were not overloaded at the previous TCC.
4. Select suitable AI models and model parameters for the development of the algorithm.
5. Transform data to prepare inputs for the AI algorithms.
6. Train and test AI models on data sets.
7. Compare model improvements against the Rule-based model.
8. Select the most suitable model to be used as the IWIM algorithm.
9. Construct a simulation data set representing industry behaviour for additional IWIM algorithm testing, using measured data as the statistical basis for the construction.
10. Add noise to the simulation data set construction for additional model performance testing.
11. Follow process steps 1 to 7 on the simulation and noise simulation data sets.

12. Indicate the provisional benefits of model implementation and the financial quantification (in Chapter 5).

4.1 Industry data

A case study data set for the IWIM model development was collected from the industry in 2021 for the Mantsole and Heidelberg TCCs. Data provided for WIM and static scale at these sites ranged from 2021-03-01 to 2021-08-31. These were the same sites as those used in Section 3.1, Site Selection for the Study. This section describes how the relevant statistics from the data sets were established and developed into input to the IWIM model that was then used to verify the practical application and benefit of the model to real-world industry data.

4.1.1 Data consolidation

An accurate representation of freight corridor activities could only be obtained by consolidating data from different industry sources. This consolidation allowed the construction of the inputs required by the algorithm with the goal of improving existing operations. The outcome of the algorithm decides whether a vehicle could be overloaded since it was previously seen at an upstream TCC.

The algorithm required a data set with complete overlapping between data from different TCCs to ensure an accurate design with optimal benefits for the stakeholders. The planned processing, as discussed in Section 3.6.3, was applied to the data set. The complete data set served as input for the design of the algorithm that should be implemented to achieve the contribution described in Section 1.6.1. The Mantsole and Heidelberg TCCs were selected to supply the input data for the algorithm, as previously indicated in Section 3.1.

The SANRAL study brief specified the North-South Corridor from Durban along the N3,

merging with the N1 towards the Beitbridge border post. The Mantsole and Heidelberg TCCs are sequential sites on the corridor, as indicated in Figure 4.1.

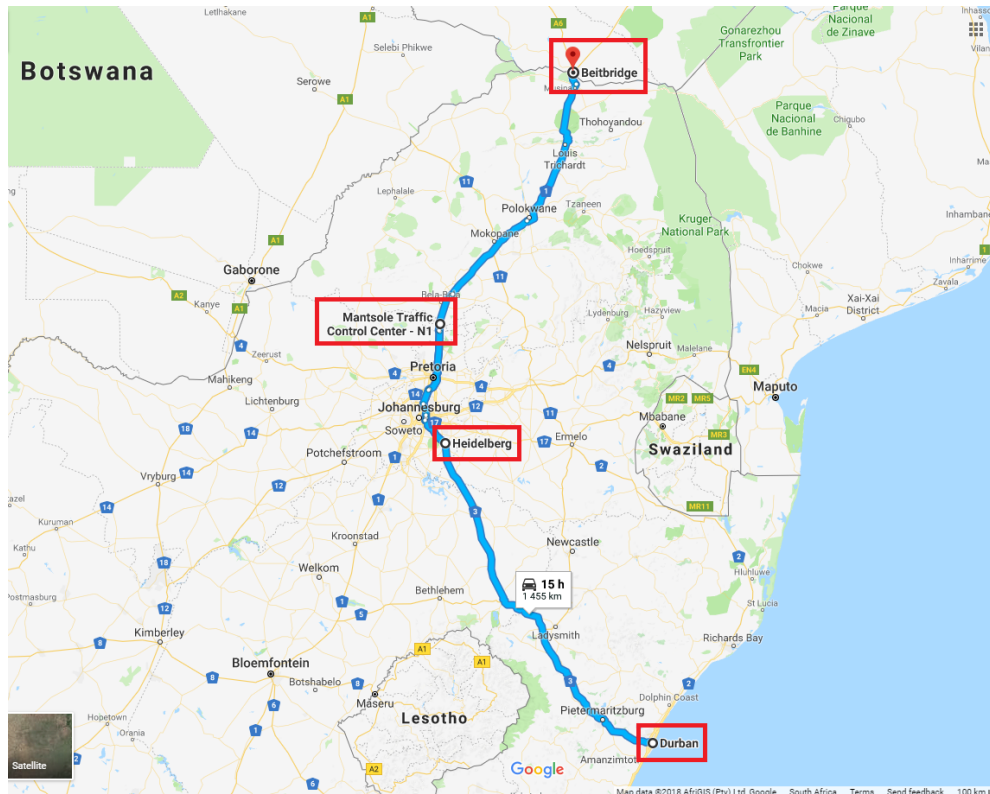


Figure 4.1: North-South Corridor from Durban to Beitbridge

The system proposed in Section 3.6.2 indicates the functional technological units that should be installed to assist implementation of the designed algorithm and its real-world implementation. *Data sharing* between TCCs, or “de-isolation”, is a key requirement before the algorithm can be implemented in this real-world solution. Data sharing has been used in multiple disciplines and the TCCs can greatly benefit from implementing the same design philosophy. It is known as *propagation* in AI and ANN training techniques and as *feed forward* in control theory.

The data time range and general statistics of the data sets were required in order to determine the overlap. The analysis of the NB data sets for WIM and static scales at the Mantsole and Heidelberg sites is given below. It is followed by the same analysis of the SB WIM and static scale data at Heidelberg and Mantsole.

Data available for this time period were:

- Static scale data – Mantsole NB and SB
- Static scale data – Heidelberg NB and SB
- WIM scale data – Mantsole NB and SB
- WIM scale data – Heidelberg NB and SB

The NB data statistics are indicated in Table 4.1 with an overlap in data from 2021-04-01 to 2021-08-31 at both sites. Data provided from the WIM data set contained just under 482 000 vehicle weigh entries and just under 152 000 distinct vehicles in the time period. The static scale data showed just over 80 000 vehicles statically weighed and just under 35 000 distinct vehicles. The WIM ANPR linking was unsuccessful, with a *NaN* or empty vehicle registration details, entry on just over 56 000 entries additional to the distinct vehicles.

Table 4.1: NB data set statistics

Northbound		
WIM	Heidelberg	Mantsole
Minimum date	2021-04-01 00:01:39	2021-04-01 00:00:04
Maximum date	2021-08-31 23:59:47	2021-08-31 23:56:31
Entry count	233 392	248 537
Distinct vehicle count	76 469	99 815
NaN values	45 000	11 032
Static	Heidelberg	Mantsole
Minimum date	2021-04-01 0:25	2021-04-01 00:15
Maximum date	2021-08-31 23:36	2021-08-31 23:49
Entry count	35 322	44 845
Distinct vehicle count	14 456	20 410

The SB data statistics are indicated in Table 4.2 with an overlap in data from 2021-03-01 to 2021-08-31 at both sites. The WIM data set contained just over 551 000 vehicle weigh entries and just over 153 000 distinct vehicles in the time period. The static scale data showed just under 72 000 vehicles statically weighed and just over 34 000 distinct vehicles. The WIM ANPR linking was unsuccessful, with a *NaN* entry on just under 70 000 entries.

Table 4.2: SB data set statistics

Southbound		
WIM	Mantsole	Heidelberg
Minimum date	2021-03-01 00:07:32	2021-03-01 00:02:09
Maximum date	2021-08-31 23:54:44	2021-08-31 23:52:28
Entry count	279 114	272 572
Distinct vehicle count	82 296	71 187
NaN values	18 238	51 455
Static	Mantsole	Heidelberg
Minimum date	2021-03-01 00:20	2021-03-01 02:19
Maximum date	2021-08-31 23:54	2021-08-31 23:53
Entry count	37 336	34 585
Distinct vehicle count	17 057	17 449

The overlapping data statistics gave some additional insight into the traffic going past the TCC and how much of it was directed to be statically weighed. At Heidelberg, 15,13% of the NB traffic was directed to the static scale, and 18,04% of the traffic was statically weighed at Mantsole. SB traffic had 13,38% directed to the static scale at Mantsole, and 12,69% at Heidelberg.

The next step in the process of constructing the input data set was to reliably link the data. This was essential, and challenging when considering that WIM data sets had as much as 19,28% *NaN* or no registration information to be used for linking purposes. This

emphasises the need for more accurate identification by means of RFID, as discussed in Section 3.6.3.

Vehicle linking

Since reliable linking of vehicle records was essential, as previously discussed, real-world data linking was a critical process step. The linking step was first applied in the NB direction for vehicles travelling between Heidelberg (*as site 1 NB*) and Mantsole (*as site 2 NB*). The SB direction reversed this, with vehicles travelling between Mantsole (*as site 1 SB*) and Heidelberg (*as site 2 SB*). Vehicle records for WIM and static scale records were linked in the static scale data set and used in the linking process. The process of linking vehicle records for WIM and static scales was as follows:

1. Determine vehicle registration to be used as identifier.
2. Search following site records for the same identifier.
3. Determine the time variance between entries.
4. Store values of vehicles that travelled between the sites in the past 24 hours.

The values stored for the linking process were as follows:

- Site 1 Vehicle identifier
- Site 1 Date and time
- Site 1 WIM axle configuration
- Site 1 WIM axle count
- Site 1 WIM axle unit weights
- Site 1 WIM AVCM
- Site 1 Travelling speed over WIM
- Site 1 Static scale axle configuration
- Site 1 Static scale axle count
- Site 1 Static scale axle unit weights
- Site 1 Static scale AVCM
- Site 1 Static scale axle unit permissible weights

- Site 1 Static scale permissible AVCM
- Site 1 Overload status
- Site 1 Identifier
- Site 2 Date and time
- Site 2 WIM axle configuration
- Site 2 WIM axle count
- Site 2 WIM axle unit weights
- Site 2 WIM AVCM
- Site 2 Travelling speed over WIM
- Site 2 Static scale axle configuration
- Site 2 Static scale axle count
- Site 2 Static scale axle unit weights
- Site 2 Static scale AVCM
- Site 2 Static scale axle unit permissible weights
- Site 2 Static scale permissible AVCM
- Site 2 Overload status
- Site 2 Identifier

The linking process resulted in a total of 3 167 entries when combining NB and SB traffic, with 2 226 distinct vehicles. The results are shown in Table 4.3.

Table 4.3: Linked data set statistics

Northbound	
Minimum date	2021-04-01 01:25:00
Maximum date	2021-08-31 09:54:00
Southbound	
Minimum date	2021-03-01 03:37:00
Maximum date	2021-08-31 17:55:00

Linked data set	
Total NB and SB	3 167
Distinct vehicle count	2 266

The next step was to normalise the weights against the permissible axle legal limits. Each of the axles had permissible weights in the data set that could easily be converted to normalised weights. When the overload status was available, the rule-based performance of the data set will be used to establish whether performance improved in the AI models.

Rule-based performance testing

The SQ rule-based system currently implemented determined whether a vehicle's WIM mass was potentially overloaded and whether it should be directed to the static scale. The WIM threshold is set at 10% from the maximum allowed mass or 90% of the legal permissible mass before it directed a vehicle to the static scale. This meant that a legally loaded vehicle that is loaded close to the permissible mass was directed to the static scale to determine its statically weighed load, even though it was not over the limit. The purpose of the AI model developed in Section 4.1.3 below was to decrease the number of legally loaded vehicles that are statically weighed.

Implementation of the rule-based system simply checked whether the maximum value for any axle and AVCM mass was above the threshold and whether the vehicle should be marked as overloaded. The steps were as follows:

- Determine the maximum of WIM axle masses and AVCM.
- Determine whether the load is more than 0,90 of the normalised mass.
- Direct to the static scale for mass above 0,90.
- Direct to the corridor for mass below 0,90.

The *first* rule-based performance was applied to the current station's WIM to determine the number of vehicles incorrectly directed to the static scale. The performance of the developed model was measured against this to determine whether it improved (reduced) the number of vehicles incorrectly sent to the static scale.

The *second* Rule-based model still used rule-based decision-making but had access to data that was shared between the TCCs. It therefore used WIM mass from the current and the previous TCC. The performance of the developed models will also tested against this performance. The rule simply checked the maximum value in the measured data of both sites and marked a vehicle as overloaded if the value was above 0,90, as indicated in equation 4.1.

$$\text{Mark overloaded} = \text{Maximum (Axle loads)} > 0,90 \quad (4.1)$$

The data for the rule-based performance of the data sets are indicated in Tables 4.5 to 4.9. The labels in these tables are explained below:

- *Data count*: The total number of data points in the specific data set.
- *Data count overloaded from industry data*: The number of vehicles that were overloaded in the generated simulation data sets.
- *Percentage of overloaded of the total*: The percentage of overloaded vehicles in the total data set count.
- *Data count not overloaded from industry data*: The number of vehicles in the generated data sets that were not overloaded.
- *Percentage not overloaded of the total*: The percentage of vehicles that were not overloaded out of the total data set count.
- *Percentage of vehicles that were not overloaded but sent to the static scale*: Rule-based performance was determined by comparing the number of not overloaded vehicles detected in the simulation data set with the number in the rule-based outcome.

The fact that the rule-based system directed to the static scale any vehicle that was within 10% of the permissible mass ensured that a vehicle would not be incorrectly sent

to the corridor and therefore not included in the performance testing. The performance of the rule-based system for "incorrectly sent" is indicated in equation 4.2, with I as the variable for the percentage incorrectly sent to the static scale.

$$I = (\text{Rule-based \% sent incorrectly to static scale}) - (\% \text{ vehicle overloaded data set}) \quad (4.2)$$

The results of the rule-based performance testing are indicated in Table 4.5. The number of static scale visits was expected to be high due to the linking of data to the static scale data sets, as required for input into the AI model. The data sharing component requires vehicles to visit both TCCs at the WIM and static scale. The data however indicated that 99,46% of vehicles were not overloaded and the Rule-based 1 and 2 showed that 1,47% and 0,13%, respectively, of the vehicles were not overloaded. This indicates that the rule-based approach would have sent between 97,98% and 99,33% incorrectly to the static scale.

This performance was slightly worse when taking two WIM tolerances into account for the threshold. Analysis showed that this was because the two instances of tolerances were added to the WIM data and there was therefore a higher chance of having a vehicle within the rule-based system limits. This was an unfortunate effect of using the tolerances in the WIM mass as input into the current operations. The usage of a fixed threshold limit for the WIM scale triggers in the SQ rule-based system was not intelligent and using an IWIM should address this issue directly and minimise the number of vehicles incorrectly sent to the static scale.

Another aspect to be tested alongside the IWIM model performance was the impact of the adjusted threshold of the WIM. This added an additional dimension of testing to vehicles specifically not overloaded at site 1 and increased the WIM threshold to a normalised axle and AVCM at site 2. It was expected that the adjusted threshold would decrease the number of vehicles sent to the static scale, similar to the goal of the IWIM implementation. Achieving this would also require the "de-isolation" between the sites. The WIM thresholds were adjusted only for a non overloaded state at site 1 for this

additional test. The current rule-based system directed to the static scale vehicles within 10% of permissible mass or normalised weight above 0,90. The testing of the adjusted threshold was firstly to gradually increase the threshold to 1,00 from the current SQ threshold of 0,90. Additional testing Was conducted by adjusting the threshold closer to the permissible mass as follows:

- Rule-based model 3: WIM weight threshold adjusted to normalised 0,95
- Rule-based model 4: WIM weight threshold adjusted to normalised 0,98
- Rule-based model 5: WIM weight threshold adjusted to normalised 1,00

These thresholds were purely incremental increases to determine the improvement on the SQ performance but testing was also conducted on the linked data set to determine the accuracy between the WIM and static scale. The linked values from all the WIM and static scales at Mantsole and Heidelberg in both NB and SB directions were individually checked for the deviation between the WIM and the static scale using equation 4.3. The average discrepancies in both directions were combined and Heidelberg had an average difference of 4,2%, where the WIM weight was lower than the static scale. Mantsole had an average of -5,41%, that is, the WIM weight was higher than the static scale. These two values were tested as additional rule-based scenarios as follows:

- Rule-based model 6: WIM weight threshold adjusted to normalised 1,0541
- Rule-based model 7: WIM weight threshold adjusted to normalised 0,958

$$\text{Weight accuracy} = \frac{(\text{Static scale weight} - \text{WIM weight})}{\text{Static scale weight}} \quad (4.3)$$

The SQ Rule-based model applied to the linked data set and the Rule-based models 3 to 7 (hereafter referred to simply as Rule-based 3 to 7) with adjusted WIM thresholds are indicated in Table 4.5. Rule-based 3 with a 0,95 threshold increase sent 96,12% incorrectly to the static scale, which was a 1,86% improvement on Rule-based model 1 performance that was the better performance of the SQ Rule-based model. Rule-based 4 with a 0,98 threshold increase sent 91,80% incorrectly to the static scale, which was a 6,18% improvement on the current rule-based performance. Rule-based model 5 with

a 1,00 WIM threshold sent 82,38% vehicles incorrectly to the static scale, which was an improvement of 15,60% on the current rule-based performance. Rule-based model 6 with a 1,0541 threshold only sent 28,22% of vehicles incorrectly to the static scale, which was a significant improvement of 69,76%, while Rule-based model 7 with a 0,958 threshold sent 96,16% incorrectly to the static scale, which was a 1,82% improvement on Rule-based 1.

The results of adjusting the threshold indicate this simple change could further reduce the number of vehicles sent incorrectly to the static scale by also making use of data sharing from the previous station if it confirms that a vehicle is not overloaded.

The high improvement in Rule-based 6 does, however, raise concerns because the threshold is above prosecution limits and there is a high chance that vehicles directed to the corridor may be overloaded. This critical measurement was determined by constructing a confusion matrix that is typical of AI model performance testing.

The data are analysed and the *true positives*, *true negatives*, *false positives*, and *false negatives* are determined. The output format can be seen in Figure 4.7. The accuracy is checked by combining the two positive results and using the two negative results to determine, in this case, whether the model directed vehicles incorrectly to the static scale (false positive) or to the corridor (false negative). Ideally, the models would have a very high accuracy, with a minimal number of vehicles sent incorrectly to the corridor. Sending vehicles to the corridor incorrectly would result in overloaded vehicles on the corridor that had not been not statically weighed.

The confusion matrix results for the linked data set are indicated in Table 4.6. The accuracy was determined by combining the *true positive* and *true negative*. This was then used in conjunction with the AI models in Section 4.4 to determine the improvement against the SQ rule-based performance. The confusion matrix results are displayed in terms of accuracy and the percentage of overloaded vehicles incorrectly sent to the corridor (false negative). Accuracy is simply indicated as the sum of true positive and true negative, while the false negative performance was calculated as indicated in

		Predicted class	
		<i>P</i>	<i>N</i>
Actual Class	<i>P</i>	True Positives (TP)	False Negatives (FN)
	<i>N</i>	False Positives (FP)	True Negatives (TN)

Figure 4.2: Sample confusion matrix layout for the binary classification model [172]

equation 4.4 and false positive performance as indicated in equation 4.5.

$$\text{False negative performance} = \frac{\text{False negative count}}{\text{Total overloaded vehicles}} \quad (4.4)$$

$$\text{False positive performance} = \frac{\text{False positive count}}{\text{Total non overloaded vehicles}} \quad (4.5)$$

The performance of the rule-based approaches is compared in Table 4.4. The results indicate an increase in accuracy as the threshold is adjusted but also an increase in vehicles incorrectly directed to the corridor. These false negatives increase quickly but this is largely due to the small number of overloaded vehicles in the data set – 17 vehicles. Rule-based 3 missed 2 of the vehicles and this equates to 11,76% of the overloaded vehicles missed. Rule-based 6 had a very high accuracy of 71,01% but missed 12 of the 17 overloaded vehicles and thus incorrectly sent vehicles to the corridor 70,59% of the time.

Table 4.4: Linked rule-based false-negative performance

	Accuracy	False negative	False positive
Rule-based 1	2,02%	0%	100%
Rule-based 2	0,67%	0%	100%
Rule-based 3	3,33%	11,76%	98,97%
Rule-based 4	7,66%	35,29%	96,79%
Rule-based 5	17,07%	35,29%	96,44%
Rule-based 6	71,01%	70,59%	82,55%
Rule-based 7	3,68%	11,76%	98,96%

Table 4.5: Status quo rule-based performance on Linked data set

Rule-based 1: Current WIM		
	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	3076
Data count not overloaded from linked results	3105	46
Percentage of overloaded of the total	0,54%	98,53%
Percentage of not overloaded of the total	99,46%	1,47%
Percentage not overloaded and sent to static scale		97,98%
Rule-based 2: Both WIMS		
	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	3118
Data count not overloaded from linked results	3105	4
Percentage of overloaded of the total	0,54%	99,87%
Percentage of not overloaded of the total	99,46%	0,13%
Percentage not overloaded and sent to static scale		99,33%

Rule-based 3: Not overloaded and WIM threshold 0,95

	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	3031
Data count not overloaded from linked results	3105	91
Percentage of overloaded of the total	0,54%	97,09%
Percentage of not overloaded of the total	99,46%	2,91%
Percentage not overloaded and sent to static scale		96,54%

Rule-based 4: Not overloaded and WIM threshold 0,98

	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	2888
Data count not overloaded from linked results	3105	234
Percentage of overloaded of the total	0,54%	92,50%
Percentage of not overloaded of the total	99,46%	7,50%
Percentage not overloaded and sent to static scale		91,96%

Rule-based 5: Not overloaded and WIM threshold 1,00

	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	2594
Data count not overloaded from linked results	3105	528
Percentage of overloaded of the total	0,54%	83,09%
Percentage of not overloaded of the total	99,46%	16,91%
Percentage not overloaded and sent to static scale		82,54%

Rule-based 6: Not overloaded and WIM threshold 1,0541

	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	898
Data count not overloaded from linked results	3105	2224
Percentage of overloaded of the total	0,54%	28,76%
Percentage of not overloaded of the total	99,46%	71,24%
Percentage not overloaded and sent to static scale		28,22%

Rule-based 7: Not overloaded and WIM threshold 0,958

	Linked data set	Rule-based
Data count	3122	3122
Data count overloaded from linked results	17	3020
Data count not overloaded from linked results	3105	102
Percentage of overloaded of the total	0,54%	96,73%
Percentage of not overloaded of the total	99,46%	3,27%
Percentage not overloaded and sent to static scale		96,19%

Table 4.6: Confusion matrix results for rule-based performance on the linked data set

Rule-based 1: Current WIM	
[True positive]	[False Negative]
17	0
[False Positive]	[True Negative]
3059	46
Rule-based 2: Both WIMS	
[True positive]	[False Negative]
17	0
[False Positive]	[True Negative]
3101	4
Rule-based 3: Not overloaded and WIM threshold 0,95	
[True positive]	[False Negative]
15	2
[False Positive]	[True Negative]
3016	89
Rule-based 4: Not overloaded and WIM threshold 0,98	
[True positive]	[False Negative]
11	6
[False Positive]	[True Negative]
2877	228
Rule-based 5: Not overloaded and WIM threshold 1,00	
[True positive]	[False Negative]

11	6
[False Positive]	[True Negative]
2583	522
Rule-based 6: Not overloaded and WIM threshold 1,0541	
[True positive]	[False Negative]
5	12
[False Positive]	[True Negative]
893	2212
Rule-based 7: Not overloaded and WIM threshold 0,958	
[True positive]	[False Negative]
15	2
[False Positive]	[True Negative]
3005	100

Testing the performance of the model on real world data provided a good opportunity to test the scenarios of vehicles that changed overload status between TCCs. This was for a subset of vehicles in the linked data set that were not overloaded at site 1 but were overloaded at site 2. These tests indicated the benefit of implementing the IWIM model implementation instead of the rule-based system.

Additional testing was conducted on the subset by changing the rule-based thresholds at the second site to determine whether it could successfully identify overloaded vehicles. The linked data set had a total of 17 vehicles or 0,54% that were not overloaded at site 1 and overloaded at site 2. Another scenario was tested on 20 vehicles or 0,64% overloaded at site 1 and not overloaded at site 2.

When training AI models on a data set where the observations with overloaded inputs or outcomes represent a small minority of the total training set, the training process

tends to ignore the overloaded observations. By duplicating the small number of data points where vehicles were overloaded, we therefore trained the model on a more balanced data set. This padded linked data set had 3692 data entries with an increase from 0,54% overloaded vehicles to 7,37% or from 17 vehicles to 272.

The results of the rule-based performance testing implemented on the padded linked data set are shown in Table 4.8. Rule-based 1 sent 91,39% of vehicles incorrectly to the static scale and Rule-based 2 sent 92,52%. The SQ rule-based model on the padded linked data set and Rule-based models 3 to 7 with adjusted WIM thresholds are indicated in 4.8 as well. Rule-based 3 with a 0,95 threshold increase sent 84,04% of vehicles incorrectly to the static scale, which was a 7,35% improvement on Rule-based 1 performance that was the better performance of the SQ rule based. Rule-based 4 with a 0,98 threshold increase sent 75,73% incorrectly to the static scale, which was a 15,56% improvement on rule-based 1 performance. Rule-based 5 with a 1,00 WIM threshold sent 67,77% vehicles incorrectly to the static scale, which was an improvement of 23,62% on the rule-based performance. Rule-based 6 with a 1,0541 threshold showed significant improvement by only sending 19,39% of vehicles incorrectly to the static scale, which was a 72% improvement; while Rule-based 7 with a 0,958 threshold sent 81,74% incorrectly to the static scale, which was nevertheless a 9,65% improvement on Rule-based 1.

These values once again did not reflect the true picture and the critical measurement was determined by constructing of a confusion matrix similar to what was conducted for the linked data set. The accuracy and the false negative results are reported as follows:

Table 4.7: Padded linked rule-based false-negative performance

	Accuracy	False negative
Rule-based 1	8,61%	0%
Rule-based 2	7,48%	0%
Rule-based 3	16,22%	11,76%
Rule-based 4	19,07%	35,29%
Rule-based 5	27,03%	35,29%
Rule-based 6	70,21%	70,59%
Rule-based 7	16,52%	11,76%

Table 4.8: Status quo rule-based performance on Padded
Linked data set

Rule-based 1: Current WIM		
	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	3646
Data count not overloaded from linked results	3420	46
Percentage of overloaded of the total	7,37%	98,75%
Percentage of not overloaded of the total	92,63%	1,25%
Percentage not overloaded and sent to static scale		91,39%
Rule-based 2: Both WIMS		
	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	3688
Data count not overloaded from linked results	3420	4
Percentage of overloaded of the total	7,37%	99,89%
Percentage of not overloaded of the total	92,63%	0,11%
Percentage not overloaded and sent to static scale		92,52%

Rule-based 3: Not overloaded and WIM threshold 0,95

	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	3301
Data count not overloaded from linked results	3420	391
Percentage of overloaded of the total	7,37%	89,41%
Percentage of not overloaded of the total	92,63%	10,59%
Percentage not overloaded and sent to static scale		82,04%

Rule-based 4: Not overloaded and WIM threshold 0,98

	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	3068
Data count not overloaded from linked results	3420	624
Percentage of overloaded of the total	7,37%	83,10%
Percentage of not overloaded of the total	92,63%	16,90%
Percentage not overloaded and sent to static scale		75,73%

Rule-based 5: Not overloaded and WIM threshold 1,00

	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	2774
Data count not overloaded from linked results	3420	918
Percentage of overloaded of the total	7,37%	75,14%
Percentage of not overloaded of the total	92,63%	24,86%
Percentage not overloaded and sent to static scale		67,77%

Rule-based 6: Not overloaded and WIM threshold 1,0541

	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	988
Data count not overloaded from linked results	3420	2704
Percentage of overloaded of the total	7,37%	26,76%
Percentage of not overloaded of the total	92,63%	73,24%
Percentage not overloaded and sent to static scale		19,39%

Rule-based 7: Not overloaded and WIM threshold 0,958

	Linked data set	Rule-based
Data count	3692	3692
Data count overloaded from linked results	272	3290
Data count not overloaded from linked results	3420	402
Percentage of overloaded of the total	7,37%	89,11%
Percentage of not overloaded of the total	92,63%	10,89%
Percentage not overloaded and sent to static scale		81,74%

Table 4.9: Confusion matrix results of the rule-based performance on the padded linked data set

Rule-based 1: Current WIM	
[True positive]	[False Negative]
272	0
[False Positive]	[True Negative]
3374	46
Rule-based 2: Both WIMS	
[True positive]	[False Negative]
272	0
[False Positive]	[True Negative]
3416	4
Rule-based 3: Not overloaded and WIM threshold 0,95	
[True positive]	[False Negative]
240	32
[False Positive]	[True Negative]
3061	359
Rule-based 4: Not overloaded and WIM threshold 0,98	
[True positive]	[False Negative]
176	96
[False Positive]	[True Negative]
2892	528
Rule-based 5: Not overloaded and WIM threshold 1,00	
[True positive]	[False Negative]

176	96
[False Positive]	[True Negative]
2598	822
Rule-based 6: Not overloaded and WIM threshold 1,0541	
[True positive]	[False Negative]
80	192
[False Positive]	[True Negative]
908	2512
Rule-based 7: Not overloaded and WIM threshold 0,958	
[True positive]	[False Negative]
240	32
[False Positive]	[True Negative]
3050	370

Improvement in any other model implemented was measured against these rule-based performances. The improvement on the second adjusted weight threshold was also tested to indicate the benefit of data sharing with a simple rule adjustment.

The next step was to determine which models to use for the classification of the overloaded state in the IWIM model.

4.1.2 AI classifier model selection

It was necessary to classify the binary outcome variable of *overloaded* as *output 1* or *not overloaded* as *output 0* from the input data set prepared by the data manipulation described above in Section 4.4.1. The most suitable machine learning model to perform the classification had to be identified. Several classifier models were discussed for possible implementation in Section 2.5 of the literature review. The typical classifiers for the outcome were [155]:

- kNN
- Logistic regression
- Decision tree
- Random Forest Tree (RFT)
- SVM
- Naive Bayes classifiers
 - Gaussian
 - Multinomial
 - Bernoulli
- ANN

kNN is known as a lazy classifier that memorises the training data set to predict a label classifier [167,173]. Any new data is then fitted against the closest solution to predict the label outcome. This memorisation of the training set can have overfitting and any slight variations can have a drastic effect on the performance of the model.

Logistic regression is typically used to determine a target class output after training [167]. This is perfect to predict an outcome of 0 or 1 such as that required for the IWIM development [155]. Its disadvantage is that the classification does not converge if the classes are not perfectly linearly separable [155].

Decision tree classification generates a tree-like structure with the data point determined by simple logic to produce the outcome [155]. A complex data set can be expected to have lower performance and this is addressed by combining several decision trees into

a RFT.

A RFT is an example of ensemble learning by combining several machine learning models together to increase performance [167]. Several decision trees are created by looking at a subset of the input variables. Each of the trees makes a decision and the majority decision is used as the output decision [153,155,167,169].

SVM is a machine learning model that can be used for classification or regression problems. SVM is however mostly used for tasks such as text classification, spam e-mail classification, sentiment analysis, or image recognition [155,167]. The model can capture more complex relationships between data points but unfortunately is less effective on larger data sets, noisier data, and overlapping classes [155,167]. This drawback means the model is not suitable for data sets from industry data.

Naive Bayes classifiers are probabilistic classifiers inspired by Bayes' theorem [167]. These models assume that all features are unrelated, even when there is a relationship between them [153]. The models are typically implemented on spam e-mail detection similar to the SVM. The naive Bayes classifiers available are the Gaussian, multinomial, and Bernoulli. The fact that these models assume variables are independent means they are not suitable for the current problem.

ANNs can be implemented for several purposes because they attempt to determine patterns in the data [153,173]. ANNs take several repetitions/epochs to assign different weights to each variable to determine the appropriate outcome [153]. They can thus be used for several tasks, such as regression and classification [153]. The classification of the outcome for the current problem makes an ANN a suitable candidate but the computational power required is significantly higher than for other classifiers and training time may be increased as well.

Selecting the correct model to test on the data is based on several parameters, with a mix of technical and non-technical factors [174]. These do not just include accuracy but may include runtime, resource costs, and the ease-of-use of the tools [174]. The practical implication of the model selection for the IWIM had to be a low number of overloaded

vehicles sent incorrectly to the corridor.

A preliminary test was conducted on the training techniques to determine their accuracy to further define which models could be used for formal training. The models with low performance – 80% or less – were eliminated as they tend to perform better with other applications. These included kNN, SVM, Gaussian, naive Bayes, multinomial naive Bayes, and Bernoulli naive Bayes. The performance of the logistic regression, RFT, and ANN classifiers was higher and so they were selected for testing.

The three classifier models tested were:

- Logistic regression
- RFT
- ANN

Logistic regression models

The logistic regression classifier had several solvers available to be used on the data sets, based on the *scikit-learn* models. Three solvers were chosen that were suited to the data set size. A maximum iteration of 1500 was chosen after testing established convergence of the data set. The solvers implemented on the data sets were:

1. Logistic regression 1: maximum iterations = 1500 and solver = *lbfgs*
 - where *lbfgs* is the scikit-learn model described as: Limited-memory Broyden–Fletcher–Goldfarb–Shanno [175,176].
2. Logistic regression 2: maximum iterations = 1500 and solver = *newton-cg*
 - where *newton-cg* is the scikit-learn model described as a Newton method. It uses an exact Hessian matrix and is slow for large data sets because it computes the second derivatives [175,176].
3. Logistic regression 3: maximum iterations = 1500 and solver = *liblinear*
 - where *liblinear* is the scikit-learn model described as: Library for Large Linear Classification [175,176].

Random forest tree models

The RFT takes the input data set and constructs a tree to determine the output value. The first parameter to be adjusted was the maximum depth of the number of branches that would be generated for the tree. Several hyper parameters were tested by adjusting the n estimators, maximum depth, and minimum sample splits that served as input into selection of the models to be implemented. The default value of the model was set to have no depth constraints that should build trees for all possible outcomes. This was expected to increase the training time required to build the model. The second parameter set to be adjusted was the maximum depth the branches would generate, and it was set to 15. The third model had a maximum depth of 10 and the n estimator was set to 50, with the n estimator as the maximum number of trees generated in the forest. The RFT models tested were therefore as follows:

1. Random forest tree 1: default
2. Random forest tree 2: maximum depth = 15
3. Random forest tree 3: maximum depth = 10, n estimators = 50

Artificial neural network models

The ANN implementation uses a *Keras classifier*. First, the input layer was defined with the 79 input variables. Work described in the upcoming Section 4.1.3 indicated the input variables after preprocessing the data sets. Two hidden layers were added, with double the number of nodes in the input layers, and set to 158. The dropout was varied between the data sets, with the batch sizes chosen at 25 because the size did not influence the performance of the models during preliminary testing.

Three ANN models were produced to test on the data sets. Testing indicated that a large number of epochs did not change the results so 10 epochs were chosen for the models, while 100 epochs were used in preliminary testing and it was established that increased hidden layers did not influence the accuracy of the models. The hidden layer units were

selected as double the number of input units that are often used as a standard industry implementation. This lowered the processing times.

1. ANN 1: 79 units on input layer. 158 units on hidden layers. *20% dropout applied.*
Batch size of 25. 10 epochs
2. ANN 2: 79 units on input layer. 158 units on hidden layers. *40% dropout applied.*
Batch size of 25. 10 epochs
3. ANN 3: 79 units on input layer. 158 units on hidden layers. *No dropout applied.*
Batch size of 25. 10 epochs

4.1.3 AI model implementation

The data were linked as described in Section 4.1.1 by making use of the vehicle identifier in the WIM and the static scale data sets at Mantsole and Heidelberg TCCs. Rule-based performance to measure model performance has been completed in Section 4.1.1. An additional rule-based performance was proposed with adjusted WIM threshold to be combined with data sharing between stations.

The models described in this section were selected for implementation as discussed in Section 4.1.2 and the data required some additional manipulation/preprocessing into the correct format for the models before testing. The data were then split in the training and test sets to be used for the model training. The best performing models were selected for more in-depth analysis and final selection for the IWIM usage.

Data manipulation for input into AI models

The format of the data input into any AI, machine learning, or deep learning is of utmost importance because a common saying applies directly to this situation: *garbage in, garbage out*. Correct data formatting and structuring are required so that the algorithm implementation does not produce an invalid output. Correct format and structure are achieved by formulating a plan of action to manipulate the input data right from the

start.

The industry linked and padded linked data sets constructed represented the two linked sites in this study, as has previously been stated. The sites are referred to as the *previous station* and the *current station*, where the first station the vehicle enters on the corridor is the *previous station* and the next station it enters is the *current station*. The practical study had two data sets for these sites:

- 1) Heidelberg NB (*previous site*) to Mantsole NB (*current site*); and
- 2) Mantsole SB (*previous site*) to Heidelberg SB (*current site*).

This generalisation helped simplify the idea that the same concept can be applied on the same site configuration for future expansion of the principle.

The objective was to use the data shared by the *previous station* with the *current station* to predict the probability that a vehicle was in an overloaded state and whether the vehicle should be statically weighed or not. This was achieved by using current data and the AI models had weights that were assigned to the input variables and used for predicting the overloaded state.

Legislation dictates several limits to the input parameters that were used as the scaling factor to normalise the weights. This scaling of the input variables ensured that legislation changes will not affect the principle of the algorithm design. It should be stated that this was the first step in the scaling process to ensure the input vehicle permissible masses are 1 at legal permissible mass maximum. This will cause overloaded inputs that will be higher than 1 if overloaded. The *legal limits* included from Section 2.2.1 that were used for scaling were:

- Driving single-axle maximum threshold – 7 700 kg
- Driving two-axle maximum threshold – 15 400 kg
- Driving three-axle maximum threshold – 23 100 kg

- Non-driving single-axle two wheels threshold – 8 000 kg

- Non-driving two-axle two wheels threshold – 16 000 kg
- Non-driving three-axle two wheels threshold – 24 000 kg

- Non-driving single-axle four wheels threshold – 9 000 kg
- Non-driving two-axle four wheels threshold – 18 000 kg
- Non-driving three-axle four wheels threshold – 24 000 kg

- 5% grace is allowed above legal limits.
- **Charging** occurs if the 5% grace is exceeded for axles and 2% on AVCM.
- **Prosecution** occurs if 25% overloaded on axle/axle unit *and/or* AVCM
- **Prosecution** occurs if 35% overloaded on axle/axle unit *and* more than 5% overloaded on AVCM
- Maximum vehicle mass not to exceed 56 000 kg

AI normalisation, however, requires scaling to be between [0,1] and [-1,1]. This distinction is addressed by AI normalisation (or standardisation).

Algorithm design requires a distinction between *classifier or categorical variables* and *independent variables* in the input, which alters how the variables are transformed for the algorithm input. Classifier variables were used for *vehicle classification* and *vehicle identification* and were used to ensure the vehicle information was accurately linked with the appropriate permissible masses for the vehicle. Independent variables were more extensive in their inputs, which are listed below:

1. Previous WIM driving axle mass, scaled to the legal threshold.
2. Sum of all axle masses at previous WIM scale, scaled to the legal threshold.
3. Previous WIM AVCM, scaled to the legal threshold.
4. Travel time between stations, benchmarked with previous statistical analysis.
5. Previous static scale driving axle, scaled to the legal threshold.
6. All previous axles at static scale, shown as the sum, scaled to the legal threshold.
7. Previous static AVCM, scaled to the legal threshold.
8. Current WIM driving axle, scaled to the legal threshold.

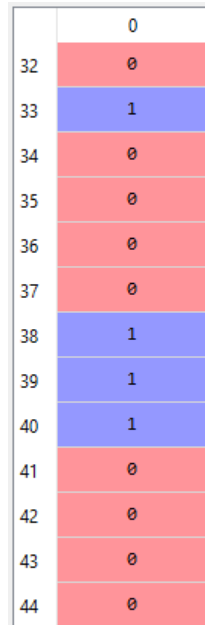
9. All current axles at WIM, shown as the sum, scaled to the legal threshold.
10. Current WIM AVCM, scaled to the legal threshold.

The data of unique vehicles were thus linked through several joining queries to ensure the input data will be matched correctly when implementing the proposed system. This formatting structure produced an input array or table to be used in the algorithm, as seen in Figures 4.5 and 4.6.

The data transformation required several steps to obtain the correct structure for developing the algorithm. This section describes how the data from the measured data sets were taken through a step-by-step process to render them usable for AI implementation in Python. The output from the steps is also described.

- The *first* step was to import the data from a Microsoft Excel spreadsheet with comma-separated values (csv) to simply replicate the study. The Python code included some import packages required for the data transformation.
- The *second* step was to split the data sets into *inputs* (X) and *outputs* (Y). The X data set consisted of various inputs that appeared as columns in a matrix, with each row representing one observation, as shown in Figures 4.5 and 4.6. The Y target variables were what the algorithm tended to predict as part of the test data set and the training data set.
- The *third* step was to implement label encoding to convert potentially text-based data sets to the numerical values required for model construction. The categorical columns in the data sets were the *vehicle classification* columns. (It was previously mentioned that the data sets had categorical data and independent variables.)
- The *fourth* step was to convert the categorical data and implement *One Hot Encoding*. Simply put, this involved taking specific categorical data and separating them into binary columns for use in the model. There was thus a column for each vehicle class stating what class the specific record represented.
- The *fifth* step was to linearly map the data to fit around [0,1] or [-1,1], as required for the input into the AI models. (This was the second step required for the input, where the first step was to scale the AVCM and axle mass by the legal threshold.)

- The *sixth* step was to split the data into training and test data sets, as required with supervised learning models.



	0
32	0
33	1
34	0
35	0
36	0
37	0
38	1
39	1
40	1
41	0
42	0
43	0
44	0

Figure 4.3: Sample of output or target variable

	0	1	2	3	4	5	6	7
0	0	1	0	0	0	0	0	0
1	0	0	0	0	1	0	0	0
2	0	0	0	1	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0
5	0	1	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	1	0	0	0	0	0
8	0	0	0	0	1	0	0	0
9	0	1	0	0	0	0	0	0
10	0	0	0	1	0	0	0	0
11	0	0	0	0	1	0	0	0
12	0	1	0	0	0	0	0	0
13	0	1	0	0	0	0	0	0
14	0	0	0	1	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	1	0	0	0	0
17	0	0	0	0	1	0	0	0
18	0	0	0	0	1	0	0	0
19	0	0	0	1	0	0	0	0
20	1	0	0	0	0	0	0	0
21	0	0	0	0	1	0	0	0
22	0	0	0	0	1	0	0	0
23	0	0	0	1	0	0	0	0
24	0	0	0	1	0	0	0	0
25	0	1	0	0	0	0	0	0
26	0	1	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0

Figure 4.4: One Hot Encoding data example

Construction of the training and test data sets

Test size for this study was selected at 20% of which, in turn, 80% was for the training data set. This variable was used to ensure the replication of the training and test set data can be reconstructed if the study is replicated.

The output of the data set construction is indicated in Figures 4.5 and 4.6 on pages 195 and 196. It generated a 51x *entry generation input array* that matched the original output table generated as the first step. The column heading descriptions have the following structure:

- Column 1
 - Index of the industry data manipulation
- Columns 2–16 and 18–35
 - The first digit is the axle number of the vehicle. 1 is axle 1.
 - The letter in position 2 in the description indicates the station, with *p* for the details from the previous station.
 - The final characters indicate whether it is WIM or static scale.
- Columns 17 and 36
 - gvm indicates the AVCM of the vehicle.
 - The letter in position 2 indicates the station, with *p* as previous station details, as in columns 2–16 and 18–35.
 - The final characters indicate whether it is WIM or static scale.
- Columns 37–52
 - The first digit is the axle number of the vehicle. 1 is axle 1
 - The letter in position 2 in the description indicates the station, with *c* as current station details.
 - The final characters indicate whether it is WIM or static scale.
- Column 53
 - gvm indicates the AVCM of the vehicle
 - The letter in position 2 indicates the station with *c* as current station details, like columns 2–16.
 - The final characters indicate whether it is WIM or static scale.
- Column 54
 - Travel time is normalised to the average travel time between the two stations.

CompleteInputSet - DataFrame

Index	1pwim	2pwim	3pwim	4pwim	5pwim	6pwim	7pwim	8pwim	9pwim	10pwim	11pwim	12pwim	13pwim	14pwim	15pwim	gvpwim	1pstatic	2pstatic	3pstatic	4pstatic	5pstatic	6pstatic	7pstatic	8pstatic	9pstatic	10pstatic	11pstatic	12pstatic	13pstatic	14pstatic	15pstatic	gvpstatic
0	0.061898	0.829534	1.02096	0.382862	0.829534	0.765724	0.638103	0	0	0	0	0	0	0	0	0.760889	0.8442	0.8125	1	0.375	0.8125	0.75	0	0	0	0	0	0	0	0	0	0.745069
1	1.01786	1.11035	0.718459	0.718459	0	0	0	0	0	0	0	0	0	0	0	0.890804	0.974	1.0625	0.6875	0.6875	0	0	0	0	0	0	0	0	0	0	0	0.851729
2	0.95603	0.429686	0.982139	0.429686	0.49107	0.613837	0.429686	0	0	0	0	0	0	0	0	0.617139	0.974	0.4375	1	0.4375	0.5	0.625	0.4375	0	0	0	0	0	0	0	0	0.628363
3	0.708005	0.371695	0.309746	0.805339	0	0	0	0	0	0	0	0	0	0	0	0.547189	0.7143	0.375	0.3125	0.8125	0	0	0	0	0	0	0	0	0	0	0	0.552054
4	0.803861	0.83319	0.773676	0	0	0	0	0	0	0	0	0	0	0	0	0.803572	0.8442	0.875	0.8125	0	0	0	0	0	0	0	0	0	0	0	0	0.843896
5	0.834038	0.987963	1.04971	0.987963	0.246991	0.926215	0.740972	0	0	0	0	0	0	0	0	0.824786	0.8442	1	1.0625	1	0.25	0.9375	0.75	0	0	0	0	0	0	0	0	0.834836
6	0.778338	0.874032	0.409447	1.06133	0.249724	0.988894	0	0	0	0	0	0	0	0	0	0.743408	0.7792	0.875	0.5	1.0625	0.25	1	0	0	0	0	0	0	0	0	0	0.744231
7	0.815136	0.653824	0.588442	0.915354	1.04612	0.326912	0	0	0	0	0	0	0	0	0	0.723727	0.7792	0.625	0.5625	0.875	1	0.3125	0	0	0	0	0	0	0	0	0	0.691821
8	0.79633	1.02198	0.766488	0	0	0	0	0	0	0	0	0	0	0	0	0.862427	0.7792	1	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0.843875
9	0.805703	0.775448	0	0	0	0	0	0	0	0	0	0	0	0	0	0.790287	0.8442	0.8125	0	0	0	0	0	0	0	0	0	0	0	0	0	0.828047
10	0.751518	1.14531	1.02475	0.361678	1.08503	1.32615	0	0	0	0	0	0	0	0	0	0.950317	0.7792	1.1875	1.0625	0.375	1.125	1.375	0	0	0	0	0	0	0	0	0	0.985322
11	0.817393	1.02876	0	0	0	0	0	0	0	0	0	0	0	0	0	0.925097	0.8442	1.0625	0	0	0	0	0	0	0	0	0	0	0	0	0	0.955436
12	0.738371	0.0646062	0.775274	0	0	0	0	0	0	0	0	0	0	0	0	0.523397	0.7143	0.0625	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0.506334
13	1.00008	1.09095	0	0	0	0	0	0	0	0	0	0	0	0	0	1.04638	0.974	1.0625	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0191
14	0.869352	0.956278	0.537906	0.657441	0.478139	0.657441	1.01605	0	0	0	0	0	0	0	0	0.738241	0.9091	1	0.5625	0.6875	0.5	0.6875	1.0625	0	0	0	0	0	0	0	0	0.771994
15	0.890627	1.04091	0	0	0	0	0	0	0	0	0	0	0	0	0	0.967205	0.9091	1.0625	0	0	0	0	0	0	0	0	0	0	0	0	0	0.987266
16	0.938236	1.03205	1.09655	0.709534	0.774037	1.03205	0	0	0	0	0	0	0	0	0	0.93036	0.9091	1	1.0625	0.6875	0.75	1	0	0	0	0	0	0	0	0	0	0.901469
17	0.687405	0.902201	0.18044	0.902201	0.300734	0.661614	0.72176	0	0	0	0	0	0	0	0	0.621986	0.7143	0.9375	0.1875	0.9375	0.3125	0.6875	0.75	0	0	0	0	0	0	0	0	0.646322
18	0.940759	0.517412	1.03482	0.452736	0.970148	1.03482	0	0	0	0	0	0	0	0	0	0.82439	0.9091	0.5	1	0.4375	0.9375	1	0	0	0	0	0	0	0	0	0	0.796647
19	0.744735	0.912282	0.977445	1.04261	1.04261	0.912282	0	0	0	0	0	0	0	0	0	0.939879	0.7143	0.875	0.9375	1	1	0.875	0	0	0	0	0	0	0	0	0	0.90147
20	0.600802	0.514033	1.02807	0.835304	0.77105	0.899558	0.706796	0	0	0	0	0	0	0	0	0.765972	0.5844	0.5	1	0.8125	0.75	0.875	0.6875	0	0	0	0	0	0	0	0	0.745061
21	0.905128	0.435589	0.560042	0.435589	0.622269	0.373362	0.373362	0	0	0	0	0	0	0	0	0.52731	0.9091	0.4375	0.5625	0.4375	0.625	0.375	0.375	0	0	0	0	0	0	0	0	0.529624
22	1.17984	1.13563	1.19872	1.13563	1.19872	1.13563	1.3249	0	0	0	0	0	0	0	0	1.18705	1.1688	1.125	1.1875	1.125	1.1875	1.125	1.3125	0	0	0	0	0	0	0	0	1.17594
23	0.701597	1.04361	0.42972	0.920828	0.798051	0.982216	0.920828	0	0	0	0	0	0	0	0	0.828802	0.7143	1.0625	0.4375	0.9375	0.8125	1	0.9375	0	0	0	0	0	0	0	0	0.843808
24	0.0669542	0.500304	0.838217	0.386869	0.451347	0.838217	0.386869	0	0	0	0	0	0	0	0	0.509338	0.0649	0.5625	0.8125	0.375	0.4375	0.8125	0.375	0	0	0	0	0	0	0	0	0.493711
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0.741965	1.10365	1.03873	0	0	0	0	0	0	0	0	0	0	0	0	0.964226	0.7143	1.0625	1	0	0	0	0	0	0	0	0	0	0	0	0	0.920275
27	0.742859	0.536266	0.595851	0.893776	0.35751	0.774606	0	0	0	0	0	0	0	0	0	0.649561	0.7792	0.5625	0.625	0.9375	0.375	0.8125	0	0	0	0	0	0	0	0	0	0.681338
28	0.74492	0.537754	0.717005	1.01576	0	0	0	0	0	0	0	0	0	0	0	0.753944	0.7792	0.5625	0.75	1.0625	0	0	0	0	0	0	0	0	0	0	0	0.788638
29	0.7038	1.04688	0.923719	0.615813	1.04688	0.431069	0	0	0	0	0	0	0	0	0	0.795266	0.7143	1.0625	0.9375	0.625	1.0625	0.4375	0	0	0	0	0	0	0	0	0	0.80713
30	0.833024	0.925089	1.11011	1.11011	1.11011	0.493381	0	0	0	0	0	0	0	0	0	0.930914	0.8442	0.9375	1.125	1.125	1.125	0.5	0	0	0	0	0	0	0	0	0	0.943403

Format Resize ☒ Background color ☒ Column min/max OK Cancel

Figure 4.5: Industry data set constructed 1

gvmstatic	1cwim	2cwim	3cwim	4cwim	5cwim	6cwim	7cwim	8cwim	9cwim	10cwim	11cwim	12cwim	13cwim	14cwim	15cwim	gvmcwim	travelTime	axleCount	vehClass
0.745069	0.836684	0.805266	0.991097	0.371661	0.805266	0.743323	0.619436	0	0	0	0	0	0	0	0	0.738436	0.990488	7	16
0.851729	0.943619	1.02936	0.666056	0.666056	0	0	0	0	0	0	0	0	0	0	0	0.825162	1.02295	4	9
0.628363	0.953754	0.428406	0.979213	0.428406	0.489607	0.612008	0.428406	0	0	0	0	0	0	0	0	0.615301	1.06847	7	16
0.552054	0.715286	0.375517	0.312931	0.813621	0	0	0	0	0	0	0	0	0	0	0	0.552816	1.07461	4	6
0.843896	0.880551	0.912678	0.847486	0	0	0	0	0	0	0	0	0	0	0	0	0.880234	0.951583	3	8
0.834836	0.843529	0.999206	1.06166	0.999206	0.249801	0.936755	0.749404	0	0	0	0	0	0	0	0	0.834172	0.925815	7	16
0.744231	0.786397	0.883081	0.504618	1.07231	0.252309	1.00924	0	0	0	0	0	0	0	0	0	0.751105	1.01653	6	13
0.691821	0.753852	0.604668	0.544201	0.846535	0.967469	0.302334	0	0	0	0	0	0	0	0	0	0.669315	0.977131	6	13
0.843875	0.764235	0.980794	0.735596	0	0	0	0	0	0	0	0	0	0	0	0	0.827668	0.99661	3	9
0.828047	0.871552	0.838825	0	0	0	0	0	0	0	0	0	0	0	0	0	0.854875	0.993547	2	5
0.985322	0.799073	1.21779	1.0896	0.384564	1.15369	1.41007	0	0	0	0	0	0	0	0	0	1.01045	1.05318	6	13
0.955436	0.834563	1.05037	0	0	0	0	0	0	0	0	0	0	0	0	0	0.944528	0.928375	2	5
0.506334	0.704016	0.0616002	0.739202	0	0	0	0	0	0	0	0	0	0	0	0	0.499044	0.94279	3	6
1.0191	0.998389	1.0891	0	0	0	0	0	0	0	0	0	0	0	0	0	1.04461	1.02461	2	5
0.771994	0.946622	1.04127	0.585716	0.715875	0.520637	0.715875	1.10635	0	0	0	0	0	0	0	0	0.803857	1.05252	7	16
0.987266	0.95337	1.11424	0	0	0	0	0	0	0	0	0	0	0	0	0	1.03534	1.02935	2	9
0.901469	0.903261	0.993577	1.05568	0.683084	0.745183	0.993577	0	0	0	0	0	0	0	0	0	0.895679	0.965494	6	13
0.646322	0.685325	0.899471	0.179894	0.899471	0.299824	0.659612	0.719577	0	0	0	0	0	0	0	0	0.620104	0.981155	7	16
0.796647	0.895776	0.492672	0.985343	0.431088	0.923759	0.985343	0	0	0	0	0	0	0	0	0	0.784971	1.05364	6	13
0.90147	0.713296	0.87377	0.936182	0.998594	0.998594	0.87377	0	0	0	0	0	0	0	0	0	0.900203	1.05781	6	13
0.745061	0.58805	0.503123	1.00625	0.817575	0.754685	0.880465	0.691794	0	0	0	0	0	0	0	0	0.749714	1.00166	7	16
0.529624	0.935571	0.450239	0.578879	0.450239	0.643198	0.385919	0.385919	0	0	0	0	0	0	0	0	0.545046	1.05255	7	16
1.17594	1.16858	1.12479	1.18728	1.12479	1.18728	1.12479	1.31226	0	0	0	0	0	0	0	0	1.17572	1.31536	7	16
0.843808	0.705245	1.04903	0.431954	0.925616	0.8022	0.987324	0.925616	0	0	0	0	0	0	0	0	0.833112	0.998276	7	16
0.493711	0.0626131	0.542679	0.78387	0.361786	0.422084	0.78387	0.361786	0	0	0	0	0	0	0	0	0.476314	1.00841	7	16
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.976881	16	17
0.928275	0.694407	1.03291	0.972151	0	0	0	0	0	0	0	0	0	0	0	0	0.902423	1.06432	3	9
0.681338	0.782426	0.564829	0.627588	0.941381	0.376553	0.815864	0	0	0	0	0	0	0	0	0	0.684159	0.956616	6	13
0.788638	0.784657	0.566439	0.755252	1.06994	0	0	0	0	0	0	0	0	0	0	0	0.794161	1.08094	4	9
0.80713	0.703334	1.04619	0.923108	0.615405	1.04619	0.430784	0	0	0	0	0	0	0	0	0	0.794739	1.00891	6	13
0.943403	0.804861	0.893814	1.07258	1.07258	1.07258	0.476701	0	0	0	0	0	0	0	0	0	0.899442	1.23303	6	13

Figure 4.6: Industry data set constructed 2

Overview of model performance

Performance was tested on the three Logistic regression, three RFT, and three ANN models to determine the best performing model. The model implementation was split into training and testing data sets for the linked data set. The data were split at 80% (2 497 data points) in the training data set and 20% (625 data points) in the test data set. Training on the padded linked data set used the same split with 80% (2 953 data points) of the data in the training data set and 20% (739 data points) in the test data set. Training data were used for the initial training of the models and performance was tested against the test data set. Further testing was conducted on the entire linked and padded linked data sets to determine further model performance testing.

Performance measurement of the models used a confusion matrix. The predicted values were compared with the test data sets to determine the *true positives*, *true negatives*, *false positives*, and *false negatives*. The output from the code was in the format seen in Figure 4.7. Accuracy was determined by combining the two positive results and using the two negative results to determine whether the model directed vehicles incorrectly to the static scale or the corridor.

Ideally, the models would have a very high accuracy, with a minimal number of vehicles sent incorrectly to the corridor. Sending vehicles to the corridor incorrectly would result in overloaded vehicles on the corridor that had not been statically weighed. Since vehicles are currently incorrectly sent to the static scale, the SQ figures were used to determine whether the model improved on the current rule-based system.

		Predicted class	
		<i>P</i>	<i>N</i>
Actual Class	<i>P</i>	True Positives (TP)	False Negatives (FN)
	<i>N</i>	False Positives (FP)	True Negatives (TN)

Figure 4.7: Sample confusion matrix layout for the binary classification model [172]

An overview of the models' performance was completed by a statistical overview of the data sets. A summary was selected to determine which model should be selected for the in-depth analysis described in Section 4.1.4. The summary included the models' confusion matrix results and the improvement or decline against the rule-based performance's false positive and false negative scores. The accuracy of the average, standard deviation, minimum, and maximum values is recorded in Table 4.53 and the improvement over the rule-based system combined with the false negatives is shown in Table 4.54. The rule-based testing excluded Rule-based 6 with its adjusted threshold of 1,0541 because the number of false negatives of this model was extremely high and could not be considered for implementation.

The abbreviated headings in Tables 4.53 and 4.54 are explained below:

- Max: Maximum accuracy achieved over all the data sets.
- Min: Minimum accuracy achieved over all the data sets.
- Average/Avg: Average accuracy over all the data sets.
- Stdev: Standard deviation over all the data sets.

The models in each of these tables correspond to the configurations previously discussed and are abbreviated as explained below:

- ANN 1: ANN model 1.
- ANN 2: ANN model 2.
- ANN 3: ANN model 3.
- Log reg 1: Logistic regression model 1.
- Log reg 2: Logistic regression model 2.
- Log reg 3: Logistic regression model 3.
- RFT 1: RFT model 1.
- RFT 2: RFT model 2.
- RFT 3: RFT model 3.

Improvement of the models against the rule-based performance of the WIM measurements and the adjusted WIM threshold was checked by firstly testing the false negative and false positive results. The results of the model performance were calculated on each of the data sets. The improvement on the rule-based performance is summarised in Table 4.10 while the false positive and false negative results are displayed in Table 4.11 for the linked data set. The accuracy is indicated in Table 4.12.

The best performing models ideally had the best accuracy, that is, a combination of true positive and true negative with the lowest false negative. A false negative indicates that the model incorrectly directed a vehicle that was overloaded to the corridor. The desired best solution was a model with the lowest false negative and the highest accuracy. A false positive sends a non overloaded vehicle to the static scale but this fault causes much less economic damage than a false negative.

Improvement was measured against the rule-based systems. Tables 4.10 to 4.15 indicate the improvement the models showed over the data sets, as well as the false negatives, which refer to vehicles incorrectly sent to the corridor. Equation 4.6 indicates the calculation used for improvement calculations.

$$\text{Improvement} = \frac{(\text{Rule-based \% sent to static scale}) - (\text{Model \% of vehicles sent incorrectly to the static scale})}{(\text{Rule-based \% sent to static scale})} \quad (4.6)$$

The average improvement of all the models was fairly close, with the ANN models and logistic regression models having an improvement of 87,09% against the rule-based models. The RFT models had a very slightly lower improvement of 86,65%. The lowest false negative performance was by the RFT models, with an average of 1,94% compared to the ANN and logistic regression models' average of 2,24%. The RFT models had the slightly better performance with an average of 97,91%, while the ANN and logistic regression achieved 97,76%.

An in-depth analysis further investigated performance against rule-based false negative and false positive performance.

Table 4.10: Improvements on rule-based performance in Linked data set training

	Improvement			
	Max	Min	Average	Stdev
ANN 1	99,33%	65,60%	87,09%	10,92%
ANN 2	99,33%	65,60%	87,09%	10,92%
ANN 3	99,33%	65,60%	87,09%	10,92%
Log reg 1	99,33%	65,60%	87,09%	10,92%
Log reg 2	99,33%	65,60%	87,09%	10,92%
Log reg 3	99,33%	65,60%	87,09%	10,92%
RFT 1	99,30%	65,17%	86,85%	11,06%
RFT 2	99,30%	65,17%	86,85%	11,06%
RFT 3	99,30%	65,17%	86,85%	11,06%

Table 4.11: False-negatives and False-positives in the
Linked data set training

	False Positive				False Negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
ANN 1	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
ANN 2	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
ANN 3	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
Log reg 1	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
Log reg 2	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
Log reg 3	0,00%	0,00%	0,00%	0,00%	7,37%	0,48%	2,24%	3,42%
RFT 1	0,43%	0,00%	0,16%	0,20%	7,37%	0,00%	1,94%	3,62%
RFT 2	0,43%	0,00%	0,16%	0,20%	7,37%	0,00%	1,94%	3,62%
RFT 3	0,43%	0,00%	0,16%	0,20%	7,37%	0,04%	1,96%	3,61%

Table 4.12: Accuracy in Linked data set training

	Accuracy			
	Max	Min	Average	Stdev
ANN 1	99,52%	92,63%	97,76%	3,42%
ANN 2	99,52%	92,63%	97,76%	3,42%
ANN 3	99,52%	92,63%	97,76%	3,42%
Log reg 1	99,52%	92,63%	97,76%	3,42%
Log reg 2	99,52%	92,63%	97,76%	3,42%
Log reg 3	99,52%	92,63%	97,76%	3,42%
RFT 1	100,00%	92,20%	97,91%	3,81%
RFT 2	100,00%	92,20%	97,91%	3,81%
RFT 3	99,96%	92,20%	97,89%	3,80%

The padded linked data set performance was considered next. This data set was padded with additional overloaded vehicles to measure the performance to be expected when the data set is expanded to include more sites in future. The same models were implemented on these data sets, with the improvements indicated in Table 4.13. Their false positives and false negatives are shown in Table 4.14 for the linked data set, and their accuracy in Table 4.15.

The RFT models had the best false negative performance average at 0,08% and an improvement against the rule-based performance of 86,64%. ANN model 3 had the next best false negative performance at 0,60% with an average improvement of 86,81%. The logistic regression models had slightly better improvement with model 3 at 86,82% but had an average false negative of 5,53%. The RFT models all achieved a maximum accuracy of 100%, which none of the other models had – ANN model 3 had a maximum of 98,92% and logistic regression 3 had a maximum of 99,17%.

Table 4.13: Improvements on rule-based performance
in Padded Linked data set training

	Improvement			
	Max	Min	Average	Stdev
ANN 1	98,31%	64,73%	86,14%	10,87%
ANN 2	98,47%	64,95%	86,33%	10,85%
ANN 3	98,31%	64,84%	86,19%	10,83%
Log reg 1	98,98%	65,41%	86,81%	10,87%
Log reg 2	98,98%	65,41%	86,81%	10,87%
Log reg 3	99,01%	65,38%	86,82%	10,89%
RFT 1	98,34%	65,57%	86,57%	10,60%
RFT 2	98,40%	65,57%	86,61%	10,62%
RFT 3	98,47%	65,57%	86,64%	10,64%

Table 4.14: False-negatives and False-positives in Padded Linked data set training

	False Positive				False Negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
ANN 1	1,02%	0,81%	0,90%	0,09%	5,01%	0,29%	2,96%	1,97%
ANN 2	0,86%	0,41%	0,66%	0,19%	6,50%	0,38%	4,24%	2,66%
ANN 3	1,02%	0,68%	0,81%	0,15%	0,98%	0,16%	0,60%	0,39%
Log reg 1	0,35%	0,00%	0,19%	0,15%	7,98%	0,51%	5,53%	3,39%
Log reg 2	0,35%	0,00%	0,19%	0,15%	7,98%	0,51%	5,53%	3,39%
Log reg 3	0,32%	0,00%	0,20%	0,14%	7,98%	0,51%	5,53%	3,39%
RFT 1	0,99%	0,00%	0,29%	0,47%	0,32%	0,00%	0,08%	0,16%
RFT 2	0,93%	0,00%	0,27%	0,44%	0,32%	0,00%	0,08%	0,16%
RFT 3	0,86%	0,00%	0,26%	0,41%	0,32%	0,00%	0,08%	0,16%

Table 4.15: Accuracy in Padded Linked data set training

	Accuracy			
	Max	Min	Average	Stdev
ANN 1	98,69%	94,18%	96,14%	1,88%
ANN 2	98,75%	93,10%	95,10%	2,50%
ANN 3	98,92%	98,24%	98,59%	0,33%
Log reg 1	99,14%	92,02%	94,28%	3,27%
Log reg 2	99,14%	92,02%	94,28%	3,27%
Log reg 3	99,17%	92,02%	94,27%	3,29%
RFT 1	100,00%	98,69%	99,63%	0,63%
RFT 2	100,00%	98,75%	99,65%	0,60%
RFT 3	100,00%	98,81%	99,66%	0,57%

The tables above portray the performance improvements achieved by the rule-based models described in Section 4.1.1, excluding Rule-based 6 because it had extreme false negative results. The models used WIM measurements, with each scenarios increasing the WIM threshold. However, an in-depth analysis of the performance of the padded linked data set trained models was required to further test the models' performance.

4.1.4 In-depth analysis of data sets

The in-depth analysis was conducted on the best performing models, ANN 3 and RFT 1. RFT 1 was selected because all three models had an accuracy of 99,97% and false negatives of 0% so any of the three RFT models could be investigated. The logistic regression models were excluded because of their much higher false negative performance than the other models. The ANN 3 and RFT 1 models had the best performance, as indicated in the overview in Section 4.1.3. The in-depth analysis of both models' performance indicated the following:

- Numbered performance results.
- Confusion matrix of the padded linked data set results.
- Model improvement or decline against the rule-based performance for false negatives and false positives.
- Percentage results of model performance with accuracy percentage.
- Improvement on rule-based scenarios.

Artificial neural network classifier 3

The ANN model 3 confusion matrix results are indicated in Table 4.18 and had an accuracy of 98,37%. The model had a 0,87% false negative result, which equates to missing 11,76% of overloaded vehicles and directing them to the corridor incorrectly. The model had 0,76% false positives that would have been sent to the static scale incorrectly.

The next step was to determine the model's improvement against the false negative of the rule-based performance, as indicated in Table 4.19. ANN model 3 sent 11,76% of vehicles incorrectly to the corridor that was overloaded. Rule-based 1 and 2 sent 0% incorrectly to the corridor with a 0% false negative. Adjusting the threshold in Rule-based 3 to 7 meant that Rule-based 3 and 7 had the same false negative performance of 11,76% sent incorrectly to the corridor. ANN model 3 had an improvement of 23,53% against Rule-based 4 and 5 and 58,83% against model 6. These are significant improvements but still would have sent overloaded vehicles incorrectly to the corridor 11,76% of the time.

The false positive performance of the model sent 0,82% incorrectly to the static scale and the results are indicated in Table 4.20. The improvements against the models were fairly high, with Rule-based 1 at 97,84% improvement and Rule-based 2 at 99,07% improvement. Rule-based 3 and 7 were fairly close, at 88,59% and 88,29% improvement, respectively. Rule-based 4 had an improvement of 82,28% and Rule-based 5 had 74,32%, with Rule-based 6 at a fairly low improvement of 25,94%. These significant improvements could not be the only deciding factor because the false negative results would have the direct impact of allowing overloaded vehicles on the corridor, which could cause significant road damage.

Table 4.16: Numbered results for the artificial neural network 3 trained on the Linked data set

	True Positive	True Negative	False Positive	False Negative	Total
Train	0	2483	0	14	2497
Test	0	622	0	3	625
Linked	0	3105	0	17	3122
Linked Padded	0	3420	0	272	3692

Table 4.17: Numbered results for the artificial neural network 3 trained on the Padded Linked data set

	True Positive	True Negative	False Positive	False Negative	Total
Train	179	2722	23	29	2953
Test	61	670	5	3	739
Linked	12	3073	32	5	3122
Linked Padded	240	3392	28	32	3692

Table 4.18: Artificial neural network model 3 confusion matrix

[True positive]	[False Negative]
240	32
[False Positive]	[True Negative]
28	3392

Table 4.19: Artificial neural network model 3 improvement(+) / decline (-) performance against rule-based false negative performance

	False negative	ANN 3 False negative	ANN 3 improvement
Rule-based 1	0%	11,76%	-11,76%
Rule-based 2	0%	11,76%	-11,76%
Rule-based 3	11,76%	11,76%	0,00%
Rule-based 4	35,29%	11,76%	23,53%
Rule-based 5	35,29%	11,76%	23,53%
Rule-based 6	70,59%	11,76%	58,83%
Rule-based 7	11,76%	11,76%	0,00%

Table 4.20: Artificial neural network model 3 improvement(+) / decline (-) performance against rule-based false positive performance

Model	False positive	ANN 3 False positive	ANN 3 improvement
Rule-based 1	98,65%	0,82%	97,84%
Rule-based 2	99,89%	0,82%	99,07%
Rule-based 3	89,41%	0,82%	88,59%
Rule-based 4	83,10%	0,82%	82,28%
Rule-based 5	75,14%	0,82%	74,32%
Rule-based 6	26,76%	0,82%	25,94%
Rule-based 7	89,11%	0,82%	88,29%

Random forest tree classifier 1

The RFT model 1 confusion matrix results indicated in Table 4.23 had an accuracy of 100%. The model had a 0% false negative result, which indicates that no vehicles would be sent incorrectly to the corridor. The model had 0,03% false positives that would have been sent to the static scale incorrectly.

The next step was to determine the model's improvement against the false negative of the rule-based performance, as indicated in Table 4.24. RFT model 1 sent 0% of overloaded vehicles incorrectly to the corridor. The performance of the RFT model ensured that improvement could be expected against any of the Rule-based 3 to 7 models that sent vehicles incorrectly to the corridor. The adjusted thresholds for these rules sent 11,76% to 70,59% incorrectly and indicate improvement against the rule-based performance.

The false positive performance of the model sent 0,03% incorrectly to the static scale and the improvement is indicated in Table 4.25. The improvements against the rule-based

models were fairly high, with Rule-based 1 at 98,65% improvement and Rule-based 2 at 99,89% improvement. Rule-based 3 and 7 were fairly close, at 89,41% and 89,11% improvement respectively. Rule-based 4 had an improvement of 83,1% and Rule-based 5 had 75,14%, with Rule-based 6 at a fairly low improvement of 26,76%. These results indicated significant improvement when also taking into account the model's false negative of 0%.

Table 4.21: Numbered results for the random forest tree classifier trained on the Linked data set

	True Positive	True Negative	False Positive	False Negative	Total
Train	14	2483	0	0	2497
Test	1	621	1	2	625
Linked	15	3104	1	2	3122
Linked Padded	0	3404	16	272	3692

Table 4.22: Numbered results for the random forest tree classifier trained on the Padded Linked data set

	True Positive	True Negative	False Positive	False Negative	Total
Train	208	2745	0	0	2953
Test	64	674	1	0	739
Linked	7	3074	31	10	3122
Linked Padded	272	3419	1	0	3692

Table 4.23: Random forest tree model 1 confusion matrix

[True positive]	[False Negative]
272	0
[False Positive]	[True Negative]
1	3419

Table 4.24: Random forest tree model 1 improvement(+)
/ decline (-) performance against rule-based false negative performance

	False negative	RFT 1 False negative	RFT 1 improvement
Rule-based 1	0%	0%	0%
Rule-based 2	0%	0%	0%
Rule-based 3	11,76%	0%	11,76%
Rule-based 4	35,29%	0%	35,29%
Rule-based 5	35,29%	0%	35,29%
Rule-based 6	70,59%	0%	70,59%
Rule-based 7	11,76%	0%	11,76%

Table 4.25: Random forest tree model 1 improvement(+) / decline (-) performance against rule-based false positive performance

	False positive	RFT 1 False positive	RFT 1 improvement
Rule-based 1	98,65%	0,03%	98,65%
Rule-based 2	99,89%	0,03%	99,89%
Rule-based 3	89,41%	0,03%	89,41%
Rule-based 4	83,10%	0,03%	83,10%
Rule-based 5	75,14%	0,03%	75,14%
Rule-based 6	26,76%	0,03%	26,76%
Rule-based 7	89,11%	0,03%	89,11%

4.1.5 Model selection

Comparison of the three models' improvement shows ANN and RFT were basically the same, with the logistic regression performance below the other two. The false positive and false negative performances were therefore the important factor in determining which of the two better models to use as the IWIM algorithm. The false positive (or incorrectly sent to the static scale) was what the current rule-based system was doing on a large scale. This left the percentage of false negatives as one of the deciding factors because a false negative incorrectly sends an overloaded vehicle to the corridor.

Practical system deployment considerations also needed to be taken into account. Each of the models was trained on the same hardware so that could be used as a benchmark for the training time taken by each model. The ANN model 3 training and testing was completed in 29 minutes for all the simulation data sets. The RFT model 1 training and testing was completed in 37 minutes. This is not a large increase in time so the fact that the RFT is less computationally expensive counteracts the time increase. The processing power for training a RFT only requires a central processing unit (CPU) where the ANN

requires an additional graphics processing unit (GPU) for training [169]. This would increase hardware complexity and roll out costs. Setup of the training models is more complex for an ANN than for a RFT [177]. This needed to be taken into account when determining the staff complement required to run the system because an ANN might require additional skill sets to run it successfully.

The comparative accuracy of the models was extremely close. The ANN model had an accuracy of 98,37 % with a false negative of 0,87%. This realised a decline in performance of 11,76% against Rule-based 1 and 2 because these models sent 0% of vehicles incorrectly to the corridor, whereas the ANN model sent 11,76% incorrectly. ANN performance matched that of Rule-based 3 and 7 and improved against Rule-based 4 to 6. Improvement varied between 23,53% and 58,83% but the fact that ANN sent 11,76% incorrectly to the corridor would allow overloaded vehicles to damage the road infrastructure.

The RFT model had an accuracy of 99,97%, with a false negative of 0%. This model matched the false negative performance of Rule-based 1 and 2. The fact that this model sent 0% incorrectly to the corridor ensured that it outdid all the adjusted WIM threshold models.

This information meant that the RFT was selected for the IWIM. The deciding factors were the false negative of 0% vehicles incorrectly to the corridor and only 0,03% being sent incorrectly to the static scale. The linked data set from industry indicated that improvement could be obtained with real world data. Adding extra overloaded entries to the data set showed the benefit of including multiple sites in the future.

Rule-based adjusted WIM threshold performance on this data set sent 65,57% of vehicles incorrectly to the static scale for the RFT model. Extrapolating the impact of this simulation to the actual average over the last three years had 1 792 541 vehicles being statically weighed annually, when only 1 175 369 would have been weighed with the rule-based approach. By comparison, RFT performance sent 0,03% or 538 vehicles incorrectly to the static scale.

As well as being tested, the proposed IWIM model had to be verified and the next section addresses this.

Verification

The definition and objective of the verification process should be made clear. The *definition* is *The process of evaluating work products (not the actual final product) of a development phase to determine whether they meet the specified requirements for that phase* [178]. The *objective* is *To ensure that the product is being built according to the requirements and design specifications. In other words, to ensure that work products meet their specified requirements* [178].

Machine learning was developed several decades ago and has gained traction within several industries. It was found to be logical to integrate large data sets to automate a decision-making process while optimising the process. Data set libraries were developed and articles about them have been published in journals, gaining extensive industry adoption, which attests to the trustworthy nature of these libraries. The scikit-learn library was developed for Python [175] and the Keras library was developed and backed by Google. It has been adopted by industries, research institutions and large companies such as Netflix, Uber, CERN, and NASA. This wide adoption validates the use of libraries and the fact that they are fit for machine learning implementation to optimise road transport logistics on the freight corridors.

The proposed IWIM model also had to be validated.

Validation

The *definition* of validation is *The process of evaluating software during or at the end of the development process to determine whether it satisfies specified business requirements* [178]. The *objective* of validation is *To ensure that the product actually meets the user's needs and that the specifications were correct in the first place. In other words, to demonstrate that the product*

fulfils its intended use when placed in its intended environment [178].

The primary objective was to improve the efficiency of road transport logistics on freight corridors. Implementation of the algorithm with the focus on the TCC operations will have several benefits: The RFT model's worst performance would reduce the percentage of non-overloaded vehicles being statically weighed from between 75% and 78% annually down to 0,03%. This validates its implementation because it will achieve obvious optimisation of the freight corridor. Several stakeholders will gain financial benefits from this implementation, as discussed in Chapter 5.

4.2 Simulation data set

The RFT model significantly improved on the rule-based performance using industry data. However, given the limited number of data points, the model development would clearly benefit from including additional sites to increase the size of the linked data set. Additional testing of a larger data set was, therefore, proposed by making use of other historic data sources as a statistical basis for generating simulation data sets. The data sets were collected during a case study with SANRAL of the system proposed in Section 3.6.2 that was conducted during 2016 and 2017 at the Mantsole and Heidelberg TCCs.

The steps taken were similar to those for the industry data described in Section 4.1 and started by consolidating data from the various sources. These data were then used to create the simulation data set based on the statistics generated from these sources. The data sets were constructed and manipulated to the requirements for AI model implementation. Once again, the rule-based performance was determined so that the improvement could be measured. The larger data set was intended to indicate the performance that can be expected when implementing IWIM in additional sites.

4.2.1 Data consolidation

Data collection throughout the system implementation was difficult because there were many end user data owners. However, four overlapping data sets were obtained for the north- and southbound sides of Mantsole and Heidelberg TCCs for the period 2016-11-17 to 2016-12-31, as indicated in Figure 4.8.

Data available for this time period were:

- Static scale data – Mantsole NB and SB
- Static scale data – Heidelberg NB and SB
- WIM scale data – Mantsole NB and SB
- WIM scale data – Heidelberg NB and SB
- RFID static scale data – Mantsole SB
- RFID static scale data – Heidelberg NB and SB
- RFID WIM scale data – Mantsole NB and SB
- RFID WIM scale data – Heidelberg NB and SB

The overlapping time periods of the vehicle counts in the four data sets are indicated visually in Figure 4.8

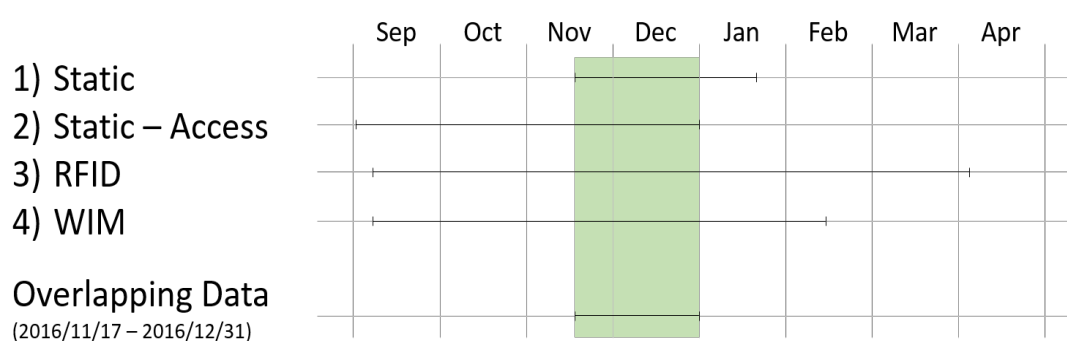


Figure 4.8: Data overlap between data sets

The vehicle counts in each data set between 2016-11-17 and 2016-12-31 are indicated in Table 4.26.

Table 4.26: Total data set entries in the overlapping periods

Data description	Data set count
Northbound	
RFID Heidelberg NB	1300
RFID Mantsole NB	0
RFID WIM Heidelberg NB	6083
RFID WIM Mantsole NB	1228
Static scale Heidelberg NB	9775
Static scale Mantsole NB	13 114
WIM Heidelberg NB	28 003
WIM Mantsole NB	42 432
Southbound	
RFID Heidelberg SB	866
RFID Mantsole SB	1393
RFID WIM Heidelberg SB	3816
RFID WIM Mantsole SB	4975
Static scale Heidelberg SB	8754
Static scale Mantsole SB	7605
WIM Heidelberg SB	27 751
WIM Mantsole SB	11 798

4.2.2 Data limitations

The lack of large overlapping data sets during this implementation and the limited industry data of 2021 meant alternative measures had to be considered to increase the data set for further testing of the algorithm design. This is indicated in Figure 4.9, where the ANPR and RFID data sets were linked in. As can be seen, Site 1 SB had no data

to be linked. There was a distinct shortage of the data required for the optimisation process: There were no NB static scale data available and there were fewer entries to match than there were vehicle classes available in the SB static scale data.

Conseq sites in database	Time based only	RFID
Site 1 NB	HeidelbergNb	Heidelberg NB WIM to Static 1455
Site 2 NB	MantsoleN1NB	Heidelberg SB WIM to Static 743
Site 1 SB		Mantsole NB WIM to Static 0
Site 2 SB	HeidelbergSb	Mantsole SB WIM to Static 1224
Count seen at both NB RFID	123	Heidelberg NB static to Mantsole NB static 0
Count seen at both NB ANPR	328	Heidelberg NB static to Mantsole NB WIM 120
Count seen at both SB RFID	430	Mantsole SB static to Heidelberg SB WIM 314
Count seen at both SB ANPR	0	Mantsole SB static to Heidelberg SB static 5

Figure 4.9: Data linking of data sets

The tolerance applied to WIM scale measurements was a large input in SQ operations to determine whether a vehicle should be directed to the static scale. WIM tolerances had a typical range of 10% positive and 10% negative, centred on the actual mass. This variation was discussed in Section 2.2.1. Some WIM scales have a range as high as 20% on either side of the actual vehicle mass, as could be verified by the static scale. Accuracy varies due to environmental factors and the speed at which the vehicle travels over the WIM scale. There are WIM scales on the market that have as little as 2.5% tolerance at 5 km/h. However, vehicles on the South African freight corridors travel over the WIM scale at higher speeds, and the WIM typically has a 10% tolerance. Tolerances were verified on a small subset of the data where WIM and statically weighed records were linked. This linking indicated that the WIM tolerance was between -8,85% and 16,37%.

The above discussion provides an understanding of the limitations of the available measured industry and corridor data in this implementation. Clearly, the measured data sets that could be linked between the different points of data collection were too small to use as the input for successfully training an AI algorithm. A larger, simulated data set therefore had to be constructed to represent industry behaviour, using measured industry statistics as the input.

Section 4.3 discusses the development of the *simulation data set* from the above statistics, as well as the constraints of the legislation.

4.3 Simulation data set construction

It was necessary to construct relevant data that displayed similar behaviour to the measured data and therefore it was essential to use real-life industry data. A larger measured data set can be obtained once the algorithm's impact is proven and it can be seen that it is economically viable, as demonstrated in Section 4.1. The system design explained in Chapter 3 allows data sharing and the collection of relevant information from the whole corridor to use alongside the simulation data set. The simulation data set can later be phased out altogether.

Some assumptions were made when constructing the simulation data sets. The assumptions did not take all real-world scenarios that might occur into account, and this is addressed by suggestions in Section 6.3, Future Work, to improve the accuracy of the IWIM model. Until then, however, the model can only represent what is observed from the statistics taken from the available SQ data to show the improvements that implementation of the IWIM model can achieve against the current rule-based system. The assumptions were:

- WIM threshold 1 used an inaccuracy factor of 10% in each direction of the static scale as the first WIM threshold scenario.
- WIM threshold 2 used the range from the statistics, from -8,85% to 16,37%, as the second WIM threshold scenario.
- All vehicles will attempt to drive close to the speed limit to reach their destination for delivery as quickly as possible.

The AI model required specific inputs to achieve the goal of determining whether a vehicle is potentially overloaded while travelling from the *previous* TCC to the *current* TCC. The data required for input into the model were similar to the previous work and

were as follows:

- Vehicle classification
- Axle count of the vehicle
- Previous TCC WIM scale mass
- Previous TCC WIM AVCM
- Previous TCC static scale mass
- Previous TCC AVCM
- Overloaded state at previous TCC
- Travel time between stations
- Current TCC WIM mass.

The distribution of vehicle classes was taken into account, with their average axle mass, AVCM, and standard deviation, as input for the simulation data set. The static scale data are indicated in Table 4.27 to 4.32, with the applicable axle load of the first axle indicated; for example, *Axle load 1* in the right-hand column of the first table. Tables 4.33 to 4.40 give the WIM scale data, with the applicable axle loads indicated as *WIM mass 1* for the first axle load, similar to the static scale tables.

There were format discrepancies between the WIM and static scale data, where one set took individual axles into account and the other looked at axle units. The tables indicate the statistics based on the vehicle classification scheme used in South Africa (SA) for the static scale information. The static scale data set did not include AVCM data. The WIM data sets indicated the axle group counts of the vehicles with the individual axles. Because there was no standardised data management structure between sites, in cases where relevant data was not available, a master data management structure was required, as proposed in Section 3.6.5.

Table 4.27: Statistics for simulation data set construction 1

Vehicle class	Entry count	AVCM	AVCM stdev	Speed	Speed stdev	Axle load 1	Axle load stdev 1
0	387	502,24	1109,70	19,45	14,96	502,24	1109,70
4	8157	12 409,74	3446,21	24,46	14,74	5177,30	1458,55
5	43 879	8439,69	3236,49	25,12	12,39	3499,84	1331,79
6	20 565	19 176,80	3564,09	25,16	13,05	6190,38	1159,84
7	316	2408,15	6016,90	95,45	41,46	722,04	1727,94
8	14 805	16 450,98	5086,91	21,69	11,52	5623,54	1226,39
9	29 975	12 800,95	10 447,63	52,58	44,58	3137,90	2466,71
10	2203	27 449,73	5242,68	22,91	12,24	6907,05	943,90
11	199	24 995,05	5487,11	10,83	9,25	6186,22	898,49
12	21 065	25 918,47	7240,87	22,43	11,49	6024,78	937,45
13	1 119 980	36710,96	10 135,20	21,60	10,09	6340,66	744,12
14	2575	25 942,29	5495,57	23,12	11,90	5666,85	761,74
15	2066	32 311,45	10 557,96	19,11	11,96	5943,06	1189,74
16	164 661	45 701,23	11 855,05	21,12	10,45	6452,85	706,69
17	5292	41 753,33	15 005,92	24,60	14,39	5858,84	1464,37

Table 4.28: Statistics for simulation data set construction 2

Vehicle class	Axle load 2	Axle load stdev 2	Axle load 3	Axle load stdev 3	Axle load 4	Axle load stdev 4	Axle load 5
0	0	0	0	0	0	0	0
4	7232,44	2196,62	0	0	0	0	0
5	4939,85	2076,63	0	0	0	0	0
6	7586,75	2071,86	5149,37	1666,41	250,30	953,03	0
7	954,55	2450,13	509,38	1441,41	222,18	910,19	0
8	5764,54	2373,30	5061,03	2199,27	1,88	66,21	0
9	4035,86	3266,02	3079,82	2749,36	2547,37	2747,52	0
10	9211,52	2040,95	5551,46	1406,67	2908,43	2283,24	2299,56
11	6107,87	2649,24	5306,11	1966,44	2596,78	2000,23	2304,35
12	5997,17	2265,41	4664,82	1743,20	4646,35	1956,03	2034,29
13	6886,58	1976,27	6646,91	2076,91	5630,04	2166,58	2026,73
14	5827,37	1498,30	4857,08	1258,65	4580,11	1368,90	1530,50
15	6497,11	2072,20	5294,46	2221,71	4985,29	2118,92	2153,79
16	6829,79	1815,61	6646,69	1881,37	6710,40	2059,87	2105,26
17	5830,17	2319,64	6067,33	2558,83	5787,61	2432,24	2328,50

Table 4.29: Statistics for simulation data set construction 3

Vehicle class	Axle load stdev 5	Axle load 6	Axle load stdev 6	Axle load 7	Axle load stdev 7	Axle load 8
0	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	2299,56	31,4	482,55	0	0	0
11	2304,35	0	0	0	0	0
12	2034,29	0	0	0	0	0
13	2026,73	5674,52	2059,85	0	0	0
14	1530,50	0	0	0	0	0
15	2153,79	4750,82	2377,70	0	0	0
16	2105,26	6361,12	2173,19	6021,31	2179,69	0
17	2328,50	5063,20	2208,02	4296,43	2116,34	4043,63

Table 4.30: Statistics for simulation data set construction 4

Vehicle class	Axle load stdev 8	Axle load 9	Axle load stdev 9	Axle load 10	Axle load stdev 10	Axle load 11
0	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	2217,04	113,95	678,28	45,82	378,45	35,90

Table 4.31: Statistics for simulation data set construction 5

Vehicle class	Axle load stdev 11	Axle load 12	Axle load stdev 12	Axle load 13	Axle load stdev 13	Axle load 14
0	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	316,99	27,79	276,07	21,46	232,88	17,68

Table 4.32: Statistics for simulation data set construction 6

Vehicle class	Axle load stdev 14	Axle load 15	Axle load stdev 15
0	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	206,97	13,03	172,31

Table 4.33: Statistics for simulation data set construction 7

Axle unit count	Entry count	Axle 1	Axle 1 stdev 1	Axle 2	Axle stdev 2	Axle 3
2	2826	6355,43	1486,63	3592,81	3592,81	0
3	9640	6567,27	936,24	3289,12	3289,12	21005,99
4	13 044	6655,96	699,59	2100,55	2100,55	15 244,39
5	9	6500	653,76	3842,86	3842,86	10906,67

Table 4.34: Statistics for simulation data set construction 8

Axle unit count	Axle stdev 3	Axle 4	Axle stdev 4	Axle 5	Axle stdev 5	WIM speed
2	0	0	0	0	0	23,78
3	5807,25	0	0	0	0	22,59
4	3586,94	14 613,90	3633,63	0	0	22,89
5	4755,54	8613,33	1904,97	8048,89	3849,01	18,00

Table 4.35: Statistics for simulation data set construction 9

Axle unit count	WIM Mass 1	WIM Mass stdev 1	WIM Mass 2	WIM Mass stdev 2	WIM Mass 3	WIM Mass stdev 3
2	6397,74	15,05	8709,18	1458,72	2718,47	1881,01
3	6628,87	12,14	8451,82	1028,75	8426,42	1689,30
4	6698,90	12,09	7884,26	830,78	7856,18	1357,01
5	6342,00	12,81	6669,56	728,72	8807,00	1949,23

Table 4.36: Statistics for simulation data set construction 10

Axle unit count	WIM Mass 4	WIM Mass stdev 4	WIM Mass 5	WIM Mass stdev 5	WIM Mass 6	WIM Mass stdev 6
2	81,58	3357,40	30,12	810,48	20,21	477,01
3	7154,03	1863,35	6955,02	2057,03	6874,42	2188,46
4	7627,63	1353,68	7736,33	1558,22	7273,24	1656,72
5	7458,89	1638,93	6784,11	1965,48	2649,22	1372,89

Table 4.37: Statistics for simulation data set construction 11

Axle unit count	WIM Mass 7	WIM Mass stdev 7	WIM Mass 8	WIM Mass stdev 8	WIM Mass 9	WIM Mass stdev 9
2	14,02	408,15	11,64	333,84	11,55	309,96
3	63,61	2541,54	15,18	612,63	7,40	324,48
4	7055,64	2131,54	272,33	2251,43	13,71	1266,39
5	2334,44	4016,87	2217,78	3613,66	0	3378,26

Table 4.38: Statistics for simulation data set construction 12

Axle unit count	WIM Mass 10	WIM Mass stdev 10	WIM Mass 11	WIM Mass stdev 11	WIM Mass 12
2	2,61	308,64	0	138,86	0
3	2,38	229,61	2,32	131,10	2,53
4	5,36	305,72	4,93	191,20	3,06
5	0	0	0	0	0

Table 4.39: Statistics for simulation data set construction 13

Axle unit count	WIM Mass stdev 12	WIM Mass 13	WIM Mass stdev 13	WIM Mass 14	WIM Mass stdev 14
2	0	0	0	0	0
3	131,98	1,58	143,43	0	109,95
4	184,24	2,19	157,14	2,15	125,98
5	0	0	0	0	0

Table 4.40: Statistics for simulation data set construction 14

Axle unit count	WIM Mass 15	WIM Mass stdev 15
2	0	0
3	0	0
4	0,50	123,56
5	0	0

The histogram analysis conducted in Section 3.4 helped ensure that the input distribution matched that of real-life data. The overload statistics from SANRAL reports served as input that was incorporated into the statistics. The simulation data set construction steps were implemented with the process flow indicated in Figure 4.10. The scenarios constructed only differed in the WIM threshold applied and the overloading percentage. SANRAL annual reports 2016 and 2019 indicated that overloading percentage varied between 21,95% and 24,91%. This, combined with the WIM tolerances, was used to construct six simulation data sets.

The first data sets constructed had the minimum overloading observed. This was followed by the average overloading over the years and, finally, the maximum overloading observed. This was then combined with the typical 10% WIM tolerance and the observed tolerances of -8.85% and 16.37%, which were used as the *adjusted WIM tolerance*. The higher upper limit was not expected to have a large impact as the threshold used was 10% but the adjusted WIM scenario was tested to thoroughly represent the statistics observed. The simulation data sets represented industry in the six scenarios as follows:

- Scenario 1: Average overload percentage of 23,36% combined with 10% WIM tolerance.
- Scenario 2: Average overload percentage of 23,36% combined with adjusted WIM tolerance.
- Scenario 3: Minimum overload percentage of 21,95% combined with 10% WIM tolerance.
- Scenario 4: Minimum overload percentage of 21,95% combined with adjusted WIM tolerance.
- Scenario 5: Maximum overload percentage of 24,91% combined with 10% WIM tolerance.
- Scenario 6: Maximum overload percentage of 24,91% combined with adjusted WIM tolerance.

The axle loads were normalised against the applicable legal thresholds for the axle load. This was done to ensure that the models will not require modification if or when a

threshold change occurs, and that the model can be used in countries that have different legal thresholds.

Travel time was similarly normalised to ensure that the model is not TCC-specific and can be implemented between any two TCCs by taking a statistically benchmarked travel time between stations. The process steps for the constructions were as follows:

1. The process steps started with an output data set that used the SANRAL statistics as the basis for the probability of legally loaded and overloaded vehicles.
2. A vehicle class was assigned for the entire output data set as per the frequency/distribution of each vehicle class in the observed data sets. The vehicle class was generated and stored.
3. The axle values and frequencies/histogram values were declared as calculated from data sets. They were split into legal threshold values and overloaded values.
4. The data sets were initialised based on the entries required to be stored in them. They were for previous WIM scale, previous static scale, current WIM scale, AVCM at previous WIM scale, AVCM at previous static scale, AVCM at current WIM scale.
5. A loop was started to generate axle loads for the static measurements, based on the mass frequency/distributions, number of axles, and overloaded state.
6. Static masses of overloaded axles were randomised between combinations of overloaded axles, based on the probability distributions of overloaded axle loads.
7. The WIM axle loads were calculated on the normal distribution with the WIM threshold to add an error value to each axle.
8. The AVCM of each entry was calculated.
9. Finally, the travel time was calculated based on normal distribution.

AI model development has the risk of overfitting while training and this is mitigated by training on one subset and testing on another subset of each simulation data set. The robustness of the models was tested against an additional noise simulation data set, as discussed in Section 4.3.1 below.

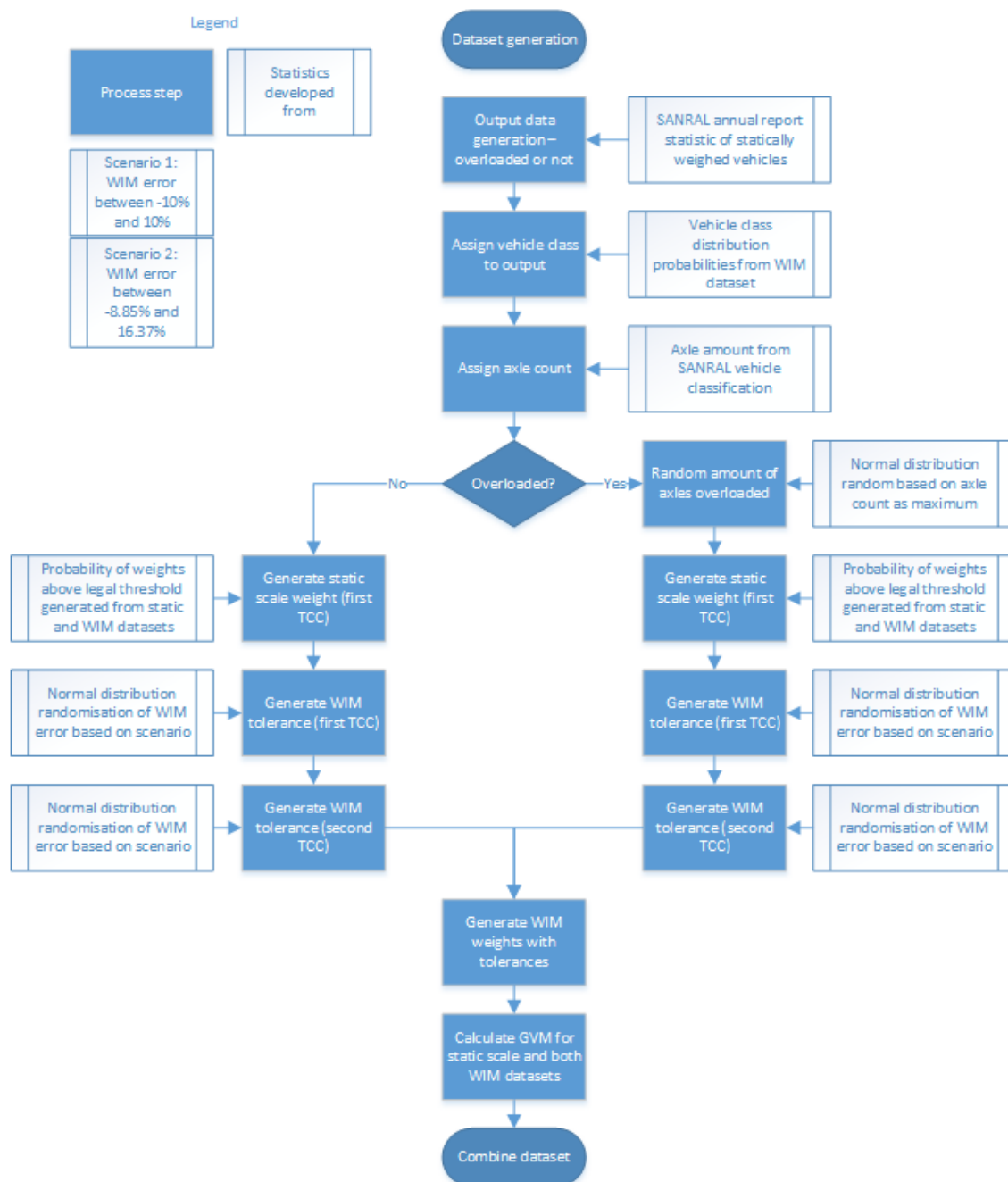


Figure 4.10: Simulation data set construction process flow

4.3.1 Noise simulation data set construction

The simulation data set constructed as described in Section 4.2.2 can be seen as an ideal representation of how vehicles travel on the corridor between TCCs. This raises concerns that the data set is too clean and does not consider slight changes that may

occur between TCCs. Additional noise had to be added to some of the simulated variables to represent the impact of potential real-world deviations on the data sets. This was achieved by constructing additional *noise simulation* data sets. The probability of noise addition was included to change the vehicle information between the two TCCs [179,180]. Noise was added to an observed normal distribution with normalised mass that had a mean of 0,96 and a deviation of 0,09 from the previous statistics of the AVCM distribution indicated in Figure 3.28. This value was used because it indicates the entire vehicle mass and distribution as observed from statistics, while still indicating that the vehicle is loaded close to permissible mass.

The noise simulation data sets were constructed with the simulation data set as base, with a 10% probability of noise being applied in the generation process. This process generated six noise data sets similar to the original simulation data sets, as indicated below:

- Noise scenario 1: Average overload percentage of 23,36% combined with 10% WIM tolerance.
- Noise scenario 2: Average overload percentage of 23,36% combined with adjusted WIM tolerance.
- Noise scenario 3: Minimum overload percentage of 21,95% combined with 10% WIM tolerance.
- Noise scenario 4: Minimum overload percentage of 21,95% combined with adjusted WIM tolerance.
- Noise scenario 5: Maximum overload percentage of 24,91% combined with 10% WIM tolerance.
- Noise scenario 6: Maximum overload percentage of 24,91% combined with adjusted WIM tolerance.

Before developing an AI model, it is essential to understand what performance it must improve upon. Section 4.3.2 below describes the performance of the SQ rule-based system on each of the data sets that was used when comparing the performance of the developed AI models.

4.3.2 Rule-based performance testing

The rule-based performance was implemented on the simulation- and noise simulation data sets. This allowed it to be compared to the performance of the AI models so that improvements could be determined, once again based on equation 4.6. The simulation and noise data sets were tested on the WIM 10% threshold of the current TCC as Rule-based 1. This was then followed by the combination of WIM with 10% threshold and the maximum axle mass between the two TCCs, as indicated in equation 4.1. The improvement was again tested against the rule-based performances to determine the benefit the model can cause. The tables comparing simulated and rule-based performance are as follows:

- Simulation data set 1: Table 4.41.
 - Simulation data set 2: Table 4.42.
 - Simulation data set 3: Table 4.43.
 - Simulation data set 4: Table 4.44.
 - Simulation data set 5: Table 4.45.
 - Simulation data set 6: Table 4.46.
-
- Noise simulation data set 1: Table 4.47.
 - Noise simulation data set 2: Table 4.48.
 - Noise simulation data set 3: Table 4.49.
 - Noise simulation data set 4: Table 4.50.
 - Noise simulation data set 5: Table 4.51.
 - Noise simulation data set 6: Table 4.52.

Table 4.41: Rule-based performance on simulation
data set 1

10 % WIM tolerance – 23,36% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	117 346	346 679
Percentage of overloaded of the total	23,47%	69,34%
Data count not overloaded from simulation results	382 654	153 321
Percentage of not overloaded of the total	76,53%	30,66%
Percentage not overloaded and sent to static scale		45,87%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	117 346	405 278
Percentage of overloaded of the total	23,47%	81,06%
Data count not overloaded from simulation results	382 654	75 992
Percentage of not overloaded of the total	76,53%	15,20%
Percentage not overloaded and sent to static scale		57,59%

Table 4.42: Rule-based performance on simulation
data set 2

Adjusted WIM tolerance – 23,36% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	116 611	387 783
Percentage of overloaded of the total	23,32%	77,56%
Data count not overloaded from simulation results	383 389	112 217
Percentage of not overloaded of the total	76,68%	22,44%
Percentage not overloaded and sent to static scale	54,23%	
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	116 611	438 130
Percentage of overloaded of the total	23,32%	87,63%
Data count not overloaded from simulation results	383 389	53 719
Percentage of not overloaded of the total	76,68%	10,74%
Percentage not overloaded and sent to static scale		64,30%

Table 4.43: Rule-based performance on simulation
data set 3

10 % WIM tolerance – 21,95% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 634	344 046
Percentage of overloaded of the total	21,93%	68,81%
Data count not overloaded from simulation results	390 366	155 954
Percentage of not overloaded of the total	78,07%	31,19%
Percentage not overloaded and sent to static scale		46,88%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 634	403 603
Percentage of overloaded of the total	21,93%	80,72%
Data count not overloaded from simulation results	390 366	77 121
Percentage of not overloaded of the total	78,07%	15,42%
Percentage not overloaded and sent to static scale		58,79%

Table 4.44: Rule-based performance on simulation
data set 4

Adjusted WIM tolerance – 21,95% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 546	385 744
Percentage of overloaded of the total	21,91%	77,15%
Data count not overloaded from simulation results	390 454	114 256
Percentage of not overloaded of the total	78,09%	22,85%
Percentage not overloaded and sent to static scale		55,24%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 546	437 255
Percentage of overloaded of the total	21,91%	87,45%
Data count not overloaded from simulation results	390 454	54 536
Percentage of not overloaded of the total	78,09%	10,91%
Percentage not overloaded and sent to static scale		65,54%

Table 4.45: Rule-based performance on simulation
data set 5

10 % WIM tolerance – 24,91% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	124 165	349 367
Percentage of overloaded of the total	24,83%	69,87%
Data count not overloaded from simulation results	375 835	150 633
Percentage of not overloaded of the total	75,17%	30,13%
Percentage not overloaded and sent to static scale		45,04%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	124 165	407 238
Percentage of overloaded of the total	24,83%	81,45%
Data count not overloaded from simulation results	375 835	74 171
Percentage of not overloaded of the total	75,17%	14,83%
Percentage not overloaded and sent to static scale		56,61%

Table 4.46: Rule-based performance on simulation
data set 6

Adjusted WIM tolerance – 24,91% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	124 801	390 930
Percentage of overloaded of the total	24,96%	78,19%
Data count not overloaded from simulation results	375 199	109 070
Percentage of not overloaded of the total	75,04%	21,81%
Percentage not overloaded and sent to static scale		53,23%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	124 801	439 850
Percentage of overloaded of the total	24,96%	87,97%
Data count not overloaded from simulation results	375 199	52 213
Percentage of not overloaded of the total	75,04%	10,44%
Percentage not overloaded and sent to static scale		63,01%

Table 4.47: Rule-based performance on noise simulation
data set 1

10 % WIM tolerance – 23,36% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	115 888	340 276
Percentage of overloaded of the total	23,18%	68,06%
Data count not overloaded from simulation results	384 112	159 724
Percentage of not overloaded of the total	76,82%	31,94%
Percentage not overloaded and sent to static scale		44,88%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	115 888	424 045
Percentage of overloaded of the total	23,18%	84,81%
Data count not overloaded from simulation results	384 112	62 706
Percentage of not overloaded of the total	76,82%	12,54%
Percentage not overloaded and sent to static scale		61,63%

Table 4.48: Rule-based performance on noise simulation
data set 2

Adjusted WIM tolerance – 23,36% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	116 174	380 896
Percentage of overloaded of the total	23,23%	76,18%
Data count not overloaded from simulation results	383 826	119 104
Percentage of not overloaded of the total	76,77%	23,82%
Percentage not overloaded and sent to static scale		52,94%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	116 174	422 406
Percentage of overloaded of the total	23,23%	84,48%
Data count not overloaded from simulation results	383 826	63 947
Percentage of not overloaded of the total	76,77%	12,79%
Percentage not overloaded and sent to static scale		61,25%

Table 4.49: Rule-based performance on noise simulation
data set 3

10% WIM tolerance – 21,95% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	108 912	336 715
Percentage of overloaded of the total	21,78%	67,34%
Data count not overloaded from simulation results	391 088	163 285
Percentage of not overloaded of the total	78,22%	32,66%
Percentage not overloaded and sent to static scale		45,56%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	108 912	422 278
Percentage of overloaded of the total	21,78%	84,46%
Data count not overloaded from simulation results	391 088	77 722
Percentage of not overloaded of the total	78,22%	12,90%
Percentage not overloaded and sent to static scale		62,67%

Table 4.50: Rule-based performance on noise simulation
data set 4

Adjusted WIM tolerance – 21,95% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 517	379 518
Percentage of overloaded of the total	21,90%	75,90%
Data count not overloaded from simulation results	390 483	120 482
Percentage of not overloaded of the total	78,10%	24,10%
Percentage not overloaded and sent to static scale		54,00%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	109 517	421 996
Percentage of overloaded of the total	21,90%	84,40%
Data count not overloaded from simulation results	390 483	78 004
Percentage of not overloaded of the total	78,10%	12,86%
Percentage not overloaded and sent to static scale		62,50%

Table 4.51: Rule-based performance on noise simulation
data set 5

10% WIM tolerance – 24,91% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	122 975	342 669
Percentage of overloaded of the total	24,60%	68,53%
Data count not overloaded from simulation results	377 025	157 331
Percentage of not overloaded of the total	75,41%	31,47%
Percentage not overloaded and sent to static scale		43,94%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	122 975	425 021
Percentage of overloaded of the total	24,60%	85,00%
Data count not overloaded from simulation results	377 025	74 979
Percentage of not overloaded of the total	75,41%	12,43%
Percentage not overloaded and sent to static scale		60,41%

Table 4.52: Rule-based performance on noise simulation
data set 6

Adjusted WIM tolerance – 24,91% overloaded		
Rule-based – current WIM	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	123 302	383 579
Percentage of overloaded of the total	24,66%	76,72%
Data count not overloaded from simulation results	376 698	116 421
Percentage of not overloaded of the total	75,34%	23,28%
Percentage not overloaded and sent to static scale		52,06%
Rule-based – both WIMs	Simulated ground truth	Rule-based
Data count	500 000	500 000
Data count overloaded from simulation results	123 302	424 441
Percentage of overloaded of the total	24,66%	84,89%
Data count not overloaded from simulation results	376 698	75 559
Percentage of not overloaded of the total	75,34%	12,39%
Percentage not overloaded and sent to static scale		60,23%

The comparisons with rule-based performance results were critical to determine whether there was an increase or a decrease in the performance of the models that were developed and tested as described in Section 4.4 below, similar to the models described in Section 4.1.1. The next section describes the process of the AI model development and data transformation to ensure it was usable as input into the models.

4.4 AI model implementation

The AI model implementation was similar to the process followed in Section 4.1.3. The data were first manipulated to be suitable as input into the models, then the model performance was tested. Thereafter, an in-depth analysis was performed on the best-performing models to determine which model would be best suited to the simulation and noise simulation data sets, while comparing them with the models applied to the industry data.

4.4.1 Data manipulation for input into AI models

Input parameters for the models included the downstream (previous) WIM scale and static scale data linked to the upstream (current) WIM scale details, combined with the travel times between them. The data set linked the vehicle identification at each point to estimate the probability that the vehicle was overloaded at the upstream/current static scale. RFID linking was included to increase the accuracy with which vehicles are identified at specific points in the system design. The data from Mantsole and Heidelberg TCCs were used as the inputs for the algorithm development, as previously discussed. The data referred to two distinct directions/corridors and the defined inputs were as follows:

- Vehicle identifier
- Vehicle class/Axle configuration
- WIM scale axles

- Static scale axles

4.4.2 Overview of model performance

Training and testing on the simulation and noisy simulation data sets was conducted for all 9 models. Each model used 80% (400 000 data points) data in the training data set and 20% (100 000 data points) for the test data sets. Performance was tested on each model trained on all the other model data sets, with 500 000 data points in each. The model performance again made use of the confusion matrix as implemented in Section 4.1.3. The target was to have very high accuracy with minimal vehicles incorrectly sent to the corridor.

An overview of the models' performance was completed by a statistical overview of all the data sets. The accuracy of the average, standard deviation, minimum, and maximum values is recorded in Table 4.53 and the improvements over the rule-based system, combined with the false negatives, are shown in Table 4.54. The abbreviated headings in these tables are explained below:

- Max: Maximum accuracy achieved over all the data sets.
- Min: Minimum accuracy achieved over all the data sets.
- Average/Avg: Average accuracy over all the data sets.
- Stdev: Standard deviation over all the data sets.

The models in each of these tables correspond to the configurations previously discussed and are abbreviated as explained below:

- ANN 1: ANN model 1.
- ANN 2: ANN model 2.
- ANN 3: ANN model 3.
- Log reg 1: Logistic regression model 1.
- Log reg 2: Logistic regression model 2.
- Log reg 3: Logistic regression model 3.

- RFT 1: RFT model 1.
- RFT 2: RFT model 2.
- RFT 3: RFT model 3.

Model performance is discussed in three parts below. First, the accuracy of the models is shown in Table 4.53. This value indicates the combined total of the true positives and true negatives. The ANN performed slightly better, with an average accuracy of 99,46% on model 3, the best performing model. The random forest tree model was just below the ANN, with the highest performance on model 3, which averaged 99,45% accuracy and had the smallest standard deviation – 0,29%. The in-depth analysis of the best performing model is discussed in Section 4.4.3.

Table 4.53: Model accuracy overview statistics over all data sets

	Accuracy			
	Max	Min	Average	Stdev
ANN 1	99,72%	98,98%	99,45%	0,25%
ANN 2	99,72%	98,92%	99,43%	0,25%
ANN 3	99,74%	98,81%	99,46%	0,26%
Log reg 1	97,48%	95,40%	96,67%	0,37%
Log reg 2	97,48%	95,40%	96,67%	0,37%
Log reg 3	97,47%	95,52%	96,67%	0,37%
RFT 1	99,98%	98,76%	99,45%	0,31%
RFT 2	99,86%	98,78%	99,45%	0,30%
RFT 3	99,82%	98,78%	99,45%	0,29%

Improvement was measured against the rule-based performance, as previously discussed. Table 4.54 indicates the improvement that the models showed over all the data sets, as well as the false negatives, which referred vehicles incorrectly to the corridor.

The RFT models performed almost exactly the same when compared to the ANN, with

all its models having an average improvement of 66,14%. The ANN models had the lowest percentage of vehicles sent incorrectly to the corridor, with an average of 0,27%. ANN model 3 and RFT model 3 has the best performance on the false positives or vehicles sent incorrectly to the corridor (0,28%) and sent incorrectly to the TCC (0,26%).

Table 4.54: Model performance overview

Model	Improvement			
	Max	Min	Average	Stdev
ANN 1	70,47%	60,06%	66,16%	2,81%
ANN 2	70,47%	60,03%	66,13%	2,81%
ANN 3	70,50%	60,04%	66,14%	2,82%
Log reg 1	69,12%	57,44%	64,10%	2,92%
Log reg 2	69,12%	57,44%	64,10%	2,92%
Log reg 3	69,12%	57,43%	64,10%	2,92%
RFT 1	70,48%	60,16%	66,12%	2,80%
RFT 2	70,48%	60,16%	66,13%	2,80%
RFT 3	70,48%	60,16%	66,14%	2,80%

Table 4.55: Model false positive and false negative performance

Model	False positive				False negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
ANN 1	0,75%	0,00%	0,28%	0,20%	0,61%	0,01%	0,27%	0,18%
ANN 2	0,81%	0,00%	0,28%	0,21%	0,64%	0,00%	0,29%	0,19%
ANN 3	0,64%	0,00%	0,26%	0,18%	0,72%	0,01%	0,28%	0,18%
Log reg 1	2,76%	0,20%	0,99%	0,45%	3,24%	1,62%	2,33%	0,35%
Log reg 2	2,76%	0,20%	0,99%	0,45%	3,24%	1,62%	2,33%	0,35%
Log reg 3	2,65%	0,20%	0,99%	0,45%	3,25%	1,62%	2,33%	0,35%

Table 4.55: Model false positive and false negative performance

Model	False positive				False negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
RFT 1	0,82%	0,00%	0,25%	0,21%	0,76%	0,00%	0,30%	0,17%
RFT 2	0,83%	0,00%	0,26%	0,20%	0,73%	0,00%	0,29%	0,17%
RFT 3	0,84%	0,00%	0,26%	0,20%	0,69%	0,01%	0,28%	0,17%

The models selected for more in-depth analysis in Section 4.4.3 below had to have the highest average readings and the lowest percentage of vehicles sent incorrectly to the corridor. The performances of the ANN model 3 and the RFT model 3 were almost exactly the same. They are compared in more detail below with the RFT model 3 to explain which was used as the IWIM algorithm.

4.4.3 In-depth analysis of highest performing models

ANN model 3 and RFT model 1 testing results are indicated for all the data sets in this section. The tables indicate which model they were trained on and which data sets they were tested on with the following descriptions:

- Train: Training results on data set used training split.
- Test: Test results on data set used test split.
- Clean 10% over 1: Simulation data set with 10% WIM tolerance and average overloading of 23,36%.
- Clean 10% over 2: Simulation data set with 10% WIM tolerance and average overloading of 21,95%.
- Clean 10% over 3: Simulation data set with 10% WIM tolerance and average overloading of 24,91%.

- Clean adjwim over 1: Simulation data set with adjusted WIM tolerance and average overloading of 23,36%.
- Clean adjwim over 2: Simulation data set with adjusted WIM tolerance and average overloading of 21,95%.
- Clean adjwim over 3: Simulation data set with adjusted WIM tolerance and average overloading of 24,91%.
- Noisy 10% over 1: Noise simulation data set with 10% WIM tolerance and average overloading of 23,36%.
- Noisy 10% over 2: Noise simulation data set with 10% WIM tolerance and average overloading of 21,95%.
- Noisy 10% over 3: Noise simulation data set with 10% WIM tolerance and average overloading of 24,91%.
- Noisy adjwim over 1: Noise simulation data set with adjusted WIM tolerance and average overloading of 23,36%.
- Noisy adjwim over 2: Noise simulation data set with adjusted WIM tolerance and average overloading of 21,95%.
- Noisy adjwim over 3: Noise simulation data set with adjusted WIM tolerance and average overloading of 24,91%.

Artificial neural network classifier 3

ANN model 3's performance can be seen in Table 4.56, which provides a statistical overview of its improvement on the rule-based approach. Table 4.57 indicates the false positive and negative values of the model's performance. The training on the simulation data sets had the best average improvement performance of 66,05%, while training on the noise simulation data sets was slightly higher with a best performance of 66,29%.

The key factor, however, was which model directed the lowest percentage of vehicles to the corridor even though they were overloaded. The training on the simulation data sets had the better performance, with the lowest average of 0,38% incorrectly sent to the

corridor, and only increased for the noise simulation data sets to the lowest average of 0,13%. False positives by this model sent an average of 0,40%, incorrectly to the static scale. This was the worst performance, although it is significantly less than the current annual SANRAL reported rates [43–46].

Table 4.56: Artificial neural network model 3 improvement summary

	Improvement			
	Max	Min	Average	Stdev
Clean 10% over 1	70,46%	60,11%	66,02%	2,88%
Clean 10% over 2	70,46%	60,04%	65,99%	2,89%
Clean 10% over 3	70,47%	60,17%	66,05%	2,88%
Clean adjwim over 1	70,47%	60,14%	66,03%	2,88%
Clean adjwim over 2	70,48%	60,13%	66,04%	2,88%
Clean adjwim over 3	70,50%	60,16%	66,05%	2,88%
Noisy 10% over 1	70,47%	60,61%	66,27%	2,85%
Noisy 10% over 2	70,42%	60,36%	66,12%	2,88%
Noisy 10% over 3	70,47%	60,64%	66,27%	2,85%
Noisy adjwim over 1	70,45%	60,61%	66,27%	2,85%
Noisy adjwim over 2	70,46%	60,60%	66,26%	2,85%
Noisy adjwim over 3	70,47%	60,65%	66,29%	2,84%

Table 4.57: Artificial neural network model 3 false negative and positive summary

	False positive				False negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
Clean 10% over 1	0,30%	0,01%	0,13%	0,13%	0,56%	0,28%	0,40%	0,12%
Clean 10% over 2	0,28%	0,02%	0,13%	0,13%	0,64%	0,28%	0,43%	0,14%
Clean 10% over 3	0,29%	0,00%	0,13%	0,13%	0,51%	0,26%	0,38%	0,11%
Clean adjwim over 1	0,27%	0,00%	0,12%	0,13%	0,53%	0,27%	0,39%	0,11%
Clean adjwim over 2	0,29%	0,01%	0,13%	0,13%	0,54%	0,26%	0,38%	0,12%
Clean adjwim over 3	0,27%	0,00%	0,13%	0,12%	0,51%	0,24%	0,38%	0,11%
Noisy 10% over 1	0,57%	0,25%	0,39%	0,14%	0,41%	0,01%	0,15%	0,14%
Noisy 10% over 2	0,51%	0,20%	0,34%	0,13%	0,72%	0,04%	0,28%	0,21%
Noisy 10% over 3	0,64%	0,26%	0,42%	0,15%	0,37%	0,02%	0,15%	0,14%
Noisy adjwim over 1	0,57%	0,24%	0,39%	0,14%	0,37%	0,02%	0,15%	0,14%
Noisy adjwim over 2	0,56%	0,24%	0,38%	0,14%	0,39%	0,02%	0,16%	0,14%
Noisy adjwim over 3	0,61%	0,25%	0,40%	0,14%	0,32%	0,01%	0,13%	0,13%

Random forest tree classifier 3

RFT model 3's performance, seen in Table 4.58, provides a statistical overview of model 3's improvement over the rule-based approach. Table 4.59 indicates the false positive and negative values of the model's performance. The training on the simulation data sets had an average improvement performance of 66,05%, while training on the noise simulation data sets was slightly higher at a best performance of 66,29%.

The key factor, however, was which model directed the lowest percentage of vehicles to the corridor, even though they were overloaded. The training on the simulation data sets had the better performance, with an average of 0,36% incorrectly sent to the corridor, and only increased for the noise simulation data sets to a maximum of 0,13%.

False positives by this model sent an average of 0,46% incorrectly to the static scale, which is significantly less than the SANRAL annual reports indicated [43–46].

Table 4.58: Random forest tree model 3 improvement summary

	Improvement			
	Max	Min	Average	Stdev
Clean 10% over 1	70,48%	60,17%	66,06%	2,88%
Clean 10% over 2	70,48%	60,16%	66,05%	2,88%
Clean 10% over 3	70,48%	60,19%	66,07%	2,88%
Clean adjwim over 1	70,48%	60,17%	66,06%	2,88%
Clean adjwim over 2	70,48%	60,16%	66,05%	2,88%
Clean adjwim over 3	70,48%	60,19%	66,07%	2,88%
Noisy 10% over 1	70,35%	60,61%	66,18%	2,83%
Noisy 10% over 2	70,27%	60,58%	66,13%	2,83%
Noisy 10% over 3	70,29%	60,64%	66,15%	2,82%
Noisy adjwim over 1	70,47%	60,64%	66,28%	2,85%
Noisy adjwim over 2	70,45%	60,62%	66,25%	2,85%
Noisy adjwim over 3	70,48%	60,65%	66,29%	2,84%

Table 4.59: Random forest tree model 3 false negative and positive summary

	False positive				False negative			
	Max	Min	Average	Stdev	Max	Min	Average	Stdev
Clean 10% over 1	0,32%	0,00%	0,13%	0,14%	0,50%	0,25%	0,36%	0,11%
Clean 10% over 2	0,27%	0,00%	0,11%	0,13%	0,51%	0,25%	0,37%	0,12%
Clean 10% over 3	0,51%	0,00%	0,21%	0,18%	0,49%	0,25%	0,36%	0,11%

Table 4.59: Random forest tree model 3 false negative and positive summary

	False positive				False negative			
Clean adjwim over 1	0,32%	0,00%	0,13%	0,14%	0,50%	0,25%	0,37%	0,11%
Clean adjwim over 2	0,27%	0,00%	0,11%	0,13%	0,51%	0,26%	0,37%	0,12%
Clean adjwim over 3	0,55%	0,00%	0,22%	0,18%	0,49%	0,25%	0,36%	0,11%
Noisy 10% over 1	0,57%	0,17%	0,34%	0,16%	0,57%	0,01%	0,22%	0,18%
Noisy 10% over 2	0,52%	0,17%	0,32%	0,16%	0,69%	0,01%	0,27%	0,22%
Noisy 10% over 3	0,78%	0,18%	0,42%	0,21%	0,67%	0,02%	0,25%	0,21%
Noisy adjwim over 1	0,62%	0,18%	0,37%	0,17%	0,37%	0,01%	0,14%	0,14%
Noisy adjwim over 2	0,55%	0,18%	0,35%	0,17%	0,47%	0,01%	0,17%	0,16%
Noisy adjwim over 3	0,84%	0,20%	0,46%	0,22%	0,33%	0,01%	0,13%	0,13%

4.5 Conclusion

Industry data allowed us to compile a suitable set of real-world linked data from data collected in 2021 from the Mantsole and Heidelberg TCCs. Accurate linking between stations by making use of vehicle registration numbers ensured that 3 167 linked entries could be collected from these sites. Padding the data set with additional overloaded entries increased the data set to over 3 600 entries that were used as input for the model training. These data were then manipulated into the format to be used in the model development that can potentially be used for the IWIM algorithm.

Nine models were constructed using ANN, RFT, and logistic regression classifiers with variations in construction hyperparameters, and were trained and tested on the data sets. A summary indicated that the highest performing models were the ANN and RFT models, with an additional test conducted on the highest performing logistic regression model. These highest performing models received in-depth analysis to determine

the accuracy of the model and which model sent the lowest percentage of vehicles incorrectly to the corridor and to the static scale. The in-depth analysis indicated that RFT model 1 had the best performance, based on the criteria required.

It was decided to do additional testing of model performance by expanding the data sets through simulations, using industry data as the basis of a larger input set for testing. The simulation and noise simulation algorithm design started by consolidating the data sources from the industry to be used as input into data sets. Several data sets were constructed from the statistics by varying the probabilities applied in the construction.

Expanded data sets were simulated, based on WIM and static scale data from both sites, travel time, and overload status. Construction of the data set represented complexity using the data available as the base. Six simulation data sets were thus constructed based on the SANRAL annual overloading statistics. An additional six noise simulation data sets were constructed by adding noise or slight mass changes, such as may occur en route between the TCCs.

The differences between the industry and simulation data sets were mostly in the number of overloaded vehicles in each data set. The industry data was based on a small linked data set with a padded linked data set of just around 3 600 entries. Comparing this number of entries to the 500 000 entries of each simulation data set based on overload statistics from SANRAL annual reports resulted in between 21,95% and 24,91% overloaded entries. The small, linked data set is expected to show a larger overloaded count when more sites are added in the future.

Training of the model on the real-world linked data indicated that the RFT model once again had the best performance. The accuracy of the model was 99,97%, with 0,0% sent incorrectly to the corridor when overloaded, similar to the results of training on the simulation data set.

Additional testing conducted on a data set with an adjusted WIM threshold when vehicles were not overloaded produced a reduction in vehicles weighed statically. The threshold was adjusted to 0,95, 0,98, 1,00, 1,0541, and 0,958 as new rule-based scenarios.

The use of the RFT for IWIM realised a 97,84% improvement on rule-based scenario 1. The adjusted WIM threshold indicated an improvement against the status quo scenarios but increased the number of vehicles directed to the corridor incorrectly. Therefore, the usage of the adjusted threshold did not yield a benefit from changing a slight rule of the current SQ.

This amount of improvement promises significant benefits, and the impact was investigated in Chapter 5.

The RFT model was trained on all the simulation data sets and had the best performance, sending only 0,03% of vehicles incorrectly to the corridor. The model had the worst performance on the simulation data sets, with 0,57% incorrectly sent to the corridor. In its best performance, this model only sent 0,17% of vehicles incorrectly to the static scale and, in its worst performance, it still only sent 0,57% to the static scale.

The model training on the real-world data as well as simulation data produced the best performance from the RFT models. This additional testing on simulation and noise simulation data sets confirmed the RFT as the best performing model.

The *random forest tree model* trained on padded linked data set will therefore be used as the *IWIM* model because it had the best performance for the industry- and the simulation data sets.

Chapter 5

Economic benefit model development

Achieve Ikigai for the stakeholders

In this chapter, we cover the development of the economic model that is directly related to **contribution 2**. Where some studies only provide a qualitative impact analysis, this study also quantifies the impact of the IWIM algorithm to provide a financial perspective.

Although there are several methods of selling a concept to a potential client, there is a universal language that is understood by most stakeholders, namely the financial cost/benefit of the concept. This chapter focuses on the quantification of variables to determine the financial impact of the IWIM concept on each stakeholder. The financial impact study estimated the benefits of the proposed concept in ZAR value for South African corridors.

A combined model was developed to quantify the impact of the improvements on the stakeholder for whom brief backgrounds were given in section 2.1.1. The model takes into account the vehicles taking part in the concept to ensure the economic model has a scalable output.

5.1 Stakeholder benefits

The stakeholder benefit quantification first looks at *delays* experienced in current operations and their *domino* effect on additional aspects of the stakeholder businesses. This is followed by conservative estimations of how the new model will potentially improve efficiency for each stakeholder. The stakeholders included in this section are, as previously discussed in Section 2.1.1:

- Cargo owners
- Cargo transporters
- Road users or the general public
- Clients of the cargo owner
- Road agencies
- The national treasury
- Cross-border operations
- TCC operators
- Toll concessionaires

Improvements

The improvement offered by reducing unnecessary static weighs will impact the stakeholders in several different ways and have financial benefits within their context. The potential improvements are listed below and the financial impact is explained later in this section. Even conservative estimates of the impact are shown to have sufficient financial benefits to justify the implementation of the proposed system.

Decreasing the number of unnecessary weighs of vehicles after implementing the IWIM algorithm will substantially reduce time wastage on the corridor. The percentage of *overloaded weighs* will increase at the static scale, with a high probability that these will include vehicles that would previously have bypassed the weigh station due to long queues at the TCC. This will have the impact of capturing previously overloaded vehicles to be weighed and forced to reduce their load to legal limits, which will **decrease road wear** because the vehicles will travel fewer overloaded tonne-kilometres.

A reduction in road wear will ensure that the surface is less damaged and has a lifespan closer to the design criteria. It has been indicated that a deteriorated road pavement increases road maintenance costs. This implementation will also **decrease vehicle maintenance costs and fuel consumed**. Maintenance is often a low priority for certain transport companies so more affordable maintenance costs will hopefully **reduce crashes**, which usually involve several persons and have a high fatality rate.

Less time spent at the TCCs will reduce the turnaround time of the trips, which will allow **more trips** per month, if there is sufficient stock to be transferred. A more efficient transport system will assist in **just-in-time delivery**, which will significantly reduce stock levels and expenses on dead stock.

A **reduction in static scale wear** is expected, due to the decrease in vehicles weighed statically at the TCCs.

5.1.1 Road users

Several of the stakeholders discussed are road users. They include *transporters, heavy vehicle drivers, cargo owners, clients, and public road users*. The impact of the improvements on each of them was investigated and the cost impact was quantified for the relevant sector.

Transporters

The transporter, as mentioned before, plays a critical part in the logistics process. This is the company that physically transports the goods from the starting point at the cargo owner's site to the destination at the client's site. South Africa has a predominant focus on transport companies that own or rent a fleet to facilitate this service. International business models tend to have more opportunities for privately owned vehicles to perform this transport service, whereas South African companies lease fleets.

Transport represents a significant portion of the total logistics costs: in excess of 55% consistently from 2010 to 2016, as seen in Figure 5.1 [21]. The transport sector has low profit margins due to extreme competition, as previously mentioned. Any cost saving on the bottom line has a significant impact: The decrease in weights for legally loaded vehicles will reduce multiple stops at the static scales; there will be less fuel consumption and tyre wear due to starts and stops at the static scale; and the reduction in the turnaround times of trips may increase the number of trips that can be conducted during the month.

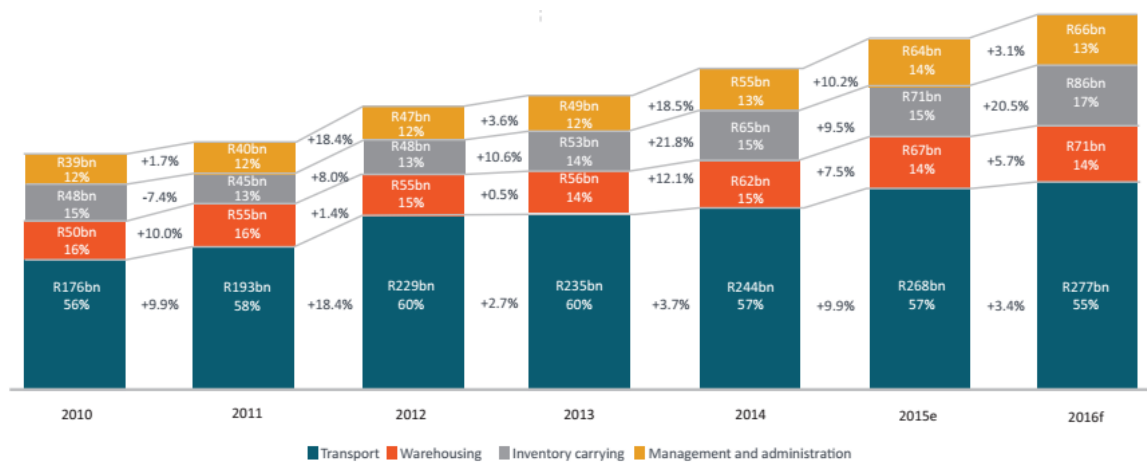


Figure 5.1: Trends in South Africa's logistics costs stack elements [21]

Financial quantification of the savings was conducted on several categories. These savings are included in the financial model in Section 5.2. A previous study quantified the savings achieved by implementing the IWIM algorithm [31] by presenting several descriptive scenarios for the trips: In a trip on a 1 000 km return route, 4 TCCs are typically visited, and 10,4 minutes is spent per static scale visited. The trip details are presented in Table 5.1. These variables are conservative compared to the current 15 minute average time at the static scale. The average reduction of 2,4 visits to the static scale reduces the trip with 0,03 days [31].

Table 5.1: Cargo vehicle trip variables before and after implementation [31]

Cargo vehicle trip variables	Old scenario	New scenario
Monthly interest rate	1%	1%
No. of monthly instalments	120	120
Average cost of truck	\$ 180 000	\$ 180 000
Monthly instalment	\$ 2 582	\$ 2 582
Average income per trip	\$ 1 500	\$ 1 500

Cargo vehicle trip variables	Old scenario	New scenario
Average distance per trip (km)	500	500
Average fuel consumption (km/l)	2	2
Cost of fuel per litre	\$ 1,50	\$ 1,50
Average cost of fuel per trip	\$ 375	\$ 325
Number of tyres per vehicle	16	\$ 16
Cost per tyre	\$ 500	\$ 500
Stop/start as fraction of tyre wear-n-tear	30%	30%
Max km per set of tyres	25 000	\$ 25 000
Average km per stop/start	\$ 150	\$ 150
Number of static scale stops saved per trip	0	\$ 2,40
Fuel cost saving per trip	0	\$ 50
Cost of tyres per trip	\$ 160	\$ 125
Savings on tyres per trip	\$ -	\$ 35
Cost of driver per trip	\$ 300	\$ 300
Other costs per trip (tolls, etc)	\$ 100	\$ 100
Total trip costs, excluding financing of truck	\$ 935	\$ 850
Profit per trip, excluding financing of truck	\$ 565	\$ 650

Fuel savings are quantified for these trips, as well as the savings on tyre wear. This ultimately increases profit for long-haul trips, while increasing the potential number of trips for the transporter. It is calculated that the worst performance of the IWIM algorithm may reduce the number of non-overloaded vehicles being statically weighed by around 1,28 million vehicles.

Heavy vehicle operators

Heavy vehicle operators/drivers are often not taken into consideration but they are essential to the vehicle's operation. Extended periods on the road require a high level of

focus as a lapse in focus can cause an crash. The driver's mental state can deteriorate, seeing that the driver is isolated for prolonged periods on cross border delivery trips. It is therefore beneficial for the driver to spend less time on trips to decrease the risk of crashes. This will also ensure that resting periods can occur sooner between trips, even if the company increases the number of trips per month. Some business models pay the drivers per trip, which will enable the driver to increase his monthly salary. Physical health issues occur in as high as 76,3% of heavy vehicle operators, and 18,7% of them have mental health issues [181]. A reduction of travelling time may assist in reducing the health issues experienced in the industry.

Cargo owners

Cargo owners have a deep interest in the goods en route as they are their capital investment in transit. Any unforeseen delays en route or any damage to the goods will incur losses. These losses are in some cases mitigated by implementing a blanket insurance of stock in transit but this insurance is an additional expense. Short-term insurance is in most cases linked to the time period spent in transit.

Payment for the goods is often only made after delivery of the goods has been confirmed. Any delay in delivery affects the potential interest that is incurred by the cargo owner with other creditors. The uncertainty of the time required to deliver stock means that minimum stock levels are too high and just-in-time delivery is not possible. Extreme cases mean that the client loses confidence in the cargo owner's delivery efficiency and moves to a competitor.

Financial quantification is complex for an entire industry, so it can simply be speculated that, qualitatively, perceptions of the business will become increasingly negative if items are delivered late.

Clients

Some factors that affect the cargo owner also affect the client who receives the intended goods. The client's business is dependent on having goods to sell or services to offer. Late receipt of goods may lower perceptions of the client's business competence. This may also result in business' being moved to competitors. Clients are similar to cargo owners in that perception of them is also qualitative.

Public road users

People who travel daily on the public roads are severely impacted by deteriorated road infrastructure. This impact includes coping with more and worse potholes, and time delays due to crashes. Their vehicle maintenance costs can be expected to increase, similar to the owners of heavy vehicles. The time delay will ensure a ripple effect to the business where the public road user works. A minor delay can accumulate to several business work hours lost because of busy corridors.

Crashes involving heavy vehicles and the public tend to have lethal consequences. Figure 5.2 indicates the statistics of crashes on the South African roads in 2015. The economic impact of these crashes is equal to 3,4% of the GDP or ZAR 142,95 billion [128]. Fatalities have an estimated impact of ZAR 58 332 million [128]. Figure 5.2 below indicates the statistics for road traffic crashes (RTCs) and road traffic injuries (RTIs) .

Number of RTCs and RTIs for 2015, adjusted for underreporting					
	Fatal	Major	Minor	Damage only	Total
Number of RTCs	11 144	40 117	132 609	648 560	832 431
	Death	Serious	Slight	No injury	Total
Number of persons	13 591	62 520	202 509	1 429 794	1 708 414

Figure 5.2: Crash statistics [128]

5.1.2 Toll concessionaires

TCCs are implemented by toll concessionaires to detect and regulate overloaded vehicles. The current inefficiency of statically weighing only around 22% of overloaded vehicles reduces the chance of capturing other overloaded vehicles because it increases the chance that bypassing may occur. The implementation of the IWIM algorithm will greatly reduce the number of non-overloaded vehicles being weighed and thereby increase the possibility of statically weighing overloaded vehicles. The potential numbers of overloaded vehicles weighed and prosecuted have been estimated.

Capturing a higher percentage of overloaded vehicles will reduce the maintenance required on the part of the corridor that toll concessionaires manage as per the PPP agreement. Reducing the maintenance required will improve their profitability levels. Increased efficiency of the operation may decrease the staff complement required at the TCCs, or the staff can spend more time attempting to recover more fines.

5.1.3 National Treasury

The National Treasury of South Africa has an extremely high interest in the road infrastructure. Any new development and maintenance is reflected in some form in its finances. The fact that high quality infrastructure has a severe effect on economic growth increases or decreases the entire country's GDP. A delay in delivery has a ripple effect on a large section of the economy as sales and services are delayed by business days. The effects accumulate quickly if several days' delay occur. Historical data has shown that 53,9% of GDP is transportable, as indicated in Figure 5.3 below.

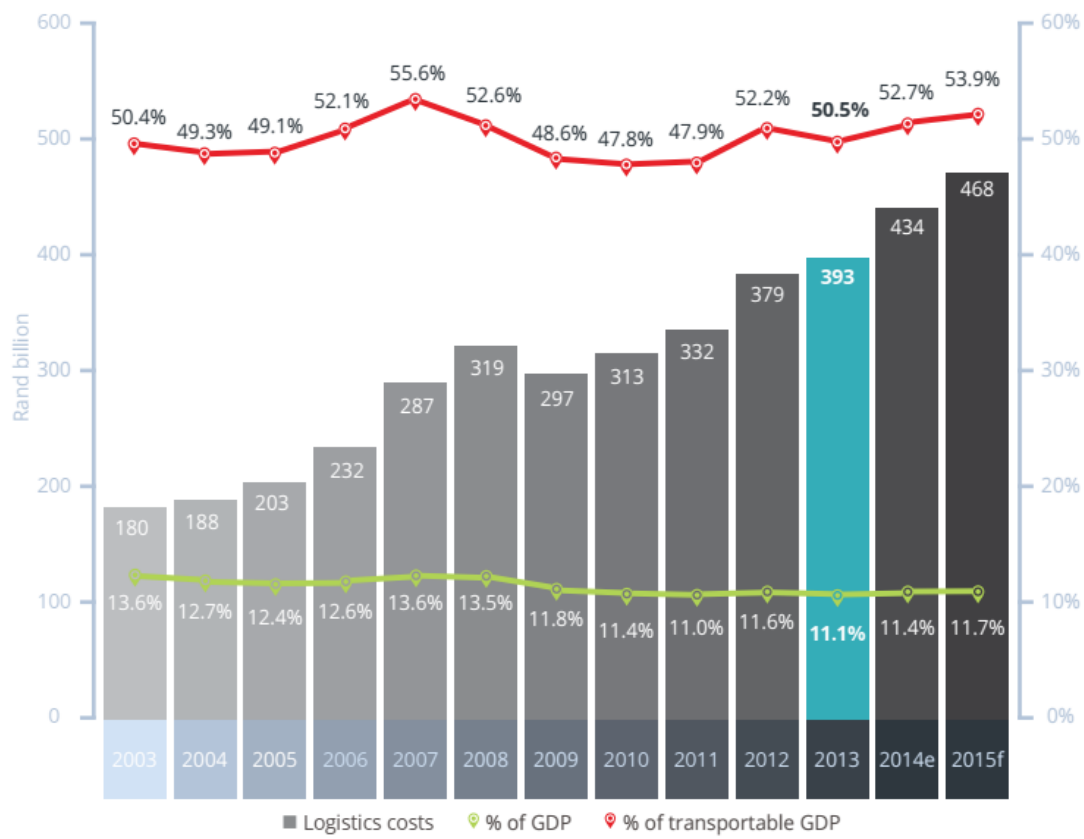


Figure 5.3: South Africa logistics costs in perspective [51]

National Treasury will benefit from a reduction in overloaded vehicles on the road and the resultant increase in the GDP of the country. The benefits to the treasury are related to the potential increased detection of overloaded vehicles. This is quantified by making the following use of figures based on literature as guidance in the conservative economic model presented in Section 5.2.

5.2 Economic model construction

An impact quantification from the literature was used as input to the economic model. The economic model incorporates the aspects discussed above. They are included in the calculations in equations 5.1 to 5.12. The calculations include literature based input values to reach the savings quantification.

Transportation constitutes a considerable percentage of the GDP. Equation 5.1 indicates the transportation GDP per day. An average of ZAR 6,2 billion is transported daily [51]:

$$\begin{aligned}
 & \frac{\text{GDP per annum} \times \text{Percentage Transportation GDP}}{365} \\
 &= \frac{\text{ZAR 4204,4 billion} \times 53,9\%}{365} \\
 &= \text{ZAR 6,2 billion}
 \end{aligned} \tag{5.1}$$

A reduction in lives lost will be greatly beneficial to the public. It is extremely difficult to estimate the cost of a life, but previous studies have attempted to do so. Equations 5.2 and 5.3 indicate the cost per life quantified by one of them as between 0,7 and 3 million euros [182,183], which ranges from ZAR 11,95 million to ZAR 51 million. The lower range was used for benefit quantification.

$$\begin{aligned}
 & 0,7 \text{ million} \times (\text{Euro to ZAR}) \\
 &= 0,7 \text{ million} \times 17,07 \\
 &= \text{ZAR 11,95 million}
 \end{aligned} \tag{5.2}$$

$$\begin{aligned}
 & 3 \text{ million} \times (\text{Euro to ZAR}) \\
 &= 3 \text{ million} \times 17,07 \\
 &= \text{ZAR 51 million}
 \end{aligned} \tag{5.3}$$

The time vehicles waste at TCCs when not overloaded is significant. Equation 5.4 indicates that 10 083 days are lost when considering the entire industry that is weighed statically [46].

$$\begin{aligned}
& (\text{Total weighed vehicles} \times \% \text{ not overloaded} \times \text{average time per visit}) \\
& = 1,79 \text{ million} \times 78\% \times 10,4 \text{ minutes} \\
& = 14\,450\,480 \text{ minutes} \\
& = 10\,083 \text{ days}
\end{aligned} \tag{5.4}$$

Implementation of the IWIM algorithm would still allow some vehicles that are not overloaded to be sent to the static scale. However, equation 5.5 shows that the days lost across the industry would be reduced to 49,13 on the worst performance that is weighed statically. The implementation of the IWIM on the padded linked data set reduced the loss to 3,88 days, as indicated in equation 5.6.

$$\begin{aligned}
& (\text{Total weighed vehicles} \times \% \text{ not overloaded} \times \text{average time per visit}) \\
& = 1,79 \text{ million} \times 0,38\% \times 10,4 \text{ minutes} \\
& = 70\,741 \text{ minutes} \\
& = 49,13 \text{ days}
\end{aligned} \tag{5.5}$$

$$\begin{aligned}
& (\text{Total weighed vehicles} \times \% \text{ not overloaded} \times \text{average time per visit}) \\
& = 1,79 \text{ million} \times 0,03\% \times 10,4 \text{ minutes} \\
& = 5\,584 \text{ minutes} \\
& = 3,88 \text{ days}
\end{aligned} \tag{5.6}$$

Long-haul vehicles travel an average of 604 km per trip on the corridor, while short-haul vehicles travel 78 km in metropolitan areas and 174 km in rural areas, with an average of 126 km on short haul trips [184]. The TCCs are, however, not necessarily far apart and should detect an overloaded vehicle before it completes its full journey. The distances between several TCCs within South Africa are listed below to illustrate the expected distance before an overloaded vehicle is detected:

- Mkondeni to Midway in KZN is a distance of 95,5 km.
- Ladysmith to Midway in KZN is between 74 and 84 km, dependant on the route.
- Mantsole to Heidelberg TCC, depending on the route, is between 174 km and 181 km.
- Bapong to Mantsole is 126 to 130 km.
- Mantsole to Beitbridge is 413 to 501 km.

Overloaded long-haul vehicles are, therefore, detected and have their mass corrected 74 km (*detection distance*) into the trip length, using the shortest distance between TCCs as a conservative distance.

Previous work indicated that implementation of an overload bypass detection system could have a positive internal rate of return by just detecting 100 vehicles in the first year of operation [75]. It can be expected that reducing the number of legally loaded vehicles that visit the static scale will reduce queue lengths so a far greater number of overloaded vehicles can be detected but a figure of 2% (*increased detection*) can be taken as a conservative value. This value should be greatly higher because the IWIM algorithm only incorrectly sends 0,03% of vehicles that are not overloaded to the static scale, compared to the status quo of around 78%.

The split between long-haul and short-haul vehicles can be determined by the ton-km travelled on the road network. Corridor or long-haul travel equates to 49,62% of the ton-km travel [184]. Metropolitan and rural or short-haul travel equates to 50,38% of the ton-km travel on the corridor [184]. This is basically a 50% split between long- and short-haul vehicles. Equation 5.7 indicates the potential reduction in travelling time per km by long-haul vehicles while overloaded before detection. Equation 5.8 indicates the short-haul reduction – which is the same distance due to the split of ton-km travelled on the road network. This is a combined total of 5,298 million km that can potentially be reduced per annum.

$$\begin{aligned}
& \text{Total weighed vehicles} \times \text{increased detection} \times \text{detection distance} \\
& = 1,79 \text{ million} \times 2\% \times 74 \text{ km} \\
& = 2,65 \text{ million km}
\end{aligned} \tag{5.7}$$

$$\begin{aligned}
& \text{Total weighed vehicles} \times \text{increased detection} \times \text{detection distance} \\
& = 1,79 \text{ million} \times 2\% \times 74 \text{ km} \\
& = 2,65 \text{ million km}
\end{aligned} \tag{5.8}$$

The cost of maintaining the road infrastructure is also expected to decrease with the potential increased detection of overloaded vehicles. The average maintenance cost per annum is currently ZAR 7 260 million. A reduction of 2%, based on the increased detection, will reduce this by ZAR 145 million per annum.

Insight into fleet sizes is required to determine the benefit to transporters. The fleets owned by short-haul operators in South Africa range quite radically in size between 16 and 198 vehicles [185,186]. Using the lowest figure would set the conservative value for a short-haul fleet to 16 vehicles (*fleet size short-haul*). The long-haul operators in South Africa also differ quite radically, from having 41 vehicles in the fleet all the way to in excess of 1000 vehicles [186–193]. Using the lowest figure would also set a conservative figure of 41 vehicles in the fleet (*fleet size long-haul*).

The savings to transporters are indicated in equation 5.9. This includes savings on fuel and tyre wear, based on previous research, engendered by a reduction of TCC visits by only 12 trips per vehicle per year – one a month at a very conservative rate – for a fleet of 41 vehicles, which equates to ZAR 1 516 560 per annum [31,194].

$$\begin{aligned}
& \text{Long-haul trips per year} \times \text{static scale weighs reduced} \times \text{cost saved per visit} \times \\
& \text{fleet size} \times \text{USD to ZAR exchange rate} \\
& = 12 \times 2,4 \times \text{USD } 85 \times 41 \times \text{ZAR } 15,11 \\
& = \text{ZAR } 1\,516\,560
\end{aligned} \tag{5.9}$$

Extrapolating these figures for the entire South African fleet provides a broader view

of the impact. There are an estimated 49 881 heavy vehicles in South Africa, based on the loads transported and vehicles required to provide this transport, and vehicle population statistics from the RTMS appears to be in line with this estimation [195,196]. Travel on freight corridors equates to 49,62% of vehicles [184]. The calculation is completed on the same terms as for a single transporter in equation 5.10.

$$\begin{aligned}
 & \text{Trips per year} \times \text{static scale weighs reduced} \times \text{cost saved per visit} \times \\
 & \text{vehicles} \times \text{percentage on corridor} \times \text{USD to ZAR exchange rate} \\
 & = 12 \times 2,4 \times \text{USD } 85 \times 49\,881 \times 49,62\% \times \text{ZAR } 15,11 \\
 & = \text{ZAR } 915\,519\,901
 \end{aligned} \tag{5.10}$$

The Road Traffic Management Corporation (RTMC) indicated that there were 11 144 fatal crashes in 2015 [197]. A conservative estimation of a 2% reduction in road deaths due to a 2% increased detection of overloaded vehicles could be realised. This is a total reduction of 222 deaths per annum, which equates to ZAR 2,65 billion, as indicated in 5.11.

$$\begin{aligned}
 & \text{Cost per life} \times 222 \\
 & = \text{ZAR } 11,95 \text{ million} \times 222 \\
 & = \text{ZAR } 2,65 \text{ billion}
 \end{aligned} \tag{5.11}$$

The reduction in trip time is extremely short when considering one instance. However, comparing the long-haul total to the daily GDP cost indicates a benefit of ZAR 92,293 million because of the reduction in daily delays [31]. This is indicated in equation 5.12.

$$\begin{aligned}
 & \text{Transportation GDP day cost} \times \text{Long-haul } \% \times \\
 & \text{trip savings} \times \text{trips day saved} \\
 & = \text{ZAR } 6,2 \text{ billion} \times 49,62\% \times 0,03 \\
 & = \text{ZAR } 92,293 \text{ million}
 \end{aligned} \tag{5.12}$$

5.3 Techno-economic analysis

The techno-economic analysis indicates the system implementation cost versus the benefit it will generate when taking the assumptions into account. The system proposed in Section 3.6.4 is the basis for the hardware included in the system implementation cost analysis.

5.3.1 System implementation cost analysis

The hardware and software are site-specific requirements and server-side requirements. The site requires ANPR and RFID readers to be installed with the relevant civil, electrical, and network infrastructure. A site-side computer is required to receive and manage data for the IWIM algorithm implementation. Site installation and specific site costs are indicated in Table 5.4, with equipment installation including any civil construction work, electrical installation, and communication infrastructure. Computer equipment for the TCC is indicated, as well as the site integration costs, because each TCC owner will require specific integration. Each TCC installation is calculated at ZAR 720 000 and the satellite site installations are estimated at half the cost due to their being fairly close to a full TCC.

The current TCC numbers were discussed in Section 2.2.1 and a roll-out to the current 19 TCCs and 16 satellite TCCs would be just below ZAR 19,44 million, with an estimated development cost of ZAR 750 000 [43, 45, 46].

Considerations for running the system annually must first consider the team required to run the system, taking into account what the market-related salaries will be. The salary used in calculations is based on the median salary on *Payscale for South Africa*. Table 5.2 indicates the planned composition of staff members able to run the system, with a 30% operational cost included that equates to ZAR 10,2 million per annum, based on the median salary of the position indicated on Payscale. Table 5.3 indicates the staff and operational cost based on the maximum salary of Payscale and equates to

ZAR 18,37 million per annum. A 2-member team, consisting of a field engineer and a senior engineering technician, should be deployed in each province of South Africa, thus equating to 9 teams.

Annual maintenance is calculated at 20% of the installation cost and is just below ZAR 4 million, giving a total running cost per annum of ZAR 14,2 million per annum for the median salary scale and ZAR 22,37 million on the maximum salary scale, with maintenance costs.

Table 5.2: Staff and operation costs for median salary [198–203]

Job description	Number	Median salary	Cost
Senior software engineer	1	R 641 000	R 641 000,00
Business Intelligence (BI) Developer	1	R 382 000	R 382 000
Data scientist	1	R 408 000	R 408 000
Field engineer	9	R 254 000	R 2 286 000
Senior Engineering Technician	9	R 417 000	R 3 753 000
Operations manager	1	R 363 000	R 363 000
		Total	R 7 833 000
		Operation cost (30%)	R 2 349 900
		Total	R 10 182 900

Table 5.3: Staff and operation costs for maximum salary [198–203]

Job description	Amount	Maximum salary	Cost
Senior software engineer	1	R 943 000	R 943 000
Business Intelligence (BI) Developer	1	R 680 000	R 680 000
Data Scientist	1	R 710 000	R 710 000

Job description	Amount	Maximum salary	Cost
Field engineer	9	R 552 000	R 4 968 000
Senior Engineering Technician	9	R 673 000	R 6 057 000
Operations Manager	1	R 771 000	R 771 000
Total			R 14 129 000
Operation cost (30%)			R 4 238 700
Total			R 18 367 700

Server-side hardware will be required to have a slightly higher specification than the site computer. The cost should be around ZAR 200 000. Development will be required for implementation and is calculated at ZAR 750 000, with an annual maintenance cost also calculated at 20%, equating to a cost of ZAR 150 000.

The total estimated cost of deployment is just over ZAR 20 million and annual maintenance cost for a 10-year life span is estimated at just below ZAR 41 million.

Capital outlay for the current TCC sites, development, and maintenance costs, with a self-managed server farm, is itemised in Table 5.4 below.

Table 5.4: Breakdown of capital outlay

ITEMISED CAPITAL OUTLAY	
Traffic Control Centres	
Number of TCCs	19
Number of satellite TCCs	16
Cost of equipment per TCC	R 500 000
Cost of computer equipment per TCC	R 100 000
Site integration	R 120 000
Total capital outlay per TCC	R 720 000
Total cost of TCC site roll out	R 19 440 000

ITEMISED CAPITAL OUTLAY	
Annual maintenance (20% of total roll out cost)	R 3 888 000
Development cost	
Interface development	R 250 000
Application server development	R 250 000
Reporting services	R 250 000
Total development cost	R 750 000
Software annual maintenance (20% of development cost)	R 150 000
Server side	
Central computer equipment	R 200 000
Annual power and internet server connectivity	R 40 000
Total cost deployment with own hardware and development	R 20 390 000
Maintenance costs over 10 years	R 40 780 000

Consideration of cost increases to existing operations need to be taken into account. Operational costs were obtained from a toll concessionaire to determine the increase to annual operational costs. The average operational cost per annum for a single TCC is ZAR 10 807 100, excluding VAT. Capital outlay per station is calculated at ZAR 720 000, which is 6,7% of the annual operational cost. Annual system maintenance and software maintenance with internet connectivity equates to ZAR 151 037 per station, which will contribute an increase in operational costs of 1,4% per annum.

5.3.2 Return on Investment

The benefits quantified are compared to the hardware implementation to demonstrate that the technology implemented is economical and has a good return on investment (ROI).

Installation in 19 TCCs and 16 satellite TCCs, with server implementation, will cost just

under ZAR 20,4 million, with around ZAR 14,2 million in annual staff, operations, and maintenance costs for a median salary scale and ZAR 22,337 million on the maximum salary scale. The first year's cost will therefore be ZAR 34,6 million.

The cost of the lives lost was calculated in equation 5.11. The implementation cost is 1,3% of the estimated value of lives saved, for an estimated 2% reduction of lives lost in heavy vehicle crashes (equation 5.13).

$$\begin{aligned}
 & \frac{\text{System cost}}{\text{Loss of life cost}} \\
 &= \frac{34,6 \text{ million}}{2,65 \text{ billion}} \\
 &= 1,3\%
 \end{aligned} \tag{5.13}$$

The question arises, however, of who should cover the implementation costs. The fact that several stakeholders benefit from the implementation of the system gives several possible entities motivation to drive it. A series of fleet operators could cover the cost, as indicated in equation 5.14. This means that just over 22,81 (rounded up to 23) fleet operators with 41 vehicles can cover the initial investment out of the benefits they receive. This is a conservative benefit as it only allows for the heavy vehicles' doing one trip per month.

$$\begin{aligned}
 & \frac{\text{System cost}}{\text{Financial benefit for transporters}} \\
 &= \frac{34,6 \text{ million}}{1\,516\,560} \\
 &= 23 \text{ operators} \\
 &= 23 \times 41 = 943 \text{ heavy vehicles}
 \end{aligned} \tag{5.14}$$

National Treasury is by far the stakeholder that will gain the best benefit, with ZAR 145 million per annum less potential maintenance to the road infrastructure. This is equal to 23,86% of the input cost indicated in equation 5.15.

$$\begin{aligned}
 & \frac{\text{System cost}}{\text{Financial benefit for Treasury}} \\
 &= \frac{34,6 \text{ million}}{145 \text{ million}} \\
 &= 23,86\%
 \end{aligned}
 \tag{5.15}$$

5.4 Conclusion

The chapter ascertained the financial gains from implementing the IWIM algorithm. Conservative assumptions were made so as not to over-estimate the impact. This conservative approach nevertheless indicated that the financial benefits are greater than the implementation costs of the hardware and integration.

Reducing fatal crashes by 222 lives will have an estimated financial benefit of ZAR 2,65 billion, while the hardware and operational staff is estimated at only ZAR 34,6 million. Transporters' reduction in trips may only require 943 vehicles that do one trip a month. A reduction of 2% on annual maintenance costs should yield a benefit of around ZAR 145 million per annum from implementation of the IWIM algorithm. Realisation of this benefit will increase operational cost of each TCC with 1,4% per annum towards system maintenance costs.

Chapter 6

Conclusion

Re-imagine, innovate, disrupt - Anonymous

In this chapter, the thesis and its contributions are summarised and conclusions are drawn from the results. It is also indicated if the research questions were satisfactorily addressed, and the contributions to existing literature are outlined.

6.1 Summary of the thesis

It is clear that international and regional trade are essential to increase economic growth. Logistic operations are one of the keys to facilitating this trade in the global and local regions. The economic hubs in the SADC region are mostly landlocked, ensuring that cargo that has to be delivered to and from ports has to make use of road or rail transport to reach its final destination. Rail infrastructure has, however, declined in the past decades, so that 79% of cargo is transported by road.

Road infrastructure therefore plays an essential role in facilitating road transport and empowering the region to trade. This road infrastructure is an asset whose value is estimated to be in the range of ZAR 1 trillion. The fact that it is so important for economic growth has given rise to a drive to protect the asset by means of TCCs on transport corridors. These stations are generally linked with WIM scales to quickly determine whether a vehicle is within permissible load limits while in motion. The WIM scales are inherently inaccurate but are used to determine whether a vehicle should be directed to a static scale for more accurate weighing.

Strict legislation is in place to determine what constitutes an overloaded vehicle. This dictates the permissible limits of loads on driving axles and axles, and AVCM in the South African context. A driver or owner of an overloaded vehicle is liable to a fine, or is arrested in severe cases. SANRAL annual reports indicate that between 21,95% and 24,91% of vehicles were overloaded in the past four years, that an average of 1,86% were charged, and that only 0,10% of drivers were arrested due to excessive overloading. Payment recovered from fines is low, at an average of 21,79% over the past few years.

The stakeholders who have some form of interest in the overload control value chain include cargo owners, transporters, clients, road agencies, treasury, road users and toll concessionaires. The impact of inefficient overload controls ranges from delays experienced to increased vehicle maintenance costs and to excessive road infrastructure maintenance costs.

The small fraction of statically weighed vehicles that are overloaded indicates inherent inefficiencies in the system. Increased efficiency will benefit the entire supply chain and its stakeholders. Investigating the current status quo operations at the TCCs is essential to determine the cause of the inefficiencies and gain a clear understanding of the overload control operations to protect the road infrastructure.

This investigation gave rise to a pilot study in cooperation with SANRAL. The study was conducted on the portion of the North-South corridor from Durban, South Africa, up towards Beitbridge border post. The sites selected for study were Mantsole TCC on the N1 and Heidelberg TCC on the N3. These sites were selected because they are in sequence on the corridor and will logically weigh the same vehicles that travel on the entire corridor.

Status quo operations were inspected on site and indicated in Chapter 3. The collection and analysis of data on current operations ensured a complete indication of the inefficiencies within the process. A 72% accurate link could be obtained from ANPR data between static scale and WIM measurements. The system has a confidence factor of the ANPR measurements that averages 69%. Average time between WIM and static scale measurements is currently 15 minutes. This is a delay that can largely be avoided when considering that around 78% of weighed vehicles are not overloaded.

It became clear that several reweighs on the same trip occur for vehicles loaded close to legal permissible mass due to the inaccuracy of the WIM scale. This causes significant delays because queuing time at the stations can be extensive. In severe cases, vehicles need to bypass the station as there is no space in the queuing lane. These bypassing vehicles may be overloaded and are not weighed and captured early in their trips. There is also segregation of data between the stations, with no data sharing between them.

These drawbacks in the current operation raised the need to improve its efficiency. The improvement proposed was to design and implement an IWIM algorithm. The first stage was to alter some of the system flows in the status quo operations and design a hardware system to support the system deployment, as discussed in Chapter 3. This

proposal included data sharing between stations, with potential RFID deployment to increase the accuracy of vehicle detection between the WIM and static scale.

The algorithm design and analysis were described in Chapter 4. During 2021 data was collected between sites and consolidated for north- and southbound traffic at the selected sites of Mantsole and Heidelberg in 2021. The IWIM design requires overlapping the relevant data and this could be achieved for 2021-04-01 to 2021-08-31. The purpose of the algorithm is to determine, with the shared data, whether the vehicle should be statically weighed or not. Accurate linking was done between the sites to construct the data set for training algorithms that could be applied to distinguish between overloaded and non-overloaded vehicles. The data set included previous WIM and static scale data from the TCCs, travel time to the following TCC, with WIM mass and the overloaded outcome. This data set was used as input for several AI and ANN models. A reduction in the percentage of non overloaded vehicle weighed statically is realised, from a 76,64% average (when applying simple rules to only the local WIM data) to 0,03% when making use of the random forest tree AI model, applied to data from both TCCs. This provides evidence that the system proposed in Chapter 3 will be beneficial if supplied with accurate linked data.

This thesis demonstrated that, in cases of limited available measured data, additional data can be generated for model training and testing through simulation. We used data consolidated between the north- and southbound traffic of Mantsole and Heidelberg TCCs as base to construct a statistical model that represents typical industry overload behaviour. A simulation data set, including additional noise to represent unpredictable field behaviour, was therefore constructed. Statistics collected from the available measured data were used as basis to ensure correct probabilities and ranges were present in the simulated data set. This simulation data set was used as input for several AI models and ANN construction.

Quantification of the impact on the stakeholders was discussed in Chapter 5. The ROI from the system implementation compared to the benefit to the stakeholders was included. The benefits range from time saved at TCCs to reduction in maintenance

costs, and from a potential reduction in loss of life to a potentially higher overloaded capture rate. These benefits were quantified by taking industry costs into consideration, with literature based figures as input. These values were specifically chosen to be conservative, to indicate that a small impact can be beneficial to the stakeholders.

The assumption was made that additional overloaded vehicles will be captured because there will be less traffic at the TCC due to the deployment of the IWIM algorithm. It was assumed that 2% of the total number of vehicles weighed currently bypasses the TCC and will now be statically weighed and found to be overloaded. The result of combining these figures with the potential travelling distance before they are found to be overloaded was used to determine the reduction in maintenance costs. The figure equated to a reduction of ZAR 145 million in maintenance costs, whereas the system implementation and staff cost is around ZAR 34,6 million. The ROI was found by analysing this information. The system is feasible, with far fewer vehicles being overloaded, even though the figures made were conservative.

6.2 Contributions

Contribution 1

Contribution 1 was addressed in Chapter 4, with the development and testing of an IWIM by means of the AI random forest model. Its performance was analysed against multiple measured, simulation and noise simulation data sets. The deployment of the algorithm indicates a large reduction in the number of vehicles being weighed statically that are not overloaded. This reduction with the implementation of the random forest tree model is expected to be from the current 76,64% average of overloaded vehicles sent incorrectly to the static scale to 0,03%.

Contribution 2

Contribution 2 was addressed in Chapter 5, with the elucidation of the economic benefits for several stakeholders that may arise from the IWIM implementation. These benefits are significant even while taking conservative assumptions into account.

Contribution 3

Contribution 3 was addressed in Chapter 3, where a hardware solution was proposed to implement business flow changes in the status quo by implementing the IWIM algorithm.

6.3 Recommended future work

The first recommendation is to implement the hardware and business process on the test site for higher integrity in data linking. A pilot study should collect data for three months and the model should be re-assessed to ensure its accuracy is relevant. This will also ensure that the model can be trained on a much larger real-world data set compared to the training set constructed from the limited volume of currently available data. It is believed that the accuracy will be improved further and in turn further reduce the vehicles being statically weighed even though they are not overloaded.

The second recommendation is to implement unsupervised AI training techniques to minimise the intervention required for repeated training of the model. This will also ease the inclusion of additional data inputs, such as from global positioning system (GPS), with minimal effort as labels and categories are not required during the training process.

The third recommendation is to investigate the feasibility of GPS-based tracking and tolling on secondary roads because the current TCCs primarily focus on national roads. There is significant road deterioration taking place, with overloaded vehicles choosing

to travel on secondary roads. The roads are not designed to take this burden and GPS-based tolling may ensure finances are funnelled to the correct region to maintain the road infrastructure in those areas.

The fourth recommendation is to test auto machine learning models' performance for the industry [204]. Implementing this recommendation would make use of automatic model testing to produce the best performing model, where the current supervised learning techniques implemented require multiple iterations of testing, as well as parameter tuning. This should significantly reduce model development in the training phase of the models.

The fifth recommendation is to include voluntary information disclosed by a company to serve as inputs for the algorithm. WIM information from a companies scale can be linked to the vehicle and RFID tag to have input prior to trip departure. This measurement data can be matched with the first TCC visit to determine accuracy. An accurate measurement of a company may potentially serve as a pseudo TCC to be used with the IWIM algorithm. This measurement is already a mandatory procedure in some international companies and could increase the likelihood of overload detection prior to a vehicle travelling on the corridor. Testing of the provided WIM weights requires one to take into account whether the weighing scales have been calibrated and to what extent. Vehicle configuration should also be captured to have prior knowledge to take into account when evaluating weight data that is captured for vehicles in transit.

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Appendix A

NATIONAL ROAD TRAFFIC ACT 93 OF 1996 - overload control extract [79]

NATIONAL ROAD TRAFFIC ACT 93 OF 1996 - extract

234. Permissible maximum axle massload of vehicle

(1) No person shall operate on a public road a minibus, bus, tractor or goods vehicle if the permissible maximum axle massload of such vehicle is exceeded.

(2) The permissible maximum axle massload of a vehicle shall be the least of the mass limits determined by—

- (a) regulation 238 (1) in respect of a vehicle fitted with pneumatic tyres or regulation 238 (2) and 243 in respect of a vehicle fitted with tyres other than pneumatic tyres;
- (b) regulation 239 (1) (a) (ii); and
- (c) regulation 240 (a), (b) and (c).

235. Permissible maximum axle unit massload of vehicle

(1) No person shall operate on a public road a minibus, bus, tractor or goods vehicle if the permissible maximum axle unit massload of such vehicle is exceeded.

(2) The permissible maximum axle unit massload of a vehicle shall be the least of the mass limits determined by—

- (a) regulation 238 (1) in respect of a vehicle fitted with pneumatic tyres or regulation 238 (2) and 243 in respect of a vehicle fitted with tyres other than pneumatic tyres;
- (b) regulation 239 (1) (a) (iii); and
- (c) regulation 240 (d), (e), (f) and (g).

236. Permissible maximum vehicle mass

(1) No person shall operate on a public road a minibus, bus, tractor or goods vehicle if the permissible maximum vehicle mass of such vehicle is exceeded.

(2) The permissible maximum vehicle mass of a vehicle shall be the least of the mass limits determined by—

- (a) the sum of all the permissible maximum axle massloads and axle unit massloads of the vehicle as contemplated in regulations 234 and 235;
- (b) regulation 239 (1) (a) (i);
- (c) regulation 239 (2);
- (d) regulation 239 (3); and
- (e) regulation 241:

Provided that the permissible maximum vehicle mass of such vehicle shall not exceed 56 000 kilograms.

237. Permissible maximum combination mass

(1) No person shall operate on a public road a combination of vehicles where the drawing vehicle is a minibus, bus, tractor or goods vehicle, if the permissible maximum combination mass of such combination is exceeded.

(2) The permissible maximum combination mass of a combination of vehicles shall be the

least of the mass limits determined by—

- (a) the sum of all the permissible maximum axle massloads and axle unit massloads of the combination of vehicles as contemplated in regulations 234 and 235;
- (b) regulation 239 (1) (b);
- (c) regulation 239 (2);
- (d) regulation 239 (3); and
- (e) regulation 241:

Provided that the permissible maximum combination mass of such combination shall not exceed 56 000 kilograms.

238. Load on tyres

(1) No person shall operate on a public road a motor vehicle—

- (a) which is fitted with pneumatic tyres, where any wheel massload is in excess of the wheel massload referred to in the appropriate part of the standard specification SABS 1550 “Motor Vehicle Tyres and Rims: Dimensions and Loads”, Part 1: “General”, Part 2: “Passenger car tyres”, and Part 3: “Commercial vehicle tyres”; or
- (b) where any pneumatic tyre is not mentioned in the standard specification referred to in paragraph (a), where the wheel massload is in excess of the wheel massload approved by the manufacturer of the tyre concerned:

Provided that for the purposes of determining the pressure in a tyre the temperature of the tyre shall be disregarded.

(2) No person shall operate on a public road any vehicle fitted with tyres, other than pneumatic tyres, if the wheel massload exceeds eight kilograms per one millimetre width of any such tyre.

239. Gross vehicle mass, gross axle massload, gross axle unit massload, gross combination mass, power to mass ratio and axle massload of driving axle to total mass ratio not to be exceeded

(1) No person shall operate on a public road a minibus, bus, tractor or goods vehicle—

- (a) if—
 - (i) the gross vehicle mass;
 - (ii) any gross axle massload; or
 - (iii) any gross axle unit massload,is exceeded;
- (b) drawing any other motor vehicle if the gross combination mass is exceeded.

(2) No person shall operate on a public road a vehicle which is a minibus, bus, tractor or goods vehicle if the mass in kilograms of such vehicle or of a combination of vehicles of which such first-mentioned vehicle forms a part, whether laden or unladen, exceeds a figure arrived at by multiplying the net power in kilowatts of the engine of such vehicle as determined in accordance with or calculated with due regard to code of practice SABS 013 “The determination of performance (at net power) of internal combustion engines”—

- (a) in the case of the drawing vehicle being a tractor by 400; or
- (b) in the case of any other vehicle by 240.

(3) No person shall operate on a public road a vehicle which is a minibus, bus, tractor or goods vehicle if the mass in kilograms of such vehicle or of a combination of vehicles of which such first-mentioned vehicle forms a part, whether laden or unladen, exceeds five times the total axle massload of the driving axle or axles of such vehicle.

240. Massload carrying capacity of road

No person shall operate on a public road a motor vehicle or a combination of motor vehicles, the wheels of which are fitted with pneumatic tyres, if—

- (a) the wheel massload of wheels—
 - (i) which are fitted to a steering axle, exceeds 3 850 kilograms; or
 - (ii) which are fitted to axles other than a steering axle, exceeds 4 000 kilograms;
- (b) the axle massload of an axle fitted with two or three wheels and—
 - (i) which is a steering axle, exceeds 7 700 kilograms; or
 - (ii) which is an axle other than a steering axle, exceeds 8 000 kilograms;
- (c) the axle massload of an axle fitted with four wheels and—
 - (i) which is fitted to a vehicle designed to compact refuse and which is carrying such refuse, exceeds 10 200 kilograms;
 - (ii) which is fitted to a breakdown vehicle, exceeds 10 200 kilograms;
 - (iii) which is placed in the rear or middle of a bus-train, exceeds 10 200 kilograms;
 Provided that in the case of a rapid transport bus-train the limit on the drive axle shall be 13 000 kilograms and on the other non-steering axle shall be 13 000 kilograms.
 [Proviso inserted by r. 13 (a) of GNR.359 of 12 May 2010.]
 - (iv) which is fitted to a bus, other than a bus-train, exceeds 10 200 kilograms; or
 Provided that in the case of a rapid transport complementary bus, or a rapid transport trunk bus, this limit shall be 12 000 kilograms.
 [Proviso inserted by r. 13 (b) of GNR.359 of 12 May 2010.]
 - (v) which is not mentioned in items (i) to (iv), exceeds 9 000 kilograms;
- (d) the axle massload of an axle unit which consists of two axles, each of which are fitted with two or three wheels, and—
 - (i) which is a steering axle unit, exceeds 15 400 kilograms; or
 - (ii) which is an axle unit other than a steering axle unit, exceeds 16 000 kilograms;
- (e) the axle massload of an axle unit which consists of two axles, each of which are fitted with four wheels, and—
 - (i) which is fitted to a vehicle, except a trailer, designed to compact refuse and which is carrying such refuse, exceeds 20 400 kilograms;
 [Sub-par. (i) amended by r. 45, GNR. 2116 w.e.f. 5 October 2001.]
 - (ii) which is fitted to a breakdown vehicle, exceeds 20 400 kilograms; or
 - (iii) which is not mentioned in items (i) and (ii), exceeds 18 000 kilograms;
- (f) the axle massload of an axle unit which consists of three or more axles, each of which

are fitted with two or three wheels, and—

- (i) which is a steering axle unit, exceeds 23 100 kilograms;
 - (ii) which is an axle unit other than a steering axle unit, exceeds 24 000 kilograms; or
 - (g) The axle mass load of an axle unit which consists of two axles, one of which is a drive axle with four wheels and the other is an axle with two wheels, and which is fitted to a rapid transport bus, if the sum of the two axle mass loads exceeds 18 200 kilograms.
- Provided that the limitations on steering axles and steering axle-units in paragraph (a), (b), (d) and (f) above, do not apply to any axle or axle-units which assist in reducing the turning circle of a rapid transport bus or rapid transport bus-train, but which is not the front axle or front axle-unit.

[Proviso inserted by r. 13 (d) of GNR.359 of 12 May 2010.]

[Para. (g) substituted by r. 13 (c) of GNR.359 of 12 May 2010.]

241. Massload carrying capacity of bridges

(1) No person shall operate on a public road a vehicle or combination of vehicles, the wheels of which are fitted with pneumatic tyres, if the total axle massload of any group of axles of such vehicle or combination of vehicles exceeds the mass in kilograms determined by multiplying the dimension of such group measured as referred to in subregulation (3) by 2 100 and adding 18 000.

(2) A group of axles referred to in subregulation (1) may comprise any series of axles, but shall not consist of one axle unit referred to in regulation 240 (d), (e), (f) or (g) alone.

(3) (a) The dimension referred to in subregulation (1) shall be measured in metres and tenths of a metre from the centre of the first axle of any group of axles to the centre of the last axle of such group.

(b) If the dimension so measured is not a definite figure in metres and tenths of a metre, the next highest number in tenths of a metre with which the dimension so measured is exceeded shall be used for the calculation referred to in subregulation (1).

(c) Where a group of axles of a combination of vehicles is measured, the vehicles of such combination shall be positioned in line and both sides of such combination of vehicles shall be measured, and if the dimensions of the two sides differ, the longer dimension shall be used for the calculation referred to in subregulation (1).

242. Distribution of axle massload and wheel massload on vehicle fitted with pneumatic tyres

Notwithstanding the provisions of regulation 240, no person shall operate on a public road a motor vehicle which is fitted with pneumatic tyres if—

- (a) on any axle with—
 - (i) two tyres, the wheel massload on one tyre exceeds the wheel massload on the other tyre by more than 10 percent; or
 - (ii) four tyres, the wheel massload on two tyres nearest to each other exceeds the wheel massload on the other two tyres by more than 10 percent;
- (b) in the case of a combination of motor vehicles consisting of a truck-tractor and at least one semi-trailer, the axle massload of any steering axle or the sum of the axle massloads of any steering axle unit is less than 11 percent of the sum of all axle massloads of the truck-tractor and the first semi-trailer that is coupled to the

truck-tractor, of the said combination of motor vehicles;

[Par. (b) substituted by r. 46, GNR. 2116 w.e.f. 5 October 2001.]

- (c) in the case of a motor vehicle, not being a combination of motor vehicles as referred to in paragraph (b), with a steering axle unit, the sum of the axle massloads of such steering axle unit is less than 30 percent of the sum of all axle massloads of such vehicle; or

Provided that in the case of a rapid transport bus-train no limit shall apply;

[Proviso inserted by r. 14 of GNR.359 of 12 May 2010.]

[Para. (c) substituted by r. 46 of GNR.2116 of 5 October 2001 and amended by r. 14 of GNR.359 of 12 May 2010.]

- (d) in the case of any other vehicle the axle massload of a steering axle is less than 20 percent of the sum of all axle massloads of such vehicle, except in the case of a tractor when the axle massload of the steering axle shall not be less than 12 percent of the sum of all the axle massloads of such tractor.

243. Axle massload of vehicles fitted with tyres other than pneumatic tyres

No person shall operate on a public road a vehicle fitted—

- (a) with metal tyres, if any axle massload of such vehicle exceeds 2 700 kilograms; or
- (b) with tyres, other than pneumatic or metal tyres, if any axle massload or the sum of all axle massloads of such vehicle exceeds 50 percent of that permitted for vehicles fitted with pneumatic tyres in terms of regulation 240 or, if the axle massload of any steering axle of such vehicle does not comply with the requirements of paragraphs (b), (c) or (d) of regulation 242.

Appendix B: Relevant published articles

Published articles peer review articles

Author

- SATNAC 2014: Freight tracking cost analysis to improve logistics management operations [205].
- ITSC 2014: Overload control centre bypass detection system (extended abstract) [75].
- SATC 2016: Proposed alternative to assist current overload operations in South Africa [206].

Co-Author

- ITSC 2014 (co-author): An intelligent freight corridor overload control system [31].
- ITSC 2014 (co-author): A simulation strategy to optimize the design of internet enabled logistics services [57].
- Journal of transport and supply chain management: Impact of a radio-frequency identification system and information interchange on clearance processes for cargo at border posts [56].
- (*Submitted article*) Traffic Control Centre optimisation on South African freight corridors through intelligent weigh-in-motion.

Freight tracking cost analysis to improve logistics management operations

A de Coning and AJ Hoffman

School of Electrical, Electronic and Computer Engineering

North-West University, Potchefstroom Campus, South Africa

Tel: +27 18 299 1971, Fax: 086 521 2569

Email: {20270186, alwyn.hoffman}@nwu.ac.za

Abstract—The cross-border freight industry suffers from inefficiencies that can be addressed by implementing technology based systems. Inefficiencies cause time delays at amongst others border posts and weigh stations that in turn increase turnaround times. Higher turnaround times affect the business bottom line as it reduces the turnover generated on capital assets and therefore decrease profit levels. Efficient logistics management will also ensure increased trade in Sub Saharan Africa which will ensure economic growth in the region. GPS tracking systems deployed on fleets of freight vehicles are currently focused on vehicle theft recovery and communication with the units is typically suspended once a national border is crossed to avoid roaming costs. This article proposes a mind shift towards the increased use of cross-border communication with freight vehicles in order to use GPS tracking and other telemetry data available from vehicles to enable improved logistics management. The article will analyse GSM and satellite communication costs and compare these costs with the potential financial benefits to be gained from the use of more frequent communications. Our analysis has shown that the use of telemetry data for logistics management offers the potential to increase profits by up to R400,000 per vehicle over its lifetime. Careful selection of the most suitable networks is however essential to achieve a positive cost-benefit ratio.

Index Terms—Freight logistics, Freight, Road freight, Cross-border, Logistics management

I. INTRODUCTION

Supply chain efficiency can greatly increase or decrease the financial turn over and profitability of a freight business [1]. This efficiency can be increased by incorporating proactive supply chain management systems into business operations [2]. Implementing intelligent transport systems (ITS) that have a focus of logistics can result in higher efficiency and productivity in the supply chain [3]. These systems are highly dependent on information from the daily supply chain operation. This in turn requires real time information sharing within the supply chain.

The scale of supply chain operations, specifically freight transport which is the focus point in this study, is on the increase in Sub Saharan Africa [4]. The use of technology within this industry for tracking purposes is not a new concept but has till present been focused on security and vehicle recovery [5]. One of the most common features implemented is global positioning system (GPS) tracking of the freight vehicle. These tracking systems are a necessity for insurance purposes. Unfortunately these services mainly focus on security tracking

with a minimal effort to improve the day to day efficiency of the logistics operation. This has resulted in a situation where tracking companies configure their systems to implement services at minimum costs causing communication with the vehicle to be suspended once it travels across a national border until the vehicle returns to within the local cellular network. Due to the pricing models applicable to roaming under the global system for mobile (GSM) communication, which is the communication option used by most tracking systems, costs increase exponentially when the unit crosses a border and has to switch over to a different network.

The purpose of this paper is to demonstrate that the benefit of utilizing GPS tracking and other types of telemetry data with a focus on logistics management will in most cases outweigh the cost implication associated with cross-border communication. Firstly the transporter, consignor and consignee can benefit from the use of tracking data by generating alarms as soon as an exception has occurred (e.g. when the doors were opened at an unauthorized location) and by sending regular updates about the current status of the consignment (e.g. advanced delivery notifications sent to client sites to allow early preparation at the goods receive depot). In the process unnecessary delays can be eliminated, resulting in decreased delivery times, and decreased turnaround times which in turn will increase revenue. Secondly governmental agencies responsible for inspecting vehicles at overload control stations and border posts can use GPS and other telemetry data received from freight vehicles to reduce the risk levels associated with such vehicles, resulting in reduced inspection frequencies; this in turn will result in reduced border crossing times and weigh station delays [4].

A number of different communication options are available for vehicle telematics units. Several GSM network operators provide coverage into most of Wouthern African Development Community (SADC) and neighbouring countries; the size of data packets that are handled by the different networks are however not identical, and there are significant discrepancies between the rates offered. In the more remote areas GSM coverage is either absent or unreliable, resulting in many transporters opting for satellite communication or a combination of GSM and satellite. The satellite based service are in general more expensive per data packet or monthly subscription, but

covers the area of roaming more reliably; it could hence be expected that a management system using satellite communications into Africa will achieve higher levels of uptime compared to a system that relies on GSM communication only.

The rest of the paper is organized as follows: section II provides a description of the research objectives; section III analyses GSM and section IV satellite communication costs; section V describes a practical case study that compares both GSM and satellite communication costs with the likely benefits from improved logistics operations; section VI concludes with a summary and a description of future work in this field.

II. RESEARCH OBJECTIVES

The following objectives were identified for the research work reported in this paper:

- 1) Identification of potential cost savings to be achieved by use of real time communications in cross-border transport.
- 2) Determining specific communication needs for optimal management of such operations (how often to communicate and how much data to communicate at a time).
- 3) Identification of communication options and the pros and cons of each approach (GSM roaming vs satellite).
- 4) Calculation of realistic costs (capital outlay and running costs) for each communication option.
- 5) Performing an estimated cost-benefit analysis for each communication option and calculating the internal rate of return (IRR) and net present value (NPV) of a telematics system.
- 6) Making recommendations about which option will be superior under which conditions.

III. GSM COST

The GSM data cost analysis is completed by making some key assumptions regarding the nature of GSM services. These assumptions are made to allow a generic cost benefit analysis without going into the details of the features of the specific tracking units (or equivalent systems) that may be installed. The assumptions are as follows:

- The GSM service providers analysed operate on a pre-paid basis given that data bundles cannot be used to roam internationally. This will minimise the risk of unexpected high billing costs when roaming takes place.
- It is assumed that the tracking device can automatically switch to another network of choice without human intervention.
- When another network selection takes place, it is assumed that the cheapest service provider partner is selected. This will ensure the best case scenario is considered for the study.

The analysis is completed for multiple service providers in Southern Africa, given that the analysis is done for vehicles travelling from South Africa into Sub Saharan Africa. These providers include Vodacom, MTN, Cell C, and Telkom mobile. The data cost vary for each service provider and for each



Fig. 1. Freight corridors in Sub Saharan Africa[6]

country. The specific destination countries to which vehicle travel will therefore be of utmost importance.

A. Destination countries

Figure 1 above depicts the geographical representation of the freight corridors in Sub Saharan Africa. The destination countries included in this study are:

- South Africa
- Namibia
- Mozambique
- Zimbabwe
- Botswana
- Zambia
- Malawi
- Democratic Republic of Congo

B. Data packets

The data packet size of each transmission will also greatly affect the data roaming costs. The standard packet of data will include the required information with a GSM header. A typical GPS coordinate data packet will vary between 60 to 70 bytes with a header file of 300 bytes making a total of 370 bytes for one information packet transmission. This will however differ for each service provider as they have a minimum data size that is billed while data roaming. Currently some of the tracking

units can string multiple different data types by making use of one GSM header. This may typically be a GPS coordinate, temperature reading, fuel level, etc.

C. Service provider data cost

The minimum roaming data packets sizes and cost vary significantly between different service providers. These costs will be tabulated for each individual service provider with the cheapest roaming cost taken into account for case study calculations. Vodacom, MTN and Cell C will offer data roaming on pre- paid packages. Telkom mobile on the other hand will only grant data roaming for contract SIM cards.

The minimum data packet size, which will greatly influence the monthly data costs, varies for each service provider. Vodacom has a 10 kB minimum data packet with the message cost as seen in Table I. MTN, Cell C and Telkom each has a minimum data packet of 25 kB. These data cost can be seen in Table 2, Table 3, and Table 4.

TABLE I
VODACOM DATA COST PER COUNTRY [7]

Countries	Vodacom per MB data	Per message cost
Namibia	R 51.10	R 0.50
Mozambique	R 51.10	R 0.50
Zimbabwe	R 51.10	R 0.50
Botswana	R 51.10	R 0.50
Zambia	R 102.40	R 1.00
Malawi	R 102.40	R 1.00

TABLE II
MTN DATA COST PER COUNTRY [8]

Countries	MTN per MB data	Per message cost
Namibia	R 106.50	R 2.60
Mozambique	R 106.50	R 2.60
Zimbabwe	R 106.50	R 2.60
Botswana	R 106.50	R 2.60
Zambia	R 106.50	R 2.60
Malawi	R 106.50	R 2.60

TABLE III
CELL C DATA COST PER COUNTRY [9]

Countries	Cell C per MB data	Per message cost
Namibia	R 21.38	R 0.52
Mozambique	R 104.69	R 2.56
Zimbabwe	R 156.04	R 3.81
Botswana	R 149.49	R 3.65
Zambia	R 20.40	R 0.50
Malawi	R 83.58	R 2.04

The cost per message is calculated by multiplying the cost per Mb with the size of each data packet. Vodacom and Cell C offer the cheapest data cost of R0.50 per message, while MTN and Telkom mobile has a message cost of R2.60 and R2.94 respectively.

TABLE IV
TELKOM MOBILE DATA COST PER COUNTRY [10]

Countries	Telkom Mobile per MB data	Per message cost
Namibia	R 120.27	R 2.94
Mozambique	R 120.27	R 2.94
Zimbabwe	R 120.27	R 2.94
Botswana	R 120.27	R 2.94
Zambia	R 120.27	R 2.94
Malawi	R 120.27	R 2.94

IV. SATELLITE COST

The costs for satellite tracking services will be analysed in the same manner as for the GSM data costs. These costs will be considered for services provided by the two main satellite communication tracking services: Iridium and Inmarsat.

These service providers support communication via satellite for most of the African continent. A redundant GSM communication module is usually in place in a tracking unit for lower cost communication when travelling within South Africa; the unit will automatically switch over to satellite communications once cross-border roaming takes place.

The main difference between the service providers are the satellite constellation configurations that they use. These constellations are either geostationary or in a geosynchronous orbit and this difference in constellation will practically change the uptime of communication. A geostationary orbit will ensure high uptime of the satellite, as it will appear that the satellite is always at the same location [11]. A satellite using a geosynchronous orbit will vary its location as it orbits the earth and may practically have communication loss for several hours with the tracking unit.

A. Service providers

1) *Iridium*: Iridium makes use of geosynchronous orbiting satellites [11]. This will cause brief delays in communication with the satellites travelling in their orbits. Practically this can result in a communication delay of between a few minutes to about two hours. Table 5 below shows a standard monthly cost for Iridium service. The minimum data bundle used is 500 messages at a cost of R377 per month.

TABLE V
IRIDIUM DATA COSTS

Description	Cost (USD)	Cost (ZAR)
500 messages (bundle)	\$ 35.71	R 376.38
Local sim (10 MB data)		R 20.00
17 messages (out of bundle)	\$ 1.07	R 11.28
Cost per message (in bundle)		R 0.75
Cost per message (out of bundle)		R 0.66
USD/Zar exchange	R 10.54	2014-04-22

2) *Inmarsat*: Inmarsat makes use of geostationary orbiting satellites [12]. This will ensure a higher communication uptime during tracking but at a higher cost than Iridium. The 500

message bundle will cost R625 per month as stated in Table 6 below.

TABLE VI
INMARSAT DATA COST

Description	
500 messages (bundle)	R 625.00
10 MB data	(included)
cost per message (in bundle)	R 1.25
cost per message (out of bundle)	R 1.60

V. CASE STUDY

A typical trip across national borders is from Johannesburg (South Africa) to Lusaka (Zambia). The route is shown in Figure 2 and Figure 3. The total distance travelled one way is 1780 km with 457 km in South Africa, 754 km in Botswana, and 569 km in Zambia. Inefficiencies in cross-border trips typically cause 50% of the travel time being lost during a 14 day trip [4].

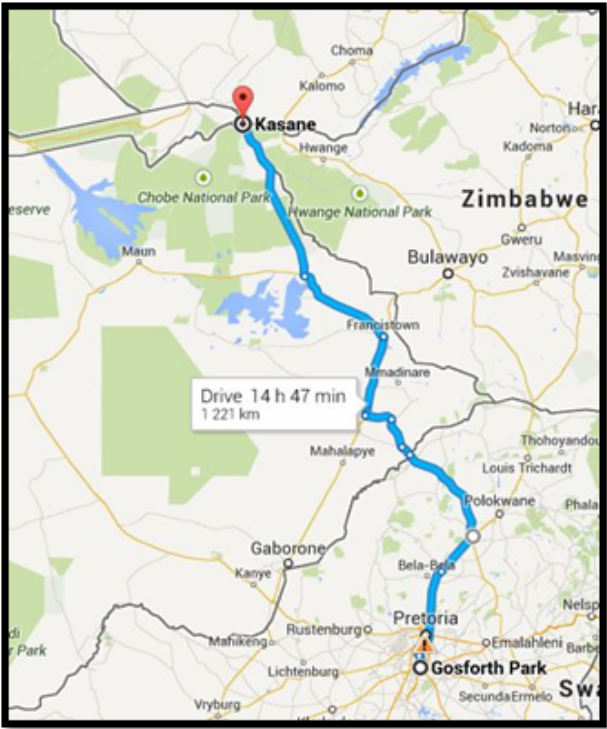


Fig. 2. Case study route part 1 of 2

As stated before various delays during the course of a trip (including border crossing delays, weigh station delays and delays at the destination) can be minimised by making use of regular data transmissions. With lower turn around time, a large monthly profit can be expected due higher utilisation of a trucks trips. If correctly implemented this will ensure a lower turnaround time per trip with an estimated increased

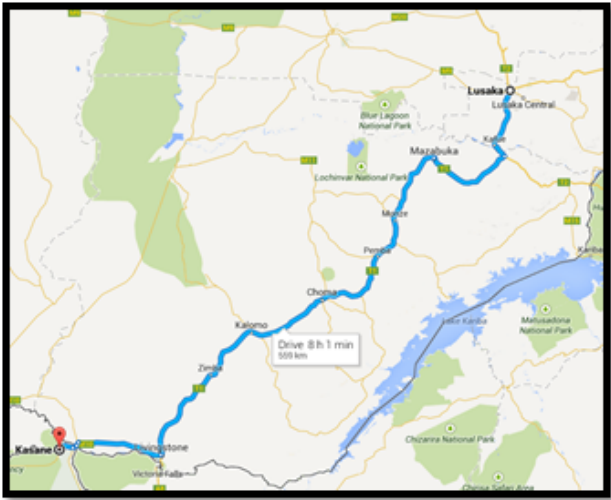


Fig. 3. Case study route part 2 of 2

revenue per month on a truck of at least 10% as previous work stated by Hoffman [4]. For the purpose of the case study we consider 5 scenarios with reductions in turnaround time ranging from 20% (optimistic scenario) to 2.5% (pessimistic scenario). An additional benefit is the increase in exports and imports from South Africa to Sub Saharan Africa [13]; this benefit is however not included in the case study as it is difficult to quantify accurately.

As GSM communication tends to be unreliable in many parts of the region we furthermore use a probability of 50% that GSM communications will be successfully established each time that the device tries to communicate with its home base the expected improvement in turnaround time is moderated by this figure to provide for non-ideal implementation of the relevant logistics management concepts due to non-ideal communications. For satellite systems a figure of 90% is used as the satellite networks cover the subcontinent more effectively compared to cellular networks.

A GSM interval of 5 minutes was chosen for the study. As the satellite communication uptime results in some delay in communication an interval of 10 minutes is used for satellite communication. By combining this with the average cost per message and assuming that a truck is on average travelling 12 hours per day the total messaging cost for each communication option could be calculated.

We assume that the telematics service will be offered at a rate of R300/truck/month, over and above the direct communication cost, that the cost to install the equipment on a truck is R10,000 and that maintenance costs amount to 20% of capital outlay per annum.

The revenue generated by a truck per annum is calculated by using an average trip length of 14 days with R70,000 revenue per trip to arrive at an annual revenue per truck (without using telematics) of R1.46 million. The gross profit margin is taken as 30%. Using the percentage improvements for each of the 5 scenarios we can calculate the increase in gross profits;

TABLE VII
VODACOM IRR AND NPV PROJECT ANALYSIS

Potential % decrease in turnaround time with ideal comms	20.0%	15.0%	10.0%	5.0%	2.5%
Initial capital cost	R -10 000.00	R -10 000.00	R -10 000.00	R -10 000.00	R -10 000.00
Year 1 potential profit increase (Vodacom)	R 31 575.20	R 18 422.04	R 5 961.16	R -5 860.70	R -11 547.16
Year 2 potential profit increase (Vodacom)	R 31 575.20	R 18 422.04	R 5 961.16	R -5 860.70	R -11 547.16
Year 3 potential profit increase (Vodacom)	R 31 575.20	R 18 422.04	R 5 961.16	R -5 860.70	R -11 547.16
Year 4 potential profit increase (Vodacom)	R 31 575.20	R 18 422.04	R 5 961.16	R -5 860.70	R -11 547.16
Year 5 potential profit increase (Vodacom)	R 31 575.20	R 18 422.04	R 5 961.16	R -5 860.70	R -11 547.16
IRR (Vodacom)	315%	183%	52%	0%	0%
Required rate of return	25%	25%	25%	25%	25%
NPV (Vodacom)	R 59 931.64	R 31 633.63	R 4 824.99	R -20 608.85	R -32 842.85

TABLE VIII
IRIDIUM IRR AND NPV PROJECT ANALYSIS

Potential % decrease in turnaround time with ideal comms	20.0%	15.0%	10.0%	5.0%	2.5%
Initial capital cost	R -10 000.00	R -10 000.00	R -10 000.00	R -10 000.00	R -10 000.00
Year 1 potential profit increase (Iridium)	R 81 633.26	R 53 845.30	R 28 805.60	R 6 125.66	R -4 431.24
Year 2 potential profit increase (Iridium)	R 81 633.26	R 53 845.30	R 28 805.60	R 6 125.66	R -4 431.24
Year 3 potential profit increase (Iridium)	R 81 633.26	R 53 845.30	R 28 805.60	R 6 125.66	R -4 431.24
Year 4 potential profit increase (Iridium)	R 81 633.26	R 53 845.30	R 28 805.60	R 6 125.66	R -4 431.24
Year 5 potential profit increase (Iridium)	R 81 633.26	R 53 845.30	R 28 805.60	R 6 125.66	R -4 431.24
IRR (Iridium)	816%	538%	288%	54%	0%
Required rate of return	25%	25%	25%	25%	25%
NPV (Iridium)	R 167 627.75	R 107 844.06	R 53 973.05	R 5 178.89	R -17 533.48

subtracting the overall communication and other system costs per truck per annum allows us to arrive at the change in net profits. The economics used for the calculation can be seen in table IX at the end of the paper.

The feasibility of a project can be determined by making use of internal rate of return (IRR) and the net present value (NPV) of the project over the intended lifetime. These calculations will take into account the initial capital expense and the net annual change in profits. The calculation is performed over the five (5) year life cycle of a truck. A 25% required rate of return is used for a project to be viable for implementation. Inflation will not be considered into the calculations in this article. The IRR and NPV were calculated for each communication options and for each improvement scenario; the best potential options for GSM and satellite will be displayed in tables VII and VIII.

Amongst the cellular services the most attractive figures were obtained for Vodacom and Cell C. Assuming a 20% decrease in truck turnaround time a telematics system using the Vodacom GSM option can potentially have an IRR of 315% and a NPV per truck of just below R60,000. As Cell C currently matches the data cost of Vodacom it will have identical IRR and NPV figures. The GSM communication will still be viable if a 10% decrease in turnaround is realised: A 10% decrease will ensure a IRR of 52% and a NPV just below R5,000. The other GSM operators will not achieve a positive NPV for any of the scenarios using their respective packet costs.

The Iridium satellite communication appear to be more attractive to implement for this application compared to the Inmarsat. A 20% decrease in turnaround time will have a IRR of 816% with a NPV of about R167,000 per truck. The implementation of the Iridium satellite communication will still be viable if the turnaround time can be decreased by just

5%. This will result in a IRR of 54% and a NPV of just above R5,000, whereas the Inmarsat option will result in a negative NPV for this scenario. An additional scenario was considered, but not displayed due to results, for the average GSM cost across the different countries which resulted in a IRR of 0% and a negative NPV.

VI. CONCLUSION

The research has shown that a shift in focus from vehicle security to improved logistics management can significantly improve the turnover and profitability of a cross-border freight operation. Additional costs incurred from implementing a telematics system aimed at a reduction in truck turnaround times can be cost effective when considering the expected profit increases resulting from a reduction in inefficiencies.

The current calculation show that a telematics system using GSM communication based on the Vodacom or Cell C pricing options can produce an IRR of 315% and NPV per truck of about R60,000 if a 20% decrease in travel times can be achieved. Using Iridium satellite communication can potentially result in an IRR of 816% and NPV per truck of R167,000 for the same decrease in truck turnaround times. The Iridium satellite communication implementation will have a lower risk of implementation as it will still be viable if the turnaround time is only decreased by 5%. Implementation of either system can potentially increase gross profits of between R240,000 and R400,000 over the lifetime of a vehicle for the 20% improvement scenario. For a small cross-border fleet that includes typically about 25 vehicles this will ensure an increased net profit of between R750,000 and R1,500,000 per annum.

Future work will be conducted to confirm the communication cost across border by performing practical in field experiments on cross-border vehicles. Currently 6 tracking

units are being tested for this purpose, using a combination of GSM and satellite communication. The tests will also determine what the actual communication interval should be for GSM and satellite. Another aspect to be investigated in more detail is the actual efficiency improvements that will be achieved by a telematics systems that uses effective cross-border communications.

Arno de Coning received his undergraduate engineering degree in 2010 from the North-West University Potchefstroom Campus and his Masters of engineering degree in 2013. He is presently studying towards his PhD degree at the same institution. His research interests include socio economic impact, freight logistics, and operational improvement. **Alwyn J. Hoffman** received his B. Eng. degree in 1985, his M. Eng. degree in 1987 and his Ph.D. degree in 1991 from the University of Pretoria in South Africa. He has been professor in the School of Electrical, Electronic and Computer Engineering at North-West University since 1994. His current research interests include artificial intelligence, RFID and business intelligence.

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TABLE IX
ECONOMIC OF TRIP MANAGEMENT

Length of trip (days)	14
% time travelling	50.00%
Travel time (days)	7
Transmit period GSM (min)	5
Transmit period Satellite (min)	10
Total no of transmissions per month	1008
Cost per transmission Vodacom	R 0.50
Cost per transmission Iridium	R 0.75
Total vehicle turnover per trip	R 70 000.00
Potential % decrease in turnaround time	10%
Potential increase in revenue per trip	R 7 000.00
Cost to install tracking equipment (once off)	R 10 000.00
Life expectancy of equipment (years)	5
Fraction of year truck active	0.8
Number of trips per annum	20.9
Number of trips over lifetime	104.3
Total comms cost over lifetime (Vodacom)	R 52 457.34
Total comms cost over lifetime (Iridium)	R 39 565.42
Maintenance cost p.a. as fraction of capital	20%
Total maintenance cost over lifetime	R 10 000.00
Total operational cost of system per truck over lifetime (Vodacom)	R 72 457.34
Total operational cost of system per truck over lifetime (Iridium)	R 59 565.42
Increase in revenue over lifetime	R 730 000.00
Gross Profit margin	30%
Increase in gross profits	R 219 000.00

Overload Control Centre Bypass Detection System (Extended Abstract)

A de Coning and AJ Hoffman

School of Electrical, Electronic and Computer Engineering
North-West University, Potchefstroom Campus, South Africa

Tel: +27 18 299 1971, Fax: 086 521 2569

Email: {20270186,alwyn.hoffman}@nwu.ac.za

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Abstract—Road transport is a significant economic necessity for freight movement in developing countries. The freight industry has a low profit margin resulting in overloading. As overloaded vehicles cause significant damage to road surfaces, Overload Control Centres (OCCs) are installed on freight corridors to identify and prosecute overloaded vehicles. Unfortunately some vehicles may bypass the OCC on purpose, accidentally or due to law enforcement errors. When an overloaded vehicle bypasses on purpose, severe damage is caused to the road surface. This paper aims to quantify the damage caused in terms of additional maintenance cost due to road wear and proposes a bypass detection system for OCCs. A cost-benefit analysis has shown that the proposed system must detect less than 100 vehicles bypassing in a year to have a positive internal rate of return for implementation.

Index Terms—Overload Control Centres, OCC, Weigh stations, SADC, Freight logistics, Freight, Road freight

I. INTRODUCTION

The growth of a regional economy is highly dependant on trade facilitation within the region. This is also true within the Southern Africa Development Community (SADC). The transport of cargo within SADC is mostly conducted by making use of road corridors. Transport of cargo has a large impact on the road infrastructure. Infrastructure decay is imminent when heavy transport vehicles frequently travel on a corridor [1]. Overloading of vehicles will take place in a competitive market to attempt to increase the bottom line of transporters with little or no regard to the impact caused to infrastructure [2].

Overload Control Centres (OCCs) are implemented on a trade corridor to determine the overloaded state of vehicles and have the responsibility to minimize overload impact on the corridor. Unfortunately governance at the OCCs is unsatisfactory and causes the system to run inefficiently. Slavik has conducted studies showing that overloading has a higher frequency when law enforcement levels fluctuate at OCCs [3]. The deduction can thus be made that, given these inefficiencies present at a OCC, it is likely that some potentially overloaded vehicles will rather bypass the OCC. This paper will propose a bypass detection system to detect freight vehicles that bypass the OCC all together. A cost-benefit analysis will be conducted to determine the potential

benefit of implementation.

II. LITERATURE STUDY

Studies have been conducted to improve the lifetime of road infrastructure and vehicle weight constraints. When these constraints are not correctly regulated, the infrastructure will decay before its intended lifetime. Permissible weight limits are used to prosecute overloaded vehicles at the OCCs. Overloading is detected by making use of Weigh-in-Motion (WIM) and static scales. WIM scales however has a level of uncertainty that vary from 6% to 10% for Gross Vehicle Mass (GVM) [4]. This WIM uncertainty will thus only indicate whether the vehicles is potentially loaded close to the permissible threshold. Axle load studies are frequently conducted to determine actual weight of vehicles travelling on the South African roads. Maintenance will have to be fast tracked when overloaded vehicles travel on these roads. This fast tracked schedule will result in additional funds being required to maintain road infrastructure.

Cross border travel for trade purposes is a common practice in Sub-Saharan Africa freight corridors. On a single trip a vehicle may be travelling on road sections covering in excess of 10 000 km in SADC [5]. This is a significant road surface that will be impacted when a vehicle is overloaded in South Africa travelling to neighbouring countries.

A. Overload control station overview

The OCCs process is designed to inform officers of a potentially overloaded vehicle. The vehicle pass over a WIM and is weighed. Vehicles are automatically classified by the axles configuration [6]. The identification will be linked to a legal threshold for the axle configuration. Once the threshold is triggered the vehicle is directed to a static scale. This station will now determine whether a vehicle and/or axle loads are overloaded.

B. Weigh station overflow and bypass

High volumes of traffic at OCC causes strain on the operation and staff. Multiple systems are implemented to alleviate pressure. Electronic pre screening is used to determine whether a vehicle will need to enter an OCC [7]. This is

used to minimize the vehicles entering the OCC when not needed [8]. South African OCCs have no electronic screening implemented to reduce WIM visits and this occasionally causes a back log so long that a queue forms into the highway [9]. These queues will in some cases force vehicles to bypass the OCC in order to reduce traffic flow on the highway. These bypassing vehicles may in fact be overloaded causing significant damage to the road infrastructure [3], [10].

III. OBJECTIVES OF INTELLIGENT CORRIDOR OVERLOAD BYPASS CONTROL SYSTEM

The results of previous studies conducted to determine road wear impact will be used in this study [11]. Based on this information a system can be proposed to assist current OCC operations while prosecuting offenders that choose to ignore overload control procedures. A cost-benefit analysis will serve as a motivating factor for implementation.

The proposed system will aim to detect the vehicles that bypass the OCC by interfacing a detection system to the current OCC or equivalent system. Vehicles will be identified by means of Automatic Number Plate Recognition (ANPR) cameras fixed to gantries over the lanes passing the OCC. These vehicles will be considered to be non compliant and deliberately bypassing. Prosecution level will have to be determined by the road agencies, but it is suggested that a maximum overloaded penalty be given to bypassing vehicles to act as deterrent and to generate additional funds to maintain the road section.

Capital outlay required will consist of a computer system, detection terminal, civil infrastructure, and integration to the OCC. We assume that a separate bypass detection systems will be installed for each direction of travel at the OCC. Each OCC will be equipped with 2 lane ANPR gantries linked with the OCC system. The total capital outlay for four (4) OCCs amounts to \$0.824 million, with annual maintenance and operational costs amounting to \$0.247 million. Only four (4) OCCs is proposed for the initial testing phase of the project and to determine feasibility.

IV. ROAD WEAR

Road wear and the cost of premature maintenance thereof is the measure chosen to quantify the financial damage caused by bypassing vehicles. Quantification of the damage is done by analysing axle weight distributions of static weight data on South African roads. Weight data was analysed over an eleven (11) month period in 2013 and over twenty seven (27) weigh stations.

Road wear calculation is done by making use of the average and standard deviation of the axle distribution. A yearly road travelled distance is calculated with the assumption the 40% of the distance within SADC is travelled on South African roads, namely 760 km per trip [5]. The number of yearly trips per vehicle of 26.4 [12] results in a total distance of 20 064 km travelled yearly. The road wear is calculated for 100, 200, 300, 400, and 500 overloaded vehicles bypassing the OCC. The financial impact of additional maintenance

cost is calculated for these vehicles. The increase in road maintenance cost will range between \$ 527 000 up to \$ 2 600 000.

V. COST-BENEFIT ANALYSIS

Evaluation of the Overload Control Bypass Detection System considered vehicle bypass scenarios for 100 (0.02%) to 500 (0.1%) vehicles. The IRR is calculated over a five (5) year period. A positive IRR is realised with less than 100 vehicles detected. This is a clear indication that the proposed system will create much more value than the estimated cost of deployment.

VI. CONCLUSION

In this paper it is demonstrated that overloaded vehicles bypassing OCCs can severely increase maintenance cost of road infrastructure. By implementing an Overload Control Centre Bypass Detection system it will be possible to prosecute overloaded non compliant vehicles that deliberately bypasses the prosecution systems. A cost-benefit analysis demonstrates that a positive IRR can be realised by detecting less than 100 vehicles over a period of one (1) year. Apart from reducing the funds required to repair road damage, the funds raised through successful prosecutions can bolster funds available for road maintenance and for improving the overload control system.

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An Intelligent Freight Corridor Overload Control System*

Alwyn J. Hoffman and Arno de Coning

Abstract— Overload control is an important aspect of freight corridors in developing countries that largely depend on road transport to move goods between ports and areas of production and consumption. As the frequent weighing of trucks slows down the supply chain and add to operational costs, effective overload control must find a balance between the potentially conflicting goals of protection of infrastructure versus logistics efficiency. In this paper we demonstrate that an efficiently designed overload control system that utilizes modern information and communication technologies can simultaneously achieve the objectives of improved accuracy of control and increased logistics efficiency. The key element that makes this possible is the real-time sharing of information between different overload control centers, combined with the intelligent interpretation of available data, in order to optimize overload control over the entire corridor. We furthermore provide evidence that the potential improvements in logistics efficiency provide an attractive financial payback, taking into account the required investment to deploy the proposed new overload control system.

I. INTRODUCTION

Increased global trade is generally viewed as the key factor to improve the economic fate of developing nations. The impact on the regional economy of inefficiently managed trade corridors has been the subject of much historic research [1, 2, 3]; the general consensus is that efficient transport systems is an essential condition for effective participation in the global economy. Several land-locked countries within the Southern Africa Development Community (SADC) region depend mostly on land transport to exchange physical goods with the rest of the world [1]. Even in a country like South Africa that boasts a long coastline most of the mining and industrial production is based in the interior, requiring the transportation of goods over road corridors to the major ports. Due to lacking rail infrastructure road transport is responsible for more than 80% of all land transport in the SADC region. Figure 1 below provides a geographical overview of the major road corridors servicing the Eastern and Southern African subcontinent. The poor state of the road infrastructure in many African countries add to the cost of transport – as a result transport represents as much as 18% of GDP in many African countries, compared to a global average of less than 10% [4].

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A. J. Hoffman is with the School of Electrical, Electronic and Computer Engineering, Faculty of Engineering, Northwest University, Potchefstroom, South Africa (phone: +27-18-2991963; fax: +27-18-2991977; e-mail: alwyn.hoffman@nwu.ac.za).

A. de Coning is studying towards the PhD degree at the School of Electrical, Electronic and Computer Engineering, Faculty of Engineering, Northwest University, Potchefstroom, South Africa (phone: +27-18-2991978; fax: +27-18-2991977; e-mail: 20270186@nwu.ac.za).

Fierce competition in the road transport sector has resulted in unwanted practices in this sector, including a tendency to overload vehicles in order to improve the bottom line [4]. At the same time there has been a decline in the efficiency of overload control measures, which can partly be ascribed to lack of good systems and a lack of governance within many of the regional authorities [5].



Figure 1. Trade corridors in Southern and Eastern Africa

Against this background an initiative was launched in cooperation between SANRAL (South African National Roads Agency), toll-road concessionaires, local academia and members of the transport sector to practically demonstrate a new concept for corridor-wide overload control. The objective of this initiative is to provide proof that a nation-wide system of overload self-regulation can be deployed that will simultaneously improve the accuracy of overload control, enforce governance onto the authorities and provide significant economic benefits to road users. More specifically it will be demonstrated that an integrated system that identifies vehicles with a high level of integrity and that shares information between different overload

control centers (OCCs) will support more accurate monitoring of overloading behavior while limiting the number of times that freight vehicles need to be statically weighed. The time savings enjoyed by transporters due to a reduction in the number of static weighing of vehicles, combined with reduced vehicle operational costs due to fewer stops, can provide the required incentive for participation in a voluntary overload control scheme. Fewer stops by trucks at OCCs will also reduce the opportunity for interaction between truck drivers and officials, which has been identified as the primary mechanism for rooting out corruption within trade corridors [6].

This paper provides an overview of the current status of the above initiative, and builds upon the results that were published in an earlier paper [3]. In section II we provide a brief overview of relevant literature and in section III the objectives of the proposed system are described, while section IV outlines the logical operation of the system. In section V we estimate the expected operational impact of the system, and in section VI we analyze the financial viability of the underlying concept. Sections VII and VIII concludes with current findings and an overview of future work.

II. LITERATURE STUDY

The optimization of weigh station operations has received significant attention in ITS literature. Kamyab [7] studied the alternatives of physical expansion and electronic screening to reduce waiting times at weigh stations and demonstrated that, with a high enough level of penetration of electronic transponders within the national fleet of trucks, electronic screening can provide specific benefits over more physical screening using weigh-in-motion stations (WIMs). Wen *et al* [8] evaluated toll station operation using simulations to determine the impact of traffic volume, truck percentage and truck service time, and found that service time was the most important parameter affecting the service efficiency. Lee and Chow [9] proposed an adaptive metering algorithm using feedback to control the level of truck traffic in weight stations and to prevent queue spillover. They demonstrated that the availability of pre-arrival information can make the algorithm more efficient. The above systems focused on improving the efficiency of weight control stations in isolation from the rest of the system, rather than the optimization of an overall corridor overload control system. There are many examples of ITS systems that are aimed at industry-wide system optimization using a variety of ICT technologies used to identify and monitor individual vehicles or transport items as part of controlling remote operations [10, 11, 12, 13, 14, 15].

In the South African transport industry a public-private partnership, called the RTMS (Road Transport Management System), was launched around 2005 to introduce industry self-regulation with respect to overload control. This initiative achieved significant successes within selected target industries [5]: the road network servicing the production areas of the timber and sugar industries in South Africa (SA) experienced a decline in the overloading of

trucks from around 40% to below 10% over a period of approximately 5 years.

The systems deployed to achieve the above successes relied on the use of passive RFID for the automated identification of vehicles and linking of the compliant load status of a vehicle to the benefits that this vehicle will enjoy across the supply chain within the respective industries. In the case of the timber and sugar industries in SA the system of self-regulation was effectively enforced by the dominant producers that could dictate terms (e.g. to carry RFID tags) to contracted transporters. To achieve similar improvements on a national and regional basis a system is needed that will target not only selected areas dominated by particular industries, but that spans across the entire network of road corridors servicing the SADC region. In order to achieve a critical mass of voluntary support for a more general system of self-regulation it will be necessary to provide sufficient economic incentives to all stakeholders. It is the objective of this paper to propose a specific approach to integrated overload control and to quantify the expected economic benefits that such a system can create.

III. OBJECTIVES OF AN INTELLIGENT CORRIDOR OVERLOAD CONTROL SYSTEM

The primary challenge faced by trade corridor systems is the fact that it must serve the needs of many independent stakeholders with different priorities. In the sections below we provide a brief overview of the objectives of the proposed system in order to accommodate the needs of the most important stakeholders.

A. Transporters

From the perspective of transporters the system must effectively protect the infrastructure that is essential to provide road transport services, while at the same time reducing the disruption of the flow of vehicles and cargo (e.g. the stopping of vehicles for weight inspections) to an absolute minimum. A third objective is to make information collected by the system available to transporters to allow these operators to improve their internal efficiencies.

B. Roads agencies and toll concessionaires

Roads agencies are tasked to develop and maintain the national roads infrastructure. The proposed system must enable these entities to implement improved controls at a lower cost, reducing long term capital outlay as well as the depreciation of this outlay, while at the same time reducing disruptions to the operations of road users. An added benefit will be to differentiate toll fees based on the actual measured impact of road users as well as their levels of compliance, to eradicate the current situation where non-compliant users tend to be subsidized by compliant users.

C. Cargo owners

The recorded successes in terms of overload control self-regulation in SA resulted from the direct participation of large producers who own most of the cargo being transported on regional road networks. An improved system must allow cargo owners to only use the services of compliant

transporters to enforce the protection of the roads infrastructure that service their areas of operation. A second objective is to provide increased visibility regarding the movement of cargo in transit to positively impact logistics efficiencies of cargo owners.

D. Cross-border agencies

There are some direct links between cross-border and overload control operations. Most border posts require trucks to visit the local OCC before their cargo can be cleared. This is usually the area that suffers the most congestion leading to cross-border delays, as vehicles that have not been cleared by customs yet tend to block the way of (potentially fully compliant) vehicles that must be weighed before they can be cleared, resulting in long queues during peak times. An improved system must reduce congestion and therefore border crossing times by eliminating the need to re-weigh compliant vehicles at the border. A second benefit will be making available the overload audit trail of vehicles to customs authorities to provide them with more accurate information about consignments to be cleared.

IV. LOGICAL OPERATION OF THE PROPOSED SYSTEM

Overload control usually spans from the origin of a freight truck, where weighing of the vehicle will form part of standard best practices, up to the destination where the vehicle is usually weighed again before the cargo is offloaded. The weight information is used firstly to verify that the vehicle will comply with the applicable regulations (in terms of overall weight as well as weight per axle). A second use of weight information is to detect any unauthorized changes in weight en route to ensure that all authorized cargo is offloaded at the intended destination(s) and that no unauthorized cargo is transported at the expense of the vehicle owner. En route the relevant roads agencies will monitor the weight of heavy vehicles to detect incidences of overloading and to remove such vehicles from the road until compliance has been achieved.

A. Limitations of existing overload control centers

Figure 2 below schematically describes the logical layout of a typical overload control center. In order to limit the unnecessary static weighing of vehicles most centers are equipped with weigh-in-motion (WIM) scales that are embedded into the road surface. Should the WIM scale indicate that a vehicle is possibly overloaded it is directed to the static scale. Due to the limited accuracy of the WIM reading prosecution can only take place based on a static scale measurement. As WIM scales have been found to have a standard error of about 10% [16] a threshold is applied to the WIM reading that is 10% lower than the legal limit. Increasing the WIM threshold to reduce the false alarm rate will increase the number of overloaded vehicles allowed to go through, leading to an increase in road damage.

Historical records indicate that 75-80% of all freight trucks are loaded to within a few percent from the legal limits [16]; all of these vehicles will fall into the range between the WIM threshold and the legal limit, and will

hence be directed by the WIM to the static scale. Most OCCs operate within isolation from the rest of the system, leading to suboptimal decision making with respect to vehicles that have been statically weighed in the system before. A large fraction of vehicles that have been statically weighed will be re-weighed on the same trip on the same corridor as consistent operation of the overload control system will cause the same vehicle to be pulled off every time that it crosses a WIM scale. As a result historical figures from SANRAL's overload control centers indicate that around 98% of vehicles that are statically weighed are not prosecuted, most often because they fall in this range of WIM uncertainty [16]. This situation could be prevented if firstly the vehicle can be reliably identified when it crosses the WIM, and if secondly the available information on prior static weighing of the vehicle can be used to decide if the same vehicle needs to be statically weighed once again.

B. Automated Identification of Registered Vehicles

The first new functional element of the proposed system is the ability to accurately identify a vehicle at the WIM scale, as displayed in figure 3 below. The recommended methodology is the use of passive UHF RFID tags attached to the windshield of vehicles – this technique has been proven to provide accuracy in excess of 99% in the detection of vehicles in such a scenario. In contrast alternative techniques like ANPR tend to only achieve accuracies of 90-94% for in-door and as low as 70% for outdoor scenarios [17], partly due to suboptimal installations and partly due to reflections, dirt on or damage to number plates. As close to 100% identification accuracy of vehicles is essential for the proposed concept to work effectively, RFID will significantly add to the value of the system.

The use of RFID implies the pre-registering of vehicles; while it will initially limit the percentage of participating vehicles it supports the concept of voluntary self-regulation where participating vehicles that enables automated in-traffic compliance checking enjoys specific benefits over non-registered vehicles that require manual static compliance checking. In the case of a vehicle that is recognized by the system the prior history of that vehicle is extracted from the system and used as part of automated real-time decision making. Should a vehicle detected through a magnetic loop found to be either not tagged or not registered in the system, only the current WIM scale reading will be used to decide whether the vehicle is guided towards the static scale or not.

C. Intelligent WIM Operation

The operation of an intelligent WIM scale is depicted in figures 4 and 5 below. Once a vehicle has been recognized by the WIM controller it is determined whether the vehicle has been processed on the same corridor in the recent past. The criteria used to decide whether the last static weight can still be accepted for that vehicle will firstly involve a comparison of the travel time since the last measurement till the present with the average travel time between the two respective OCCs. Should the maximum threshold be exceeded it is assumed that there was sufficient opportunity for the weight to be changed en route; in such a case the system will revert to the use of only the current WIM reading. In a more advanced version of the system the

criteria can include the use of GPS tracking information obtained from on-vehicle systems to determine whether a vehicle deviated from the corridor, made specific stops or even whether the trailer or container doors were opened.

Should the WIM controller decide that it can in fact rely on the integrity of the last available static weight, it will determine whether that measurement was within the legal limits. Should the weight of the vehicle hence fall within the range of WIM uncertainty the WIM controller can use the prior static weight to determine that the vehicle does not need to be directed to the static scale once again, but can be allowed to continue on its journey. Based on the previous discussion it is clear that a large proportion of cargo vehicles in fact fall into this category; using prior information can hence prevent a large number of unnecessary static weighing operations, saving not only time but also operational costs.

V. OPERATIONAL IMPACT

The expected operational impact of the system is assessed by quantifying the effect of fewer static scale visits on a typical cargo vehicle traveling on a typical trade corridor. We use the Johannesburg-Maputo corridor as our case study: it has a length of approximately 500km (1000km for the return trip) and based on figures retrieved from historical SANRAL records it handles approximately 450 long distance freight trucks per day that has to pass through 4 compulsory OCCs between origin and destination. The other operational parameters to quantify trip economics are displayed in table 1 below; the table show figures both for trucks operating within the current system as well as for trucks participating in the proposed system.

TABLE I. CARGO VEHICLE TRIP VARIABLES: BEFORE AND AFTER

	Old scenario	New scenario
Monthly interest rate	1.0%	1.0%
No of monthly installments	120	120
Average cost of truck	\$180 000	\$180 000
Monthly installment	\$2 582	\$2 582
Average income per trip	\$1 500	\$1 500
Average distance per trip (km)	500	500
Average fuel consumption (km/l)	2	2
Cost of fuel per liter	\$1.50	\$1.50
Average cost of fuel per trip	\$375	\$325
Number of tyres per vehicle	16	16
Cost per tyre (\$)	500.00	500.00
Stop/start as fraction of tyre wear-'n'-tear	30.0%	30.0%
Max km per set of tyres	25000	25000
Average km per stop/start	\$150	\$150
Number of static scale stops saved per trip	0.0	2.4
Fuel cost saving per trip	\$0	\$50
Cost of tyres per trip	\$160	\$125
Saving on tyres per trip	\$0	\$35
Cost of driver per trip	\$300	\$300
Other costs per trip (tolls, etc.)	\$100	\$100
Total trip costs excluding financing of truck	\$935	\$850
Profit per trip excluding financing of truck	\$565	\$650

The operational impact of the proposed system will be measured firstly in terms of reduced travel time resulting from fewer visits to static scales and shorter waiting time at static scales; this will translate to more trips on average per month. Secondly we estimate the reduction in vehicle operational costs in terms of the fuel cost and tyre wear resulting from fewer stops.

We use the queuing theory formula for a Markov process with arrival rate λ and service rate μ for a so-called M/M/1 queuing system to calculate the average static scale waiting time T_w [18]:

$$T_w = \frac{1}{\mu - \lambda} - \frac{1}{\mu}$$

As can be seen from table 2 below, with the current system approximately 80% of vehicles passing each control center will be directed to the static scale, resulting in 360 static scale visits (3.2 per truck per trip), a processing time of 2.2 minutes and an expected waiting time of 10.4 minutes per scale. To this is added the time lost to slow down before and speed up after the OCC visit, calculated as 5.2 minutes. The overall waiting time at one static scale counts up to 17.8 minutes; the combined impact of all OCCs adds up to approximately 4% of overall travel time.

With the introduction of the proposed system each participating truck will be statically weighed at most once during the trip, resulting in reduced stops for 0.8 static weighs per trip and only 90 vehicles visiting each static scale per day on average. This reduces the average waiting time at the static scale from 10.4 minutes to 0.5 minutes using the above queuing formula. As a result the average trip duration is reduced to 0.79 days, allowing on average 30.6 instead of 29.2 trips per month per truck.

As indicated in table 2 below, the estimated figure of 450 vehicles per overload control center per day implies a total of 13500 trips within a 30 day month. At 29.2 trips per month the number of trucks required to complete this number of trips equals 462. Assuming that an improved overload control system will not impact the number of trips for which there is a demand in the market, the implication is that a smaller number of trucks doing more trips per month (30.6 instead of 29.2) will be required to satisfy market needs: 442 instead of the original 462.

VI. COST-BENEFIT ANALYSIS

We perform the cost-benefit analysis by translating the operational benefits as calculated in the previous section into financial benefits experienced by all transporters combined using the respective corridor. This is then compared against the cost of deployment of the proposed system, including the initial capital outlay as well as operational expenses. The internal rate of return is calculated over a period of 10 years, which more or less corresponds to the expected operational life of such a system.

The set of income and cost parameters for a typical truck appear in table 1. We estimate the income per trip at \$1500, the trip cost, excluding financing cost, at \$935, and the

financing cost at \$ 2582 per month. Vehicle operational cost per stop/start was estimated by using cost figures obtained from transporters. The additional fuel consumed due to an additional stop was estimated by calculating the distance over which deceleration and acceleration will take place, and by estimating the increased level of instantaneous fuel consumption during these periods. A figure of \$21 per stop/start was obtained. Additional tyre wear due to an additional stop was estimated by using the average distance for a set of tyres, the average distance between stops for long haul trucks and the contribution of stop/starts to overall tyre wear – we arrive at a tyre cost per stop/start of \$14.40. The reduced fuel and tyre cost resulting from fewer stops are subtracted from the average trip cost used for the reference scenario, resulting in an increase in average profit per trip from \$565 to \$650.

TABLE II. COMPARISON OF INDUSTRY PROFITS: BEFORE AND AFTER

	Old scenario	New scenario
Fraction of vehicles participating	0.00	1.00
Average distance per trip (km)	500	500
Average speed of travel (km/h)	80	80
Average number of hours driving per day	8	8
Distance to accelerate (km)	3.5	3.5
Average number of days driving per trip	0.78	0.78
Number of OCCs per trip	4	4
Average number of vehicles per day at WIM	450	450
Fraction of vehicles within WIM tolerance	0.80	0.80
Number of WIM triggers per trip	3.20	3.20
Number of static scales visited per trip	3.20	0.80
Number of vehicles per day at static scale	360	90
Average operating hours per day	16	16
Average time between vehicles (minutes)	2.67	10.67
Average processing time at OCC (minutes)	2.2	2.2
Average waiting time at OCC (minutes)	10.37	0.57
Time lost per stop and depart (minutes)	5.25	5.25
Average delay at OCC (minutes)	17.82	8.02
Average total OCC delay per trip (days)	0.040	0.004
Average trip duration (days)	0.82	0.79
Fraction of time trucks on road	0.8	0.8
Number of trips per truck per month	29.24	30.55
Income per month	\$43 857	\$45 819
Costs per month excluding financing cost	\$27 337	\$25 965
Profits per month excluding financing cost	\$16 519	\$19 854
Costs per month including financing cost	\$29 920	\$28 548
Profits per month including financing cost	\$13 937	\$17 271
Total number of trips per month	13 500	13 500
Number of trucks required	462	442
Total profits per month	\$6.435m	\$7.633m
Increase in annual profits		\$14.38m

The increase in number of trips per truck per month implies and increased revenue per truck without a corresponding increase in financing cost, thus more effective utilization of capital assets. In order to compare the two scenarios (with and without the new overload control

system) we calculate the financing cost for the two fleet sizes. We arrive at a total monthly profit for the entire fleet of vehicles of \$6.435 million per month, compared to \$7.633 million per month for the reduced fleet; this implies an increased annual profit of \$14.38 million per annum for the entire fleet.

To calculate the required capital outlay to deploy the system we use the set of figures displayed in table 3 below. We assume a separate WIM scale to be used for direction of travel at each of the 12 overload control centers Each weigh bridge lane will be equipped with an RFID reader and intelligent WIM controller, while two handheld RFID terminals will be used per control center. The total capital outlay required for the 4 overload control centers amounts to \$0.984 million, with annual maintenance and operational costs amounting to \$0.295 million.

TABLE III. CAPITAL OUTLAY REQUIRED AT OCCs

Number of OCCs	4
Number of trucks	462
Number of terminals per OCC	2
Number of desktop scanners at each OCC	0
Number of lanes per OCC	2
Cost per equipped lane	\$30 000
Cost per handheld terminal	\$5 000
Cost of computer equipment per OCC	\$6 000
Cost of passive RFID tag	\$2
Cost of desktop scanner	\$550
Cost of civil infrastructure per OCC	\$20 000
Cost of software and integration per OCC	\$150 000
Total capital outlay per OCC	\$246 000
Total cost for all OCCs	\$984 000
Annual maintenance and operational cost	\$295 200

For the evaluation of the Intelligent Corridor Overload Control System we consider different scenarios where the fraction of trucks participating in the system is varied from 0 to 1. The annual costs are subtracted from the annual expected increase in profit experienced by the transporters, and all of the figures combined in a 10 year internal rate of return (IRR) calculation. As can be seen in table IV below the system only requires a level of participation of 3% to show a positive IRR, with very high IRR figures for significant levels of participation. This is a clear indication that the proposed system will create much more value than the estimated cost of deployment.

TABLE IV. INTERNAL RATE OF RETURN OF PROPOSED SYSTEM

Fraction participating	1.00	0.50	0.20	0.10	0.03
IRR (%)	1431	715	278	127	13

VII. PRACTICAL RESULTS AND FUTURE WORK

A number of overload control centers operated by SANRAL has been selected for practical deployment and evaluation of the concept as described in this paper; these centers form part of the North-South Corridor extending

from Durban in South Africa up to the DRC, via Zimbabwe, Zambia and Botswana. RFID tags have been deployed on a significant number of trucks using this corridor on a regular basis in order to generate sufficient traffic to allow the collection of a meaningful set of results. Interfaces were created between a standalone RFID monitoring system and the existing systems used to operate the WIM and static scales at the SANRAL control centers. An experimental installation was done at the Bapong control center close to a national border between SA and Botswana and it has been demonstrated that tagged trucks moving across the WIM scale can be reliably detected using the RFID readers.

On-going work involves the completion of an intelligent WIM controller that will implement the logic as described in this paper, and the deployment of the experimental system at a number of consecutive overload control centers along the above corridor. The primary practical objective is to demonstrate the capability to implement more intelligent decisions at any particular WIM scale by using information collected at other OCCs. A further objective is to extend the system into the operations of certified transporters, allowing them to submit their own static weight measurements to SANRAL prior to departure. This may allow certified participants operating calibrated scales and submitting data in this manner to travel along an entire corridor without having to be pulled off for further overload control inspections, thus reaping the benefits of reduced turn-around times, reduced costs and increased profits.

VIII. CONCLUSION

In this paper we demonstrated that it is possible to reconcile a high level of efficiency in overload control with minimization of the impact on vehicle travel time and operational costs. This is achieved by high integrity identification of vehicles at WIM scales and the sharing of information between different OCCs on the same corridor, allowing the system to avoid unnecessary reweighing of vehicles that were previously found to be within the legal limits. The benefits to industry from participation in the proposed scheme is demonstrated to include time savings, leading to better vehicle utilization, and fuel and tyre cost savings by avoiding most of the static scale stops along the way. Either of these two sets of benefits can justify the cost of system deployment when evaluated in terms of return on investment. Added benefits to the overall transportation system, that were not incorporated into the financial calculations, include increased visibility to the authorities of the behaviour of transporters and of officials, which should result in increased integrity of the overload control system, as such information could be used to act against repeated perpetrators. The same visibility regarding the status and behavior of vehicles can be used by transporters and cargo owners to improve their internal logistics efficiencies. Our overall conclusion is hence that the proposed system will

create more benefits than costs to the transport industry and should enjoy serious consideration for practical deployment.

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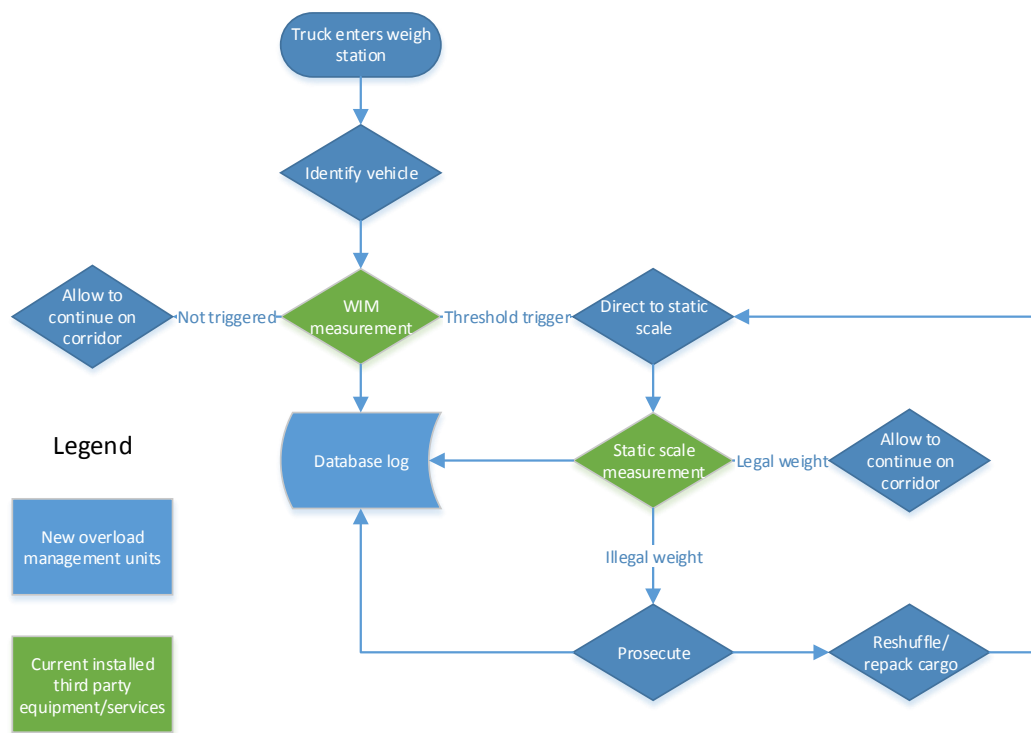


Figure 2.

Simplified logical operation of an overload control center

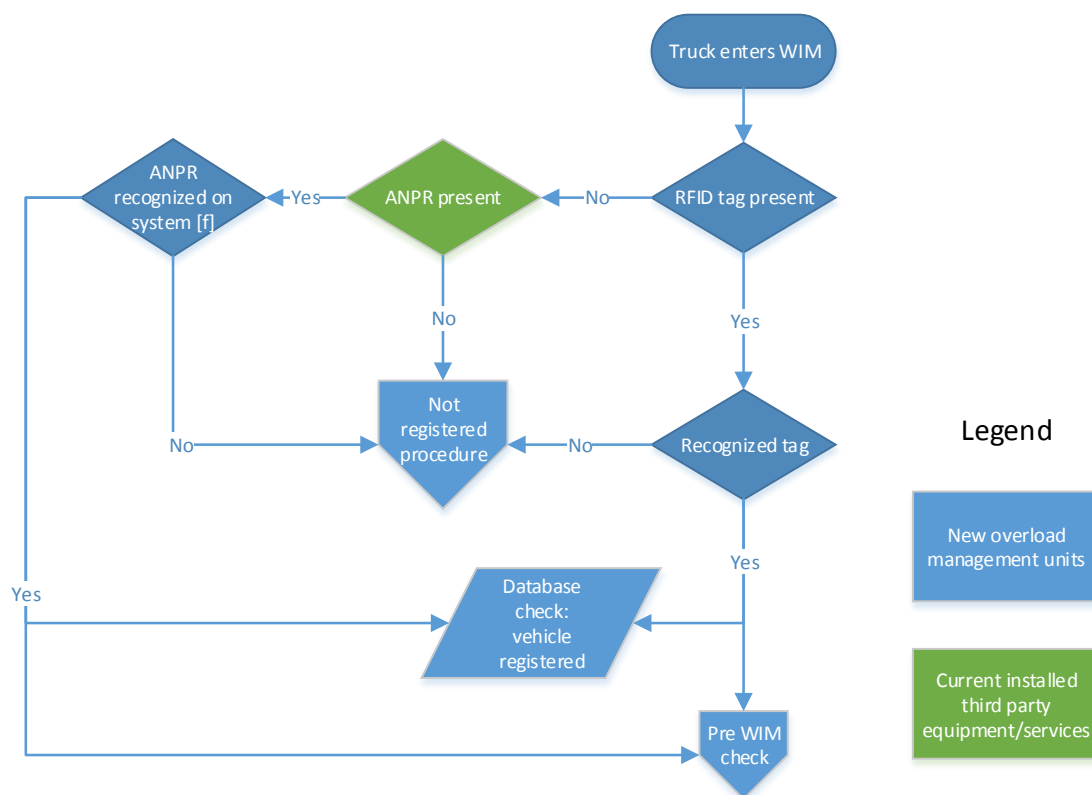


Figure 3.

Identification of registered vehicles at the WIM scale

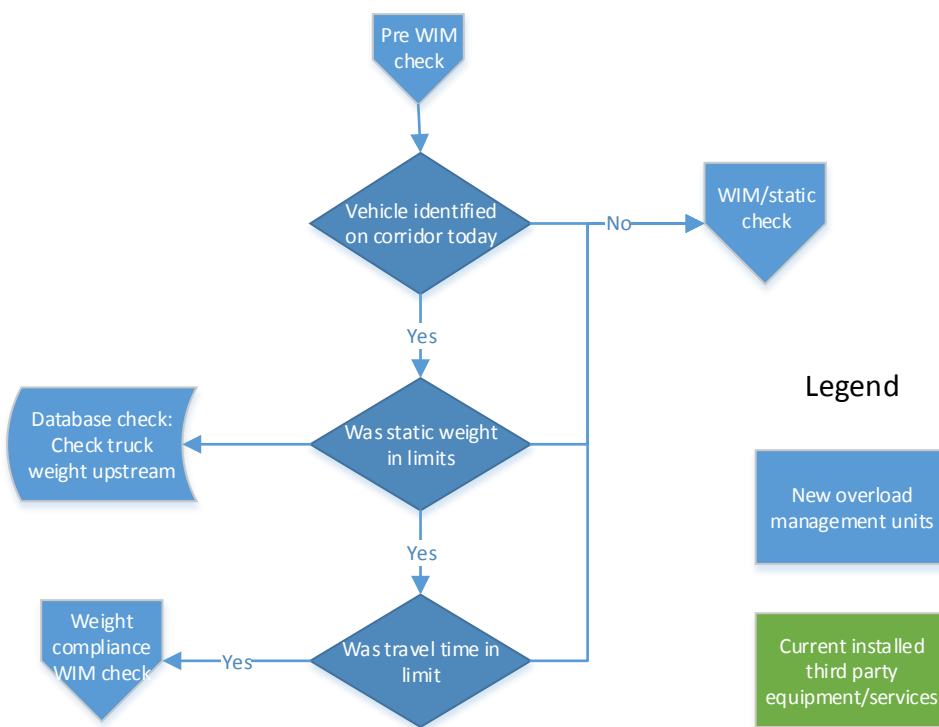


Figure 4. WIM controller verification of historical record of vehicle on corridor

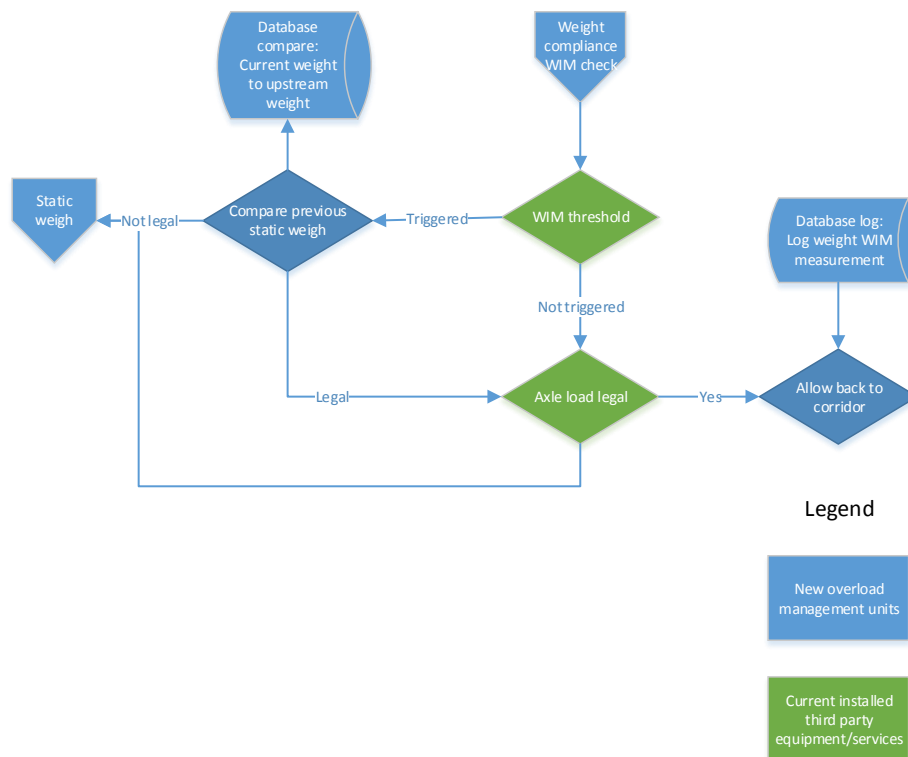


Figure 5. WIM controller verification of vehicle weight compliance

A simulation strategy to optimize the design of internet enabled logistics services

P. K. Lusanga, A. J Hoffman, A. de Coning and, E. Bhero

Abstract- The emergence of advanced communication technology has created opportunities to improve transportation in supply chains across the globe. In this paper the main contributors to inefficiencies in present road transportation chains are identified. The paper goes on to describe approaches taken by stakeholders to improve their operational efficiency. A simulation based approach to investigating the impact of any change in the operations along trade corridors is proposed. This firstly includes the use of expanded datasets for better visibility and secondly, improved operational procedures aimed at exploiting the data via an internet enabled logistics services platform. A multi-agent approach for modeling the supply chain is suggested. The paper also identifies behavioural aspects that can be investigated based on a simulation model. Possible outcomes of such a simulation study and benefits of the resulting improvement in logistics are also presented. It is hoped that the gains demonstrated will motivate practical implementation of the conclusions drawn from the study.

Index Terms—transportation, supply chains, logistics, agents, simulation

I. INTRODUCTION

A supply chain is usually a large system comprising of a number of independent interacting entities. Each one has its own objectives which may in some cases conflict with those of other entities [1]. Some players either dispatch and receive cargo or monitor key points to ensure that regulations and standards are maintained (e.g. cross-border agencies, police checkpoints and overload control centres). Transporters are the main players and rely on efficient route planning and scheduling. Distance, time, safety and cost are key considerations. As the global trend is towards satisfying a consumer orientated market, good quality of service to customers should include pre-arrival notification to aid internal planning on the receiving end [5].

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P. K. Lusanga, is with the North West University, P/Bag X600, Potchefstroom, 2520, South Africa. (email: 20878346@nwu.ac.za)

A. J. Hoffman, is with the North West University, P/Bag X600, Potchefstroom, 2520, South Africa (Phone: +27 182991963; fax: +27 18 2991977; email: Alwyn.Hoffman@nwu.ac.za)

A. de Coning, is with the North West University, P/Bag X600, Potchefstroom, 2520, South Africa. (arnodeconing@gmail.com)

Ernest Bhero is with the Department of Electronic Engineering, University of Kwazulu Natal, South Africa (email: Bhero@ukzn.ac.za)

There is a "time value" attached to goods such as perishables or where markets offer a limited window of opportunity (e.g., fashion articles). Furthermore, for retailers, buyers can be lost to competing suppliers. Therefore, maintaining "quality of delivery" and "accurate time of delivery forecasts" is important. Logistic service platforms and tools exist to help transporters in decision making and consignment movement predictability [3]. However forecasts are complicated by the time uncertainty of checks and procedures at checkpoints, borders and overload control stations. These have limited infrastructure and personnel and are often overwhelmed by the numbers of randomly arriving consignments [2]. Human error from personnel and ineffective operational procedures also contribute [1] , [4].

Problems or delays may warrant prompt corrective action to save time, maintain prescribed goods' temperature or modify customer delivery expectations, in advance. For lost goods, insurance claims would require a trace of corrective actions taken. In transit, a consignment may fail a control check and may be detained until a relief vehicle is sent by the transporter [7]. Therefore, there is a need to find solutions to acquire and process and store progress information in real time. There is also a need to revise operations at control centres to minimize bottlenecks. Various solutions can be proposed and knowing the impact of each one can aid in making the most optimal and cost effective choice.

This paper presents a simulation approach to investigate the impact of various solutions to freight logistics problems. The rest of the paper is organized as follows: Section II contains the problem statement. Section III describes supply chain operations and challenges. Section IV describes simulation aspects such as developing agent models for the supply chain, simulation requirements and platforms which can be used for implementation. It also discusses model initialization, calibration and verification. The last section contains the conclusion and recommendations for future studies.

II. PROBLEM STATEMENT

The long term objective of the study is to demonstrate the benefits of cargo visibility to support more effective supply chain management. Transporters and other stakeholders can benefit from better supporting tools both to manage real time operations and to improve their operational strategies by analyzing alternatives. Improved services will lead to improved management which will guarantee better efficiency.

The proposed list of services as described in Table I can enable transport stakeholders to enforce best operational practices and will allow them to respond more quickly to problems that occur. Expected performance enhancements that are projected based on such support systems are described in [1] and [6]. This includes reduced turn-around time for trucks, increased compliance with regulations and improved profitability for the entire sector.

As most of these services are not yet available in practice some uncertainty exists regarding the expected operational and economic impact and hence the economic viability of each service. It is however very costly to deploy such services on an experimental basis. A more viable approach is to develop an accurate simulation model to allow experimentation with such services and to measure the likely impact on operations. If the model is well calibrated to existing operations it should also produce realistic results for a changed scenario where some of the proposed services have been deployed.

TABLE I. FUTURE INTERNET PLATFORM SERVICES

No	Name of service	Intended Customer
1	Real-time performance monitoring	Transporter, client
2	Predictive trip management	Transporter, Insurer Transporter client,
3	Real-time risk alerting	Transporter, Client, Insurer
4	Consignment traceability	Transporter, Cross border operations
5	Overload control compliance	Weigh station, Transporter, SARS, Cross border
6	Fuel management	Transporter
7	Transporter performance management	Transporter
8	Electronic transport trading platform	Transporter, Client, Insurer
9	Certification and track record management	Transporter, Future clients, Future employer
10	Transporter rating	Clients
11	Cargo insurance compliance	Transporter, Insurer

III. SUPPLY CHAIN OPERATIONS

A. Stakeholder interactions

Most of the communication between stakeholders in transportation systems is manual. Fig. 1 shows the typical human to human interactions in a supply chain. In the figure, an entity labeled as the deviator is shown. It represents human beings which interact with the driver and are contributors to delays and other forms of malpractice.

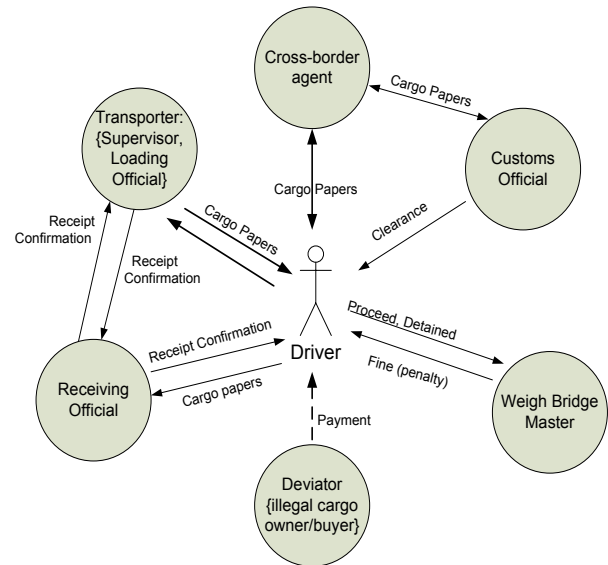


Figure 1. Human to Human Interactions

In areas where integration of computer technology is used, these systems should ideally work autonomously; in practice they are however dependent on human interaction. Machine to machine communication is shown in Fig. 2. The solid arrow-lines show current machine to machine communication. The dotted arrow-lines show proposed additional forms of machine to machine communication which can improve the efficiency of current operations, the details of which are covered in a later section.

B. Information flow from source to destination

When a customer's request to ship goods is accepted, the transporter is provided with an order listing the items to be loaded. The transporter hands this information together with a delivery schedule to the driver, who takes the truck for loading. At the loading site, the goods' receipt is given to the loading official. Once the truck is loaded, sealed and dispatched, the next stop may be a police checkpoint or weigh bridge.

When the driver reaches a weigh bridge the consignment is driven through the weigh-in-motion (WIM) scale, where a traffic signal either directs the consignment to a static scale or to proceed onto the highway. Studies have shown that there are few cases where the WIM and static scale are linked [8], [9], [10]. At every weigh bridge along the route where a truck is found to be overloaded, it is impounded and penalized. The transporter is then contacted for a relief vehicle to offload the excess goods and charged a fine.

At a border, the driver hands over the necessary documents to the clearing agent who, if satisfied, takes them to the customs official for clearance. Using a risk assessment procedure, customs may subject the consignment to physical inspection. Any problems should be reported to the transporter by the driver.

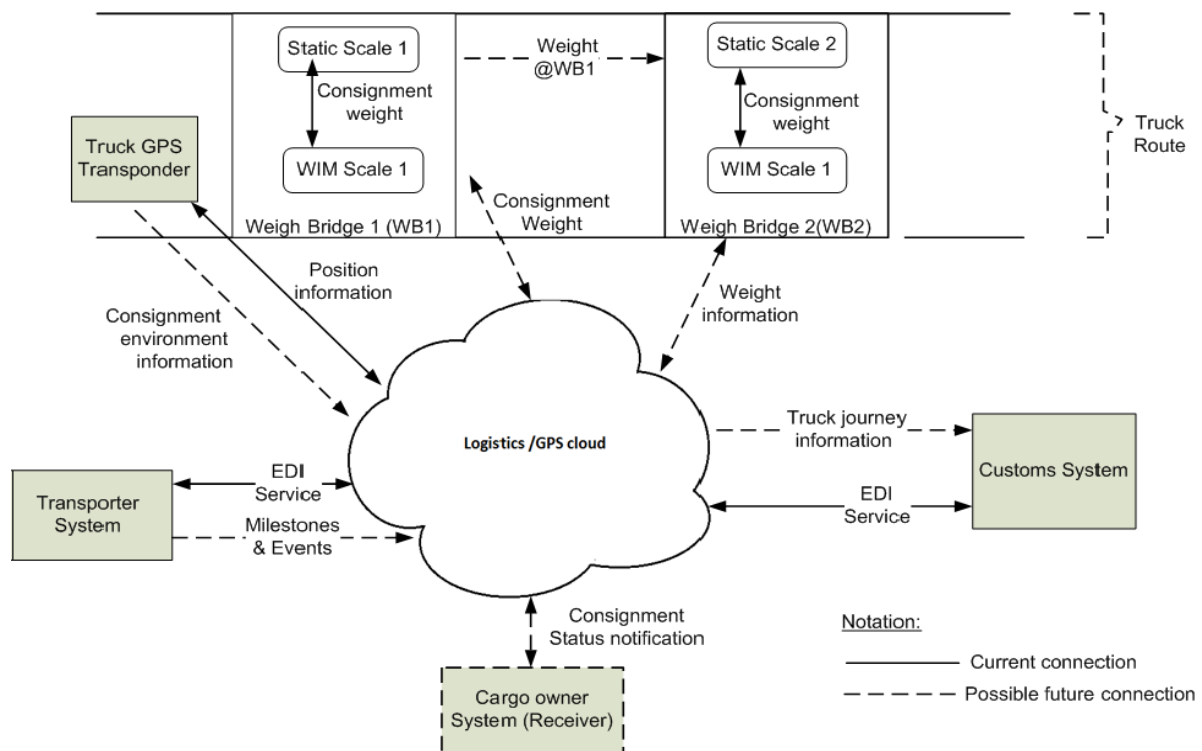


Figure 2. Machine to machine communications - present and future communications.

Once cleared the documents are given back to the agent who hands them back to the driver. This process is repeated on the other side of the border and every other subsequent border.

At the destination, the documents are handed to the receiving official who checks the delivered goods. If satisfied, he signs a document to confirm receipt of the goods. The document is sent back to the transporter by the driver or by fax or email from the receiving end.

In the entire journey, most of the same information is handed from one role player to the other. These exchanges are usually manual, time consuming and error prone. Weighing and clearing processes are also repeated on the same consignment. This would not be necessary if information was readily accessible to all parties via an integrated information platform. There is hence a need to communicate the outcomes of all steps to a central point from where data can be shared with other supply chain participants.

C. Improving supply chain efficiency

In supply chains as in any other process, measures often have to be taken to address known inefficiencies in the operation or system. Solutions may be simple adjustments or a complete overhaul of existing processes. Often, emerging technologies and products are used and offer a variety of alternatives [1]. These may however come with technical complications requiring a significant amount of time to address.

When prototype solutions are deployed the actual impact of the proposed solution can often not easily be quantified. The costs incurred are usually more than what was initially planned due to the cyclic nature of the design process, requiring several iterations before the desired effect is achieved. Required interactions with third parties who may not always be readily available or cooperative also contribute to practical complications. The situation becomes even more complex for multi-national corridors. A lot of dialogue is necessary before any meaningful progress can be made and this can take a significant period of time with no certainty on the outcome [11].

A number of prototypes have been developed across the world to address supply chain inefficiency. An example of such a project is INTEGRITY, which was funded by the EU. In this project, a "single" software platform to manage the supply chain using telemetry data was developed for a supply chain from Europe to China [12]. A few equipment problems were experienced during implementation. The project showed that technology can be deployed to enhance transportation and coordination. However, it lacked in clearly quantifying the gains and only generalizations based on assumptions could be made. In order to investigate all the aspects possible, the project would have to be sustained over a long period of time, which is costly. This demonstrates the shortcomings and constraints of physical prototypes. It provides the motivation to pursue more convenient and less expensive options, especially for Southern Africa which does not have the same financial muscle as the EU.

IV. SUPPLY CHAIN SIMULATION

A. Model considerations

In order to obtain realistic results through simulations it is necessary to have an accurate model of the system. An inaccurate model would deem the simulation results as irrelevant to practice. In a supply chain, most models are functional and event driven. One way of representation is by using state-based models [11], [12].

In addition to having accurate models the simulation platform used also plays a very important part. Since supply chains are usually complex and large, a distributed simulation is usually preferred by most researchers when dealing with model scalability [14]. While this holds true most of the time, Pawlaszczyk and Strassburger showed that an efficient time synchronization scheme plays a significant role in the scalability of the system and they developed a tool to address this requirement [4].

B. Agent based modeling

Accurate modelling of supply chain operations calls for the development of models which include human behavioural tendencies. Most of the communication between stakeholders is human to human or human to machine. It has been found that inefficiencies in supply chains are mainly due to human behaviour [2]. In software agent applications where human activities are automated using software agents, these agents are aimed at performing tasks previously implemented manually in a more efficient way [5], [15], [16]. However, most of these models do not incorporate human behaviour and are only suited for certain types of applications. They may lose relevance when simulating real systems where human influence is inevitable.

In literature, human behaviour models are used in the design of "ease of use" agents such as driving aids [17]. This paper integrates both the human functions in supply chain processes as well as the undesirable but common human tendencies. Model complexity may increase with the addition of more behavioural features to be as close as possible to reality as "Fig. 3" illustrates. It shows a driver's behaviour model comprising both the wanted and unwanted behaviours. It can be seen that there are as many unwanted as wanted states and state transitions. The same principle is implemented with all the human agents playing a role in the supply chain. The agent structures used implement the belief, desire and intention model (BDI). Agents possess a memory component referred to as belief which is basically the knowledge model of the agent [18].

Within a simulation platform, all the agents can be identified by type and location. The knowledge of the existence of other agents, and how they interact with one another and the environment can be incorporated into the knowledge-base of the agents. For example, a truck should be able to recognise the presence of other trucks and driver agents should react to and recognise and respond the environment near them.

C. Communication in a Supply chain

The previous sections described how role players currently communicate in the real world. The most important element that can have unpredictable impacts on overall system behaviour is the physical communication between the agents. In a typical supply chain system the communication technologies that are used to enhance cargo visibility include the following [1]:

- GPS Tracking
- GSM and Satellite communications
- Electronic Seals and Active RFID
- Passive RFID
- Internet

The simulation model can be used to determine what the impact will be on supply chain efficiency if e.g. RFID is used to detect the presence of vehicle at particular check points in the system, allowing other parties to react to this information. A typical example is where a vehicle passing through the WIM is automatically identified and prior information associated with this vehicle accessed by the system and applied to the current decision that must be made (e.g. to divert it to the static scale or not).

D. Simulation requirements

Successful simulation of supply chain transportation depends on the choice of a suitable software platform that satisfies the objectives of the simulation. Below are some requirements which must be supported to enable simulations to be as close as possible to the real world:

- It must be a multi agent platform.
- It must allow user defined agent behaviour.
- It must allow agent to agent communication.
- It should be able to generate results similar to the data collected from industry such as manifest, weight, tracking, weigh bridge truck volumes, border truck volumes and planning data.
- It should be able to integrate GIS information such as shapefiles and GPS coordinates for roads and locations of interest along trade routes into the simulation.
- It should be scalable since supply chains can be large and complex.

E. Communication cost within a supply chain

Agents communicate using predefined protocols involving more than one message exchange. In a transportation system, single messages are the "uploading" of sensor and position data. Data uploaded per minute from all the consignments can be computed as follows.

$$mC_v = (s_N \times d_{sn} + d_{GPS}) \text{Truck}_{\text{sum}} \quad (1)$$

where s_N is the number of sensors, d_{sn} and d_{GPS} are number of data uploads per minute for sensors and GPS transponder, respectively. mC_v is the number of messages uploaded. $\text{Truck}_{\text{sum}}$ is the total number of trucks in the simulation.

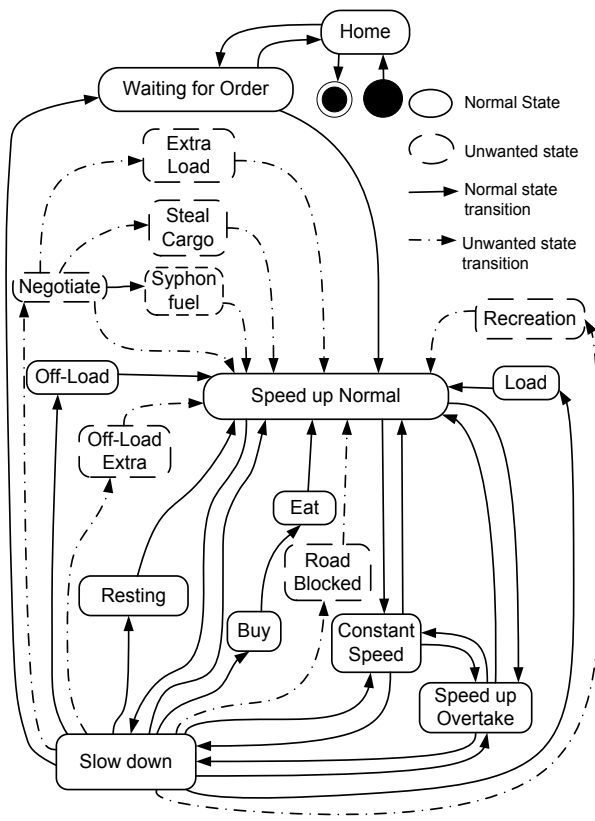


Figure 3. Driver state model - with deviations

To simulate cross-border supply chains across southern Africa, we need to consider that the region has about 6000 trucks involved in cross-border transport [1]. If only the position data is uploaded, the worst case would be 6000 messages at one instant. However, for better cargo visibility additional telemetry (sensor) data e.g. container humidity, temperature, door open/closed, is required. If other messages between role players such as a transporter and customer negotiations are included, the total number of messages can rise exponentially. The simulation model can be configured to log all the messages transmitted through third party service providers. The communication cost when the actual system is implemented, can therefore be computed by using the charge issued by the service providers. To date there is no investigation which focuses cross-border freight in this region and implementing the strategy outlined in this paper will be beneficial.

F. Multi-Agent simulation platforms

Many agent and multi-agent based simulation platforms have emerged. A detailed comparison can be found in [19]. The social sciences have seen the evolution of agent platforms from Swarm, to Repast, and then to Repast Symphony which can process GIS data from platforms like ArcGIS. Gama was written to fix problems not addressed in Repast Symphony. In other areas, Arena has been used in even-based systems like manufacturing. It competes with Simio, which was developed from Arena but has better visualization properties and predefined objects whose properties are user defined [25].

To set standards for agent communication on these platforms, FIPA was formed [19]. FIPA based platforms include JADE and SPADE [16], [20]. Improvements such as SimJade have been designed over time [4]. Both have an agent messaging and addressing service but no GIS functionalities. Agent communication and GIS functionalities were combined in [21]. This was addressed in A-globe and its variants, AgentPolis and the one most relevant to this study, Flexible Services Mobility Testbed [21], [22].

Applications of Agent Technology in transport control and management can be found in [22]. Determining the best platform to use is not a trivial process [26]. Any of these can be used to simulate a supply chain such as the one discussed in this paper. However, the simulation exercise would vary in difficulty, presentation and the type of results generated. Apart from capability, the simulation objectives, required expertise, technical support and cost are other factors to consider.

G. Initialization

In the case of a supply chain simulation, the starting point is the interaction between the customer and the supplier [26]. This is in the form of customer orders which are forwarded to the transporter who acts as a mediator between the two. Customer orders therefore trigger the movement of transporting vehicles. In actual multi agent supply chain systems, real-time information has been used [27], [28]. On the other hand simulation models have used historical order information that has been stored on a database [26].

Since the objective is to investigate the impact of change in existing trade corridors, knowledge of all the role players and their contributions is cardinal to the success of the investigation. In order to have relevant results, models of existing roads, borders, weighbridges, checkpoints, customers, suppliers and transporters are essential. The information required is readily available. The operational procedures currently followed at weighbridges and border-posts would be the starting point for weigh bridge and border models, including the personnel. Proposed changes to these procedures can be built into the simulation model to experiment with improved operational design.

To trigger cargo dispatches one method is to use order information. This can be order information from customers, or transporter schedules. The transporter agents can simply dispatch consignments using schedule information. The second approach is to analyze existing orders or schedules and developing models which can generate orders which are statistically equivalent to the existing ones as shown in [26]. Random number generators together with appropriate distributions can be used to generate similar orders, truck allocations, and destinations. Fig. 4 shows the variation in destinations, dispatches per day, and trucks for a week's schedule.

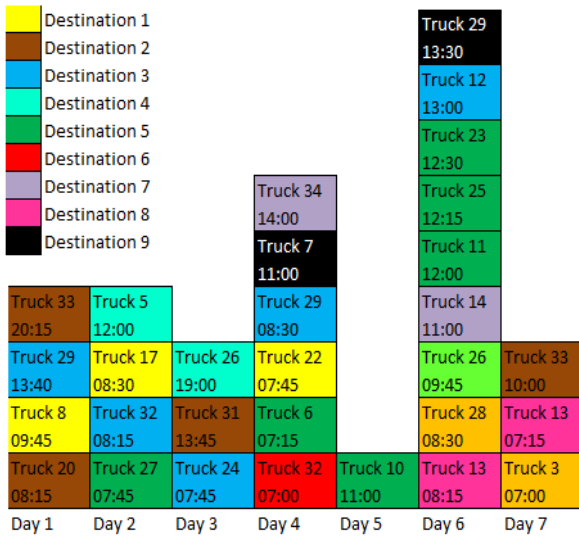


Figure 4. Dispatch data from a truck schedule sheet [29]

When automatically generating dispatch orders, aspects such as time of issuing the order, the destination, the cargo carried and its amount or weight need to be addressed. The order can be randomly generated but the time of dispatch should take the "border crossing time" into consideration for international deliveries. The dispatch time can be computed as follows,

$$t_{\text{dispatch}} = \frac{bcd}{\bar{s}_{\text{truck}}} - bct - \delta_{\text{tim}}, \quad (2)$$

where bcd and bct are border crossing distance and border-crossing time respectively. δ_{tim} is the overall en route time delay and $\bar{s}_{\text{truck}}$ is the average speed of the truck. The time delay, δ_{tim} has got many constituents such as,

$$\delta_{\text{tim}} = \delta_{\text{wb}} + \delta_{\text{cp}} + (n_{\text{rob}} \times \bar{t}_{\text{rob}}) + \delta_{\text{b}} + \delta_{\text{TJ}}, \quad (3)$$

where δ_{wb} , δ_{cp} and δ_{b} are the average weigh bridge, checkpoint and border delays. n_{rob} is the number of traffic lights and $\bar{t}_{\text{rob}}$ is the average time spent at each one. A random variable δ_{TJ} , specifies possible traffic jams or road blocks. Lists of destinations and loads can be linked to the loading centres. For an order, the type of consignment and customer can be randomly selected based on existing associations in the lists.

It is important to consider the dynamic nature of supply chains [26], [28]. This can be due to the volatility in exchange rates, changes in market associations and simply canceled orders. Incorporating future trends makes it necessary to develop a dynamic model. A customer such as a retailer normally orders goods. When the average rate is known, future order rates can be generated as follows,

$$\text{Future}_{\text{orde r}_{\text{rate}}} = \text{Past}_{\text{orde r}_{\text{rate}}} \times \alpha \frac{f(\beta_{\text{OLD}})}{f(\beta_{\text{NEW}})} \quad (4)$$

where $f(\beta_{\text{OLD}})$ and $f(\beta_{\text{NEW}})$ are functions of the old and new exchange rates. α is a tuning factor.

It is non-trivial task to initialize, calibrate and run such a supply chain model because it is impossible to obtain all the information about every transporter using a particular corridor. Furthermore, the corridors also have other traffic, moving on them. These too, have an impact on the journey. Such information is necessary in order to analyze the operations at border-posts and weigh bridges. A strategy is therefore necessary to calibrate the model using a limited dataset before investigating the impact of other operational and monitoring options.

H. Calibration and verification

In order to accurately calibrate a model, historical data is required [26] [28]. The following strategy can be used to calibrate the model. Firstly, generation of orders to transport should be as close as possible to historical records. Secondly, traffic volume data or statistics at a choke point in a corridor should be available. The network can be constructed as shown in Fig. 5.

From Fig. 5, "A", "B" and "E" are loading centers on the transporter side. "D" and "C" are customers or destinations. The supplier "B" and destination "D" are used to tune the network i.e. to generate traffic to compensate for the unknown traffic volumes from other sources, reflecting in the historical "traffic volume data". The volume data for the checkpoint can be used as a threshold. Once the model has been tuned, the operations at the checkpoints can then be adjusted to analyze their impact on the overall performance of the supply chain.

A calibrated transportation chain model can be of great benefit to all the stake holders. The advantage it has is to be able to live through what happened in the past and be able to see the actual occurrences of what would have been the case had operational procedures been different. On the other hand, using automatic scheduling, has the advantage of taking into account the major market changes, infrastructure development or depreciation and any other future changes which can have an impact

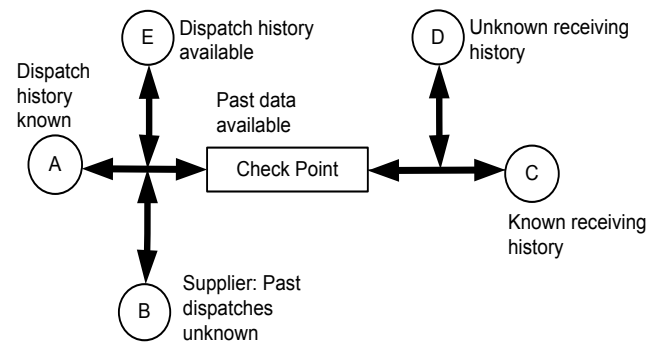


Figure 5. Network construction for calibration

V. CONCLUSIONS AND FUTURE WORK

In this paper, the current scenario and operations of a supply chain have been described. Some causes of the inefficiencies in supply chains have been discussed. Methods which can be taken to improve current scenarios have been described and the development of a simulation platform was motivated. The modeling aspects such as model construction, initialization, and calibration, have been described. The options available to use as simulation platform have also been identified and compared. Such a platform will be the most cost-effective approach for performing simulated experiments to investigate the impact of potential improvements.

The model can be extended to include economic and financial aspects to also simulate the costs and gains of implementing the various systems and to provide a more accurate perspective than what was done in previous studies e.g. [1]. Furthermore, including communication network elements to determine the most optimal networking alternatives can be beneficial. This will generate the required evidence to guide supply chain stakeholders regarding investments into future systems.

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Impact of a radio-frequency identification system and information interchange on clearance processes for cargo at border posts

Authors:

Ernest Bhero¹
Alwyn Hoffman²
Kabanda Lusanga²
Arno de Coning²

Affiliations:

¹Discipline of Electrical,
Electronic and Computer
Engineering, University of
KwaZulu-Natal, South Africa

²School of Electrical,
Electronic and Computer
Engineering, North-West
University, South Africa

Correspondence to:

Ernest Bhero

Email:

bhero@ukzn.ac.za

Postal address:

PO Box 51442, Durban 4062,
South Africa

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Background: Improved operational efficiency is important to role players in cross-border logistics and trade corridors. Cargo owners and cargo forwarders have been particularly concerned about long delays in the processing and clearing of cargo at border posts. Field studies suggest that these delays are due to a combination of factors, such as a lack of optimum system configurations and non-optimised human-dependent operations, which make the operations prone to corruption and other malpractices.

Objectives: This article presents possible strategies for improving some of the operations in this sector. The research hinges on two key questions: (1) what is the impact of information interchange between stakeholders on the cargo transit time and (2) how will cargo transit time be impacted upon by automatic identification of cargo and the status of cargo seals on arriving vehicles at the border?

Method: The use of information communication systems enabled by automatic identification systems (incorporating radio-frequency identification technology) is suggested.

Results: Results obtained by the described simulation model indicate that improvements of up to 82% with regard to transit time are possible using these techniques.

Conclusion: The findings therefore demonstrate how operations at border posts can be improved through the use of appropriate technology and configuration of the operations.

Introduction

There is a strong connection between the economic growth of a country and the efficiency of its logistics (Laksmanan & Anderson 2002). This article presents an investigation of cross-border operations with a view of improving their efficiency. Cross-border operations are an integral part of the economic activities of any country as all countries need to import or export goods owing to the increasing globalisation of trade. The Beitbridge border post, which is located between South Africa and Zimbabwe, will be investigated in detail as it is one of the busiest border posts in sub-Saharan Africa. The aim of this investigation is two-fold: (1) to determine the nature and the underlying causes for the observed delays at this border post and (2) to determine how the observed delays would be affected if the border post operations were to be modernised and reconfigured.

To quantify the impact of the various proposed measures on improving the efficiency of a border post, a few possible approaches can be followed. Firstly, through logical reasoning one can estimate the likely impact of individual factors (e.g. the sharing of data) on processing time. This will, however, ignore the interactions between different activities involving the same consignment, as well as between the simultaneous processing of large numbers of different consignments. Most of the difficulties around border post delays result specifically from the somewhat chaotic behaviour that is observed when high levels of congestion are experienced, resulting in one process being delayed by another and one consignment queuing behind others. The cumulative effect of delayed processes becomes intolerable. This approach will therefore not be able to quantify the likely impact of permutations of various scenarios accurately.

A second possible approach is to perform practical experiments of actual delays at border posts by implementing different sets of operational practices and supporting systems. Although this may yield the most reliable results, the costs and involvement required from independent stakeholders renders it not practically feasible. To some extent this approach was used by Fitzmaurice (2009, 2012) in studies at various border posts, including Chirundu, a border post between Zimbabwe and Zambia. The results from the Chirundu One Stop Border Post (OSBP) study describe the

impact of a specific set of measures against which the current study can be compared. However, the Chirundu OSBP systems do not include any of the measures investigated in this article.

We opted to construct an accurate model of the current border post and the proposed improved system, and to simulate the expected performance of different scenarios as defined by the different modes of operating the cross-border systems. This allowed the investigation of several different options at a lower cost than with physical deployments. It also allowed for comparing the expected levels of performance for the different scenarios. Based on the results, recommendations could be made for future border systems.

We first present the problem statement for this study, followed by a literature review that informs the analysis of an empirical study performed at a typical border post to measure the average delays experienced by freight (Curtis 2009; Fitzmaurice 2009, 2012). A description of a simulation model for the present border post operations follows, together with validation of the model. Here we discuss the impact of possible alternative configurations for the border post operations based on scenario analysis using the simulation model. The impact of each of the following scenarios was investigated:

- the pre-declaring of consignments
- changing customs processing capacity in response to expected congestion
- information exchange between consignors and customs enabled by auto-identification systems
- the use of a more intelligent customs risk engine and management system (CREMS).

The results of the simulation study are subsequently presented and discussed, followed by concluding remarks. Suggestions for future work are included in the conclusion.

Problem statement

The need for improving border posts and trade corridors' operational efficiencies has been debated for a long time (Barka 2012; Norov & Akbarov 2009). In the case of cross-border clearance processes, cargo owners, freight forwarders and cargo transporters are interested in shorter delays in crossing the border posts. However, many governments, particularly in Africa, want to maximise the revenue from customs duties. These governments therefore implement stringent measures at the borders to achieve their objective, which causes long delays at the border posts.

Effective management of road transport is further complicated by a wide spectrum of independent stakeholders being involved. The cross-border movement of a freight consignment involves at least the cargo owner (or consignor), the transporter, sometimes a transport broker, a freight forwarder, a clearing agent, roads agencies, customs authorities on each side of the border, and a customer (or consignee). Commercial players have objectives that are well aligned

TABLE 1: Monitored transit delays at Chirundu border post for north-bound traffic before and after the border post being converted to a one-stop system.

Comparative category	Delay time (hours) in current system (OSBP)	Delay time (hours) in previous system (pre-OSBP)
Clearing agent	12.31	6.00
Customs	45.27	21.00
Driver idle time	14.06	11.00
Immigration	0.31	< 1 min
Document processing	57.58	27.00
Inspection time	1.14	1.00

Source: Fitzmaurice, M., 2012, 'TLC report on Beitbridge, Chirundu, Kasumbalesa and Nakonde', report, Transport and Logistics Consultants (TLC), Port Elizabeth OSBP, One Stop Border Post.

and aimed at improved operational efficiencies. Agencies responsible for protecting roads infrastructure and collecting customs duties are, however, more concerned about the effectiveness of control measures aimed at the prevention of illegal practices (Siror *et al.* 2010) and collection of maximum duties.

Current cross-border freight management systems are characterised by a lack of transparency from the perspective of the consignor and consignee and by little coordination between the actions of different role players. The lack of visibility of operations at ground level typically results in long delays at border posts accompanied by many corrupt practices, which often go hand in hand (Fitzmaurice 2009; Thomas, Khadr & Girishankar n.d.). Although the lack of integration between the systems operated by different stakeholders is partly to blame, deliberate manipulation of the process by human operators (who know that their actions are difficult to police) also plays a notable role, as shown by empirical data from a comparative study at the Chirundu border post (Fitzmaurice 2012; Mpata 2011) between Zimbabwe and Zambia (Table 1). In an effort to improve the operational efficiency of the Chirundu border post, it was converted from a legacy border post (two different and separately housed customs or immigration authorities) to an OSBP (both authorities housed in one building). Observations from Table 1 indicate that some of the delay times have instead doubled after the conversion, eroding the objectives of an OSBP.

At present, the average transit time for goods to cross the Beitbridge border is 26.88 hours (Fitzmaurice 2012). This average transit time is too high if the exporters or importers are to be competitive at the global level. The aim of this study, therefore, is to investigate the possibility of an improved system that can cater for the needs of all stakeholders. Governments in Africa should be able to enforce regulations effectively as well as maximising collection of revenue in the form of duties. On the other hand, exporters, importers and transporters should enjoy shorter transit times at the border posts. Different measures aimed at improvements are proposed and the impact of each of these, as well as their combined effect, is determined using a simulated model.

Literature review

Fitzmaurice (2009, 2012) conducted fieldwork at designated border posts to determine the causes for long delays. The

work formed part of the activities of Trade Mark South Africa, which was a trade facilitation initiative funded by the UK government through its Department for International Development. The results of this fieldwork have been used extensively in this article to calibrate the simulation model. As there is limited relevant literature for the work discussed in this article, the work of Fitzmaurice (2009, 2012) was useful in many respects. For example, the results of the Chirundu border post study (Table 1) shows that human conduct can have adverse effects on the operation of various systems. The transaction time was expected to be shorter for an OSBP than for a legacy border post. In contrast, the results show the opposite to be true. This was attributed to negative human conduct: customs officials who receive information about approaching consignments earlier have more time to select consignments to be subjected to extortion, leading to increased rather than reduced delay times for such consignments. This observation further supports the view that automating most of the operations and close monitoring of human conduct to foster accountability offer a solution.

In a similar study (Hsu, Shih & Wang 2009), the processing of import cargo at an air cargo terminal was investigated. A flow network model that includes cargo, information and human flow was developed and the performance was tested. A system based on radio-frequency identification (RFID) was

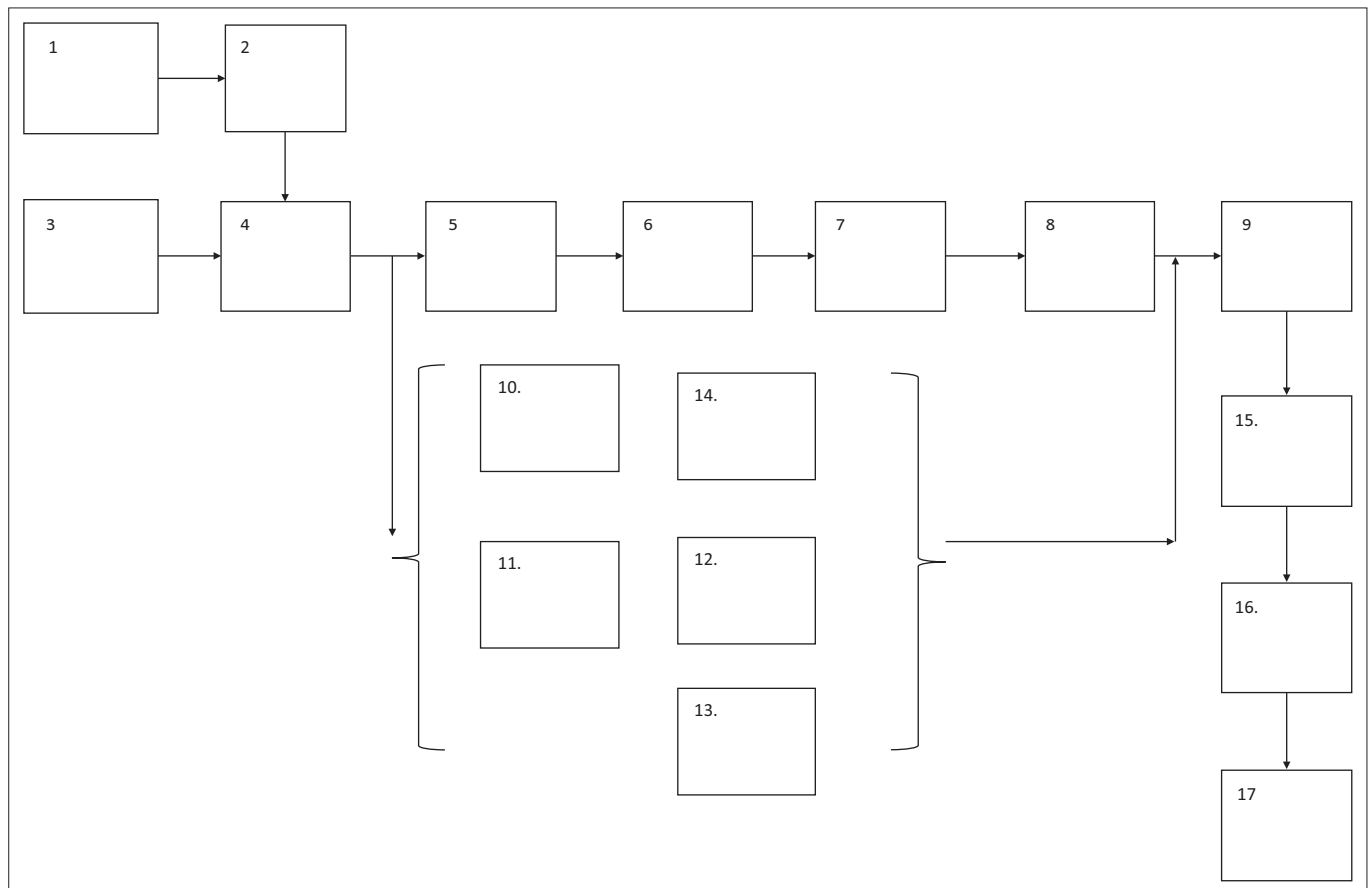
introduced in some operational units to replace some manual operations, such as the cargo identification function and locating the position of cargo. The results showed a decrease in cargo owners' inventory costs and terminal operators' labour costs by about 63%. Following from the approach proposed by Hsu *et al.* (2009), Hoffman, Lusanga and Bhero (2013) proposed and developed a related approach for border cargo clearance in the case of non-air cargo. The model reported on in this article essentially builds on that approach through the formulation, design and building of a simulation model.

Fieldwork at the Beitbridge border post

In this section, the empirical work conducted to evaluate cargo processing time at the Beitbridge border post will be considered. The result of this analysis formed the basis for developing a cargo processing model for border post operations.

Typical flow diagram for border post processes

Figure 1 shows the process flow diagram for a consignment crossing a typical border post (Fitzmaurice 2012). The activities in the flow diagram in Figure 1 are defined in Table 2. It should be noted that the steps in Figure 1 are for only one side of a border; these steps are repeated on the other side of a border. Also worth noting is that some operations are performed



Source: Bhero, E. & Hoffman, A., 2014, 'Optimizing border-post cargo clearance with auto-ID systems', *Journal of Machine to Machine Communication* 1, 17–30

FIGURE 1: Typical work flow at a border post, such as Beitbridge between South Africa and Zimbabwe.

in parallel. For example, when customs officials collect declarations documents for processing (Figure 1, block 8), processes such as the driver going through immigration, vehicle weighing and vehicle scanning can go ahead.

Beitbridge border post cargo transit times

The cargo transit times presented in this section were obtained from the fieldwork of Fitzmaurice (2009, 2012). These results were comparable with those from other sources (Curtis 2009; Globaltrack 2015).

Table 3 shows a breakdown of the processing steps and associated times for consolidated cargo type at the Beitbridge border post. Consolidated cargo was chosen because its processing steps and associated waiting times result in consistently long delays compared with other cargo types. This is because multiple, separate consignors and consignees use a single transporter in a consolidated cargo consignment.

Thus, each cargo owner will have to complete separate declaration forms and each is likely to use a different clearing agent. This explains the long delays reflected in Table 3 and, more importantly, the long delay in waiting for payment of

duties. The total average border transit time (60.9 hours) was calculated as the total delay time (for the steps in Table 3) over 4 months (1950.25 hours) divided by 32 observed cargo trucks (Fitzmaurice 2009).

Table 4 shows the average transit times measured for the four main cargo types that were observed by Fitzmaurice (2009, 2012). These transit times represent the time to cross the border. The notable difference in transit time between consolidated cargo and refrigerated cargo relates to refrigerated cargo often consisting of a single commodity or only a few different commodities (usually) from the same exporter, whereas consolidated cargo often has multiple, separate exporters using a single transporter. The same argument applies to the tanker cargo type. The average transit time across all cargo categories shown in Table 4 is 26.88 hours.

Table 5 shows average transit times at a number of regional border posts (South Africa–Zimbabwe, Zimbabwe–Zambia and Zambia–Democratic Republic of Congo) for four consecutive weeks in 3 months in 2015 (Globaltrack 2015). The times are based on satellite, GPS and GSM tracking data.

The average transit time for all cargo types at Beitbridge (South African and Zimbabwean sides combined) has been calculated as 23.75 hours, which is comparable to that reported by Fitzmaurice (2009, 2012). In this article, the findings of Fitzmaurice (2009, 2012) are used extensively because they present detailed data and analysis not only of the delays associated with each cargo type but also of the delays at every step in the cross-border processing. However, the average transit time calculated from the data in Table 5 conceals underlying disparities (e.g. a delay of up to 60 hours for consolidated cargo). It would be prudent to investigate the economic impact of such delays on operators whose primary means of transport is the consolidated cargo arrangement.

TABLE 2: Processing steps at a border post.

Step	Description of activity
1	Lodging manifest for pre-clearance
2	Pre-clearance and pre-payment
3	Travel from origin to the border
4	Cargo arrives at the border
5	Driver submits documents to the clearing agent
6	Agent works on the documents before submitting to customs
7	Agent submits documents to customs
8	Customs process clearance
9	Payment of customs duties and other payments
10	Driver goes through immigration
11	Vehicle weighing
12	Vehicle goes through scanning process
13	Physical inspection of cargo
14	Inspections by other border agencies
15	Customs release cargo documents to the agent
16	Agent hands documents to driver
17	Cargo leaves the border

Source: Bhero, E. & Hoffman, A., 2014, 'Optimizing border-post cargo clearance with auto-ID systems', *Journal of Machine to Machine Communication* 1, 17–30

TABLE 3: Transit times for various processing steps applicable to consolidated cargo at the Beitbridge border post.

Transaction type	Average transit time (hours)
South African clearing agent	3.7
Zimbabwean clearing agent	2.7
South African revenue services	26.2
Zimbabwe revenue authority	28.5
Driver idle time	1.8
Weighbridge	0.6
Waiting for duties	25.8
Documentation errors	0.9
Transporter delays	1.8
Total border transit time	60.9

Source: Fitzmaurice, M., 2012, 'TLC report on Beitbridge, Chirundu, Kasumbalesa and Nakonde', report, Transport and Logistics Consultants (TLC), Port Elizabeth

TABLE 4: Average transit times for different cargo types based on data measured at Beitbridge border post.

Cargo type	Average transit time (hours)
Consolidated	60.9
Refrigerated	7.5
Break bulk	30.2
Tanker	8.9
Across all cargo types	26.9

Source: Fitzmaurice, M., 2012, 'TLC report on Beitbridge, Chirundu, Kasumbalesa and Nakonde', report, Transport and Logistics Consultants (TLC), Port Elizabeth

TABLE 5: Average transit times at a number of regional border posts, based on satellite, global positioning system or mobile system tracking.

Border post†	Week 1	Week 2	Week 3	Week 4	Average over period
Beitbridge (South Africa)	17	15	14	14	15
Beitbridge (Zimbabwe)	8	9	8	10	9
Chirundu (Zambia)	15	14	14	22	16
Chirundu (Zimbabwe)	12	11	13	9	11
Kasumbalesa (Democratic Republic of Congo)	26	29	28	26	27
Kasumbalesa (Zambia)	70	18	17	26	32

Source: Transit times supplied by Globaltrack (<http://www.globaltrack.com>)

†, Country designations refer to the side of the border.

Simulation of processes at a border post

In this section, a simulation model for typical border post processes is discussed, based largely on what Hoffman *et al.* (2013) proposed. The simulation results for the legacy system (i.e. the status quo of operations and systems) are first compared to the empirical data, with the model then being refined until the simulated results concur with reality. This serves to validate the model, increasing the level of confidence in the results generated for modified scenarios. Once the simulated model is calibrated in this way, the proposed new concepts can be added and the associated changes in behaviour can be studied.

The simulation model was implemented using Simio simulation software (Simio 2013). Simio supports object-oriented simulation and facilitates rapid development and simulation of complex systems (Kelton, Smith & Sturrock 2014). In developing the simulation model, the steps causing the longest delays (Table 3) were incorporated. In a queuing system, the step associated with the longest delay is a determining factor of the time spent in the queuing system. Thus, a detailed state flow diagram was constructed for each participating entity and for each of the essential steps in the process (see Figure 2). This allows the model to measure time spent within each process step and the impact of each input factor on these process times, exposing the internal variability for various system steps and their sensitivity to

various factors. In the process it was possible to develop a realistic simulation model that can be used to refine the various design parameters of an overall cross-border system.

Flow diagram of operations at a typical border post

Figure 2 shows a portion of the flow diagram for operations at a border post:

- Block 1 represents the number of clearing agents stationed at the border. In the simulation model, eight clearing agents were assumed; in reality, the number of agents at the border far exceeds eight. A Poisson distribution is used for the processing time associated with a clearing agent (Kelton *et al.* 2014). A Poisson distribution was preferred over a Gaussian distribution as it ensured that processing time would always be positive whilst allowing for a gradual reduction in probability as processing time increases beyond the average time.
- Block 2 represents a number of customs teams. In the simulation model, the number of working teams was variable. A triangular distribution model is applied owing to the large variability in processing time due to the type of cargo; even for the same cargo type, there is substantial variability in processing time. The triangular distribution caters for the minimum, mean and maximum observed transit times.
- Block 3 represents possible delays that can occur due to error in documentation. A Poisson distribution is used.

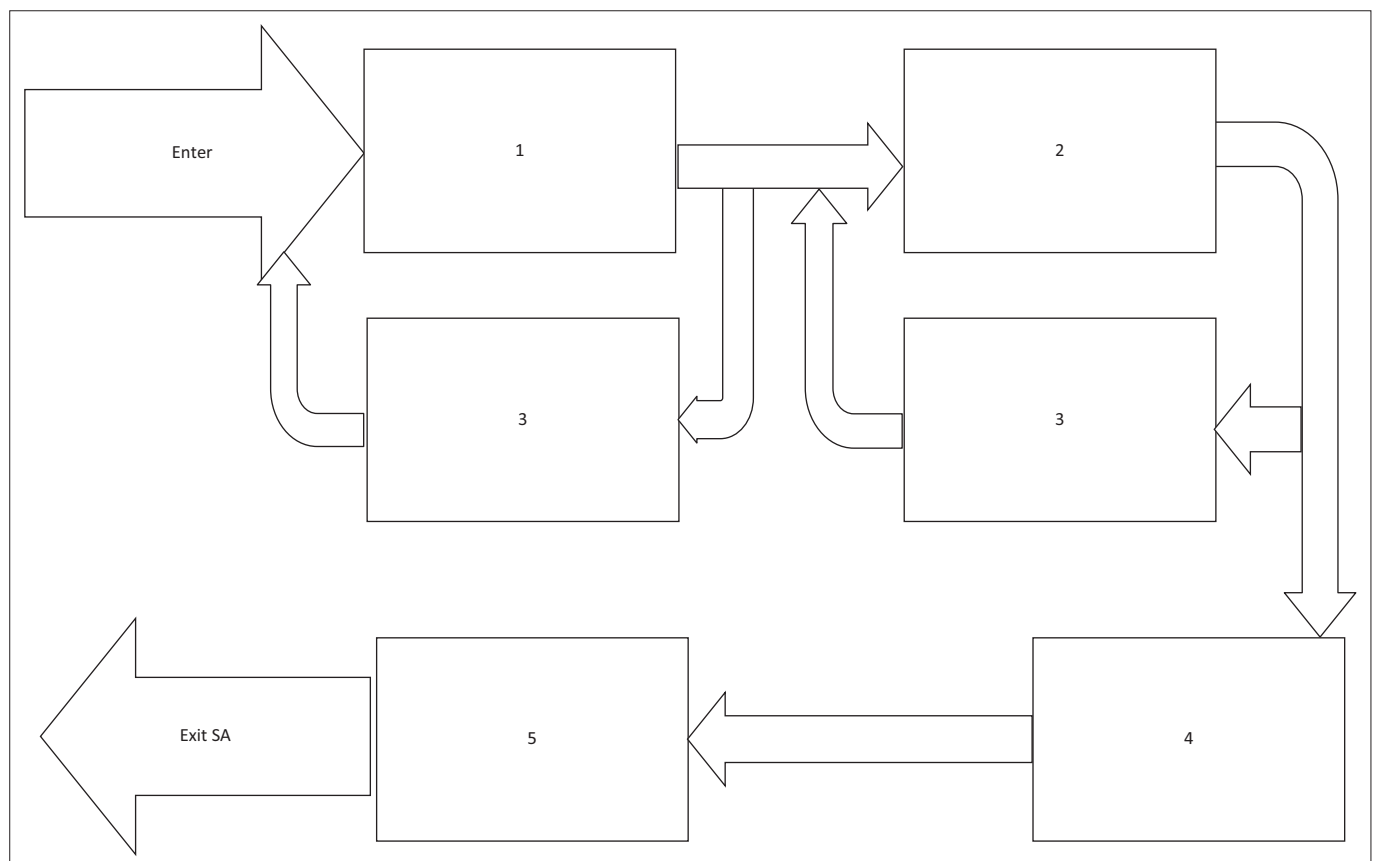


FIGURE 2: Flow diagram of typical processes at a border post.

- In block 4 a triangular distribution is used owing to the large variability in processing time based on cargo type.
- Block 5 includes steps such as immigration, weighing and scanning processes. These operations represent minimal delay times at the border posts and a Poisson distribution is used for each.

Owing to restricted space, Figure 2 represents a condensed version of the actual flow diagram that was fed into the simulation software. It is worth noting that the steps shown in Figure 2 are repeated when cargo enters the destination country at the next border.

Figure 3 shows a detailed logic flow diagram for border post operations.

This flow diagram indicates possible sources of long delays in the present operations at border posts:

- Block 1: Both Fitzmaurice (2009, 2012) and Curtis (2009) reported that drivers often do not submit clearing documents to the clearing agent immediately when they arrive at the border. Drivers are likely to first engage in personal activities before handing over documents to the clearing agent. The reports indicate that these delays can last up to 4.5 hours. Therefore, this part of border processes needs to be improved if border transit time is to improve.

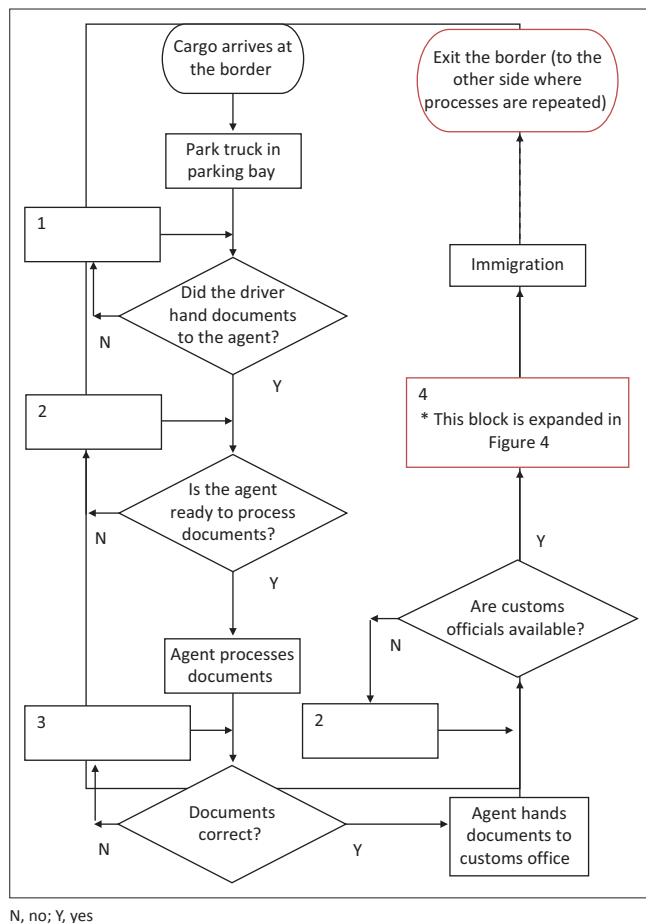


FIGURE 3: Logic flow diagram for typical operations at a border post.

- Block 2: Adding declaration documents to a queue is understandable because the number of clearing agents at the border is finite and a minimum of 1.1 hours is required to process documents (Fitzmaurice 2009, 2012). The same argument applies to the customs officials when there is no available (i.e. unoccupied) customs official to start processing an incoming declaration (block 2). Queuing documents causes the average processing time at these steps to increase unduly. It can therefore be stated that these parts of border processes need to be improved if transit time is to improve.
- Block 3: The delays due to errors in the documents are minimal compared with delays associated with other processes such as customs (Fitzmaurice 2009, 2012). For example, consolidated cargo was reported to have an average delay of approximately 1 hour whereas refrigerated cargo had no delay time. As consolidated cargo often consists of cargo from several separate importers or exporters, multiple declarations are often tendered, which increases the probability of errors.
- Block 4 represents the most significant component of delays in border transit time. For this reason, the internal processes within this block are expanded and illustrated in Figure 4.

The flow diagram in Figure 3 offers a suitably accurate process model for operations at a border post. However, there are other minor delays that are not apparent from Figure 3. These include queuing of trucks to go through the border gates, queuing to enter the inspection bay, queuing to enter the scanning bay, and so on.

Figure 4 shows a detailed state diagram for customs processes. A state diagram shows the behaviour of a system that is triggered by a specific event. The customs officials manually inspect the declaration documents for errors and infractions, physically inspect the majority of cargo and then capture declarations (for duty determination) on a computer.

It is evident from Figures 3 and 4 that in most of the steps associated with delays, notable human action is required. What is being proposed, therefore, is the reduction of human involvement in operations at a border post and, at a bigger scale, in all multinational trade corridors. Extensive use of auto-identification systems is proposed, including GPS tracking of consignments from origin to border post, barcodes to scan documents, and RFID technology to identify vehicles arriving at processing points and to check cargo seals. In this article only a subset of the proposed auto-identification techniques is investigated; the rest will be addressed in future research.

From Figure 1 and Table 3 it is apparent that customs processes (document processing performed by customs officials and the clearing agents) contribute the longest delays. Currently customs authorities such as the South African Revenue Services already use electronic data interchange between the cargo owners or their agents and the customs

authorities. The manual verification of documents carried by the driver at the border is, however, still compulsory. This not only results in delays and mistakes, but also offers a convenient opportunity for drivers who wish to extend their stay at the border.

Thus, it is proposed that electronic documents (with essential information encoded as 2D barcodes or embedded with an RFID tag) are used to carry the most important information as normally found in the manifest document and declaration or consignment data. Scanning of documents will not only eliminate many human errors, but also provide an electronically captured record of when documents changed hands. This will allow the consignor and consignee to obtain valuable insight into the status of operations at the border

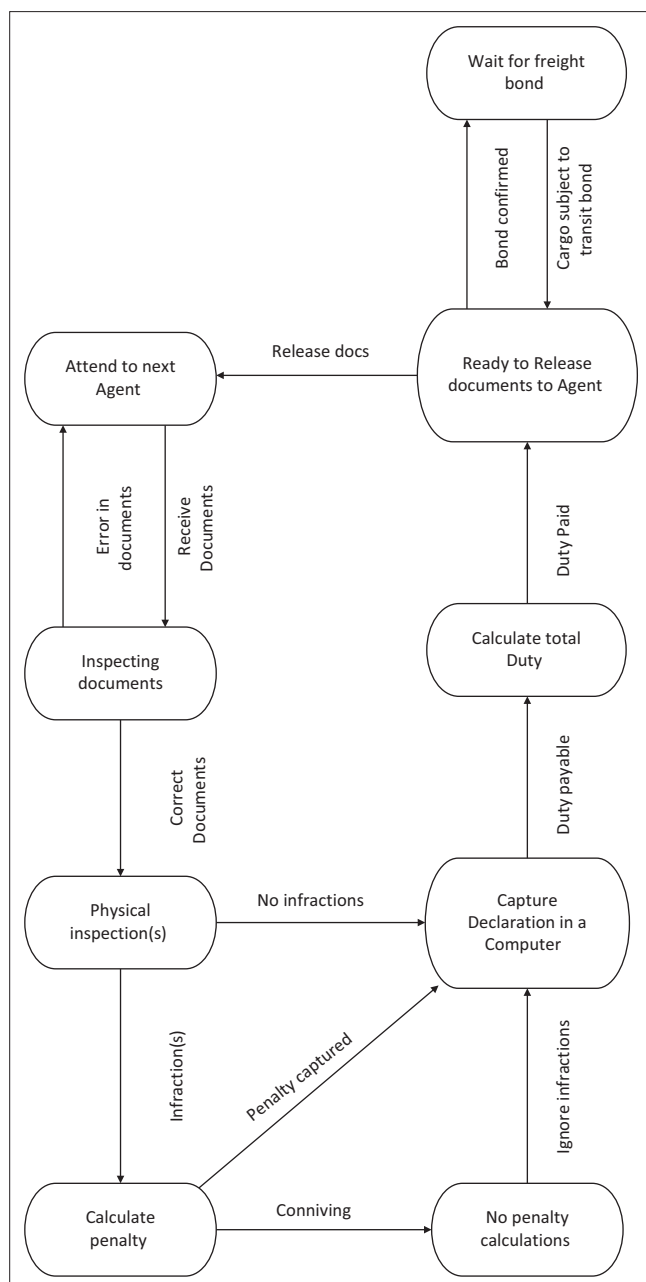


FIGURE 4: State diagram of internal processes during customs processing at a border post (expanded from Figure 3).

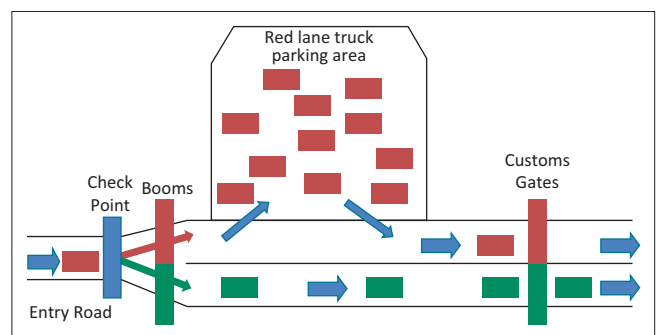
and allow delays and processing times to be recorded and measured.

In addition, it is proposed that cargo vehicles are tagged so that the RFID readers at the entrance to the border can automatically identify consignments as they arrive. The consignment identity can then be fed to the control centre, which initiates immediate processing of the consignment. The CREMS of the customs authority will determine the risk profile of the consignment and alert the inspection team(s) whether to physically inspect a particular cargo or not. This will furthermore enable compliant consignments to be separated from potentially non-compliant consignments upon arrival at the border, preventing a situation where fully compliant consignments have to queue behind non-compliant ones. This process of physically separating consignments upstream from where the clearing process takes place is depicted in Figure 5 (Hoffman *et al.* 2013).

All the mentioned information interchange is achieved electronically, which improves the rate of document and vehicle processing. The human labour freed from these tasks can thus be deployed elsewhere, typically to inspect suspicious consignments detected earlier. Implementing the described system can substantially reduce human involvement in the processing of consignments and can eliminate face-to-face contact between customs officials and transporters for fully compliant consignments. This can eliminate the primary cause of corruption and unnecessary delays. The proposed system is therefore expected to improve the performance at border posts with regard to not only speed but also accuracy and transparency (Bhero & Hoffman 2014).

Simulation model for typical border post processes

Based on the process flow diagrams representing the current system (Figures 2, 3 and 4), a simulation model was developed using the Simio simulation package. The simulation model was calibrated using historical field data on transit times



Source: Bhero, E. & Hoffman, A., 2014, 'Optimizing border-post cargo clearance with auto-ID systems', *Journal of Machine to Machine Communication* 1, 17–30 and Hoffman, A., Lusanga, K. & Bhero, E., 2013, A combined GPS/RFID system for improved cross-border management of freight consignments, in *Proceedings of AFRICON 2013*, Pointe-aux-piments, Mauritius, September 9–12, 2013

FIGURE 5: Schematic layout at a border post to facilitate separating consignments upstream from the clearing process. Compliant cargo is processed along the green lane, whereas non-compliant cargo is processed along the red lane.

TABLE 6: Comparison of simulated and measured transit times for processing of various cargo types at the Beitbridge border post.

Cargo type/Process stage	Time in system		Standard deviation
	Field data (hours)	Simulation (hours)	
South African side: Customs	11.95	10.69	3.44
Zimbabwean side: Customs	15.05	9.66	2.81
South African side: Break bulk	8.40	11.08	3.28
Zimbabwean side: Break bulk	12.80	10.22	2.72
Break bulk	30.20	27.01	5.11
Consolidated	60.90	51.25	5.18
Refrigerated	7.50	15.17	5.51
Tankers	8.90	14.82	5.34
All cargo	26.88	26.37	5.50

for various cargo types. For each scenario investigated, the simulator was run for a period of 500 hours, with each run comprising 200 replications. The results of the simulation are shown in Table 6.

The simulation results in Table 6 are within an acceptable range compared with the field data. Considering simulation results and the corresponding standard deviations (σ), we note that five of the simulation results are within a 1σ range and three of the results are within a 2σ range. Confidence intervals of 90%, 95% and 99% are common for studies of this nature (Wegner 2012). Furthermore, it is unrealistic to expect very high precision levels, given the inherent uncertainties related to human actions.

The simulated times for tanker and the refrigerated cargo are higher than those observed in field data. As the simulated system is essentially a queuing problem, the delay of other cargo still impacts on the average delay of all other cargo. The transit times associated with tanker and refrigerated cargo are the shortest and are likely to be affected the most.

The average delay simulated across all cargo types is 26.37 hours compared to 26.88 hours for field data (Table 4) and 23.75 hours for tracking data (Table 5). All simulated times are within the 1σ range. It can, therefore, be concluded that the simulator has been calibrated within an acceptable range of statistical uncertainty (Wegner 2012).

After calibrating the model, experiments were set up to test the following scenarios.

Pre-declaring facility (scenario 1)

In this scenario, the objective was to determine the potential effect of pre-declaring cargo on the border transit time. In pre-declarations, the declaration documentation is sent to the clearing agent before the cargo leaves the depot of origin. The rationale is that the clearing agent will process the documents, hand them over to customs for processing and possibly pay any required duties before the cargo arrives at the border. Therefore, by the time the cargo arrives, less time is expected to be spent at the border. However, although cargo would have been pre-declared,

it is possible that it could still be subjected to intrusive inspection by customs officials depending on the cargo or exporter risk profile or any other reasons that the customs officials may see fit.

In running this scenario, the percentage of cargo that is pre-declared was varied from 0% to 100%. Customs capacity was set at six on either side of the border. The border transit time was expected to decrease as the delays associated with the steps in block(s) 2 and block 3 in Figure 3 were expected to be eliminated or substantially reduced. In Figure 4, delays associated with inspecting documentation and physical inspections are expected to be similarly mitigated. It should be mentioned that in the simulation only the input percentage of pre-declared cargo is deterministic and all other processes are stochastic.

Processing capacity at customs (scenario 2)

Here the objective was to determine the impact of the processing capacity at customs on the border transit time. As customs processing contributes the longest delay in cargo processing, the rationale for this scenario was to determine the impact of parallel processing by customs on border transit time.

The processing capacity was varied from a minimum of six officials to a maximum of 25 officials working on processing and clearing cargo on either side of the border. The procedure for varying capacity involved increasing the number of customs officials by one in a sequential way on both sides of the border post and then recording the impact on processing time.

Combined strategies (scenario 3)

In this scenario, the objective was to determine the combined impact of pre-declaring cargo and customs processing capacity on the border transit time – a combination of scenarios 1 and 2. The proportion of cargo that is pre-declared was gradually increased whilst the processing capacity was kept constant. This procedure was repeated several times, with the processing capacity being changed for each new repeat. Border transit times were observed and compared.

An radio-frequency identification-enabled system (scenario 4)

Here the objective was to determine the impact of using the proposed RFID-enabled system on the border transit time. A combination of electronic pre-declaration, use of auto-identification systems (based on RFID technology) and the intelligent and dynamic changing of processing capacity at customs were investigated. In the proposed system, the term ‘compliant cargo’ is preferred to ‘pre-declared cargo’. Compliant cargo can loosely be defined as cargo for which the importer or exporter has made information available upfront to allow automated verification by means of appropriate technologies and is administrated by an importer or exporter who has a track record of good business ethics and integrity.

For intelligent, dynamically changing customs processing, it is proposed that customs authorities will be running a more intelligent risk engine. CREMS can, amongst others:

- communicate with the exporter or importer systems to facilitate electronic pre-declarations; information about when cargo leaves the depot of origin is used for estimating arrival time and hence volumes at the border at certain times
- communicate electronically with road agents, for example the South African National Roads Agency, to get information on cargo deviations on the way to the border
- advise the supervisory customs authority on expected arrival volumes at certain periods to allow anticipative increase in processing capacity
- keep a record of individual customs officials' efficiency profile or the type of cargo or specific exporter or importer often attended to by the official, which could expose potential malpractices.

The majority of these attributes of CREMS will be considered in future work; however, some preliminary features of CREMS were implemented in the current study. In this article, the research focuses on the impact of information interchange between exporters or importers and the customs

system. Therefore the proportion of compliant cargo was gradually increased from 0% to 100% whilst the simulation model was set to change processing capacity at the border adaptively in response to alerts from cargo as it left the depot of origin. The message packet includes the town of origin and departure time, which enables CREMS to estimate travelling time and hence possible arrival volumes. The border transit times were then observed.

Figure 6 shows a condensed process flow diagram at the border for the proposed RFID-enabled system. The essential features of the system include:

- substantial information exchange amongst stakeholders
- automation of many of the cross-border trade operations
- faster processing of compliant cargo as many human-dependent stages will be automated
- monitoring and policing of infractions throughout the cross-border trade corridor, with officials being held accountable.

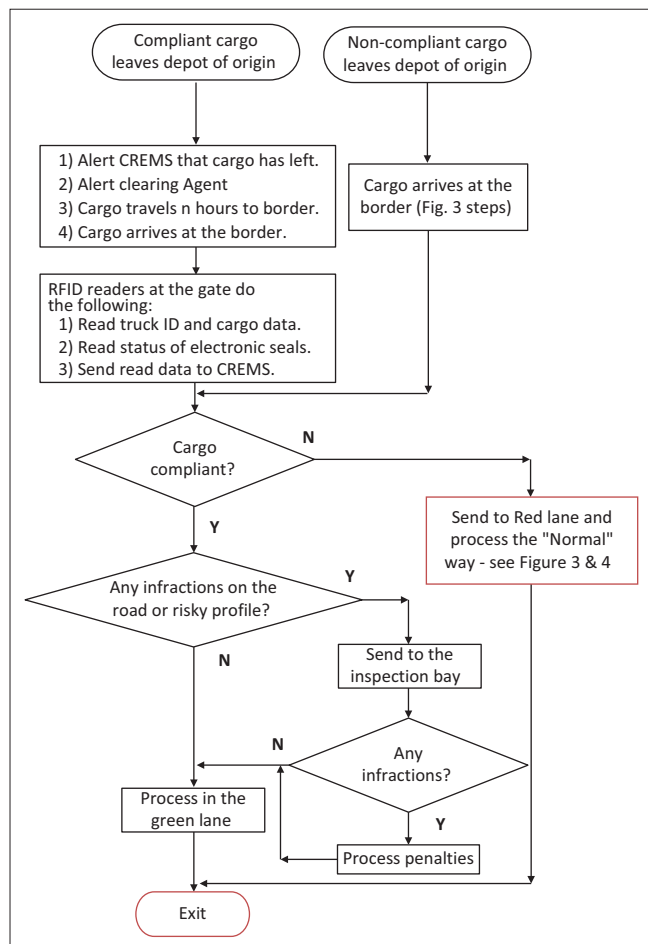
Simulation results

The results of the scenarios discussed in the previous section are presented here.

The impact of pre-declaring (scenario 1)

The proportion of cargo that is pre-declared was gradually increased and border transit times determined. The results are summarised in Table 7, with the resultant graph shown in Figure 7.

The results show that the average transit time across all cargo types decreased from 26.41 hours to a minimum of 12.53 hours at 70% of pre-declared cargo and then increased slightly to 13.60 hours at 100% pre-declared cargo. A continuous decrease is observed only for consolidated cargo; transit times for all other cargo types decrease to a minimum and then increase again slightly. This is because the number of customs officials was fixed in the simulation. Thus, as more cargo is pre-declared the demand to process pre-declarations increases beyond the processing capacity. Consignments that are normally processed very quickly (refrigerated and



N, no; Y, yes.

FIGURE 6: Condensed process flow diagram with proposed implementation of an RFID-enabled system at a border post.

TABLE 7: Simulated total transit times for different types of cargo at Beitbridge border post when pre-declaring was implemented.

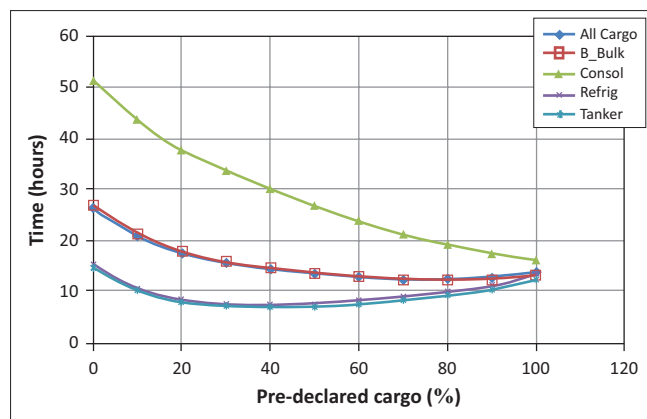
Percentage pre-declaration	All cargo (hours)	Break bulk cargo (hours)	Consolidated cargo (hours)	Refrigerated cargo (hours)	Tanker cargo (hours)
0	26.41	27.01	51.29	15.16	14.85
10	20.87	21.36	43.68	10.46	10.14
20	17.52	18.04	37.68	8.47	8.03
30	15.63	16.03	33.78	7.59	7.17
40	14.44	14.64	30.15	7.42	6.96
50	13.51	13.68	26.88	7.69	7.11
60	12.89	13.00	24.05	8.18	7.61
70	12.53	12.52	21.38	8.87	8.34
80	12.54	12.37	19.41	9.95	9.37
90	12.76	12.48	17.57	11.21	10.64
100	13.60	13.20	16.32	13.04	12.52

tankers) now have to compete with pre-declared consolidated consignments for the available customs processing capacity. Consolidated cargo shows continuous decrease because it was originally associated with a very high transit time compared with other cargo types.

The impact of processing capacity at customs (scenario 2)

The processing capacity at customs was varied from a minimum of six officials to a maximum of 25 officials on either side of the border. The resulting border transit times are summarised in Table 8, with the resultant graph shown in Figure 8.

The results show that as the processing capacity at customs increases (more customs officials available), cargo transit time decreases. This is in line with the expected outcome. A notable observation from these results is that the transit time across all cargo types levels off close to 17 hours, which is associated with a processing capacity of about 20 (10 officials on each side of the border). Beyond this capacity, the decrease in transit time becomes almost negligible. For example, at a capacity of nine officials on each side (total of 18 across both sides), the transit time is 17.85 hours. At a capacity of



B_Bulk, break bulk cargo; Consol, consolidated cargo; Refrig, refrigerated cargo.

FIGURE 7: Graph showing the effect of pre-declaration on simulated total transit times for different types of cargo at Beitbridge border post.

TABLE 8: Simulated border transit time for different types of cargo at Beitbridge border post for varying levels of processing capacity at customs.

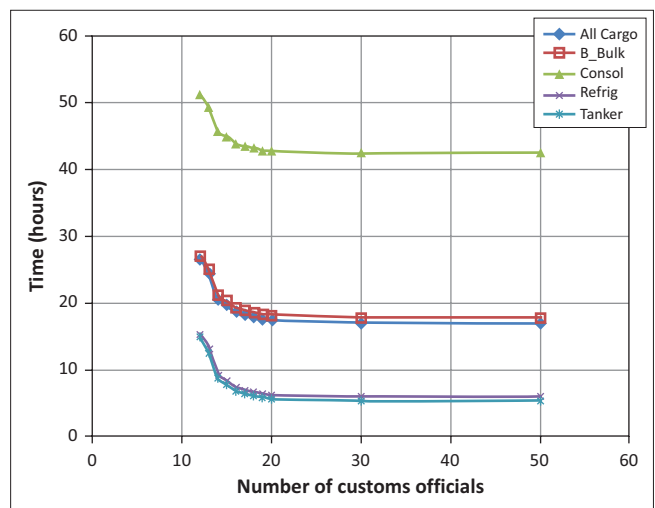
Processing capacity (number of officials)	All cargo (hours)	Break bulk cargo (hours)	Consolidated cargo (hours)	Refrigerated cargo (hours)	Tanker cargo (hours)
12	26.41	27.01	51.29	15.16	14.85
13	24.27	24.99	49.36	12.95	12.53
14	20.49	21.13	45.71	9.01	8.68
15	19.52	20.31	44.97	8.10	7.72
16	18.59	19.26	43.88	7.19	6.78
17	18.14	18.81	43.55	6.75	6.34
18	17.85	18.53	43.23	6.47	6.04
19	17.47	18.22	42.80	6.23	5.75
20	17.39	18.09	42.84	6.11	5.61
30	17.12	17.83	42.49	5.80	5.33
50	17.10	17.82	42.55	5.83	5.34

25 officials on each side of the border (a total of 50 across both sides), the transit time is 17.10 hours. This represents a change of 0.75 hours for a 15-official increase in capacity.

The result shows that simultaneous processing by customs officials has a limit beyond which it ceases to be beneficial. It further shows that to achieve better performance in a system that involves a series of potentially parallel processing units, coordination of the various units is required; that is, some form of inter-unit (inter-process) communication is needed. For example, increasing customs capacity may require a corresponding increase in the number of duty payment counters or clearing agents.

The impact of combined strategies (scenario 3)

The percentage of cargo that is pre-declared was gradually increased whilst the processing capacity was kept constant for each run. Earlier results (Figure 8) showed that a capacity of ten officials on either side of the border is optimal. Therefore, only the results for the case of varying the percentage of pre-declarations with ten officials on either side are shown. It



B_Bulk, break bulk cargo; Consol, consolidated cargo; Refrig, refrigerated cargo.

FIGURE 8: Graph showing the effect of varying levels of processing capacity on simulated border transit time for different types of cargo at Beitbridge border post.

TABLE 9: Simulated border transit time for different types of cargo at Beitbridge border post with combined effect of pre-declaration and processing capacity.

Percentage pre-declaration	All cargo (hours)	Break bulk cargo (hours)	Consolidated cargo (hours)	Refrigerated cargo (hours)	Tanker cargo (hours)
0	17.40	18.09	42.84	6.11	5.61
10	16.34	16.99	39.34	6.15	5.71
20	15.48	15.92	36.00	6.36	5.87
30	14.61	15.00	32.63	6.61	6.15
40	13.91	14.19	29.70	7.05	6.50
50	13.29	13.48	26.58	7.58	6.95
60	12.85	12.90	24.17	8.11	7.51
70	12.54	12.52	21.36	8.90	8.37
80	12.53	12.37	19.40	9.97	9.36
90	12.77	12.48	17.57	11.20	10.64
100	13.60	13.20	16.32	13.04	12.52

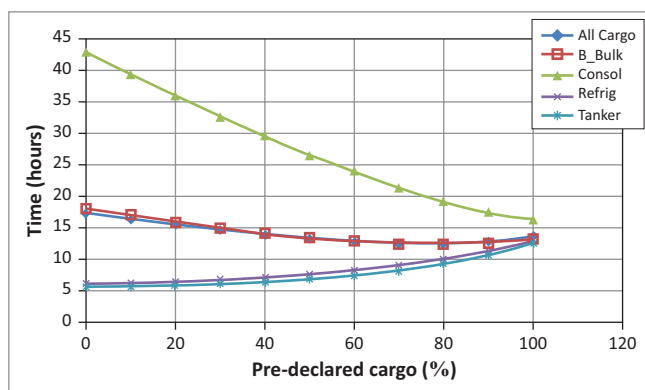
Note: Processing capacity was set at ten on either side of the border.

should be noted that the starting value for average transit time for all cargo types is set at 17.40 hours, because the starting customs capacity is ten officials (see Table 8). The results for scenario 3 are summarised in Table 9 and the resultant graph is shown in Figure 9.

The average transit time across all cargo types decreased from 17.40 hours to a minimum of 12.53 hours at 80% of pre-declared cargo and then increased slightly to 13.60 hours at 100% pre-declared cargo. As explained earlier, this is because the number of customs officials was set to a fixed number in this scenario of the simulation. Thus, as more and more cargo is pre-declared, the demand for customs processing capacity increases beyond what is available; hence the increase after reaching a minimum.

The impact of an radio-frequency identification-enabled system without information exchange (scenario 4)

In scenario 4, the percentage of compliant cargo (which is therefore processed along the green lane [Figure 5]) was gradually increased and border transit times determined. The results are summarised in Table 10, with the resultant graph shown in Figure 10.



B_Bulk, break bulk cargo; Consol, consolidated cargo; Refrig, refrigerated cargo.

FIGURE 9: Graph showing the combined effect of pre-declaration and processing capacity on simulated border transit time for different types of cargo at Beitbridge border post.

TABLE 10: Simulated border transit time for different cargo types at Beitbridge border post based on a radio-frequency identification-enabled system.

Percentage pre-determined compliance	All cargo (hours)	Break bulk cargo (hours)	Consolidated cargo (hours)	Refrigerated cargo (hours)	Tanker cargo (hours)
0	26.41	27.01	51.29	15.16	14.85
10	20.42	21.05	42.84	10.30	9.94
20	16.63	17.30	36.16	7.65	7.32
30	14.15	14.63	31.22	6.31	6.03
40	12.39	12.80	27.00	5.71	5.45
50	11.06	11.35	22.98	5.42	5.24
60	9.86	10.09	19.37	5.43	5.26
70	8.91	9.11	15.92	5.59	5.49
80	8.17	8.33	12.83	5.94	5.88
90	7.58	7.61	10.01	6.47	6.40
100	7.17	7.16	7.16	7.18	7.19

RFID, radio-frequency identification.

The results show that the average transit time across all cargo types decreased from 26.41 hours to a minimum of 7.17 hours for 100% compliant cargo. The refrigerated and tanker cargo are the only types that initially decrease and then slightly increase as the percentage of compliant cargo approaches 100%.

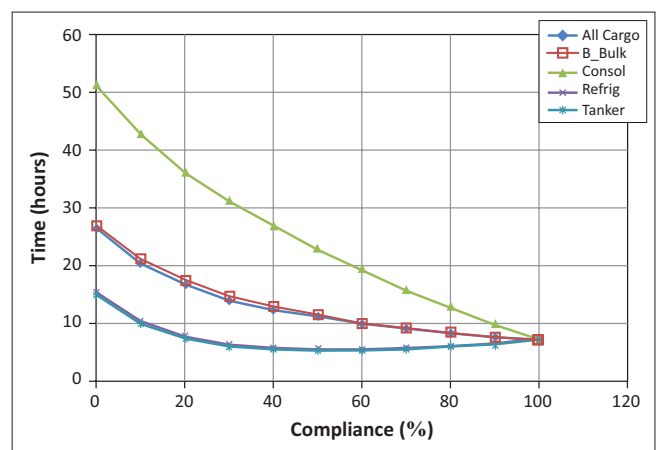
In this scenario, the processing capacity associated with the red lane was set at six on either side of the border, whereas the processing capacity associated with the green lane was set at three on either side of the border.

A similar explanation for the results is offered as for scenario 1. As shown in Figure 6, compliant cargo in the proposed system is processed through the 'green lane' (Figure 5). Thus, as the percentage of compliant consignments increases, the processing capacity of the green lanes is adversely affected. Therefore, cargo with shorter processing time is expected to experience additional queuing time. In this experiment, the processing capacity of the green lane was kept constant. As human-dependent processes are eliminated or minimised in the green lane (Figure 6), the RFID-enabled system is expected to process cargo faster. This explains the minimum of 7.17 hours observed for scenario 4.

The impact of an radio-frequency identification-enabled system with information exchange (extension of scenario 4)

Here the proportion of compliant cargo was gradually increased and border transit times determined. In addition, exchange of information was enabled. As explained earlier, as cargo leaves the depot of origin it sends a message to the customs system. This information exchange allows CREMS to estimate expected volumes of arrivals and allocate processing capacity accordingly. The results are summarised in Table 11, with a graphical representation shown in Figure 11.

The results show that, compared to the basic conditions of scenario 4, information exchange further improves



B_Bulk, break bulk cargo; Consol, consolidated cargo; Refrig, refrigerated cargo; RFID, radio-frequency identification.

FIGURE 10: Graph showing the effect of implementing an RFID-enabled system on simulated border transit time for different cargo types at Beitbridge border post. In this system, no information exchange was possible.

performance in an RFID-enabled system. With information exchange, all cargo types experience steady decreases in transit time as the percentage of compliant cargo increases (minimum transit time of 4.83 vs 7.17 hours).

In this experiment, the processing capacity of the red lane was fixed at six on either side of the border, whereas the capacity for the green lane changed dynamically from a minimum of three to a maximum of six on either side of the border.

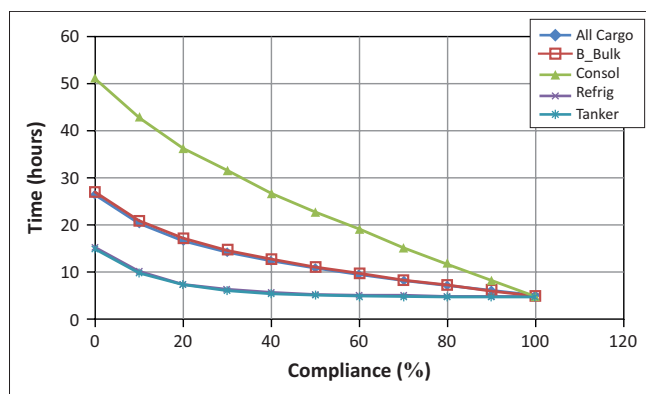
Comparison of transit time for the various investigated solutions

Figure 12 compares the simulated transit times found with the various investigated solutions. The figure shows the impact of the following conditions on transit time across all cargo types:

- pre-declaration
- processing capacity at customs
- combined pre-declaration and processing capacity at customs
- an RFID-enabled system without information exchange other than at the border itself
- an RFID-enabled system with information exchange throughout the trade corridor.

TABLE 11: Simulated border transit time for different types of cargo at Beitbridge border post based on a radio-frequency identification-enabled system that allows information exchange.

Percentage pre-determined compliance	All cargo (hours)	Break bulk cargo (hours)	Consolidated cargo (hours)	Refrigerated cargo (hours)	Tanker cargo (hours)
10	20.29	20.90	42.86	10.07	9.79
20	16.45	17.04	36.15	7.39	7.15
30	14.17	14.63	31.47	6.30	6.04
40	12.28	12.74	26.78	5.57	5.29
50	10.72	11.03	22.74	5.16	4.94
60	9.38	9.59	18.99	4.95	4.78
70	8.12	8.35	15.03	4.86	4.72
80	7.04	7.15	11.72	4.82	4.73
90	5.89	5.93	8.17	4.81	4.75
100	4.83	4.83	4.83	4.83	4.83



B_Bulk, break bulk cargo; Consol, consolidated cargo; Refrig, refrigerated cargo.

FIGURE 11: Graph showing the effect of implementing an RFID-enabled system on simulated border transit time for different cargo types at Beitbridge border post. In this system, information exchange was possible throughout the trade corridor.

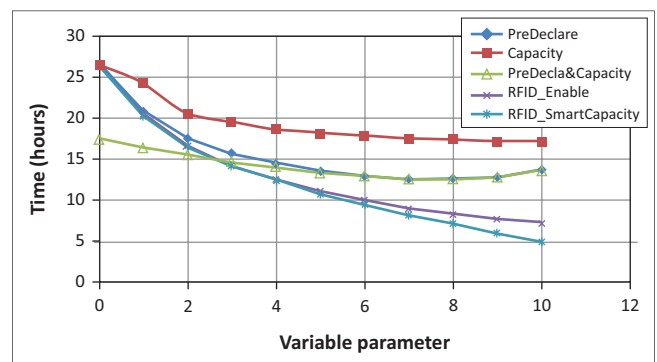
From Figure 12 it is clear that RFID-enabled systems provide a steady decrease in transit time, with the lowest value observed being 4.83 hours.

It should be noted from Tables 7–11 that for each scenario investigated, a different variable parameter was relevant (e.g. percentage pre-declarations or number of customs officials); in each case the transit times were calculated for 11 different values of the relevant variable parameter. In Figure 12, which compares transit times between the different scenarios, transit times are displayed for the 11 values used in each case; the *x*-axis therefore corresponds to different variable parameters as obtained from the respective tables.

Discussion

It is clear that the greatest reduction in transit time was obtained with the RFID-enabled system that allowed for continuous information exchange (RFID_SmartCapacity in Figure 12). Besides the exchange of information between customs and other stakeholders, this system also permitted the dynamic scheduling of processing capacity at customs based on the anticipated cargo arrival volumes. Across the different scenarios investigated, the average transit time reduced from 26.41 to 4.83 hours across all cargo types, which represents an efficiency improvement of about 82% compared to the status quo. The least reduction in transit time was obtained in scenario 2, where only processing capacity at customs was changed. In this case, the transit time reduced from 26.41 to 17.10 hours. This represents a 35% reduction in transit time. Other scenarios (see Figure 12) resulted in transit times between these two extremes.

These results are in line with the expected outcome. Changing processing capacity only at customs, without changing the processing capacities at other stations within the border post system, cannot cause substantially improved overall system performance. For example, once cargo has gone through customs clearance (Figure 1, block 8), it proceeds to the customs duty payment stage (Figure 1, block 9).



PreDeclare, pre-declaration varied; PreDecla&Capacity, pre-declaration and capacity varied; RFID_Enable, radio-frequency identification enabled; RFID_SmartCapacity, radio-frequency identification enabled combined with adaptive information exchanged.

FIGURE 12: Comparison of simulated transit times achieved with various process changes across all cargo types.

If the processing capacity at customs is increased without increasing capacity at the payment stage, more and more cargo will have to queue at the latter point. This erodes the gains of increasing customs processing capacity. In contrast, an RFID-enabled system supports data and information interchange between stakeholders and allows for dynamic and intelligent change in processing capacities at various stages. Furthermore, in the proposed system, many of the processing stages found in the present systems will be streamlined and most of the operations will be automated through the use of technology.

Literature pertaining to cross-border operations and associated delays, specifically in reference to developing countries, is limited. The work by Hsu *et al.* (2009) is closely related to the research described in this article, although it focused on improvement of customs processing of air cargo at an airport in Taiwan. Hsu *et al.* (2009) tested how the use of RFID systems would affect automating some of the operations. Their results indicated an improvement of about 63% with regard to performance and cost serving. Therefore, the results in this article are within range of the expected improvements as found in closely related literature.

The findings of our study may have far-reaching implications for stakeholders. For example:

- Governments will benefit from improved revenue collection as more cargo will be passing through the borders in a set period and there will be fewer opportunities for corruption.
- Exporters and importers will benefit from the improved turnaround time as they will be able to do more trips per month.
- Road agencies will spend less money on repairing roads if effective monitoring and controlling of overload are in place.
- Governments will need to restructure the infrastructure at the respective border posts in order to support the envisaged green lanes (improved system).
- Governments will need to revamp their customs processing software and risk engines to the modernised CREMS.
- Transporters will need to equip their trucks with GPS- and RFID-supporting equipment.
- Cargo owners will need to acquire RFID equipment such as RFID readers, RFID tagging equipment and support for the electronic scanning of documents.
- Road agencies will need to acquire RFID readers and RFID software.
- Integration across the respective systems will be needed to facilitate the proposed information exchange.

For the envisaged system to be realised, a joint task force comprising government and other stakeholders should be formed. This task force will have to define measurable objectives and design a clear road map of each stakeholder's responsibilities.

Conclusion and future work

Regional initiatives to reduce transit time (Disenyana 2009; Nour, Siyengo & Kidane 2011) by, for example, introducing OSBPs, have not produced the intended improvement (see Table 1, for the Chirundu border post). Long delays at the borders and the apparent failure of OSBPs have been attributed to human conduct (Curtis 2009; Fitzmaurice 2012). The simulation study reported on in this article has demonstrated that long delay times experienced at border posts can be eliminated by using a combination of information systems to enable information exchange between different stakeholders and modified operational processes. Our results show that the use of RFID-enabled systems can achieve an improvement of up to 82% with regard to average transit time for all cargo at a border post. The minimum average transit time for the improved system was found to be 4.83 hours; however, this may still be too high if Africa is to become competitive in international trade (Barka 2012; Norov & Akbarov 2009).

In the present simulation model human conduct was not specifically included. However, in developing the simulation model, field data were heavily relied upon, in which the human element is presumed to have been inherently included. Further research is therefore proposed to:

- include human behaviour modelling in the model for trade corridors, including border posts (Schmidt 2002)
- determine compliance for arriving consignments not only from RFID checks at the point of origin of the route, but also by using GPS tracking data to verify compliance based on pre-agreed (geo-fenced) routes (Lusanga *et al.* 2014; Siror *et al.* 2010)
- include a reward system for drivers with a good road compliance record and for customs officials with the shortest processing time
- perform a cost-benefit analysis for each scenario to verify which of the scenarios will be able to pay for itself in the shortest time, taking into account the situation for each group of stakeholders
- complete development of an internet-enabled system that would allow transparency and visibility of cargo as it traverses the cross-border trade corridor(s) (Lusanga *et al.* 2014).

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

E.B. (University of KwaZulu-Natal) was responsible for developing the simulation model, running the simulation

and compiling, analysing and presenting the results. E.B. was also responsible for writing the manuscript. A.H. (North-West University) was the project leader. K.L. (North-West University) and A.d.C. (North-West University) contributed to analysing historical data and final results.

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PROPOSED ALTERNATIVE TO ASSIST CURRENT OVERLOAD OPERATIONS IN SOUTH AFRICA

A DE CONING, AJ HOFFMAN

North-West University Potchefstroom
School for Electrical, Electronic and Computer Engineering
Email: arnodeconing@gmail.com , alwyn.hoffman@nwu.ac.za

ABSTRACT

Efficient overload control is of utmost importance to protect the road infrastructure in any region. An investigation into the status quo of overload control in South Africa provided evidence of low efficiencies and many instances of systematic evasion of overload control regulations without effective enforcement. In this article, we analyse data to obtain empirical evidence of the level of inefficiencies and to identify the primary factors that affect overload behaviour and the efficiency of current enforcement measures. The data used consist of traffic flow, weigh-in-motion and static scale data over the period 2012 to 2015. We propose an improved overload control system based on more accurate monitoring of road user behaviour using a combination of technologies and the more intelligent use of available data, and discuss the legal implications of the proposed application and steps needed for a pilot deployment of the proposed system.

1. INTRODUCTION

Overload control is implemented throughout the world by roads agencies as part of general road management. These systems are implemented to minimize the damaging effect on the road caused by overloaded vehicles. The negative impact of overloaded vehicles is not limited to physical damage to the road surface, but have a large economic impact as well (Szary & Maher, 2009). The manner in which current overload control procedures are applied results in significant time delays, even for fully legal vehicles, but is viewed by the relevant roads agencies as essential to enforce legal driving weight limits of trucks (Hoffman, et al., 2013). These inefficiencies sometimes cause long queues at weigh stations resulting in trucks being ordered to bypass the weigh station; this effectively creates loopholes in the enforcement system (Kamyab, et al., 1998), (Lee & Chow, 2012). This bypassing to avoid delays could easily include overweight vehicles that will damage the road infrastructure. Freight vehicles may also deliberately choose to bypass weigh stations based on knowledge that the vehicle is overweight in order to avoid prosecution (Szary & Maher, 2009). In some cases it occurs that the drivers of overloaded trucks deviate from main routes to skip weigh stations all together by following secondary roads; this cause severe damage to such secondary roads, resulting in the deteriorating status of South Africa's general road infrastructure (Crickmay, 2010).

Overloading may increase the competitive edge of freight companies as it allows them to haul larger quantities of goods (de Pont, 2012). This overloading ensures higher productivity and utilisation of freight vehicles (Kienhofer, et al., 2013). Multiple industry approaches have been developed and implemented to reconcile productivity within logistics with overloading compliance and vehicle design. (de Saxe, et al., 2013), (Bosman & D'Angelo, 2011). A relevant example is the Road Transport Management System (RTMS), a South African initiative for self-regulation of road freight transporters that was initiated in the timber and sugar industries (Crickmay, 2010). These initiatives intend to lower illegal activities and increase the accuracy of overload control to minimize the large economic impact on the road infrastructure.

2. DEFICIENCIES IN EXISTING OVERLOAD CONTROL MEASURES

The current overload control system implemented in South Africa is characterised by lack of uniformity across different regions and lack of integration between different subsystems. The different variations of TCCs (traffic control centres) found on our national roads may consist of

- static scales,
- weigh-in-motion (WIM) scales inside the road surface,
- screener lanes forcing heavy vehicles to correctly travel over the WIM scale,
- cubicles providing traffic officials with alarms and photographic images of vehicles triggering the WIM scale,
- ANPR (automated number plate recognition) cameras that identify vehicles in all lanes based on registration number,
- piezo-electric vehicle counters that detect vehicle axle configurations,
- RFID (radio frequency identification) readers combined with RFID tags mounted on vehicle wind screens, and
- manual enforcement by traffic officials stationed at WIM and static scales.

The pros and cons of the most common TCC configurations in use are discussed below:

1. Static scales used in isolation: The primary disadvantage of this configuration is the fact that all heavy vehicles, whether legally or illegally loaded, are forced to visit the scale. This can lead to very long delays, typically at border posts during times of high congestion, disrupting the operations of fully compliant road users which is detrimental to the national economy.
2. Combined WIM and static scales: this allows vehicles to be screened before informed whether they must visit the static scale. Several disadvantages however still remain:
 - As WIM scales are less accurate than static scales, the threshold to direct vehicles to the static scale is normally set at 10% below the legal limit – legal vehicles that are loaded close to capacity (as is often the case) can still be repeatedly directed to a static scale during the same trip.

- Illegal vehicles can evade this system simply by not driving in the WIM lane or by ignoring the WIM signal. This is supposed to be prevented by the traffic official on duty, but practical observations have shown that in a large fraction of cases this does not happen.
3. Adding screener lane to WIM scales: this can help prevent heavy vehicles from either pretending that they were not aware of a WIM lane or driving in the WIM lane without properly driving over the WIM scale (i.e. keeping to the edge of the lane). If the WIM screener lane is ignored and no official is on duty such an offense will however go unnoticed.
 4. ANPR cameras: By adding ANPR cameras in all lanes at the position of the WIM it is possible to detect heavy vehicles in non-WIM lanes by linking their registration numbers to other information on the eNATIS system. This still leaves the loophole that if the vehicle carries an illegal number plate then the wrong vehicle owner may be implicated. It is known that the heavy vehicle industry suffers from a high incidence of illegal number plates.
 5. Adding RFID to the WIM scale: RFID provides the option of a much higher level of integrity of vehicle identification (Hoffman *et al*, 2013). The use of secure RFID tags either on the windscreen or number plate can ensure that vehicles are correctly identified and that the true vehicle owner is prosecuted. It however requires the deployment of RFID tags on the entire vehicle population which is not currently the case.

From the above it can be seen that all system configurations currently used in practice suffer from specific limitations and deficiencies. The combined use of a WIM scale with screener lane and ANPR camera to verify the potential non-compliance and identity of a vehicle, followed by a static scale for enforcement is currently the most effective configuration being used.

3. THE ROLE OF LAW ENFORCEMENT

A common factor applicable to all TCC scenarios is the dependence on some form of manual supervision and enforcement by officials. A weakness inherent to the status quo is that the parties that financially suffer from overload offenses (roads agencies and toll road operators) do not have direct control over the enforcement agencies (local traffic authorities). Based on discussions with a representative set of industry players this appears to be the single biggest contributor to current deficiencies in the overall system, as the following types of behaviour is commonly observed within the overload control enforcement process:

1. Traffic officials stationed at WIM cubicles often experience difficulty to correctly identify the relevant heavy vehicle that has triggered the WIM scale, resulting in the wrong vehicles being diverted to the static scale.

2. The traffic official on duty often has the intention to reach his/her daily quota for number of heavy vehicles weighed as quickly as possible, and hence indiscriminately directs all heavy vehicles on the road towards the static scale. Once the prescribed quota has been reached the official will go off duty, allowing all vehicle to pass the static scale.
3. A vehicle is directed to the static scale, weighed, found to be overloaded, directed to the designated area and fined. In such an instance, the driver is supposed to request a relief vehicle to collect the excess weight before the journey can commence. A bribe is however paid to the traffic official and the weigh master who overrides the internal control system and the vehicle is allowed back onto the road with its illegal load.
4. An illegally loaded vehicle triggers a WIM scale but ignores the signal and passes the static scale. A notification is sent to a central control office from where a traffic official is dispatched to pull off and impound the vehicle. A bribe is subsequently paid and the vehicle is allowed back onto the road with no traceability or records of these events.

In all of the cases above there are currently no records of what actions were taken by traffic officials based on specific information that was provided to them. There is furthermore no traceability of the actions of vehicles found to be illegally loaded, and whether subsequent detections of these vehicles indicate that their illegal loading status was in fact corrected. There is also no formal record of systematic law evasion and/or overloading by specific fleets of vehicles, even though there is awareness of the serious nature of these offenses and of the fact that information is available within the system to identify and act against such players.

4. VERIFICATION OF THE NATURE OF CURRENT OVERLOAD BEHAVIOUR

Our discussion so far provides proof that the current overload situation results from a variety of underlying causes:

- Economic incentives to road users to offend and a lack of incentives to comply, resulting in high levels of overloading and evasion of the control system;
- Limitations within existing technology systems to correctly monitor and control overloading behavior;
- Opportunities that exist for enforcement officials towards self-enrichment by selectively acting against offenders without being caught out.

Before an improved overload control concept can be proposed it is important to verify the extent to which the above factors are indeed present in practice. The need also exists to verify which are the dominant underlying causes for consistent overloading; this would assist efforts towards the design of a more effective control system.

In order to study these issues, we collected and analysed historical data available from existing overload control and traffic monitoring systems. Our analysis was aimed at characterizing

- the behavior of road users during different times of day when different levels of physical law enforcement could be expected to be present, as well as

- the performance of existing overload control systems, including enforcement officials.

The data that was used represents the movement of vehicles along South Africa's busiest internal corridor (Durban to Johannesburg) as well as on South Africa's busiest corridor to neighbouring countries (Johannesburg to Beitbridge).

5. DISCUSSION OF RESULTS

The main results are displayed in figures 1 to 4 below. Figure 1 indicates that the pattern of vehicle movements as function of time of day is quite different for heavy vehicles than for all vehicles: during the middle of the day heavy vehicles represent only about 10% of the total count, going up to between 40 and 80 % before 7 am and after 7 pm.

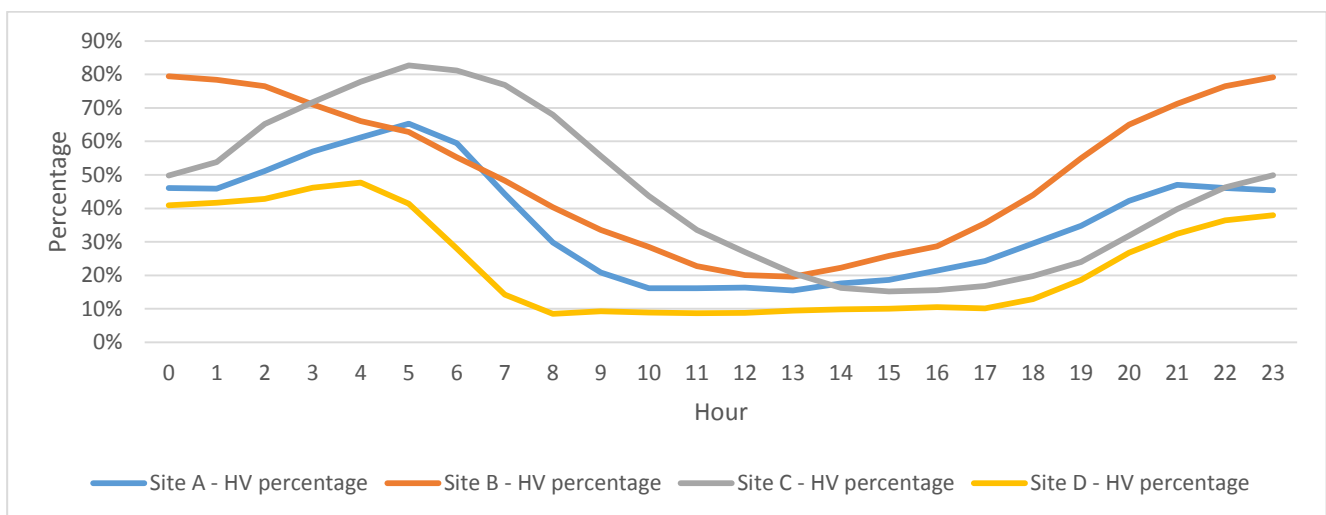


Figure 1 Heavy vehicle count as fraction of total vehicle count as function of hour of day for different monitoring stations

Figure 2 indicates overload statistics for eight weigh-in-motion monitoring sites on the corridor from Durban to Beitbridge. The vehicles were weighed over a three-year period; 78% to 82% of total traffic was weighed and only 7% to 9% of these vehicles are stated as overloaded. A total of 19.7 million vehicles weighed during the three-year period were not overloaded. If all of these vehicles were forced to repeatedly visit all static scales on any given trip a huge amount of time would have been wasted, providing a clear argument against the use of static scales in isolation. The WIM scale information interpreted in isolation does however not provide a clear indication of the efficiency of TCC configurations that combine a WIM scale with a static scale. For that purpose, we also need to also study static scale data.

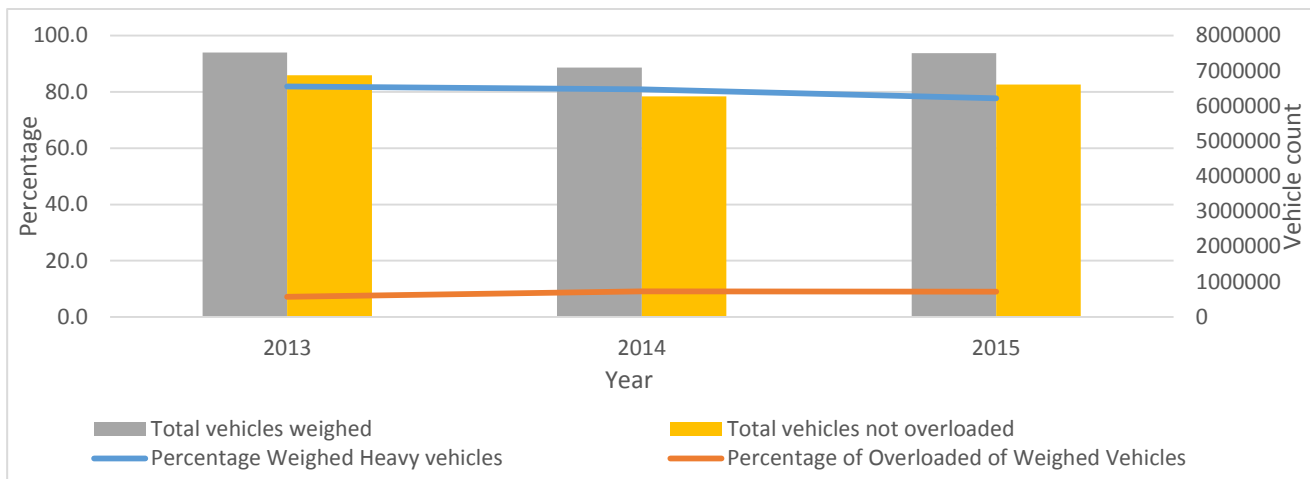


Figure 2 Average overload statistics from weigh-in-motion sites for 2013 to 2015

Currently installed TCCs that include both a WIM and a static scale does not have a reliable method to verify if a specific vehicle that triggered the WIM scale was in fact seen at the static scale; similarly there is no reliable measurement to indicate whether a vehicle that is statically weighed did trigger the WIM scale. The accuracy of current schemes used to direct heavy vehicles to static scales can however be quantified to some extent by studying the weight statistics of vehicles that are statically weighed. If the installed systems are functioning correctly (i.e. WIM scales correctly trigger vehicles that are within 10% from the legal limit) and operational procedures are correctly implemented by traffic officials, then the vast majority of statically weighed vehicles should be above a level set at 10% below the legal limit. Vehicles weighing in at below this threshold should not have ended up at the static scale, as WIM scales are in general more accurate than the allowed 10% tolerance; such vehicles were directed to the static scale due to the incorrect functioning of some element of system operation.

Against this background we analysed the statistics of vehicles weighed at static scales that are preceded by a WIM scale that triggers vehicles within 10% of the legal threshold and then directs them to the static scale. Figure 3 displays the fraction of vehicles, visiting such static scales, of which the static weight was more than 10% below the legal threshold. This fraction of vehicles, which varies around 60% of all weighed vehicles, could not reasonably have triggered the preceding WIM scale. Based on the available evidence it can thus be argued that only around 40% of vehicles at the static scale should have been directed there as the remaining 60% of the vehicles never triggered the preceding WIM scale. It is unlikely that vehicles not triggering the WIM would have voluntarily visited the static scale; the reasonable conclusion is that this 60% of vehicles visiting static scales were incorrectly directed to the static scale by traffic officials, either by mistake or deliberately to make up the daily quota. This data provides clear and tangible evidence of the general observations described in sections 2 and 3 regarding the inaccuracies inherent to the current system.

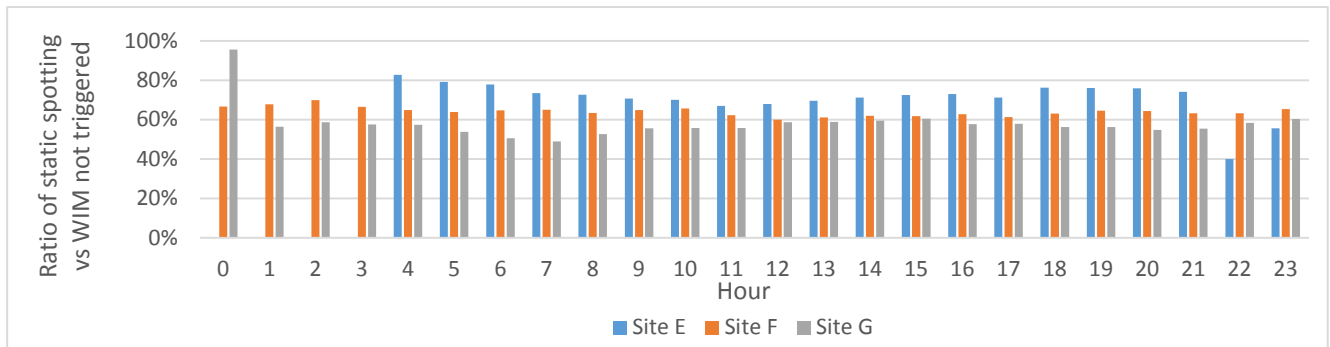


Figure 3: Fraction of vehicles visiting the static scale that could have triggered the WIM scale, for different sites and as function of hour of day

While figure 3 provides evidence of the inefficiency of the current system to correctly direct vehicles to the static scale, it does not address the issue of the potential unnecessary repeated static weighing of those vehicles that are correctly directed from WIM to static scale. As described in section 2 above, a vehicle that is legally loaded but that is within 10% of the legal limit will trigger the WIM scale and should, according to current procedures, be directed to the static scale. If it passes several TCCs along the same corridor it will be repeatedly pulled off, as the different TCCs are not linked and are therefore not aware of the outcome of a static measurement at a preceding TCC.

In order to determine the fraction of vehicles that falls within this category we performed the following calculations:

- Firstly the vehicles that, based on their static weights, could have triggered the preceding WIM are identified and counted;
- Secondly the overloaded vehicles at the same static scales are identified and counted;
- The overloaded vehicles are then expressed as a fraction of vehicles that triggered the WIM scale.

Figure 4 shows the percentage of all the vehicles that triggered the WIM (based on their static weights) and that were actually overloaded. This figure is around 10% for most of the day. The implication is that around 90% of vehicles that triggered the WIM (and that were correctly directed to the static scale according to current procedure) were in fact not overloaded. A vehicle falling into this category and following a corridor with multiple TCCs would therefore be repeatedly pulled off to static scales even though it was legally loaded; on the route from Durban to Beitbridge this could happen 6 to 8 times. If however the different TCCs were linked and could respond intelligently to data received from other TCCs on the same corridor then most of these unnecessary static scale visits could have been eliminated.

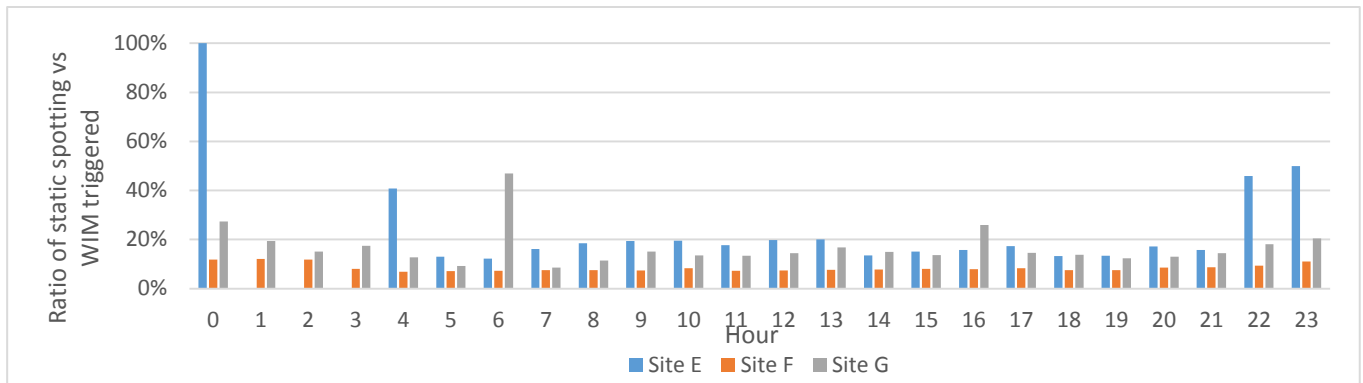


Figure 4: Fraction of heavy vehicles visiting the static scale after triggering the WIM scale that were actually overloaded, for different sites and as function of hour of day

We can summarise our findings as follows:

1. Heavy vehicles tend to travel mainly during after hour periods when there tend to be a low presence of traffic officials around TCCs (Figure 1).
2. On average less than 9% of vehicles weighed by WIM scales are overloaded (Figure 2).
3. Of all vehicles directed to static scales based on current procedures only 30 to 40 % should have been statically weighed, based on the outcome of their actual static weights (Figure 3).
4. Of all vehicles that were supposed to be directed to the static scale only around 10% are actually overloaded. This means that only around 3-4% of all vehicles visiting the static scale are overloaded (Figure 4).
5. Most of these unnecessary static scale visits can be eliminated should different TCCs on the same corridor be interlinked; this will have a significant beneficial economic impact on the operations of road transport operators and can also reduce wear and tear on TCC infrastructure (Hoffman, 2014).

6. INCENTIVISING ROAD USERS TO BECOME COMPLIANT

From the above results, it is clear that the current approach to overload control as applied on South Africa's primary freight corridors is largely ineffective: it does not deter road users with a tendency towards breaking the law for financial gain, while it penalizes compliant road users who load their vehicles effectively and strictly keep to overload procedures. On the other hand, the current system offers few benefits to compliant road users to obey the law, especially as they directly compete against offenders who are improving their profit margins based on overloading.

The RTMS was a first effort towards creating a system of self-regulation that allows compliant road users to make their vehicles identifiable in exchange for preferential treatment. This system proved to be very effective within specific industries where the supply chain principals effectively enforced the rules of the system and created clear obstacles for offenders (Crickmay, 2010). Our results however show that the

system has been much less effective for the road freight industry in general where the control system is operated by roads agencies and depends on enforcement by traffic authorities.

Based on our own observations and discussions with many participants in this industry our conclusion is that a more effective system will have to provide tangible benefits for compliant road users, implement more severe penalties for offenders and provide traceability of efforts towards enforcement. In order to achieve this an improved system is required that can clearly differentiate between compliant and non-compliant road users; this must involve a much higher level of automation that eliminates the human element from critical steps in the process. This is applicable both regarding the benefits created for compliant road users as well as enforcement actions against offenders. The next section describes a proposed system that could achieve at least a significant improvement upon the status quo.

7. PROPOSED IMPROVED OVERLOAD CONTROL SYSTEM

Existing telemetry technology can support a total redesign of the existing overload control concept. Taking into account the to be expected resistance against change in any system involving a large number of stakeholders, we propose that a new system is deployed in two phases: Phase 1 will improve the efficiency of existing elements of the current system, while Phase 2 will add new elements that will drastically change the philosophy behind the system.

For Phase 1 the following changes are proposed:

1. It must provide for an extended system of certification of compliant heavy vehicle operators, using the RTMS as point of departure, and requiring certified vehicles to carry a secured RFID tag. Untagged vehicles must be tagged when visiting static scales.
2. All static scales must be complemented by upstream WIM scales that are equipped with screener lanes, RFID readers for high-integrity identification of certified vehicles and ANPR cameras on all non-WIM lanes to detect heavy vehicles that do not use the WIM lane.
3. Different WIM scales must be connected in real time and provided with a sufficient level of intelligence to prevent legally loaded vehicles that are close to the threshold from being repeatedly directed to the static scale. This will create a clear incentive for legal operators that accurately load their vehicles to comply with system requirements.
4. Instructions provided by WIM scales to potentially overloaded vehicles must be automatically enforced by a system of booms that direct heavy vehicles from the screener lane either to the static scale or back to the main road. This will eliminate the ineffective directing of vehicles by traffic officials who are not held accountable for their actions.

5. Vehicles operated by uncertified road users (that do not carry registered RFID tags) will be regarded as representing a higher risk and will be subjected to stricter enforcement measures (e.g. using lower triggering thresholds at the WIM scale) and higher tolling fees.
6. Should any heavy vehicle evade the WIM lane an ANPR camera will detect its registration number, allowing the vehicle to be identified and linked to its legal owner using eNATIS.
7. Should an uncertified vehicle use illegal number plates and evade the WIM lane, its illegal status can be manually verified by comparing the corresponding camera image with eNATIS data linked to the same registration number. If a vehicle carrying illegal number plates is spotted, a task force will have to be dispatched to intercept it while still *en route*, impound it and identify the owner. Successful enforcement against such vehicles will obviously require a high level of integrity from this task force, or else it will fall victim to the same weaknesses of the existing system.
8. By using the above elements of monitoring and control, it will be possible to build up a long term track record of overload behavior for all major road users. Even if the odd vehicle manages to evade the system, the major system objectives will be achieved, as there will be effective action against large road users who systematically overload and evade enforcement. At the same time the compliant behavior of certified users will allow them to qualify for preferential treatment, not only in terms of reduced frequency of static scale visits but also in terms of differentiated tolling fees.

For Phase 2 the following elements are proposed to be added:

1. The internal scales of certified road operators must be regularly calibrated and linked to the centralized overload control system; if such internal load measurements are accepted by the roads agency as sufficient proof of the loading status of a vehicle upon departure then almost all static scale visits by certified vehicles can be eliminated.
2. The existing GPS tracking systems of certified operators must be linked to the centralized system to provide summary data to the roads agency about the movements of the vehicle as from the time when it was internally weighed until it reaches its final destination.
3. A system must exist to allow certified operators to submit electronic declarations to the centralized system before a vehicle is dispatched, in the process informing the roads authority about the intended route, the origin and destination, the nature of the load and the overload control stations to be passed along the way. This will allow the system to process the GPS tracking information about such vehicles in real time to determine if the vehicle displayed any kind of behavior that could represent an overloading risk (e.g. stopping for a sufficient period along the way to allow cargo to be added).

4. When the GPS system of a tagged certified vehicle indicates that it is passing a TCC the system will automatically verify if it was correctly observed by an ANPR camera as well as by an RFID reader, if it followed the correct lane and if the WIM scale measurement can be reconciled with its originally submitted weight. This will allow the system to optimally handle such vehicles in real time as it passes through control stations.
5. Should all of the above elements of the proposed system be in place, it can be used to implement a compulsory GPS based electronic tolling system for heavy vehicles. This will discourage non-compliant road users from evading high tolling fees by taking secondary roads around tolling stations; as such behavior will be detected and will further increase their tolling rates.

Non-compliant transport operators can be expected to attempt efforts towards sabotaging a system of this kind, e.g. by damaging RFID tags or switching off tracking devices when TCCs are evaded. Continuous collection of fleet behaviour will however easily detect such patterns of behaviour; this can be used to automatically downgrade the status of such operators, enforcing the highest level of tolling fees onto them or even suspending their business licenses.

8. CONCLUSIONS AND RECOMMENDATIONS

The existing overload control system as employed on South Africa's road network has been demonstrated to be deficient in many respects. This results from non-uniform system configurations at different TCCs, many of these leaving serious loopholes for offenders, lack of integration between different data sets reflecting various aspects of overload behaviour, critical dependence on enforcement by a fragmented set of traffic authorities, and lacking control over the accuracy and integrity of these enforcement agencies.

The proposed alternative will be based on a more uniform design of control infrastructure, integration of data from different sources, including systems operated by fleet owners, a system of incentives to compliant road users, and on-going real time system supervision based on real time data collection. The proposed system must have the necessary built-in logic to correctly interpret combined data sets originating from different sources allowing correct diagnostic decisions and enabling real time enforcement. Such enforcement must be automated as far as practically possible, but will also require a dedicated task force whose actions will have to be closely monitored to ensure a high level of integrity, in contrast to the status quo.

Future work will involve the analysis of field data from a larger number of TCCs representing all identified overload system configurations to accurately determine the extent to which current overload behaviour from road users is influenced by system design. A simulator is in the process of being developed to allow the simulation of different system designs and to measure its impact on time delays experienced by road users as well as the impact of incentives and penalties on the behaviour of truck drivers and enforcement officials. A prototype system is in the process of being deployed along a portion of the N3 and N1 North-South corridors to demonstrate the

beneficial impact that the addition of RFID and the sharing of information between different TCCs can have on overall system performance. A financial impact study will also be conducted for multiple stakeholders using the corridor.

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Appendix C: Patent

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(71) Applicant: NORTH-WEST UNIVERSITY [ZA/ZA];
Private Bag X 6001, 2520 Potchefstroom (ZA).

(72) Inventors: HOFFMAN, Alwyn Jakobus; 73 Hoffman
Street, 2520 Potchefstroom (ZA). DE KOKER, Eon; 1291
Whistletree Drive, Queenswood, 0186 Pretoria (ZA).

(74) Agents: VON SEIDELS INTELLECTUAL PROP-
ERTY ATTORNEYS et al.; P O Box 440 Century City,
7446 Cape Town (ZA).

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(54) Title: VEHICLE OVERLOAD MANAGEMENT SYSTEM

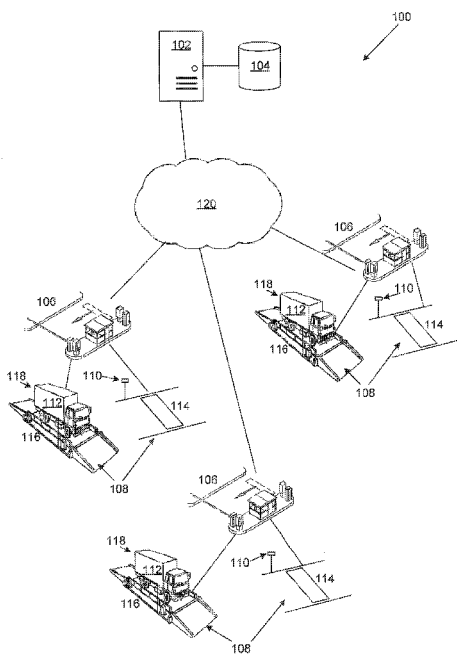


Figure 1

(57) Abstract: A vehicle overload monitoring system (100) is provided which includes a plurality of control stations (106) situated along a road transportation corridor. Each control station (106) has a unique identifier associated therewith and includes at least one vehicle weighing mechanism (108), at least one electronic identification mechanism (110) for identifying a vehicle (112) passing therethrough and a communications module for communicating with other control stations (106) along the corridor. Each control station (106) is configured to receive, by way of the communications module, weight measurement data and vehicle identifiers gathered by one or more other control stations (106) along the road transportation corridor, and to associate the received information with the unique identifiers of the control stations (106) by which they were gathered. The control station (106) may then at least partially utilize the associated information to determine whether a vehicle (112) passing through the control station (106) should be weighed by way of the vehicle weighing mechanism (108).



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VEHICLE OVERLOAD MANAGEMENT SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

- 5 This application claims priority to South African provisional patent application number 2013/07494, which is incorporated by reference herein.

FIELD OF THE INVENTION

- 10 This invention relates to a system and method for vehicle overload management and, more particularly, it relates to a system and method for vehicle overload management for use along an entire road transport corridor that includes several load control stations.

15 BACKGROUND TO THE INVENTION

- Overloading of vehicles, particularly transportation vehicles, is a major problem across the globe. Overloading not only causes considerable damage to road networks and road surfaces, but also contributes to the problem of
- 20 improving and maintaining road safety for all road users. Furthermore, heavy vehicle operators that adhere to loading standards are placed at a disadvantage as they cannot compete fairly with unscrupulous operators that deliberately overload their vehicles.

- 25 Vehicle overload management is typically performed on road transportation corridors through the weighing of heavy vehicles at overload control stations, generally referred to as weigh bridges. These weigh bridges typically include weigh-in-motion (WIM) scales configured to quickly determine, while the vehicle is moving, whether the vehicle's weight is within allowable loading
- 30 limits, and static scales configured to more accurately determine the load on each axle of the vehicle, as well as the combined weight of the vehicle, while the vehicle is stationary. Due to WIM scales determining a vehicle's weight

while the vehicle is in motion, the weight measurements are generally too inaccurate to be used for prosecution purposes, thus in the event of the WIM scale indicating that a vehicle may be overloaded, the vehicle's weight will have to be more accurately determined by means of a static scale. A heavy vehicle is therefore generally, as a first step, directed through a WIM scale and if the vehicle's load is considered to be close to or over the permissible loading limit, the vehicle is directed towards a static scale so as to be weighed more accurately. Where it is found that the vehicle has been overloaded, the vehicle owner is sanctioned and often required to unload a portion of the load, or otherwise reduce the load, prior to the vehicle being permitted to continue along the corridor.

Various forms of overload monitoring systems have been developed to effectively streamline and increase the efficiency of the monitoring process described above, however, these systems typically exhibit various deficiencies.

It is common practice for good transport operators to load their vehicles at or near the allowable load limit. As a result, the inherent inaccuracies associated with most WIM scale measurements mean that vehicles loaded at or close to the permissible limits tend to be identified as overloaded, and are thus directed toward static scales for more accurate measurements. This renders WIM scale readings largely ineffective, while at the same time being time consuming to the vehicle operator as well as labour and cost intensive to control stations.

This problem is exacerbated by the fact that, if a vehicle has been loaded at or near the allowable load limit, the vehicle can be reasonably expected to be identified as being potentially overloaded by WIM scales at all or most of the control stations along a corridor. The vehicle will therefore generally have to be weighed by means of a static scale at every control station along the corridor.

A further deficiency often exhibited by existing monitoring systems is that vehicles are not reliably identified at WIM scales, which in turn leads to many unnecessary or incorrect static weighing actions being performed, resulting in wasted costs and loss of time to both vehicle operators and control stations. Furthermore, the unreliable identification of vehicles at control stations results in the loss of statistical data which could otherwise be used to accurately determine when a vehicle's load determined by a WIM scale is above the permissible limit or not.

10

SUMMARY OF THE INVENTION

In accordance with this invention there is provided a vehicle overload monitoring system, comprising:

15 a plurality of control stations situated along a road transportation corridor;

each control station having a unique identifier associated therewith and including at least one vehicle weighing mechanism, at least one electronic identification mechanism configured to uniquely identify a vehicle passing through the control station, and a communications module;

20 wherein each control station is configured to receive, by way of the communications module, weight measurement data and vehicle identifiers gathered by one or more other control stations along the road transportation corridor, associate the received vehicle identifiers and the weight measurement data with the unique identifiers of the control stations by which they were gathered, and to at least partially utilize the associated information to determine whether the vehicle should be weighed by way of the vehicle weighing mechanism.

30 Further features provide for the system to further comprise a remotely accessible server in data communication with a system database; and for the remotely accessible server to be configured to receive weight measurement

data and a vehicle identifier from a control station, to associate the vehicle identifier and the weight measurement data with the unique identifier of the control station, and to store the associated information on the system database for use by other control stations along the road transportation
5 corridor.

Further features provide for the server to be further configured to receive location data of a vehicle traveling along the road transportation corridor; for the location data to be transmitted to the server by way of a location
10 detection system associated with the vehicle; for the server to be configured to determine, in real-time, a likelihood of whether the vehicle stopped and/or deviated from the road transportation corridor, so as to determine a likelihood of the vehicle's weight having changed along the corridor and/or in between one or more control stations based on the location data; and, if a high
15 likelihood that the vehicle weight has changed is determined, flag the vehicle identifier stored on the system database to that effect.

Still further features provide for the server to be configured to receive loading area access data of a vehicle; for the loading area access data to be
20 transmitted to the server by way of electronic sealing devices and/or electronic door sensors secured to the loading area of the vehicle; for the electronic sealing devices to be enabled to detect opening, closing and/or tampering events of the loading area of the vehicle; and for the server to be configured to determine the likelihood of the vehicle weight having changed
25 along the corridor and/or in between one or more control stations based on the loading area access data.

A further feature provides for the location detection system to be one or more of a Global Positioning System (GPS), a Local Positioning System (LPS), a
30 Wireless Positioning System (WPS) and the like.

- Yet further features provide for the electronic identification mechanism to include any one or more of a radio-frequency identification (RFID) reader, a quick response (QR) code reader, a barcode reader, and the like; and for each vehicle to have any one of an RFID tag, a QR code, a barcode or the like secured to the vehicle which uniquely identifies the vehicle. Alternatively or in addition, the electronic identification mechanism may include an automated number plate recognition (ANPR) system configured to automatically identify a vehicle from its number plate.
- 10 Further features provide for the weighing mechanism of each control station to include one or more of a weigh-in-motion (WIM) scale or a static scale; and for each control station to preferably include a WIM scale and a static scale.
- 15 In a preferred embodiment, each control station includes a secondary electronic identification mechanism configured to identify vehicles that are not weighed at the control station; and the remotely accessible server is configured to receive vehicle identifiers from the secondary electronic identification mechanism, to store the vehicle identifiers in the system
- 20 database and to flag the vehicle identifiers received from the secondary electronic identification mechanism to indicate that the identified vehicle was not weighed. Alternatively, if the vehicle cannot be identified by way of the secondary electronic identification mechanism, for the server to be configured to notify control stations further along the road transportation
- 25 corridor that an unidentified vehicle is traveling towards it.
- A still further feature provides for the server to be configured to pro-actively transmit the associated information to one or more subsequent control stations located further along the road transportation corridor than the control
- 30 station from which the information was received, in preparation for an identified vehicle's arrival at the subsequent control stations, the associated information being useful by the subsequent control stations to determine if an

identified vehicle indicated by the WIM scale at the subsequent control station as being within predefined weight limits, should again be weighed on the static scale of the subsequent control station.

- 5 The invention extends to a method for monitoring the load of a vehicle along a road transportation corridor, the method including the steps of, at a control station situated along the road transportation corridor:
 - receiving a vehicle identifier and weight measurement data of a vehicle being weighed with a WIM scale of the control station;
 - 10 receiving weight measurement data and vehicle identifiers gathered by one or more other control stations (106) situated along the road transportation corridor and associating the vehicle identifiers and the weight measurement data with the unique identifiers of the control stations by which they were gathered; and
 - 15 determining whether the vehicle should be weighed again by way of a static scale at the control station, based at least partially on the received weight measurement data gathered by the other control stations along the corridor.
- 20 Further features provide for the step of determining whether the vehicle should be weighed again by way of the static scale at the control station includes the steps of:
 - determining whether the vehicle has previously been inspected at one or more other control stations along the road transportation corridor within a
 - 25 pre-determined time frame, this time frame being calculated based on normally expected travel time from the respective previous control station to the current control station, and whether the vehicle identifier has been flagged by the server to indicate a likelihood that the vehicle's weight has changed since its last inspection;
 - 30 if the vehicle has not been inspected at a static scale within the pre-determined time frame or the vehicle identifier has been flagged, determining whether the WIM scale weight measurement data exceeds a first pre-

determined parameter and, if it does, permitting the vehicle to continue travelling along the road transportation corridor, alternatively, if the WIM scale weight measurement data exceeds the first pre-determined parameter, transmitting a notification to the control station that the vehicle is potentially
5 overloaded and should be weighed again at the associated static scale; and

if the vehicle has been inspected at a static scale within the pre-determined time frame and the vehicle identifier has not been flagged, determining whether the WIM scale weight measurement data exceeds a second pre-determined parameter, set at a level higher than the first pre-determined parameter, and, if it does, permitting the vehicle to continue
10 travelling along the road transportation corridor, alternatively, if the weight measurement data exceeds the second pre-determined parameter, comparing the weight measurement data with the previously received weight measurement data to determine whether the vehicle is potentially overloaded
15 and should be weighed again.

Still further features provide for the method for monitoring the load of a vehicle to be performed at a remotely accessible server and wherein associated information is stored on a system database.

20

The invention also provides a method of calibrating a vehicle weighing mechanism at a control station situated along a road transportation corridor, the method including the steps of:

identifying a vehicle entering the control station;
25 weighing the vehicle utilizing the vehicle weighing mechanism to obtain a current weight measurement;

gathering previous weight measurements relating to the vehicle, the previous weight measurements having been recorded by one or more other weighing mechanism associated with one or more other control stations
30 situated along the road transportation corridor;

comparing the current weight measurement to the previous weight measurements to determine a level of variation between the measurements; and

5 adjusting the calibration of the vehicle weighing mechanism in accordance with the level of variation.

Further features provide for the current weight measurement and the previous weight measurements to each include weight measurements obtained utilizing a weigh-in-motion (WIM) scale and a static scale; for each
10 WIM measurement and static scale measurement to comprise a data set; to compute the difference between the WIM scale measurement and the static scale measurement for each data set; to compute an average of the differences computed; and for the WIM scale to be calibrate in accordance with the average obtained.

15

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example only with reference to the accompanying representations in which:

20

Figure 1 illustrates a vehicle overload monitoring system in accordance with the invention;

25

Figure 2 illustrates one embodiment of a control station forming part of the system illustrated in Figure 1;

30

Figure 3 illustrates a flow diagram of a method for monitoring the load of a vehicle along a road transportation corridor making use of the system of Figure 1; and

Figure 4 illustrates a method for calibrating a vehicle weighing mechanism at a control station along a road transportation corridor employing the system of Figure 1.

5 DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

Figure 1 illustrates one embodiment of a vehicle overload monitoring system (100) in accordance with the invention. The system (100) comprises a remotely accessible server (102) in data communication with a system
10 database (104) and a plurality of control stations (106) stationed along a road transportation corridor. Each control station has a unique identifier within the system (100) and includes vehicle weighing mechanisms (108) and at least one electronic identification mechanism (110). The electronic identification mechanisms (110) are capable of uniquely identifying a vehicle (112) passing
15 through the control station (106). In a preferred embodiment and as illustrated in Figure 1, the weighing mechanisms (108) of each control station include a weigh-in-motion (WIM) scale (114) and a static scale (116).

Furthermore, in a preferred embodiment, the electronic identification
20 mechanism (110) of each control station (106) includes any one of a radio-frequency identification (RFID) reader, a quick response (QR) code reader, a barcode reader or the like, and each vehicle (112) passing through the control station (110) has any one of a RFID tag, a QR code, a barcode or the like secured to the vehicle (112). The electronic identification mechanisms
25 (110) are capable of uniquely identifying each vehicle (112) passing through the control station (110) so as to ensure that the weight measurement data of each vehicle (112) may be accurately associated with the correct vehicle (112) identified. Preferably, low cost passive RFID tags will be secured to each vehicle (112), as these will ensure accurate identification of a vehicle
30 (112) while at the same time keeping costs to a minimum.

In an alternative embodiment, the electronic identification mechanism (110) may include an automated number plate recognition ("ANPR") system that is capable of accurately identifying a vehicle (112) based on the vehicle's number plate.

5

A preferred embodiment of the system (100) may further include location detection mechanisms (not shown) installed on each vehicle (112), which are in data communication with the server (102). The location detection mechanisms may include any one of a Global Positioning System (GPS), a
10 Local Positioning System (LPS), a Wireless Positioning System (WPS) or the like and enable the server (102) to determine, in real-time, the location of each vehicle (112) at any given time. The server (102) is therefore enabled to track and determine, in real-time, whether a vehicle (112) travelling along the corridor has stopped and/or deviated from the corridor at any point during its
15 travel.

In addition, in a preferred embodiment, the system (100) further provides for electronic sealing devices (not shown) and/or electronic door sensors (not shown) to be secured to the cargo areas (118) of vehicles (112) traveling on
20 the corridor. It will be appreciated that such sealing devices and/or door sensors will generally only be used for vehicles (112) where the construction of the vehicle (112) allows for the cargo area (118) to be locked and/or sealed and such devices to be secured thereto. The sealing devices and/or door sensors are in data communication with the server (102) and are
25 capable of transmitting loading area access data to the server (102) so as to enable the server (102) to detect tampering with the vehicle's (112) cargo area (118). Alternatively, the door sensors may be configured to record opening, closing and tampering activities on a local memory module, preferably together with accurate date- and timestamp information. The
30 memory module may then be interrogated by a wireless communication device installed in the proximity of a control station (106) as the vehicle (112) passes through the control station (106), and the recorded data may be

inspected by the control station (106) to determine if the cargo was accessed or tampered with along the corridor.

In use, the server (102) is configured to receive from a control station (106)
5 the weight measurement data and vehicle identifier for each vehicle (112) passing through the control station (106), and to associate the weight measurement data with the correct vehicle identifier as well as the control station's identifier and store the data on the system database (104). In a preferred embodiment, during travel of a weighed and identified vehicle (112)
10 along the corridor, the server (102) is capable of tracking the vehicle's (112) movement by means of the location detection mechanism of the vehicle (112) and to detect any potential tampering with the vehicle's cargo area (118) by means of the sealing devices and/or door sensors secured to the cargo area (118) of the vehicle (112).

15 If it is detected that the vehicle (112) had made an unexpected stop, or deviated from the expected corridor, or the sealing devices or door sensors indicate that the cargo area (118) of the vehicle (112) was accessed or tampered with, the server (102) is configured to determine the likelihood of
20 the vehicle's (112) weight having changed from its last weighing at a control station (106). Where there is a likelihood that the vehicle's (112) weight has changed during its travel on the corridor, the server (102) is configured to mark or flag the identifier of the vehicle (112) stored on the system database (104) to that effect.

25 It will be appreciated that communication between the server (102) and the control stations (106) as well as location detection systems and electronic sealing devices and/or door sensors will all take place wirelessly over a mobile communications network (120) such as the Global System for Mobile
30 Communications (GSM), Universal Mobile Telecommunications System (UMTS), satellite communication or the like. Alternatively, the server (102) and control stations (106) may communicate by means of a wired

connection, such as telephone networks, fibre optic communication networks or the like.

Figure 2 illustrates the vehicle overload monitoring system (100) described with reference to Figure 1, in use at one of the control stations (200) situated along the corridor. The control station (200) includes a WIM scale (202) and a static scale (204) as well as electronic vehicle identification mechanisms (206) at or near each scale (202, 204). In a preferred embodiment², the control station (200) includes at least a first and a second boom gate (208, 210) in order to direct vehicles (212) into and through the control station (200).

In use, a vehicle (212) travelling along the road transportation corridor is, at a first stage, directed toward the WIM scale (202) where the vehicle (212) is identified by means of the electronic vehicle identification mechanism (206) and then weighed while passing over the WIM scale (202). The direction of travel of a vehicle along the corridor is indicated by arrows (213). If the vehicle's (212) weight is determined by the WIM scale (202) to be below a pre-determined minimum loading limit, the first boom gate (208) is opened, thereby permitting the vehicle (212) to return onto the road (214) and continue travelling along the corridor. However, where the vehicle's (212) weight is determined by the WIM scale (202) to be above the pre-determined minimum loading limit, the second boom gate (210) is opened, directing the vehicle (212) toward the static scale (204). At the static scale (204), the vehicle (212) is optionally again identified by means of an electronic identification mechanism (206) and then weighed. It will be appreciated that the weight measurements obtained at the static scale (204) are significantly more accurate than the weight measurements of the WIM scale (202). Once the vehicle (212) has been accurately weighed at the static scale (204), it will either be permitted to return to the road (214) and continue travelling on the corridor or the vehicle's (212) cargo may have to be adjusted so as to ensure that the vehicle's (212) weight falls within the permitted loading limits. It will

be appreciated that instead of using boom gates (208, 210) to direct vehicles (212) within the control station (200), signage, preferably electronic signage, may be used.

- 5 It should be noted that the procedure described in the previous paragraph is the procedure that will be followed at the first control station (200) encountered by a vehicle (212) along a corridor. Where the vehicle (212) has been weighed at a static scale (204) at a previous control station (200) within a pre-determined time frame, and the vehicle identifier has not been flagged
10 by the server, then the vehicle (212) may not be required to proceed to the static scale (204) even where the WIM scale (202) indicates that the vehicle (212) may be overloaded. The determination as to whether a vehicle (212) needs to be weighed at a static scale (204) once the WIM scale (202) indicates that the vehicle (212) may be overloaded will be described in more
15 detail below.

In addition, it will be appreciated that additional factors such as the vehicle type, the loading and type of loading on the vehicle, and the like, may also be taken into account when determining whether the vehicle is permitted to
20 return onto the road or whether the vehicle should be weighed by means of the static scale.

In a preferred embodiment and as illustrated in Figure 2, each control station (200) includes a secondary electronic identification mechanism (216) in order
25 to enable the identification of vehicles (212) that are not weighed at the control station (200). The secondary electronic identification mechanism (216) may also be used to identify vehicles (212) that were classified and/or directed to being weighed at a static scale (204), but were not so weighed. This would particularly be relevant where vehicles (212) are directed within a
30 control station (200) through signage, and not by boom gates. The secondary electronic identification mechanisms (216) are typically located along the road (214) and are capable of transmitting vehicle identifiers to the server for

storage by the server on the system database and for flagging the vehicle identifier to indicate that the vehicle (212) has not been weighed. Where a vehicle identifier has been flagged as not having been weighed, a control station (200) further along the corridor may be notified of such vehicle (212) and will be able to alert and/or sanction the vehicle (212) for passing the control station (200), alternatively, the vehicle (212) owner will simply be sanctioned for not having obeyed the rules and/or regulations. It will be appreciated that where the vehicle (212) passing the control station (200) cannot be identified, because the vehicle (212) does not have an RFID tag or the like secured thereto, the server will be enabled to notify a control station (200) along the corridor that an unidentified vehicle (212) is traveling on the corridor and the control station (200) will be able to halt and/or alert the vehicle (212). The secondary electronic identification mechanism (216) may also be equipped with an automated number plate recognition (ANPR) system so as to enable the server to record the number plate of the vehicle (212) which passed the control station (200) without being weighed.

Due to the weight measurement data and vehicle identifiers of each vehicle (212) passing through the control station (200) being stored on the system database, the data can be effectively used by other control stations (200) located further along the corridor as will be described below. It will immediately be apparent that a substantial advantage of the system is that, once a vehicle's weight has been accurately measured on a static scale (204) of one of the control stations (200) and found to be within the legal limits and recorded as such in the system database, WIM scale measurements at subsequent control stations that are close to the pre-determined minimum load limit, be it slightly over or slightly under, may still allow the vehicle in question to pass through the control station (200) without having to be weighed on the static scale again. This may substantially reduce the number of weighs a given vehicle (212) may have to undergo along the corridor, in turn leading to a substantial cost and time saving to both the vehicle operator and control station.

- Figure 3 illustrates a flow diagram of a method for monitoring the load of a vehicle along a road transportation corridor making use of the system illustrated in Figures 1 and 2. At a first stage (300), the remotely accessible server (102) receives a vehicle identifier and weight measurement data from a control station (106) located along a road transportation corridor. The weight measurements may have been taken by a WIM or static scale at the control station and flagged as such.
- Where the vehicle (112) has not previously been weighed and identified at a control station (106), then at a next stage (302), the server (102) associates the weight measurement data with the vehicle identifier and control station identifier and stores the associated data on the system database (104).
- Alternatively, if the vehicle (112) has been previously weighed at a control station (106) along the corridor, then at a next stage (304), the server (102) identifies the vehicle (112) and retrieves information associated with the vehicle identifier from the system database (104). This information is then forwarded to the control station through which the vehicle (112) is in the process of passing. The information associated with the vehicle identifier will include weight measurement data previously received as well as the identifier of the control station (106) from which such weight measurement data was received.
- While still at this control station, at a next stage (306), the server (102) determines whether the vehicle (112) had been weighed at a previous control station (106) within a pre-determined time frame or whether the vehicle identifier had been flagged, thereby indicating that there is a likelihood of the vehicle's (112) weight having changed since the last weighing of the vehicle (112). As described above, a vehicle identifier will typically be flagged where the vehicle (112) exhibited some characteristic or behaviour, such as halting for a specified period of time or deviating from the corridor or the electronic

sealing devices and/or door sensors indicating that tampering with the cargo area (118) of the vehicle (112) may have occurred, thereby indicating that the vehicle's (112) weight may have changed during travel along the corridor.

- 5 Where the vehicle (112) has not been weighed within the pre-determined time frame or where the vehicle identifier has been flagged, then at a next stage (308), the control station (106), being in communication with the server (102), determines whether the weight measurement data falls within pre-determined allowable parameters or limits, for example below the maximum
- 10 loading limit. This first weighing of the vehicle (112) is typically done by means of a WIM scale (114). Where the weight measurement data falls within the pre-determined allowable parameters, then at a next stage (310), the vehicle (112) is permitted to continue travelling on the corridor.
- 15 Where on the other hand the weight measurement data does not fall within the pre-determined allowable parameters, then at a next stage (312), the control station (106), at which the vehicle (112) is being weighed, determines that the vehicle (112) is potentially overloaded. The vehicle (112) will then be directed toward the static scale (116) so as accurately determine the
- 20 vehicle's (112) weight.

At stage (306), where the vehicle (112) has been weighed within the pre-determined time frame and the vehicle identifier has not otherwise been flagged, then at a next stage (314), the control station (106), being in

25 communication with the server (102), determines whether the weight measurement from the current WIM scale falls within the pre-determined parameters.

Where the weight measurement data falls within the pre-determined

30 parameter, then at a next stage (316), the vehicle (112) is permitted to continue travelling on the corridor.

Alternatively, where the weight measurement data does not fall within the pre-determined parameters, then at a next stage (318), the control station (106), being in communication with the server (102), compares the weight measurement data received from the WIM scale with the allowed weight limits as well as with the weight measurement data associated with the vehicle identifier as captured at one or more previous control stations (106) and stored on the system database (104). Where the comparison indicates that the WIM scale measurement is over the pre-determined limits, then at a next stage (320) it is determined by the control station (106) that the vehicle (112) is potentially overloaded. The vehicle (112) will then again be directed toward the static scale (116) for a more accurate weighing. If the comparison also indicates that the same vehicle (112) was found to be over the limit at a previous control station (106) on the corridor, and that it is still over the limit, the vehicle (112) will be directed to the static scale (116) and, in addition, a notification will be transmitted to the server (102) that the prescribed control procedures at the previous control station (106) were possibly not properly applied.

Where on the other hand the comparison indicates that a variation in the weight of the vehicle from previous weight measurement data received by the server (102) and, more specifically, the weight measurement data from a previous weighing by means of a static scale (116), is within allowable limits, and where the vehicle identifier has not been flagged, then at a next stage (322), the vehicle (112) will be permitted to continue travelling along the corridor.

It will be appreciated that by interconnecting control stations along a corridor and enabling them to share the vehicle identifiers and weight measurement data, the system (100) is enabled to compare the various weight measurements as described above. The comparison of the weight measurements will in particular enable the system (100) to more accurately determine whether a vehicle (112) that has been loaded close to the

maximum permitted load, in fact needs to be weighed by means of the static scale (116) again, where the WIM scale (114) indicates that the vehicle (112) is close to its maximum permissible load. This system will therefore decrease the number of static scale (116) weighs a vehicle (112) will have to undergo where the vehicle (112) has been loaded close to the maximum permissible load, thereby significantly decreasing the wasted time and cost involved with unnecessary static scale (116) weighing.

It will further be appreciated that the use of the location detection systems and electronic sealing devices and/or door sensors will enable the system (100) to effectively monitor a vehicle's (112) behaviour while travelling along the corridor, thereby enabling the system (100) to determine whether the vehicle's (112) weight may have changed since its last weighing. Thus, where a vehicle (112) has been loaded close to the maximum permitted limit, and the static scale (116) weighing has indicated that the vehicle (112) is within the maximum allowable limits, the system (100) will be able to determine whether the vehicle (112) exhibited behaviour which may indicate that its weight has changed since the last weighing. If the vehicle (112) exhibited such behaviour, and the WIM scale (114) reading again indicates that the vehicle's (112) weight falls outside the pre-determined allowable parameters, then the system (100) will direct the vehicle (112) toward the static scale (116) for a more accurate weighing. This will not only significantly increase the efficiency of control stations (106), but at the same time enable the effective overload monitoring of vehicles (112) and reduce the number of static scale (116) weighs a vehicle (112) may otherwise have undergone while travelling along a corridor.

It will further be appreciated that due to each control station being in communication with the server, each control station is enabled to use the information stored on the system database so as to determine whether a vehicle which has been identified by a WIM scale as possibly being overloaded should be directed to a static scale. This determination may, for

example, be based on current WIM scale weight measurement data, the most recent WIM scale and/or static scale weight measurement data at a previous control station, the time of travel of the vehicle from the previous control station to the current control station as well as any other weight
5 measurements associated with the vehicle identifier that have been stored on the system database. The determination as to whether the vehicle should be weighed at a static scale can then be made by using all these factors in an algorithm which is capable of maximizing the probability of effectively selecting overloaded vehicles while at the same time minimizing the
10 probability of selecting vehicles that have merely been loaded very close to the maximum permissible limit, but do not exceed the limit.

It should be noted that the system and method described above also lends itself to facilitate the calibration of weighing mechanism positioned at control
15 stations along a road transportation corridor.

Figure 4 illustrates a flow diagram of a method for calibrating vehicle weighing mechanisms (108) located at control stations (106) by making use of the system described above. At a first stage (400), the server (102)
20 receives a plurality of data sets comprising a first weight measurement from a first weighing mechanism, preferably a WIM scale (114), and a second weight measurement from a second weighing mechanism, preferably a static scale (116). Each of the data sets will thus include a weight measurement of a vehicle (112) both from a WIM scale (114) and a static scale (116).

25
At a next stage (402), the server (102) computes the difference between the first weight measurement and the second weight measurement for each data set, after which, and at a next stage (404), the server (102) computes an average of the differences computed during the previous stage (402). Taking
30 into consideration that the sets of weight measurements obtained will represent a range of different values, the combination of averaged differences will comprise a regression line that represents the relationship

between the WIM scale (114) and static scale (116) measurements over the relevant range of weight values.

At a next stage (406), the server (102) calibrates the weight measurement
5 readings of the WIM scale (114) by adjusting any weight measurement data received from the WIM scale (114) by the averaged difference corresponding to that WIM scale (114) value computed during the previous stage (404).

It will be appreciated that calibrating WIM scales (114) in accordance with the
10 method described above, may ensure that the corrected WIM scale (114) readings will be more in line with weight measurement readings obtained from static scales (116). This may increase the accuracy of WIM scale (114) readings, thereby potentially increasing their reliability and enabling their use for prosecution purposes. Furthermore, the increase in accuracy of WIM
15 scale (114) readings may at least partially negate the need for each control station (106) to have both a WIM scale (114) and a static scale (116). Further, due to the significant costs involved with static scales (116) when compared to WIM scales (114), the decrease in static scales (116) required along road transportation corridors may enable the more widespread
20 overload control along corridors by means of WIM scales (114) at a lower capital cost.

It will be appreciated that the method of calibrating a WIM scale described above may, of course, also be utilized to calibrate a static scale. In this case,
25 instead of computing a difference for each data set and then computing an average therefor, an average of all previous static scale weight measurements for the same vehicle can be computed and the static scale readings calibrate according to the computed average.

30 It is envisaged that vehicle operators could also be permitted to communicate weight measurement data obtained from their own weighing mechanisms to the server. This could in turn increase the weighed measurement data used

for the calibration procedure as described above, as well as permit vehicle operators to effectively calibrate their own WIM scales thereby avoiding possible sanctions at a static scale.

- 5 The above description of the invention is by way of example only and it should be appreciated that numerous changes and modifications may be made to the embodiments described without departing from the scope of the invention. In particular, it should be noted that the system may utilise a complex set of rules and tests to determine if a vehicle should be flagged as
10 having potentially altered its load while travelling along the corridor.

In addition, it should be noted that apart from a centralised, remotely accessible server, each control station may simply be provided with a local storage facility and communications capabilities allowing it to communicate
15 with other controls stations along the corridor. In such an embodiment control stations may simply forward gathered vehicle identification and associated weight measurement information to subsequent control stations positioned further along the transportation corridor in the direction of the vehicle's travel, where the information may be locally stored until it is required, and decisions
20 made by a local processor as to the progression of a vehicle through the control station can then at least partially be based on the gathered information from previous control stations. It should be appreciated that information may be shared between control stations by means of any number of wired or wireless communications technologies.

25

The invention in its broadest sense provides control stations with the ability to compare locally measured weight information with previously measured, potentially more accurate, weight information as measured by other control stations, in order to make more informed decisions as to whether or not it is
30 necessary to conduct further, more detailed and time consuming, weighing of the vehicle.

It will be apparent to those skilled in the art that these and numerous other changes and modifications may be made to the system described without departing from the scope of the invention.

CLAIMS:

1. A vehicle overload monitoring system (100), comprising:
a plurality of control stations (106) situated along a road transportation
5 corridor;
each control station (106) having a unique identifier associated therewith and including at least one vehicle weighing mechanism (108), at least one electronic identification mechanism (110) configured to uniquely identify a vehicle (112) passing through the control station (106), and a
10 communications module;
wherein each control station (106) is configured to receive, by way of the communications module, weight measurement data and vehicle identifiers gathered by one or more other control stations (106) along the road transportation corridor, associate the received vehicle identifiers and the
15 weight measurement data with the unique identifiers of the control stations (106) by which they were gathered, and to at least partially utilize the associated information to determine whether the vehicle (112) should be weighed by way of the vehicle weighing mechanism (108).
- 20 2. A vehicle overload monitoring system (100) as claimed in claim 1, wherein the system (100) further comprises a remotely accessible server (102) in data communication with a system database (104), the remotely accessible server (102) being configured to receive weight measurement data and a vehicle identifier from a control station (106), associate the vehicle
25 identifier and the weight measurement data with the unique identifier of the control station (106), and store the associated information on the system database (104) for use by other control stations (106) along the road transportation corridor.
- 30 3. A vehicle overload monitoring system (100) as claimed in claim 1 or 2, wherein the weighing mechanism (108) of each control station (106) includes one or more of a weigh-in-motion (WIM) scale (114) and a static scale (116).

4. A vehicle overload monitoring system (100) as claimed in any one of the preceding claims, wherein each control station (106) includes a WIM scale (114) and a static scale (116).

5

5. A vehicle overload monitoring system (100) as claimed in any one of claims 2 to 4, wherein the remotely accessible server (102) is further configured to receive location data of a vehicle (112) traveling along the road transportation corridor which is transmitted to the remotely accessible server (102) by way of a location detection system associated with the vehicle (112).

10

6. A vehicle overload monitoring system (100) as claimed in claim 5, wherein the remotely accessible server (102) is configured to determine a likelihood of whether the vehicle (112) stopped and/or deviated from the road transportation corridor, so as to determine a likelihood of the vehicle's weight having changed along the corridor and/or in between one or more control stations (106) based on the received location data and, if a high likelihood that the vehicle weight has changed is determined, flag the vehicle identifier stored on the system database (104) to that effect.

15

20

7. A vehicle overload monitoring system (100) as claimed in any one of claims 2 to 6, wherein the remotely accessible server (102) is configured to receive loading area access data of a vehicle (112) which is transmitted to the remotely accessible server (102) by way of electronic sealing devices and/or electronic door sensors secured to the loading area of the vehicle (112).

25

8. A vehicle overload monitoring system (100) as claimed in claim 7, wherein the electronic sealing devices are enabled to detect opening, closing and/or tampering events of the loading area of the vehicle (112) and wherein the remotely accessible server (102) is configured to determine the likelihood

30

of the vehicle weight having changed along the corridor based on the received loading area access data.

9. A vehicle overload monitoring system (100) as claimed in any one of
5 claims 2 to 8, wherein each control station (106) includes a secondary
electronic identification mechanism (216) configured to identify vehicles (112)
that are not weighed at the control station (106) and the remotely accessible
server (102) is configured to receive vehicle identifiers from the secondary
electronic identification mechanism (216), to store the vehicle identifiers in
10 the system database (104) and to flag the vehicle identifiers received from
the secondary electronic identification mechanism (216) to indicate that the
identified vehicle (112) was not weighed.

10. A vehicle overload monitoring system (100) as claimed in claim 9,
15 wherein the remotely accessible server (102) is configured to notify control
stations (106) further along the road transportation corridor that an
unidentified vehicle (112) is traveling towards it, if the vehicle (112) cannot be
identified by way of the secondary electronic identification mechanism (216).

20 11. A vehicle overload monitoring system (100) as claimed in any one of
claims 3 to 10, wherein the remotely accessible server (102) is configured to
pro-actively transmit the associated information to one or more subsequent
control stations (106) located further along the road transportation corridor
than the control station (106) from which the information was received, in
25 preparation for an identified vehicle's arrival at the subsequent control
stations (106), the associated information being useful by the subsequent
control stations (106) to determine if an identified vehicle weighed by the
WIM scale (114) at the subsequent control station (106) should again be
weighed on the static scale (116) of the subsequent control station (106).

30

12. A vehicle overload monitoring system (100) as claimed in any of the
preceding claims, wherein the electronic identification mechanism (110, 216)

includes any one or more of a radio-frequency identification (RFID) reader, a quick response (QR) code reader, or a barcode reader and wherein vehicles (112) operating along the corridor have any one or more of an RFID tag, a QR code and a barcode secured to the vehicle (112) which uniquely
5 identifies the vehicle (112).

13. A vehicle overload monitoring system as claimed in any of claims 1 to 11, wherein the electronic identification mechanism (110, 216) includes an automated number plate recognition (ANPR) system configured to
10 automatically identify a vehicle (112) from its number plate.

14. A vehicle overload monitoring system (100) as claimed in any one of claims 5 to 13, wherein the location detection system is one or more of a Global Positioning System (GPS), a Local Positioning System (LPS), and a
15 Wireless Positioning System (WPS).

15. A method for monitoring the load of a vehicle (112) along a road transportation corridor, the method including the steps of, at a control station situated along the road transportation corridor:

20 receiving a vehicle identifier and weight measurement data of a vehicle (112) being weighed with a WIM scale (114) of the control station;

receiving weight measurement data and vehicle identifiers gathered by one or more other control stations (106) situated along the road transportation corridor and associating the vehicle identifiers and the weight
25 measurement data with unique identifiers of the control stations (106) by which they were gathered; and

determining whether the vehicle (112) should be weighed again by way of a static scale (116) at the control station (106), based at least partially on the received weight measurement data gathered by the other control
30 stations (106) along the corridor.

16. A method as claimed in claims 15, wherein the step of determining whether the vehicle (112) should be weighed again by way of the static scale (116) at the control station (106) includes the steps of:

determining whether the vehicle (112) has previously been inspected
5 at one or more other control stations (106) along the road transportation corridor within a pre-determined time frame, this time frame being calculated based on normally expected travel time from the respective previous control station (106) to the current control station (106), and whether the vehicle identifier has been flagged by the remotely accessible server (102) to
10 indicate a likelihood that the vehicle's weight has changed since its last inspection;

if the vehicle (112) has not been inspected at a static scale (116) within the pre-determined time frame or the vehicle identifier has been flagged, determining whether the WIM scale (114) weight measurement data
15 deceeds a first pre-determined parameter and, if it does, permitting the vehicle (112) to continue travelling along the road transportation corridor, alternatively, if the WIM scale (114) weight measurement data exceeds the first pre-determined parameter, transmitting a notification to the control station (106) that the vehicle (112) is potentially overloaded and should be
20 weighed again at the associated static scale (116); and

if the vehicle (112) has been inspected at a static scale (116) within the pre-determined time frame and the vehicle identifier has not been flagged, determining whether the WIM scale (114) weight measurement data
25 deceeds a second pre-determined parameter, set at a level higher than the first pre-determined parameter, and, if it does, permitting the vehicle (112) to continue travelling along the road transportation corridor, alternatively, if the weight measurement data exceeds the second pre-determined parameter, comparing the weight measurement data with the previously received weight measurement data to determine whether the vehicle (112) is potentially
30 overloaded and should be weighed again.

17. A method as claimed in claim 15 or 16, which is performed at a remotely accessible server and wherein associated information is stored on a system database.

- 5 18. A method of calibrating a vehicle weighing mechanism (108) at a control station (106) situated along a road transportation corridor, the method including the steps of:

identifying a vehicle (112) entering the control station (106);

weighing the vehicle (112) utilizing the vehicle weighing mechanism

- 10 (108) to obtain a current weight measurement;

gathering previous weight measurements relating to the vehicle (112), the previous weight measurements having been recorded by one or more other weighing mechanisms (108) associated with one or more other control stations (106) situated along the road transportation corridor;

- 15 comparing the current weight measurement to the previous weight measurements to determine a level of variation between the measurements; and

adjusting the calibration of the vehicle weighing mechanism (108) in accordance with the level of variation.

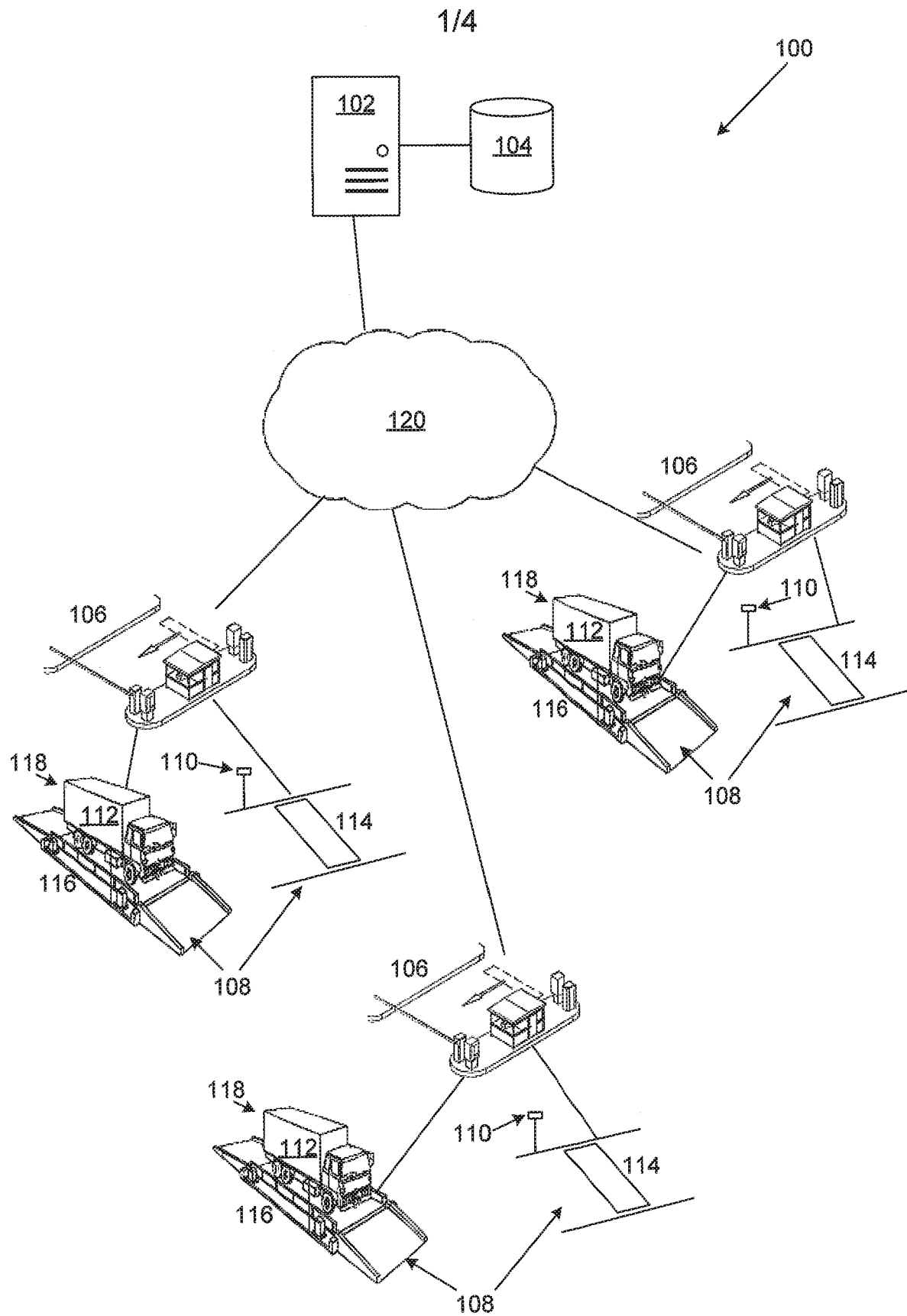
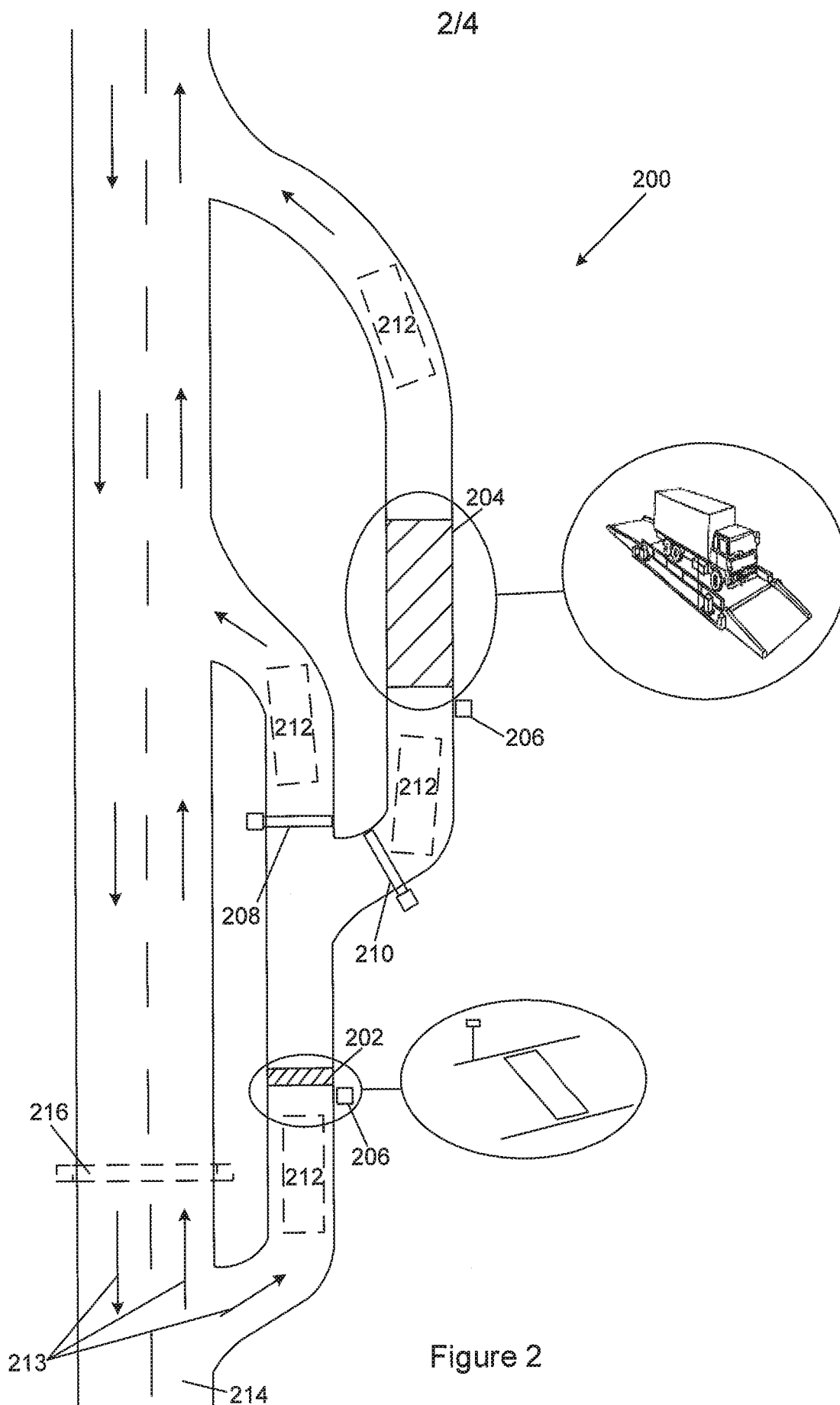


Figure 1



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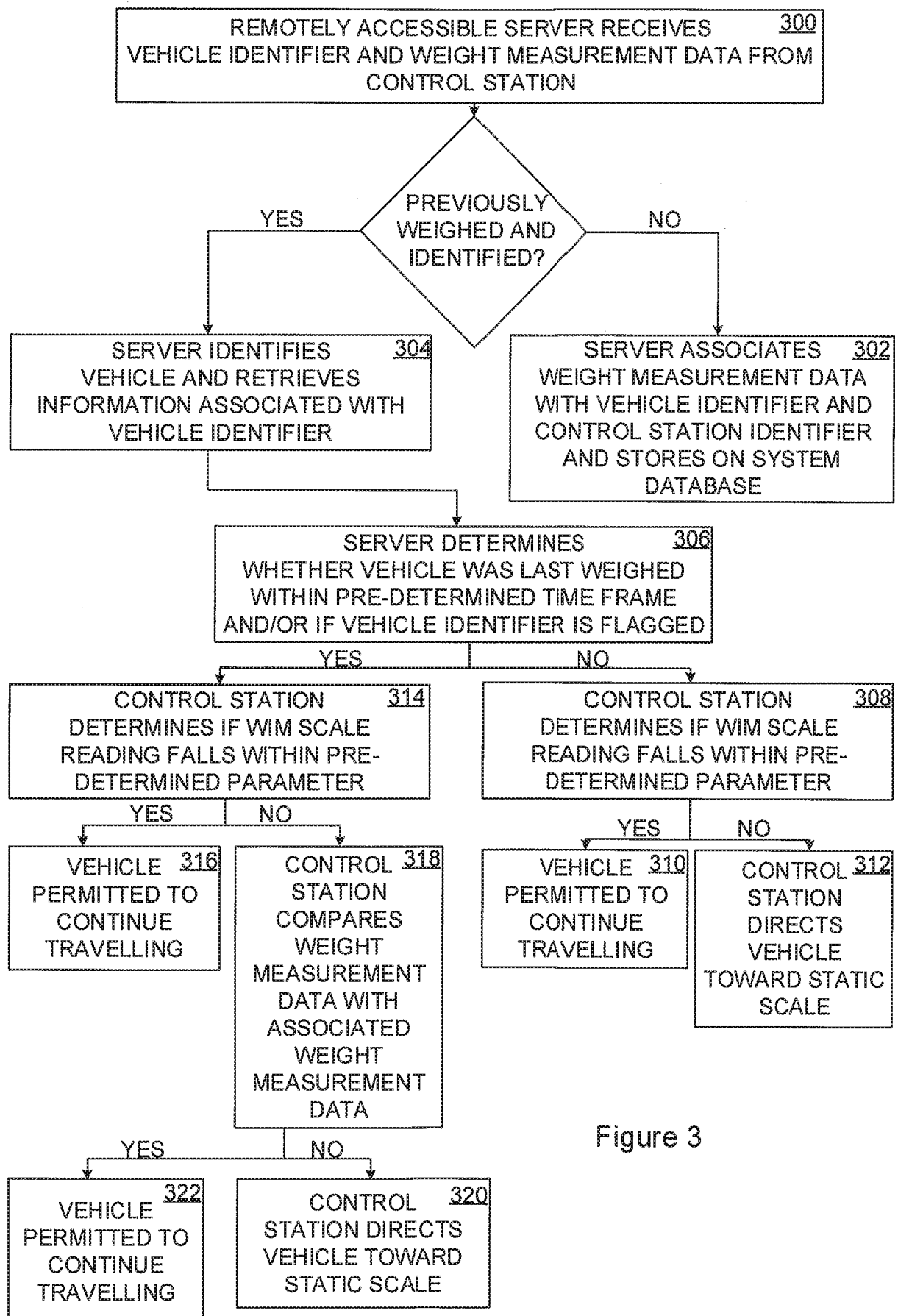


Figure 3

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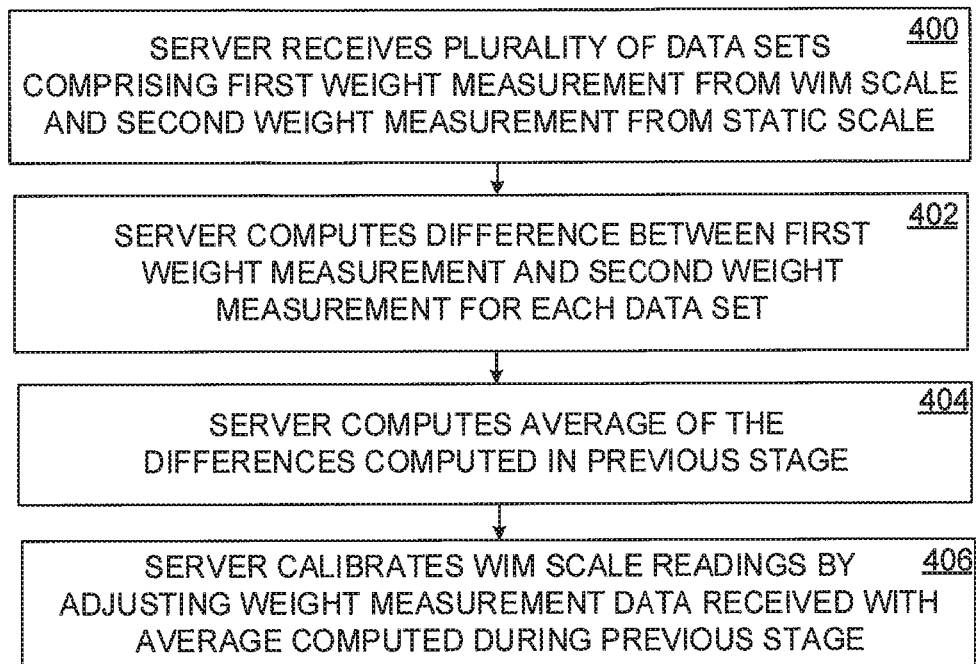


Figure 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2014/065145

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01G19/02 G01G23/01 G01G23/37 G01G23/42
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/151421 A1 (SUSOR ROBERT [US]) 18 June 2009 (2009-06-18) paragraph [0005] - paragraph [0009] paragraph [0025] - paragraph [0044] claims 1, 7, 13, 16, 22, 23 figures 1-5 -----	1-18
X	DE 10 2005 055663 A1 (WINGTEC GMBH [DE]) 14 September 2006 (2006-09-14) paragraph [0012] - paragraph [0020] paragraph [0025] - paragraph [0028] paragraph [0037] - paragraph [0041] paragraph [0044] paragraph [0051]; claims 11,12 figures 1-5 -----	1-18



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

18 February 2015

Date of mailing of the international search report

27/02/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Koch, Florian

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2014/065145

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2009151421 A1	18-06-2009	CA 2625269 A1	17-06-2009
		US 2009151421 A1	18-06-2009

DE 102005055663 A1	14-09-2006	AT 403923 T	15-08-2008
		DE 102005055663 A1	14-09-2006
		EP 1856680 A1	21-11-2007
		WO 2006094652 A1	14-09-2006

OVERLOADING FIELD SHEET													
Weigh Bridge					Route/road code				Vehicle configuration				
Weigh date & time					Origin				Destination				
Registration no 1					Registration no 2 & trailer type		Semi-trailer Trailer		Registration no 3 & trailer type		Semi-trailer Trailer		
Vehicle make					Vehicle colour				Consignment note no				
Company/owner					Cargo				Driver ID				
Release date & time					Usage (eg truck, bus, tow truck)		Abnormal Yes No		Driver name				
		A		B		C		D		E		F	
Bird's eye view		Axle unit		Double or single		Reg 239 (Manufacturer specification)		Reg 240 (Road carrying capacity)		Reg 238 (Tyre specifications)		Permissible (Smallest of B, C, D + 5%)	
												Weighed scale mass	
												Enter first weight (1)	
												Correction Reweigh (2)	
												Overload (F-E without 5%)	
												% Overload (Gx100/E without 5%)	
		(1) Steering axle		S		GA Front on 245		Reg 240		SABS 1550		Permissible + Reg 234 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(2) Driving axle / unit		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(3) Axle / unit 3		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(4) Axle / unit 4		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(5) Axle / unit 5		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
Sum of the permissibles (axle's and axle units) Reg 236 (2)(a)						Reg 236 (2)(a)		Permissible's of all axle's and units added together					
Permissible vehicle mass (if single vehicle) Reg 239 (1)(a)(i)		GVM on 245		Reg 236		Smallest of: 1) Sum of permissibles 2) GVM on 245 3) Engine capacity 4) Driving axle/unit		Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Permissible combination mass (if combination of vehicles) Reg 239 (1)(b)		GCM on 245		Reg 237		Smallest of: 1) Sum of permissibles 2) GCM on 245 3) Driving axle/unit 4) Engine capacity 5) Group - maximum 6) Proviso - 56 000 kg		Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Driving axle mass x 5 Reg 239 (3)		Scale mass of driving axle/unit		Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Engine P/D x 240 / 400 Reg 239 (2)(a) or (b)		P/D on 245		Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Minimum steering axle weight (11% / 12% / 20% / 30%) Reg 242 (b)/(d) / (d)/(c)				Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Group 1: L x 2100 + 18 000 Reg 241 (1) (max. group)				Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Group 2: L x 2100 + 18 000 Reg 241 (1)				Calculation				Permissible		Scale mass		Scale mass	
								+5%				Overload	
Group 3: L x 2100 + 18 000 Reg 241 (1)				Calculation				Permissible		Scale mass		Scale mass	
								+5%				Overload	
Proviso Reg 236				56 000 kg				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Additional defects to prosecute													
Action taken by official													
Police station		CAS number				Summons number				Weighing officer			
										Prosecuting officer			

Appendix D: Overloading Field Sheet

Overloading field sheet usable by traffic officers

OVERLOADING FIELD SHEET													
Weigh Bridge					Route/road code				Vehicle configuration				
Weigh date & time					Origin				Destination				
Registration no 1					Registration no 2 & trailer type		Semi-trailer Trailer		Registration no 3 & trailer type		Semi-trailer Trailer		
Vehicle make					Vehicle colour				Consignment note no				
Company/owner					Cargo				Driver ID				
Release date & time					Usage (eg truck, bus, tow truck)		Abnormal Yes No		Driver name				
		A		B		C		D		E		F	
Bird's eye view		Axle unit		Double or single		Reg 239 (Manufacturer specification)		Reg 240 (Road carrying capacity)		Reg 238 (Tyre specifications)		Permissible (Smallest of B, C, D + 5%)	
												Weighed scale mass	
												Enter first weight (1)	
												Correction Reweigh (2)	
												Overload (F-E without 5%)	
												% Overload (Gx100/E without 5%)	
		(1) Steering axle		S		GA Front on 245		Reg 240		SABS 1550		Permissible + Reg 234 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(2) Driving axle / unit		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(3) Axle / unit 3		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(4) Axle / unit 4		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
		(5) Axle / unit 5		S/D		GA/U Rear on 245		Reg 240		SABS 1550		Permissible + Reg 234/5 +5%	
												Scale mass	
												Scale mass	
												Overload	
												% Overload	
Sum of the permissibles (axle's and axle units) Reg 236 (2)(a)						Reg 236 (2)(a)		Permissible's of all axle's and units added together					
Permissible vehicle mass (if single vehicle) Reg 239 (1)(a)(i)		GVM on 245		Reg 236		Smallest of: 1) Sum of permissibles 2) GVM on 245 3) Engine capacity 4) Driving axle/unit		Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Permissible combination mass (if combination of vehicles) Reg 239 (1)(b)		GCM on 245		Reg 237		Smallest of: 1) Sum of permissibles 2) GCM on 245 3) Driving axle/unit 4) Engine capacity 5) Group - maximum 6) Proviso - 56 000 kg		Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Driving axle mass x 5 Reg 239 (3)		Scale mass of driving axle/unit		Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Engine P/D x 240 / 400 Reg 239 (2)(a) or (b)		P/D on 245		Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Minimum steering axle weight (11% / 12% / 20% / 30%) Reg 242 (b)/(d) / (d)/(c)				Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Group 1: L x 2100 + 18 000 Reg 241 (1) (max. group)				Calculation				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Group 2: L x 2100 + 18 000 Reg 241 (1)				Calculation				Permissible		Scale mass		Scale mass	
								+5%				Overload	
Group 3: L x 2100 + 18 000 Reg 241 (1)				Calculation				Permissible		Scale mass		Scale mass	
								+5%				Overload	
Proviso Reg 236				56 000 kg				Permissible		Total scale mass		Scale mass	
								+5%				Overload	
Additional defects to prosecute													
Action taken by official													
Police station		CAS number				Summons number				Weighing officer			
										Prosecuting officer			