A PRAGMATIC APPROACH TO EVALUATE OPTIMISATION STRATEGIES IN ROAD FREIGHT TRANSPORTATION

P LUSANGA, A HOFFMAN

North West University
School of Electrical, electronic and Computer engineering,
P/Bag X600, Potchefstroom, 2520, South Africa.
Email: plusanga@gmail.com, Alwyn.Hoffman@nwu.ac.za

ABSTRACT

Road freight is one of the most common means of inland transportation in Africa. Other forms include rail, air and marine transport. Road freight use has grown due to the increase in cross-border trade. This increased economic activity has put a strain on the road infrastructure and processing procedures at various checkpoints along the trade routes. Consequently, a number of bottlenecks have surfaced along the transportation corridors. In response, individual efforts have been and are still being made by the relevant stakeholders to improve the status quo. Most of them involve the use of communication technology. Examples include electronic declarations, e-tolling and one-stop border posts. Post-implementation results show little or no improvement in corridor efficiency. This implies that more detailed studies are required before deployment of proposed solutions. In this paper the results of a pragmatic approach to evaluate improvement strategies in overload control are presented. This approach is multi-dimensional. It looks at all the role players and how they would be affected or respond to the deployed system. The method employed is primarily based on the modelling of activities, processes and the responses from stakeholders and simulating various scenarios in Simio. The impact of the WIM threshold level, nature of the charging system, and extent of data sharing among stakeholders on the corridor are shown and discussed.

Index Terms— freight, technology, Simio, transport, optimisation, behaviour, cross-border, telemetry, overload control, intelligent, supply chain

1. INTRODUCTION

With the emergence of auto-identification, faster communication technology and artificial intelligence, there is a growing trend towards automated monitoring of large complex systems (Chen, et al., 2014). Data captured at identification points can be stored to keep track of events, study trends, and for billing or charging purposes. In transportation, tracking has been one of the leading technologies employed by transporters and security organizations such as police and vehicle tracking companies. In addition to tracking for theft or loss prevention, traffic police have made use of data storage systems to recall past driving records of offending motorists and used the motorist's historical record to determine the penalty or charge/s. Such systems which have many interacting role players can be expedited with more efficient communication and identification technology (Hoffman, et al., 2013).

Multinational road corridors have many players, the main being transporters, road agencies, customs authorities, and immigration (Hoffman, et al., 2013), (Fitzmaurice, 2012), (Hoffman & de Coning, 2014). These interact with one another but there is little or no collaboration between the stakeholders. The benefits of advanced electronic systems, communication technology and computing power have not been adequately exploited. Examples of collaboration that do exist are between,

I. Security organizations and transporters : information exchanged = GPS tracking data

II. Freight agents and customs authorities: information exchanged = Electronic declarations (electronic data interchange, EDI)

Several proposals have been suggested in (Fitzmaurice, 2012), (Hoffman & de Coning, 2014) and (Hoffman, 2017) to integrate stakeholder interactions and improve communication between stakeholders. Some performance projections and cost benefit analysis were given in (Hoffman & de Coning, 2014). Hoffman and de Coning (2014), used the number of static scale visits per journey, the average number of static weighs per day, average processing times and the queuing theory for the Markov process to compute averages for the current and new waiting times for trucks (Hoffman & de Coning, 2014). However these are estimates and not all the corridor dynamics were incorporated in the methods used. Better results can be obtained from pilot projects or accurate simulations. A simulation strategy was presented by Lusanga *et.al.* (2014) to investigate these proposals. It consisted of a preliminary design but no actual results were presented.

The study presents preliminary simulation results for selected proposals. The study is an extension of the work done in (Lusanga, et al., 2014). It shows that the agent based approach can indeed be sufficient to simulate the impact of implementing various technologies and operational procedures on a trade corridor. Two parameters can be used as performance indicators. Time and cost (or profit) are used as measures to compare various system configurations. In the future, models can be calibrated to match the real world. Pertinent data includes traffic flows volumes and loading behaviour of transporters. The Simio simulation environment as suggested in (Pegden, 2007) and (Lusanga, et al., 2014), is used to model the stakeholders' behaviour, characteristics and source-destination flows along the corridor.

The focus of this paper is on overload control. The impact of current and proposed weighbridge systems and their impact on the operations of road transporters is presented.

The paper is organized as follows: Section II describes the research objectives. Section III looks at current and proposed corridor systems. Section IV looks at the proposed systems in more detail. Section V describes how the model was calibrated. The simulation results are shown in section VI and lastly the conclusion is presented in section VII.

2. RESEARCH OBJECTIVES

This study is a part of ongoing research on cargo visibility at the North-West University, South Africa. The motivation has come from recognition that supply chain management, specifically road transportation can be more effective if more data parameters are captured and information is shared among stakeholders. Management for each stakeholder on a transportation corridor would be improved with increased cargo visibility and the resulting increased system intelligence. This would have an effect on processing times at control locations. It is expected that they would decrease. Since turnaround time for transporters is highly dependent on processing time at weighbridges and border posts, this too would be reduced. To implement this, the use of an internet based platform to enhance and control data sharing (visibility) was proposed in (Lusanga, et al., 2014). The visibility platform discussed was based on several proposals to improve the road corridor performance.

However, their economic impact and the feasibility of implementation still requires further research. This is backed by, a study at Chirundu border post which showed that the "one - stop border" proposal did not yield expected border performance (Fitzmaurice, 2012). Therefore, to minimize risk, it is necessary to test each proposal before actual deployment. The simulation results can then be used to choose the most optimal proposal which can be verified by a pilot project.

The model design and methodology used was presented in (Hoffman & de Coning, 2014), (Lusanga, et al., 2014) and (Bhero, et al., 2015). Nevertheless, the main aim of this paper is to present preliminary results using the road corridor model shown in Figure 1. The proposals considered are discussed further in section IV. Future work will be to apply the modeling approach to an actual road corridor.

3. CURRENT AND SIMULATED ROAD CORRIDORS

A. The Road Corridor

Road corridors comprise of many stakeholders. These include transporters, security, immigration, government and private officials at control points, weighbridges and checkpoints. These have officials implementing the organizational mandates which differ across countries and corridors in Sub-Saharan Africa (Fitzmaurice, 2012). However, the general operations can be found to be similar across the board (Fitzmaurice, 2012), (Hoffman & de Coning, 2014), (Bhero, et al., 2015). Details of border post operations can be found in (Fitzmaurice, 2012), and (Bhero, et al., 2015).

The simplified corridor used in this study focused more on overload control but the same principles used, can be applied to other corridor operations as shown in Bhero *et. al*. (2015). For the corridor in Figure 1, the aim is to demonstrate the impact of different corridor scenarios or configurations.

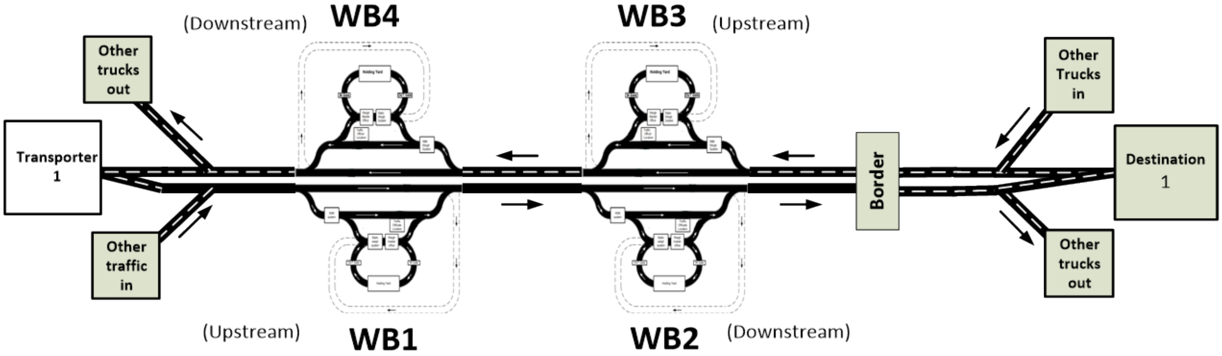


Figure 1. The Simulated road corridor

where WBX = weighbridge X. Weighbridges for each direction are treated separately.

Source blocks labeled as "other trucks in," generate the traffic using random functions. To demonstrate the reaction of a transporter to the overload control system, the transporter and destination blocks were used. The Border was modeled simply as a time delay since it was not the main focus of the study. Detailed Border studies can be found in (Bhero, et al., 2015).

B. **Transporter**

The transporter comprises of a parking base, trucks, drivers and logistics management personnel. The transporter or management's reaction to load control restrictions is modeled in this study. The trucks and driver are combined as a "Truckdriver" entity based at "Transporter 1".

The transporter usually only reacts to the environment. Therefore, the transporter's behaviour is influenced by the overall trade corridor systems. It is assumed that change in behaviour is aimed at maximizing profit in the prevailing conditions (Hoffman, et al., 2013). In this paper we simulate the transporter's loading decisions in response to overload control enforcement by authorities. The transporter's aim is to increase earnings through loading more cargo. Traffic, representing other transporters on the corridors is modeled as trucks which enter and leave the corridor.

C. **Overload control centre**

At an overload control center, heavy vehicles are weighed at the weigh in motion scale (WIM). From there, the WIM signaling system directs them to the road or static scale based on the weight measured. From the static scale, the static signaling system directs the heavy vehicle (Truckdriver) to the holding yard if overloaded, to offload, or reshuffle the load. If not, it is directed to the road. Overloaded trucks are fined. Traffic officials monitor the process while weigh officials classify the vehicle and determine whether a truck is overweight or not. Detailed weighbridge operations can be found in (Hoffman & de Coning, 2014).

Table 1 summarizes weigh bridge interactions. The grey –shaded boxes denote areas which are prone to error or malpractice.

Table 1. Interactions at a weighbridge

From Object 1	**To** Object 2	**Data item**	**Use** by Object 2	**Operation**
Driver	Overload Control Authority (OCA)	Driver & Consignment details	Identification	Manual
Truck (Freight)	WIM/Static scale	Weight	Measurement	Auto
WIM/Static scale	WIM/Static Signalling system	Weight	Decision making	Auto
OCA	WIM/Static Signalling system	WIM/Static threshold	Decision making	Manual & Auto
WIM Signalling system	Driver	WIM signal: Green – to road, Red – to static	Decision making	Auto
Static Signalling system	Driver	Static signal: Green – to road, Red – to holding yard	Decision making	Auto
Static charging system	Official	Charge	Decision making	Auto
Official	Driver	charge	Decision making	Manual &Auto

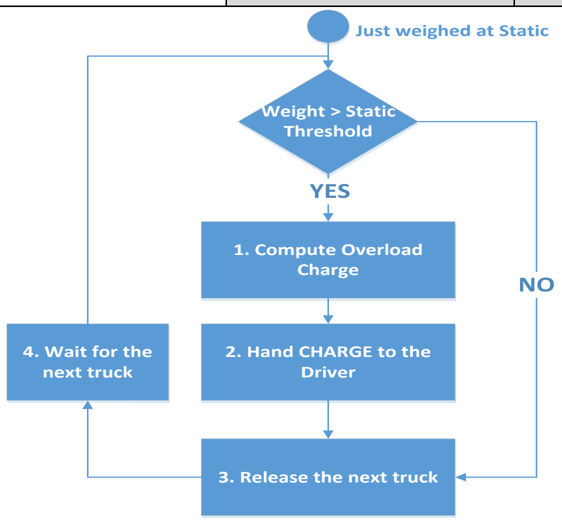


Figure 2. Manual Charging system at a weighbridge

Figure 2 Shows how charging is carried out at present. Weighbridges on corridors are not linked and historical data is not used in the charging process or in the signaling at the WIM and static scales.

The WIM signaling system depends on the WIM limit $(0.9 \times legal\ weight\ limit)$ while the static signaling system depends on the static limit $(1.02 \times legal\ weight\ limit)$. The legal weight limit refers to the total weight allowed for a particular truck. In this study, 45 000kg is the limit. It happens sometimes that the total weight is below the WIM or static limit but, one of its axle weights is above the threshold. In such cases, the load is detained for reshuffling the load until the axle weight is legal. This aspect is not covered in this study.

In the simulated corridor, the weighbridges can be set to operate as described above or, in a more efficient manner as described in the proposed systems in (Hoffman, 2017), (Lusanga, et al., 2014), (Anon., n.d.) and (Slavik, 2013). The following is a summary of these proposals.

(i) Linking the weighbridges along a corridor: In a linked corridor system, weighbridges communicate with one another and the interactions are not only between the truck and weighbridge, but also between weighbridge and weighbridge (Hoffman & de Coning, 2014).

(ii) Using more telemetry data

(iii) Using signaling systems which make use of (i) and (ii)

(iv) Using overload charging systems which make use of (i) and (ii)

(v) Using personnel management systems which make use of (i) and (ii).

Some of the above proposals would require large amounts of capital and represent major changes to the current mode of operations. Other changes or improvements can be less capital intensive. The impact of any change can be investigated by use of a simulation model before a decision is made whether to commit to the implied capital investment.

4. CORRIDOR IMPROVEMENT PROPOSALS

A. **Minor changes: WIM threshold**

Examples of non-capital intensive changes and systems include:

- Auto-calibration systems: Over time, WIM and static scales wear out and may need repairing. This can take a lot of time and the weigh bridge may be non-operational for the maintenance period. An alternative to repairing is “recalibration” which may take less time but still makes the weighbridge non-operational. As a result, overloaded vehicles would travel unchecked through the corridor, thereby increasing damage to the roads. Auto-calibration can solve this but has not yet been implemented.

- WIM scale threshold: This is the percentage weight below the Weight limit. If a truck is above this level, it is sent to the static scale to be reweighed. Since this affects the number of trucks sent to the static scale, an optimal value has to be chosen.
- Static threshold levels: The static grace threshold is the allowed percentage weight above the weight limit. This is fixed at 2% currently. The impact of adjusting it, can be investigated

For this paper, the impact of the WIM threshold level on percentages of trucks sent to the static scale, is simulated. The following short forms are used.

- W = truck weight
- WL = weight limit (45tons)
- SL = Static limit (2% >WL, 45.9tons)
- WimT=WIM threshold (10%<WL,40.5 tons)
- WIMlimit = the WIM limit.

$$\boldsymbol{WIM\ limit = WL\left(1 - \frac{Wim\ T}{100}\right)} \qquad \mathbf{1}$$

The signaling system is as follows:

IF the WIM reading exceeds the *WIM limit*
THEN vehicle is signaled to the Static scale
ELSE it is sent to the road

The WIM threshold is usually 10% below the weight limit. This percentage was varied from 1 to 10 to determine its impact on the fraction of vehicles sent to the static scale ($statwim$) and the weighbridge time delay ($WBtime$). It was assumed that with a lower WIM threshold, more trucks would be sent to the static scale.

B. **Major Changes: Linked systems**

Improvements such as linking the weighbridges would require implementation of a lot of capital as shown in (Hoffman, et al., 2013), (Lusanga, et al., 2014). The impact of these changes can be demonstrated in a simulation model and this would save time and cost and reduce the risk of implementing a system that will not have the desired impact.

Two areas are investigated. The “charging/billing system” and “link status” of the weighbridges on the corridor. All the weighbridges can be looked at as a single overload control system if they are linked. In a linked corridor, the control centers share data. The linked corridor makes use of an intelligent WIM algorithm proposed in (Hoffman & de Coning, 2014) for signaling. In their publication, Hoffman and de Coning (2014) showed that for a truck, it is expected that the use of this concept will result in less weighbridge time delays at downstream weighbridges. This is because, except for a WIM check, there would be no need to reweigh the truck at the static scale if it was weighed upstream. This means fewer static scale visits and consequently, less total time at weighbridges downstream (Hoffman & de Coning, 2014).

Furthermore, the enforcement of rules can have an impact on the performance of a corridor. This is comprises of the detection system and the charging/billing system. When the charging or billing system is manual, it would depend on the speed of the operator as shown in Figure 2. In an Auto-charging system, the truck does not need to wait for the charge. The transporter is sent a notification or his account is debited automatically if the truck is registered on the overload control system. Figure 3 shows the auto-charging system. Trucks do not need to wait for process 2 to take place. It is expected that this would result in shorter average times spent at the weighbridge ($\boldsymbol{WBTime}$).

$$\boldsymbol{WBTime = Time\ out\ of\ weighbridge\ (T_{OUT}) - Time\ In\ weighbridge(T_{IN})} \quad \mathbf{2}$$

For trucks which visit the static scale, time at the weighbridge can be broken down into the following:

$$\boldsymbol{WBTime = \left(T_{@SQ} - T_{IN}\right) + T_{inSQ} + T_{SW} + T_{ch} + (T_{OUT} - T_{FromWM})} \quad \mathbf{3}$$

where:
$T_{@SQ}$ = The time a truck arrives at the end of the queue to the static scale, T_{IN} =Time the truck enters the weighbridge, T_{inSQ} =,time spent in the static queue, T_{SW} =Weighing time, T_{ch} =Time taken to issue the charge if any, $\boldsymbol{T_{FromWM}}$ = Time of moving from the weigh and/or traffic officials. $\boldsymbol{T_{OUT}}$ =Time the truck leaves the weighbridge.

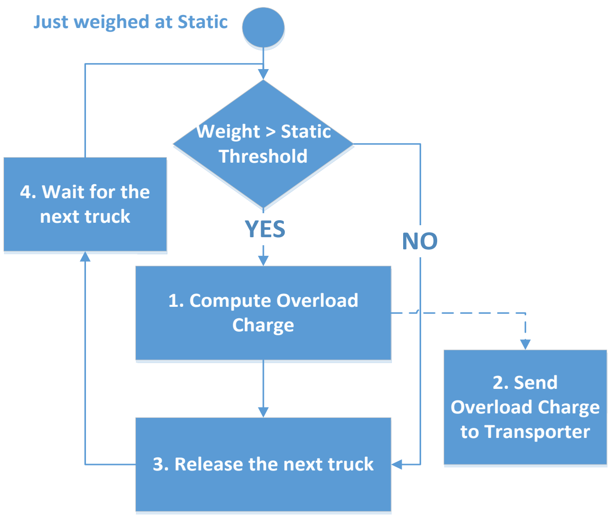


Figure 3. Auto-Charging system

The settings to investigate these two aspects are shown in Table 2 and Table 3.

Table 2. Truck weight category

Category 1	Category 2	Category 3
W < WIM limit	WIM limit<W<SL	SL < W
W<40.5 tons	40.5t <W< 45.9t	45.9 tons< W

Table 3. Corridor overload control scenarios

Setup	**1**	**2**	**3**	**4**
Charging	Manual	Manual	Auto	Auto
Linked	Yes	No	Yes	No

In total, there are 12 scenarios. The four setups are implemented with each of the three weight categories in Table 2 4 setups x 3 weight categories = 12 scenarios.

5. STAKEHOLDER BEHAVIOR

Human interactions are taken to be the major cause for inefficiencies (Hoffman, et al., 2013), (Hoffman & de Coning, 2014), (Anon., 2012). Human behavior can be modeled using various mathematical models. Of interest to transportation are traits which can have an impact on performance. These traits may differ from stakeholder to stakeholder. The tendency to overload by a transporter, can impact the corridor. This trait is driven by the desire or goal to make more profit. In modeling these traits, we show that a simple decision model can be used to approximate mathematical models. The work done by Schmdit (2002), is used as a reference.

In this work, intelligence is described as a knowledge based model. In transportation, overload tendency will also depend on knowledge i.e. the transporter’s current performance in relation to his past performance and how the system (overload control enforcement) reacted to his past behaviour.

Intelligence reflects the ability for an agent to acquire knowledge. Similar forms of functions like this are those relating to time and experience-dependent changes, of a state variable. In (Schmidt, 2002), intelligence is defined by a number of state variables and functions listed in Table 4.

Table 4: Parameters which define the personality trait of intelligence (Schmidt, 2002)

Parameter	**Description**
$KnowAct$ (K)	Variable describing the current level of knowledge which the agent has.
$KnowCap$ (P)	Is a function of learning compared to the number of opportunities to learn, or time. Its magnitude rises slowly and gradually increases exponentially, before slowing down again.
$KnowNormal$ (N)	constant
$Intelligence$ (I)	A constant reflecting the level of intelligence of an agent
$KnowActMax$ (A)	A constant which gives the maximum amount of knowledge which an agent can absorb.

The parameters are related in the following manner

$$\frac{d\boldsymbol{K}}{d\boldsymbol{t}} = \boldsymbol{a} \times \boldsymbol{P} \times \boldsymbol{N} \times \boldsymbol{I} \times \boldsymbol{K}, \qquad \textbf{4}$$

where $P = \frac{A-K}{A}$. Schmdit B (Schmidt, 2002), showed that Equation 4 results a solution whose graph is displayed in Figure 4.

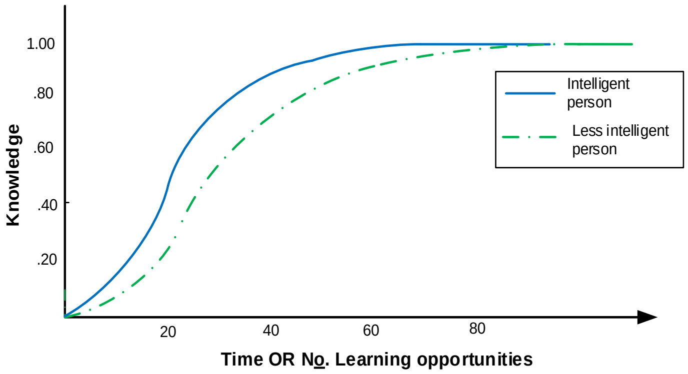


Figure 4 Knowledge variation as number of learning opportunities varies (Schmidt, 2002).

Figure 4 shows that as time passes or number of lessons increases, the knowledge level also increases but reaches a limit or steady state value. In transportation, it was assumed that over time, behaviour of human entities would also move towards steady state values over a period of time. These values would depend on the nature of the overall system. The above graph can be approximated using polynomial equations. Edwards and Parry (1993), proposed and demonstrated the use of polynomial regression equations as alternatives to difference scores in organizational research. This applies to individuals and organizations (Schmidt, 2002), (Edwards & Parry, 1993). There is a link between human behaviour and organizational behaviour because humans make up organizations such as transporters.

In this study, the transporter's tendency to overload is investigated. The first assumption is that the transporter has a goal of increasing profit. This can come by loading more cargo per vehicle and may influence the transporter in setting the limit for the load. A term defined as "tendency for the transporter to overload" was defined. This started at zero and changed over time depending on the profits made. The cargo load was defined as a function of the transporter's overload tendency using the following relation.

$$Weight = 45tons(1 + OverloadTendency)$$

The transporter's overload tendency was defined as a reaction to the profits made per period of observation. This is similar to the difference scores approach. It is shown in Figure 5 below.

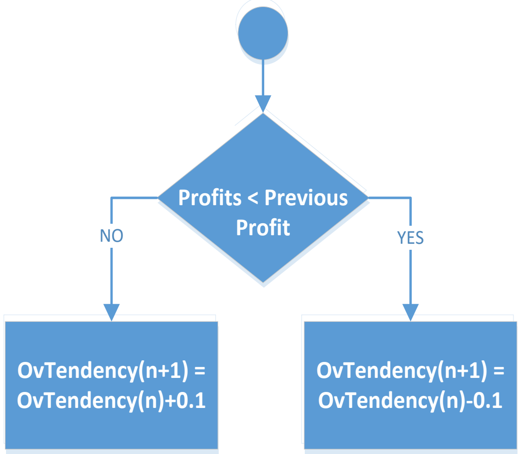


Figure 5. Overload tendency

Overload tendency coefficient is a result of the transporter's knowledge of the system e.g. how the system reacts to the transporter's loading patterns. This is reflected in the profit. Figure 5 shows that when the transporter's current profit is less than the previous profit, the overload tendency coefficient for the transporter decreases. If the transporter makes more profit than the previous, the tendency increases. It implies that the transporter is encouraged to make more profit, by increasing cargo weight. If the transporter makes less profit, in this case due to overloading fines, the transporter's tendency to increase cargo weight is reduced. Therefore, it is expected that the transporters would either increase or reduce the cargo loaded per journey. In a corridor whose overload control is well regulated, it is predicted that the transporters would eventually load close to the static grace limit. This was confirmed when historical data was analyzed in (Hoffman & de Coning, 2014).

6. MODEL CALIBRATION

As mentioned in (Lusanga, et al., 2014), there is a need to accurately calibrate a model. Two parameters were tuned to calibrate the model. These are,

I. Processing rate (Number of trucks processed per period of time)

II. Average time spent at a weighbridge

A. **Processing rate and throughput data**

Exact processing rate data was not used. Instead, the throughput (vehicles/hour) was used. The processing rate at a weighbridge is approximately equal to the throughput on a road section. Truck flow volumes at waypoints as well as statistics on times spent at the waypoints were obtained by analyzing historical GPS data in Southern Africa between September 2014 and September 2016. A summary of the extracted historical data is shown in Table 5.

Table 5. Way point and road section historical data summary (Hoffman, 2017)

Trucks per Day	Trucks in 10 days	Throughput [Trucks/Hour]	Truck seen every [seconds]	Truck seen every [minutes]
100 + to 4000 +	1000+ to 40000 +	8.33 to 166.67	432 to 21.6	7.20 to 0.36

Throughput can also be defined in terms of average time between trucks. This is more relevant to the simulation model where the average time between trucks can be used directly in the "truck generation blocks" or sources. Average times based on historical data were also presented in (Hoffman & de Coning, 2014), where the historical and proposed systems were found to have 2.67 and 10.67 minutes respectively.

B. **Weighbridge time data**

In the historical data used, Hoffman and de Coning, (2014) showed that 80% of the vehicles were within the WIM tolerance but instead of only 20% being weighed at the static scale, 64% were weighed. This also shows an anomaly in current systems which should be a subject of future research. The observation shows that there are a number of unnecessary static weighs, currently. The values used to calibrate weighbridge time were those presented in (Hoffman & de Coning, 2014). These are listed in Table 6.

Table 6. Weighbridge time data (Hoffman & de Coning, 2014)

Description	Old Scenario	New Scenario
Average processing time [minutes]	2.2	2.2
Average waiting time [minutes]	10.37	0.57
Average driving through time through Static Scale [minutes]	5.2	5.2

C. **Simulation calibration values**

To obtain a reliable model, calibration is necessary. In order to calibrate the simulations, inter-arrival times and weighbridge times were used. Inter-arrival times for the corridor were adjusted while comparing the model weighbridge times with historical data.

The average values in Table 5 and Table 6 are for all the truck weights possible. These comprise of weights (*W*) below WIM limit (*WIMlimit*) to weights above the static limit (*SL*). In contrast, in his paper, the truck weights were not distributed across the whole weight range. They were grouped into three weight categories as shown in Table 2. Therefore, the results are expected to be close, but not exactly the same as the historical data presented.

The desired results were as follows.

I. The average waiting times per weighbridge – a value less than 5.2 minutes for trucks below the WIM threshold.

II. The average waiting time per weighbridge – a value above 12.57 minutes. There are two contributing factors to this. Firstly, the time spent driving through the weighbridge. Secondly, 12.57 minutes is due to only 64 % of trucks. In the second weight category, 100% of the trucks are sent to the static scale. Consequently, a longer time is expected because more trucks results in longer queues which causes longer waiting times.

III. The average waiting times for overloaded trucks should be equal to the time it should take a relief vehicle to arrive. The minimum time is expected to be about an hour. It can vary widely depending on trucks available at the transporter's yard and the travel distance required. Therefore, weighbridge times for this weight category remains speculative.

IV. Lastly, since the corridor implemented does not have any junctions between the weighbridges, and the weighbridges are assumed to be well regulated, most of the trucks downstream should be below the static limit.

After varying the truck inter-arrival rates from the sources Transporter 1 and Transporter 2, the model results produced, are presented in Table 7 below. The inter-arrival rates varied randomly based on a triangular distribution. The {min, mean max} for Transporter 1 and 2 were {0.3, 3.3, 4.85} and {0.3, 3.1, 8.57} respectively. The border had a processing capacity of 3. A "time delay" approximation of an automated border presented in (Bhero, et al., 2015), was used. This is because it has short border times. Since focus was on overload control and not border operations, this was seemed feasible and helped to speed up the simulations. Border time was implemented using a random triangular distribution of {10, 13.3, 16.5} minutes.

Table 7. Simulation weighbridge times and processing rates per weigh category.

Weight category tons	Weigh station (WB)	Trucks per 10 Days	Processing Time (Throughput) [Trucks/Hour]	Percentage sent to static scale	Average Time at a weighbridge [minutes]	Average Time in Queue to static [minutes]
39 – 40.5 W < WL	1st WB	3613 – 5107	261 – 381	0.0028-0.0031	0.22339-0.22342	0
	2nd WB	3606-5106	276 – 367	0.0028-0.0031	0.221375	0
40.5 – 45.85 WIMlimit < W <SL	1st WB	3612–5118	11 – 18	100	3.394 -7.98	0.06 – 4.8
	2nd WB	3604 - 5113	11 - 367	0 – 0.0166	0.22 – 44.13	0 – 4.2
46 – 49 SL < W	1st WB	1711-1955	0.009 – 0.138	100	207.1 – 3340.6	24.98 – 43.91

	2nd WB	1711-1954	9.7 - 150	0	0.22 – 2.89	0 – 0.13

The results from both the historical data and simulation model were aggregated and summarized in Table 8. The values from the simulation model compare well with actual data.

Table 8. Actual Data vs simulation weighbridge data

	Trucks per Day	**Throughput [Trucks/Hour]**	**Truck seen every [minutes]**	**Time at a weighbridge [minutes]**	**Time in queue to static scale [minutes]**
Actual	100 ↔ 4000+	8.33↔ 166.67	0.36 ↔ 10.37	2.2 – 17.77 (Hof&deC2014)	0 – 10.37
Model	171↔361	0.009 ↔ 381	0.3↔ tp_n , min(tp_n)=8.57	0.22 ↔ 21.43	0 – 43.95

The time tp_n represents the new time between trucks after passing through a weighbridge.

$$\boldsymbol{New}\ \Delta \boldsymbol{Tr} = \boldsymbol{ia_0} + \boldsymbol{tp}, \qquad \mathbf{5}$$

where, ΔTr is time between two trucks following each other, tp is the time added to the initial time between two trucks. The term ia_0 is represents the queue length and processing time at the weigh bridge.

An increase in time between trucks increases the inter-arrival time at the following weighbridge. An increased inter-arrival time means a decreased rate of arrival. According to Little's law, the length, l, of a queue is proportional to the inter arrival rate, λ (Sigman, 2009).

$$\boldsymbol{l} = \boldsymbol{\lambda\varphi}\ , \qquad \mathbf{6}$$

where $\boldsymbol{\varphi}$ is the time spent in the system. Therefore, a reduced inter-arrival rate results in shorter queues. Shorter queues mean less time spent at a weighbridge.

7. SIMULATION RESULTS

A. Variation of the WIM Threshold

Truck weight was divided into three categories as Table 2 shows. The triangular distribution was used for the truck weights. This was to determine where changes in the WIM threshold changes have the most impact. Figure 6 shows the outcomes.

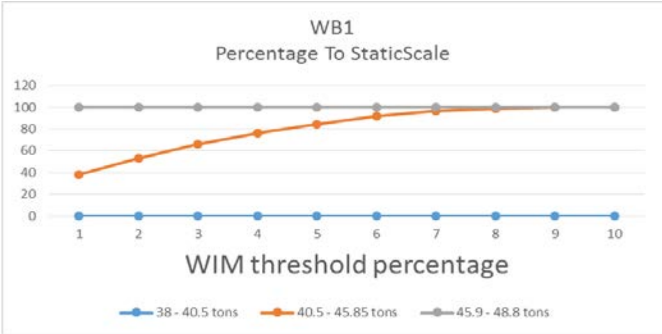


Figure 6. Upstream percentage sent to static vs WimT

All the two upstream and downstream weighbridges showed similar results with little variations.
The following was observed.

- $W < WIMlimit$: No impact, 0% sent to static scale
- WIMlimit < W < SL: Percentage sent to the static scale increases as WimT increased from 1 to 10.
- SL < W: No impact , 100% sent to static scale

Where, $W = \text{Truck weight}$, $WIMlimit = \text{WIM weight limit}$, WL = weight limit (45 000kg), SL = static grace limit.

It may be more optimal to reduce the WIM threshold percentage in order to reduce the number of static weighs. The final WIM threshold level however should consider the possibility of an error in the recorded WIM weight measurement as shown in Equation 7**.**

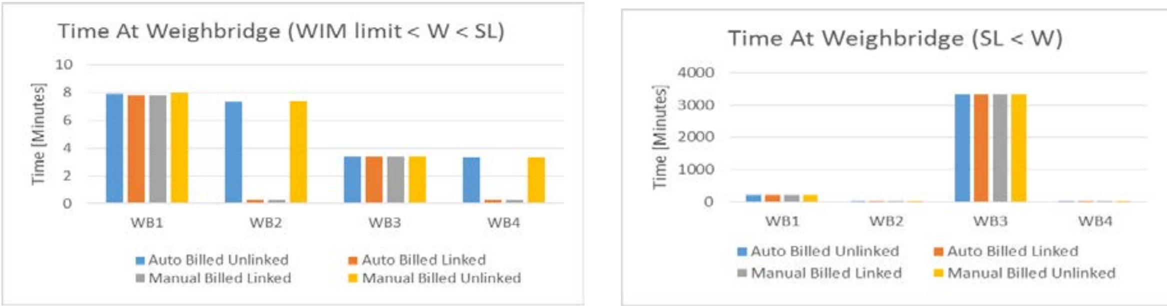
$$recorded\ weight = Truck\ Weight \pm weigh\ scale\ error \qquad \textbf{7}$$

B. **Linked vs unlinked, auto vs manual**

The scenarios described in Table 2 and Table 3 were combined to make 12 scenarios. This was done by using each of the three weight categories (Table 2) in each of the four corridor configurations (Table 2). Total time spent at the weighbridge ($WBTime$) and throughput, were plotted for each scenario. The simulation period was ten days or 240 hours and 50 replications were done for each. The averages were used.

1) Weighbridge time

Weighbridge time (WBtime) is the total time a truck spends in the weighbridge. The truck arrival and departure time at the weighbridge were captured and recorded. At the end of the simulation, the averages were computed. It was found that for the first weight category, where weight was less than the WIM threshold, Time at the weighbridge varied from 0.217 – 0.231 minutes. The differences are due to the weighbridge distance traveled within the weighbridge which is dependent on the layout of the lanes or overall size of the weighbridge. 45 tons was used as the weight limit in the simulation. WB1 and WB3 are upstream while WB2 and WB4 are downstream weighbridges.



(a) **(b)**

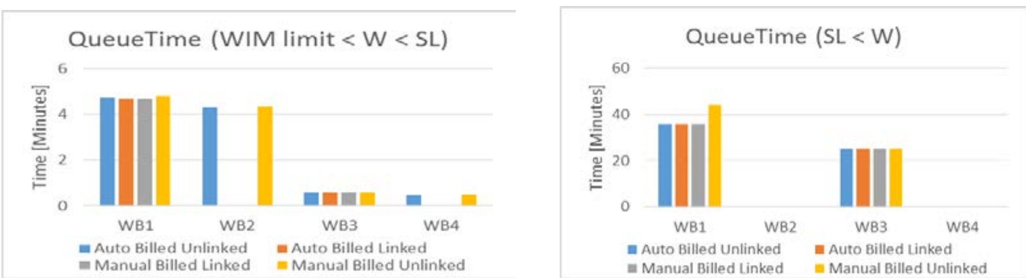
Figure 7. WBtime for truck weights: (a) WIM limit< W < SL and (b)SL < W)

As shown in Figure 7(a), time spent at the first weighbridge (upstream) is the highest. The model was a “closed corridor” meaning, there was no other traffic entering the corridor in between the weighbridges. Therefore, the time between trucks after the first weighbridge, increased by a period equal to the processing time. As a result, the time between two trucks was longer and the inter-arrival rate decreased. Inter-arrival rates, affect waiting queue length when the arrival rate is higher than the processing rate at the weighbridge. The longer the queue, the longer the truck stays at a weighbridge and vice versa. This explains why queue times (unlinked) for WB2 and WB4, are slightly less than for WB1 and WB3 respectively. Similarly, because trucks arriving at WB3 have to pass through the border, the arrival rate to WB3 is less than the arrival rate to WB1. This implies shorter queue lengths to WB3.

In the upstream weighbridges, WBtime is almost equal for all scenarios because all trucks weighing over the WIM limit have to pass through the static scale at the first weighbridge. At the downstream weighbridges (WB2 & WB4) time spent at the weighbridges is negligible when weighbridges are linked and data is shared.

In Figure 7(b), the weighbridge times for trucks overloaded over grace, are shown. The average times at the weighbridge are much higher than for the category 2, where trucks were not overloaded. Values range from 207 minutes to 3342 minutes (approximately 3.5 hours to 2.3 days). The high times are because trucks have to wait for relief vehicles to offload the excess weight. In practice the distance between the relief vehicle and the weighbridge, matter.

2) Time in Static Queue



(a) **(b)**

Figure 8.Static queue time for weights: (a) WIM limit < W < SL and (b)SL < W)

Figure 8(a) shows higher queue times for WB1 than for WB2. Both are upstream. Queue times for WB3 are lower because of a lower inter-arrival rate, due to the border delay. In linked corridors, there were hardly any queues for downstream weighbridges WB2 and WB4.
For the overloaded vehicles displayed in Figure 10 (b), there are no queues downstream due to a very low inter-arrival rate which results from the long delays at the holding yard.

3) Processing rate

The Number of vehicles processed per hour was also computed for the same simulations used to investigate weighbridge time. These are shown in Figure 9 and Figure 10.

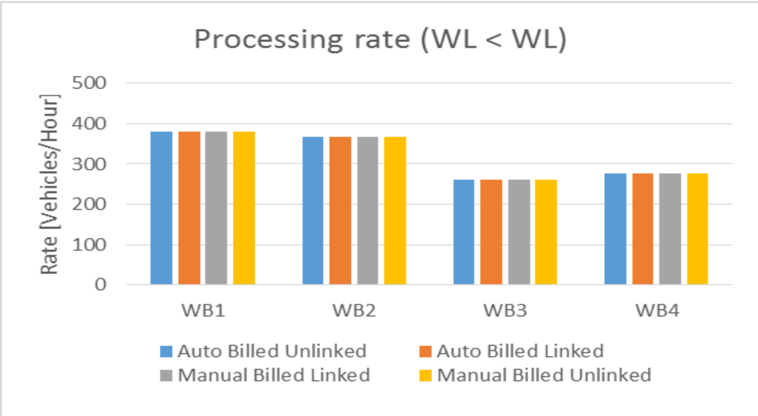
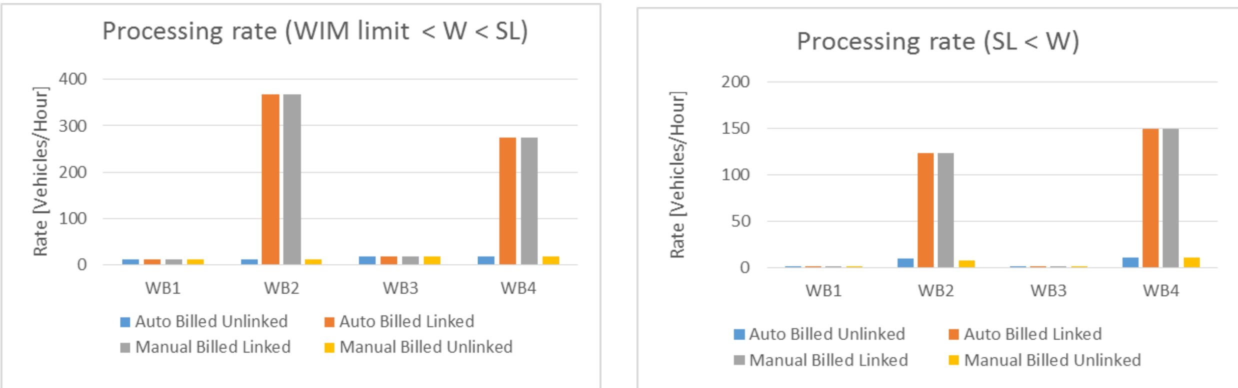


Figure 9.Processing rate for truck weight: W < WL

The difference in processing rates for this weight category is only due to rate of truck arrivals or traffic volumes. Upstream weighbridges had slightly more trucks per hour.



(a) **(b)**

Figure 10.Processing rate for weights: a) WIM limit < W < SL and (b)SL < W)

The bar graphs in Figure 10 (a) and Figure 10 (b) are similar. The throughputs or processing rates at the first weigh bridges (WB1 & WB3) are equal for all scenarios. However, for downstream weighbridges, the processing rates of trucks is much higher for the linked corridors. This means, more trucks are allowed though the weighbridge for a given period of time for downstream weighbridges when data is shared between overload control centres.

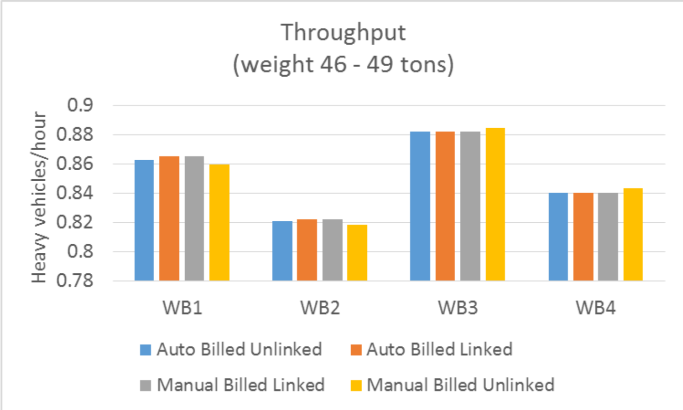


Figure 11.Throughput for truck weight: SL< W

For overloaded heavy vehicles, the processing rates are lower than for vehicles within legal limits. This is true even for downstream weighbridges. The reason is fewer truck volumes. It shows that for an economy, with good loading enforcement, overloading minimises the rate of exchange of goods or business.

C. **Transporter overload tendency**

Enforcement of overloading penalties can affect a transporter's income and influence the transporter's loading policy as shown in Figure 12.

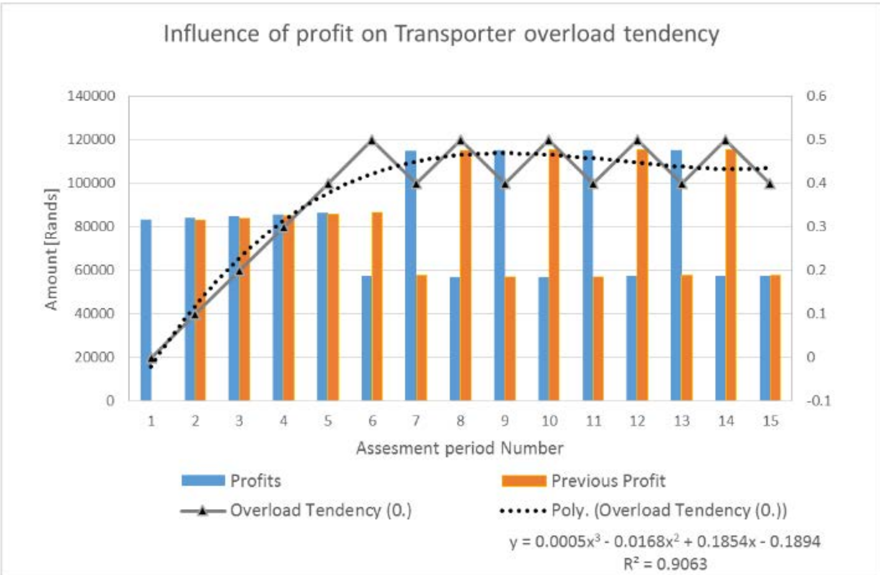


Figure 12. Changing transporter overload coefficient due to differences in past and present

The transporter's reaction over time varied as shown by the black line. This graph is approximated by a third order polynomial regression shown by the dotted line. The result shows a trajectory of the overload tendency which like Schmdit's learning models, reaches steady state values (Schmidt, 2002). This implies, that a transporter's overloading tendencies can be increased or reduced to a steady value which is dependent on the nature of the corridor. Therefore, human behavior models in transportation can be approximated from basic decision or score based models as well as polynomial regression models or differential equations (Schmidt, 2002), (Edwards & Parry, 1993). Human behaviour models can be useful in evaluating the impact of overload control strategies on transporters.

8. CONCLUSION

The aim of this paper was to demonstrate that road corridor simulation is possible and that a simulation tool can be used to investigate phenomena which may be too costly to implement in practice. Areas which would require detailed modelling were shown, i.e. particularly areas seen to pose a potential for unwanted practices.

Three areas were covered i.e. minor adjustments to current corridor systems, major adjustments and entity behaviour. For each scenario, there were certain assumed expectations. The results confirmed some of these hypotheses and provided further insight.

Higher WIM threshold values result in higher percentages of trucks sent to the static scale. Furthermore, it was found that the benefits of various proposed systems, are felt downstream. Linked systems performed better than unlinked systems. Percentages sent to the static scale downstream was 100% for unlinked systems and 0% for linked weighbridges. The auto-charging times were not so different from the manual-charging system. Transporter’s assumed behaviour, i.e. tendency to overload was modeled and compared well with literature. It can therefore be ascertained that the methods employed are reliable. For future work, the same approach will be applied to model actual corridors in southern Africa.

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