A HOLISTIC STRATEGY TO BALANCE LAW ENFORCEMENT WITH FREIGHT MOBILITY

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Abstract
Several South African Traffic Control Centres (TCCs) on heavy vehicle freight routes, where static weighbridges are used for law enforcement, become severely congested during peak hours. The South African National Roads Agency Ltd (SANRAL) embarked on a research project to determine possible ways of addressing the increase in congestion at weighbridges through a more technology-based approach. Automation of weighbridge processes, more accurate weigh-in-motion (WIM) systems and variable screening thresholds were investigated for TCCs. The possibility of direct WIM enforcement, WIMe, was also assessed. The anticipated strike rate of WIMe should be below 5%, and therefore WIMe installations would need to be used for multiple purposes to make such a project economically viable. A new holistic overload control strategy was developed whereby a WIMe network combined with other sources of information such as screening WIM records, static weighbridge data and the compliance record of the vehicle and/or operator are used in a risk-based screening approach to significantly reduce the number of vehicles directed for static weighing. The South African Road Transport Management System (RTMS) accreditation scheme was considered as the most likely prerequisite for transport operators to participate in this proposed weighbridge bypass system which aims to incentivise and monitor participation in self-regulation of overloading.
Keywords: Static Weighbridge, Direct WIM Enforcement, Weighbridge Bypass System, Risk-based Screening

1. Introduction

Overloaded heavy vehicles pose a significant threat to the life of road infrastructure, the safety of road users and the South African economy as a whole. The impacts of overloading include the increased financial burden of maintaining roads due to accelerated pavement wear, pressure on authorities to plan and implement maintenance actions at more frequent intervals, increased vehicle operating costs, damaged goods caused by bad roads, unfair competition and increased road safety risks.

Several South African Traffic Control Centres (TCCs) on heavy vehicle freight routes, where static weighbridges are used for law enforcement, become congested during peak hours. Such situations create a safety hazard for other road users (truck queuing on the highway) and cause unnecessary and costly delays for operators whose trucks are not overloaded.

The South African National Roads Agency Ltd (SANRAL) embarked on a research project in 2021 to determine possible ways of addressing the increase in congestion at weighbridges through a more technology-based approach. The research comprised three parts, viz. investigating the viability of direct enforcement using Weigh-in-Motion Systems (WIMe), optimizing weighbridge operations and developing of a holistic and integrated technology-based overload control strategy (Nordengen & De Wet, 2023).

The research confirmed that the practical maximum throughput of a static weighing facility could not be much higher than 60 trucks/hour, even if operations were optimized though technology. The focus therefore needed to shift to reducing the number of vehicles directed for static weighing. An extreme scenario could be to do away with static weighbridges and replace them with direct WIM enforcement; however the inherent inaccuracy of WIM presents challenges with the application of the data in court and the associated risk of unfair prosecution. Once the grace/tolerance has been increased sufficiently to eliminate the risk of unfair prosecution, the anticipated strike rate from direct WIM enforcement would most likely be below 5%, which would make it difficult to justify the cost of high-accuracy WIM and vehicle identification systems.

The optimization of static weighbridge and WIMe operations lies in their integration – the WIMe system would only be able to prosecute excessive overloads but its data could be used to significantly reduce the workload of static weighbridges. The envisaged solution is a weighbridge bypass system similar to the PrePass and Drivewyze systems used in the USA. Freight operators would be incentivized to participate in a self-regulation scheme whereby compliance is continuously monitored by WIM, and where static weighing and the associated time wastage is reduced to a minimum.

This paper explores and evaluates the challenges and opportunities of static weighbridge operations and WIM enforcement, and motivates and describes the architecture of a holistic, integrated overload control strategy.

2. WIM Enforcement

In most countries the use of high-speed WIM in law enforcement operations is limited to the screening and pre-selection of vehicles that are then directed to a static weighbridge for accurate weighing and processing. An increasing number of countries around the world have commenced with the development of more accurate weigh-in-motion (WIM) systems with the intention of using them for direct enforcement. SANRAL has also envisaged the development of a WIM enforcement (WIMe) network to supplement or perhaps lead overload control efforts in the country. The vision is to ultimately develop more than 350 traffic monitoring stations that would include WIM for enforcement. Direct law enforcement using WIM (WIMe) is but one component of a much larger data collection and infrastructure management programme.

The use of high-speed WIM for direct enforcement is not common. It requires the most advanced of WIM systems to meet the accuracy requirements as well as an excellent organisational structure. The three key elements of this structure are legal acceptance, system certification and data quality control. The earliest implementation of direct enforcement in the European Union (EU) was in the Czech Republic during 2011, followed by Hungary in 2017. Four more EU member states are gearing towards implementation: Belgium, France, Germany and Poland (Jacob, 2020). Some of the States in the USA are using Virtual WIM (advanced WIM screening) but only New York City has implemented direct WIM enforcement in an attempt to reduce excessive overloading (>10% on total vehicle mass) as part of their BQE bridge management project (Pandya, 2024). The slow uptake of direct WIM enforcement is testimony to the technical and judicial challenges due to the inherent limited accuracy of WIM measurements.

2.1 WIM Accuracy for Enforcement

Two of the best-known international standards for WIM systems are the American ASTM 1318 (ASTM, 2002) and the European COST 323 (COST, 1999), however they are not considered to be suited for legal metrology. The South African TMH3 Specifications for the Provision of Traffic and Weigh-in-Motion Monitoring Services (COTO, 2020) was developed from ASTM 1318, COST 323 and more than two decades of practical experience in South African with the use of these standards but is also not suited for legal metrology. The OIML 134 Requirements (OIML, 2021) are considered suitable for legal metrology, but did not initially include high-speed WIM and has therefore been under revision since 2019. It remains the most used international reference for WIM enforcement.

The South African National Regulator for Compulsory Specifications (NRCS) was tasked with the development of metrological and technical requirements for WIM systems to be used for direct enforcement. The NRCS Interim Requirement (NRCS, 2024) was based on the OIML 134 Requirements and was finalized in August 2024. Refinements may follow based on further progress by OIML and practical experience in South Africa.

The NRCS Requirements specify the tolerance interval for Maximum Permissible Error (MPE) for enforcement WIMs as shown in Table 1.

Table 1 – Maximum Permissible Error (MPE)

	Maximum Permissible Error (MPE) Rounded to the nearest scale interval
	Type Approval and Verifications
Gross vehicle mass	± 5%
Axle group load	± 8%
Single axle load (excl. driving/steering axles)	± 10%

The above accuracy requirements are very strict. If (for the purpose of statistical comparison) the MPE was interpreted as the 99.9% confidence interval for WIM error, then the 95th

percentile confidence interval for gross vehicle mass would equate to approximately ±3.0%. In comparison, the allowed 95th percentile confidence interval for the most accurate screening WIMs in South Africa is ±10%. The enforcement WIMs would therefore have to be more than 3 times more accurate than the current screening WIMs.

Achieving the required WIM accuracy during type approval and after initial installation of WIM systems should be possible because this has been accomplished in several other countries. Maintaining this accuracy in the long term may be a challenge.

The NRCS Requirements stipulate that at least three test vehicles – including an articulated vehicle and a vehicle with a drawbar trailer – must be used for accuracy verification and calibration of enforcement WIM systems. Each test vehicle must complete at least 5 passes over the WIM at three different speeds, in unloaded and loaded states. A total of at least 90 passes must therefore be conducted over the WIM. Challenges are foreseen with the use of limited test vehicles because experience has shown that test vehicles, and therefore their measured WIM errors, are often a poor representation of the majority of the vehicle fleet. The requirement to change the vehicles' load would mean that loading equipment and a static weighbridge must be available nearby. Lastly, having long heavy vehicles loop around for repeated passes over the WIM requires a suitable and safe location for U-turns on each side of the WIM, which might not always be available within a feasible distance.

The NRCS Requirements exclude the use of axle loads on steering and driving axles for prosecutions because of the load transfer between these axles when the vehicle is in motion. The scope of prosecutions is therefore effectively limited to total vehicle mass and axle units on trailers.

2.2 Prosecution Grace and Strike Rate

The inaccuracy of WIM systems presents challenges to the judicial processes. Whereas static weighbridge measurements are sufficiently accurate that measurement error may be ignored for metrological and legal enforcement purposes, WIM measurements do not have the same accuracy and may well be challenged in court. It is therefore imperative that the impact of the technical limitations of WIM on law enforcement and judicial processes are understood and mitigated.

The use of MPE is considered to be more simple than using confidence intervals for communicating the accuracy of a WIM for law enforcement purposes. Very limited statistical interpretation should be required from a judge when ruling on overload charges in court. Statistical probability will however remain a part of the process because of the possibility that a sub-standard WIM may have erroneously passed the Type Approval and/or in-service accuracy verification tests. This probability must be low enough (for example a 1/1000 chance) to allow a judge to rule that a vehicle charged by WIM was indeed overloaded "beyond reasonable doubt".

A simulation was conducted to estimate the number of vehicles that might be prosecuted on South African roads using WIMe. The simulation used actual measurements for more than 90 000 statically weighed vehicles from the Mantsole Northbound TCC as the basis, and simulated WIM error Normally distributed with only 1/1000 chance of exceeding an MPE of ± 5%. The prosecution grace/tolerance percentage, which is 2% on total vehicle mass measurements determined from a static weighbridge, was increased by the MPE value to ensure that the likelihood of unfair prosecution was minimal. Only total vehicle mass transgressions were considered because load transfer between axle units would make prosecution on axle units risky. It was concluded from the analysis that the anticipated strike rate from direct WIM enforcement will be as low as 5%. In isolation, the impact of direct enforcement on overloading behaviour will therefore be very limited and ineffective.

2.3 Vehicle Identification

SANRAL's initial WIMe concept envisaged that WIM systems would be integrated with an automated number plate recognition (ANPR) system. ANPR has been used at various static weighbridges and for speed law enforcement for many years, and until recently for electronic tolling in the Gauteng Province. A detailed investigation indicated that ANPR success rates for heavy vehicles were poor compared to light vehicles. ANPR success rates for large heavy vehicles ranged between 35% and 55% at weighbridges, and between 60% and 70% on the Gauteng Open Road Toll scheme. In addition to the technical limitations of equipment, deliberate actions by road users (e.g. obstructing, damaging, altering, removing or cloning number plates) make it difficult to read licence plates with a high degree of accuracy.

If a vehicle cannot be positively identified, it cannot be charged through the WIM enforcement project. Vehicle identification using ANPR is considered to be such a critical challenge that it could derail the WIMe scheme unless it is supplemented by other means of vehicle identification such as Radio Frequency Identification (RFID) tags, Dedicated Short-Range Communications (DSRC) tags or other means.

2.4 Viability of Direct WIM Enforcement

It was evident from the research that WIM enforcement as a standalone means of overload control would not be feasible in the South African context. Non-payment of fines would likely become worse, strike rates would be low, vehicle identification would be a challenge, and the technical difficulties of constructing, maintaining and calibrating as many as 350 WIMe stations in remote locations would be a major challenge.

3. Static Weighbridge Operations

Operations at Traffic Control Centres (TCCs) are not optimal. Issues are experienced with geometric design (queuing times and space in particular), effectiveness and accuracy of Weigh-in-Motion (WIM) screening equipment, availability and cooperation from traffic police, slow weighing procedures, errors caused by the human element, potential for bribery and corruption, ageing technology and a lack of integration of interrelated processes and systems. The negative effects of these issues are amplified by the significant growth in heavy vehicle volumes, particularly on the major freight corridors, and consequent pressure on weighbridge throughput. A further major concern is that overload control efforts are limited to specific weighbridge locations while the remainder of the road network remains unmonitored and uncontrolled.

3.1 Key Challenges in Weighbridge Operations

Time wastage of law-abiding, compliant freight companies due to congestion at weighbridges, inaccurate WIM screening, repeated weighing at several weighbridges on the same route during a single journey etc. are detrimental to freight logistics, the economy at large and create negative sentiment within the freight industry. The key challenges that need to be addressed to improve operations are summarized as follows:

- Infrastructure and Technology used at weighbridges are ageing or even becoming outdated. There are too many weighbridges without automation of the screening and directing process, and limitations with WIM screening accuracy mean that many vehicles are weighed unnecessarily in order to ensure that no prosecutable vehicles are missed.
- Law enforcement is a challenge because fines for overloading are too low to be a meaningful deterrent. The average fine issued per transgressor is about ZAR1 050 (South African Rand) and is capped at ZAR2 500 (which equates to about 140 USD). The payment rate of fines is low (typically 20% or less) because of gaps in the judicial system and lack of a back-office to assist with fines administration. Reliance on traffic officers is also problematic due to inter alia unavailability because of other duties, lack of funding, limited training and Key Performance Indicators (KPIs) that are not always aligned with overload control needs.
- The human factor often exacerbates the operational constraints that are caused by inadequate infrastructure. Activities such as checking of warrants while the vehicle is on the static scale reduces the throughput of the entire system. Queuing caused by congestion extends over the screening WIMs (compromising the WIM accuracy and verdict) and even onto the freeway, resulting in unsafe situations.
- Funding for overload control operations is a challenge. It has become increasingly more difficult to justify monthly running and maintenance costs for systems that do not perform optimally because income from fines is low while the cost of overloading (attributed to pavement deterioration, unfair competition and heavy vehicle crashes) remain high.

It is evident that, despite the dedicated efforts of some authorities, overload control in South Africa had gradually deteriorated to a point where innovative interventions are needed.

3.2 Optimising Static Weighbridge Throughput

A desktop assessment of the overload operations at 45 of the existing 71 TCCs in South Africa indicated that the typical throughput was about 60 trucks/hour. However some were as low as 30 trucks/hour. Site visits and further assessment of selected facilities highlighted inefficiencies that could be addressed through the use of technology, with a particular focus on automation and elimination of unnecessary human intervention or interference.

Even for fully automated static weighing facilities, the maximum practical throughput can hardly be much greater than 60 trucks/hour. Site inspections provided an appreciation of how slowly trucks move though this controlled environment. It typically took 60 seconds for a large, heavily loaded truck to pull onto a static scale from a stationary position, obtain a reading after the scale had stabilized, drive off the scale, and for the scale to stabilize again before signalling for the next truck to approach. Although the efforts to achieve optimal throughput remain relevant, they cannot resolve the capacity issue – more focus had to be placed on drastically reducing the demand for static weighing.

3.3 Variable Threshold for Screening WIM

Currently, heavy vehicles at TCCs are selected for static weighing using visual screening or WIM screening. Even with the use of WIM screening, the proportion of vehicles that are weighed unnecessarily is often excessive. Screening thresholds are typically set at 0.95, meaning that loads exceeding 0.95 of the applicable legal limit/s would cause the vehicle to be directed to the static scale. This is necessary to ensure that, despite the random measurement error (scatter) of the WIM, most prosecutable vehicles will be directed to the static scale; however, it also means that many legally loaded vehicles are directed unnecessarily. The emphasis is therefore on minimizing Authority Risk (the risk of allowing a prosecutable overloaded truck to bypass the static scale). An analysis of the Mantsole TCC operations for 2022 indicated that only 1 out of every 28 statically weighed vehicles was prosecuted in the northbound direction, while the ratio in the southbound direction was significantly worse at 1 out of every 102 vehicles.

WIM measures individual axle loads. Multiple axle unit loads, and total vehicle mass for that matter, are determined through the summation of individual axle loads. The percentage standard deviation of WIM measurement error decreases as more axle load measurements are combined. The use of one fixed threshold value therefore means that the Authority Risk (allowing a prosecutable overloaded truck to bypass the static scale) for vehicles with more axles is lower than for vehicles with less axles. The same principle applies to the number of axles in an axle unit.

Figure 1 indicates how the use of a fixed screening threshold of 0.95 for a TMH3 Class II axle load WIM results in an Authority Risk of 1.7%, 3.8% and 10.5% for tridems, tandems and single axles respectively. If an Authority Risk of 2.5% was chosen for all axle unit types, screening thresholds of 0.959 for tridems, 0.939 for tandems and 0.893 for single axles would need to be applied.

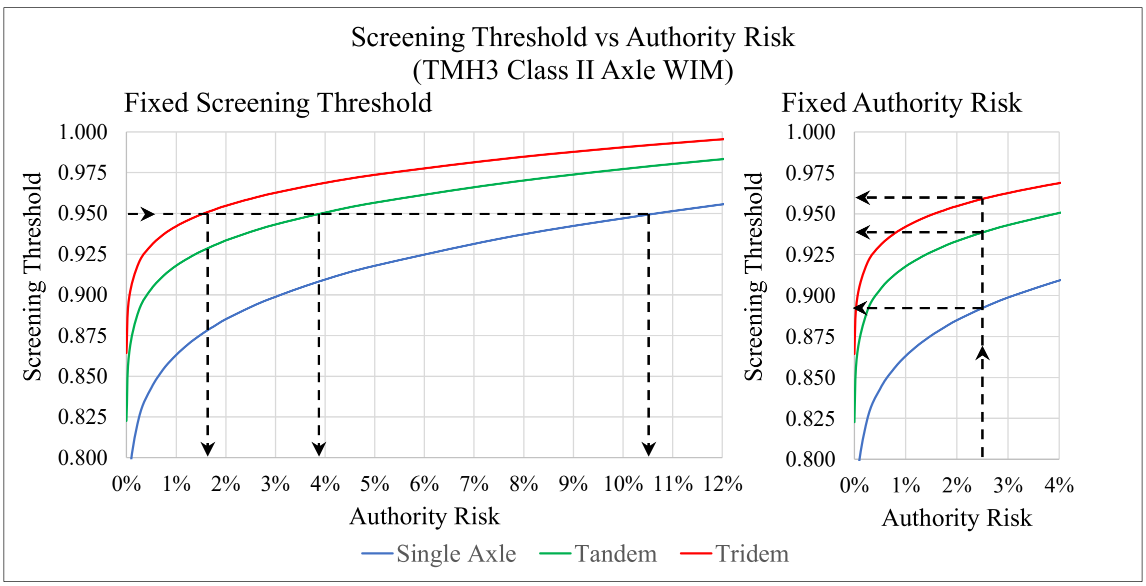


Figure 1 – Authority Risk Associated with Fixed Screening Threshold

A statistical approach and supporting formulae were developed to calculate variable screening thresholds based on the number of axles in an axle unit or vehicle being assessed, using the accuracy rating of the WIM and the chosen Authority Risk as input variables. This approach allows the authority to screen more intelligently and fairly, and to accept a higher Authority Risk in cases where the weighbridge demand exceeds capacity. The use of Authority Risk sets the platform for assessing screening WIM data and additional sources of company or loading information in in a similar way.

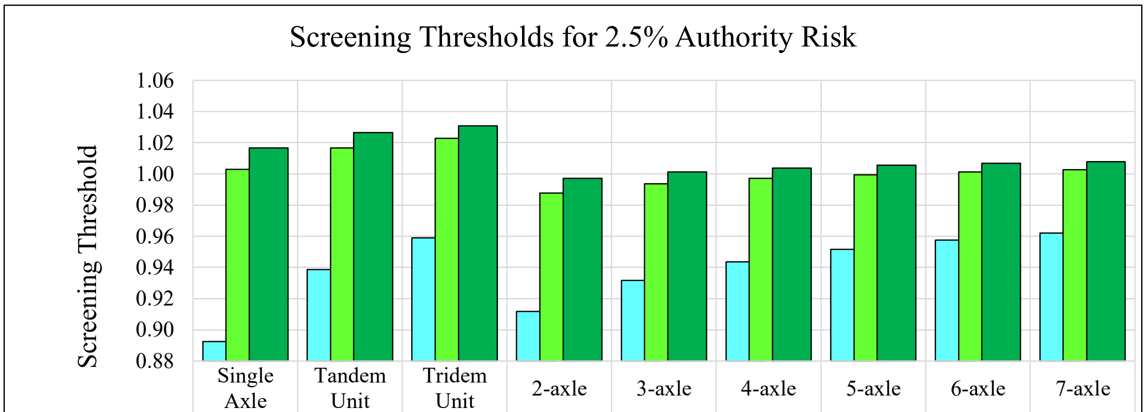
4. Integrated Strategy for Overload Control

A new holistic overload control strategy was developed whereby WIMe data, screening WIM records, static weighbridge data and the compliance record of a vehicle and/or operator are used in a risk-based screening approach to significantly reduce the number of vehicles directed for static weighing.

4.1 Opportunities for Integration of Overload Control Elements

The investigations into WIM enforcement and weighbridge operations highlighted several challenges, but also opportunities to benefit from an integrated system where various sources of information are used in conjunction in a weighbridge bypass system.

Utilising WIMe records means that current loading information for a vehicle may be available prior to arriving at a particular TCC. The WIMe measurements would be significantly more accurate than those from the screening WIMs that are currently used at TCCs. Furthermore, the combination of multiple WIM readings, if available, would allow for the calculation of even more accurate axle loads which would in turn allow for the use of higher screening thresholds. Figure 2 illustrates that thresholds can be raised when using one or even two WIMe stations to levels well above the thresholds that would apply when using only the current screening WIM. It should be noted that screening thresholds consider the prosecution grace in South Africa which is 5% on axle units and 2% on total vehicle mass (for prosecution using static weighbridge measurements).



	Single Axle	Tandem Unit	Tridem Unit	2-axle	3-axle	4-axle	5-axle	6-axle	7-axle
Screening WIM	0.893	0.939	0.959	0.912	0.932	0.944	0.952	0.958	0.962
1x WIMe	1.003	1.017	1.023	0.988	0.994	0.997	1.000	1.001	1.003
2x WIMe	1.017	1.026	1.031	0.997	1.001	1.004	1.006	1.007	1.008

Figure 2 – Screening Thresholds using WIMe System/s

Data from upstream static weighbridges should be integrated into the risk-based screening system. If a vehicle has been released from a TCC and arrives at a downstream TCC in good time (i.e. soon enough that the possibility of stopping and adding more load may be ignored) the risk of being overloaded over grace is negligible. In such a case the vehicle should not be directed to the static scale.

The South African Road Transport Management System (RTMS) self-regulation accreditation scheme was considered as the most likely prerequisite for transport operators to participate in a proposed weighbridge bypass system. The integration of RTMS into the screening process opens up several possibilities for allowing low-risk vehicles to bypass the weighbridge.

- Vehicle identification has been noted as a key consideration for a successful WIMe programme. RTMS-accredited vehicles would be required to carry vehicle identification devices such as RFID or DSRC tags to be eligible for preferential treatment, which would in turn improve overall vehicle identification and continuous auditing of compliance.
- RTMS-accredited companies implement processes to ensure inter alia that vehicles are loaded safely, efficiently and within legal limits. They are also subjected to audits every 12 months. Risk profiles of companies could be assessed and used for pre-screening.
- Many large consignors (companies dispatching road freight) have weighbridges at their own premises. It may be considered to allow such consignors to accredit their own weighbridges and link their static weigh records into the SANRAL database.
- Many RTMS vehicles (particularly those transporting bulk commodities) are fitted with on-board loadcells. If these loadcells are well calibrated, they produce reliable average axle loads because they are determined from a very large sample of repetitive measurements. The risk of overloading can be accurately assessed.
- The arrival of vehicles "in good time" from upstream weighbridges will become a key discussion point. The possibility exists to allow truck stops to participate as service providers in the RTMS programme. Vehicles entering such facilities could be monitored to ensure that no loads are altered, and in return the time spent inside this monitored zone would not be added to the travel time of the vehicle.
- Independent research has proved that RTMS accredited companies' compliance with overload regulations is generally better than other companies. The more companies that participate in self-regulation, the better the overall compliance will be.

4.2 Overload Risk Categories

The following colour-coded risk categories and associated actions were developed for use in a proposed weighbridge bypass system:

- <u>Green</u> – Free to bypass the weighbridge based on knowledge of current load determined from:
  - A different SANRAL or Provincial weighbridge on the network.
  - An accredited private weighbridge.
  - On-board loadcells from an RTMS-certified vehicle.
- <u>Yellow</u> – Free to bypass the weighbridge based on based on prior knowledge of acceptable Authority Risk based on WIMe data, and/or compliance history of vehicle and/or company, determined from:
  - WIMe measurements.
  - RTMS-certified companies/vehicles with a proven track record of compliance, i.e. with a percentage of transgressions below the accepted Authority Risk.
- <u>Amber</u> – Cleared to return to the road only after having also been screened by the TCC's screening WIM and, if available, WIMe measurements.
- <u>Red</u> – Directed to the static weighbridge after having been screened at the TCC using screening WIM information and, if available, also WIMe measurements.
- <u>Black</u> (black-listed vehicles) – Direct vehicles for static weighing based on current overload status from upstream weighbridge/s or on-board loadcells, a history of non-compliance, outstanding Warrants of Arrest etc.

4.3 Weighbridge Bypass Concept

Static weighbridges will continue to play an important part in the integrated system to prosecute offenders, correct the loads of offenders, maintain a police presence, and process vehicles that choose not to participate in self-regulation. Although congestion at TCCs will over time become much reduced, the time spent in queues and at the static scale should still provide the impetus for operators to rather join the self-regulation scheme. The WIMe network will be used for prosecution of excessive overloads, to provide screening data for the weighbridge bypass system and much needed network loading information for planning purposes, and for continuous compliance monitoring of RTMS vehicles.

The envisaged layout and TCCs incorporating the bypass system is shown in Figure 3.

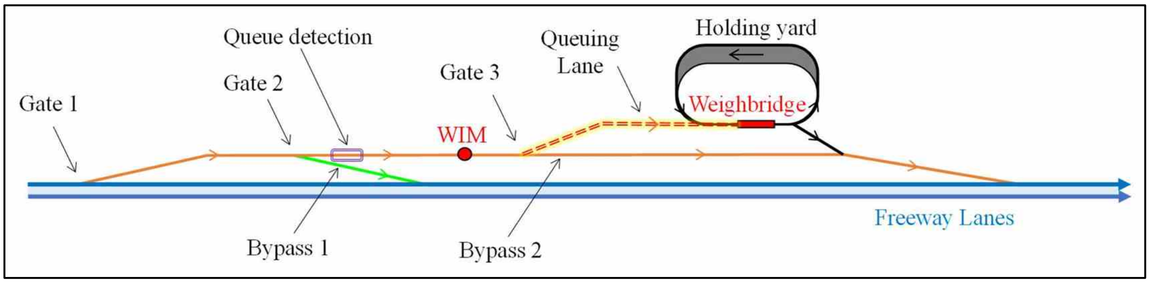


Figure 3 – Weighbridge Bypass Concept

The actions at each directing Gate, as shown schematically in Figure 3, are highlighted as follows:

- At Gate 1:
  - All heavy vehicles weighing more than 3.5 t are directed into the screening lane.
- At Gate 2:
  - "Green" vehicles are directed into the green bypass lane (Bypass 1). These vehicles proceed directly back to the freeway.
  - "Yellow" vehicles for which valid WIMe measurements are available and whose likelihood of being overloaded are below the chosen Authority Risk for the TCC are directed to Bypass 1.
  - The remaining vehicles proceed to the screening WIM.
- At Gate 3:
  - Black-listed vehicles (based on known overload status, outstanding Warrants etc.) are directed to the weighbridge.
  - Red vehicles, for which the likelihood of being overloaded exceeds the chosen Authority Risk for the TCC, are directed to the weighbridge.
  - Amber vehicles are vehicles that remained below the screening thresholds after being further assessed at the screening WIM (and combining any prior information if available) and are sent back to the road via Bypass 2.

The integration of information for the weighbridge bypass system will require sophisticated software, communication protocols and a large database. Although not part of the database, it is envisaged that additional communication links will be established so that information queries would also include the South African Police Service (SAPS), Cross-Border Road Transport Agency (CBRTA) and the electronic National Traffic Information System (eNaTIS). The envisaged flow of data from the various data sources is summarised in Figure 4.

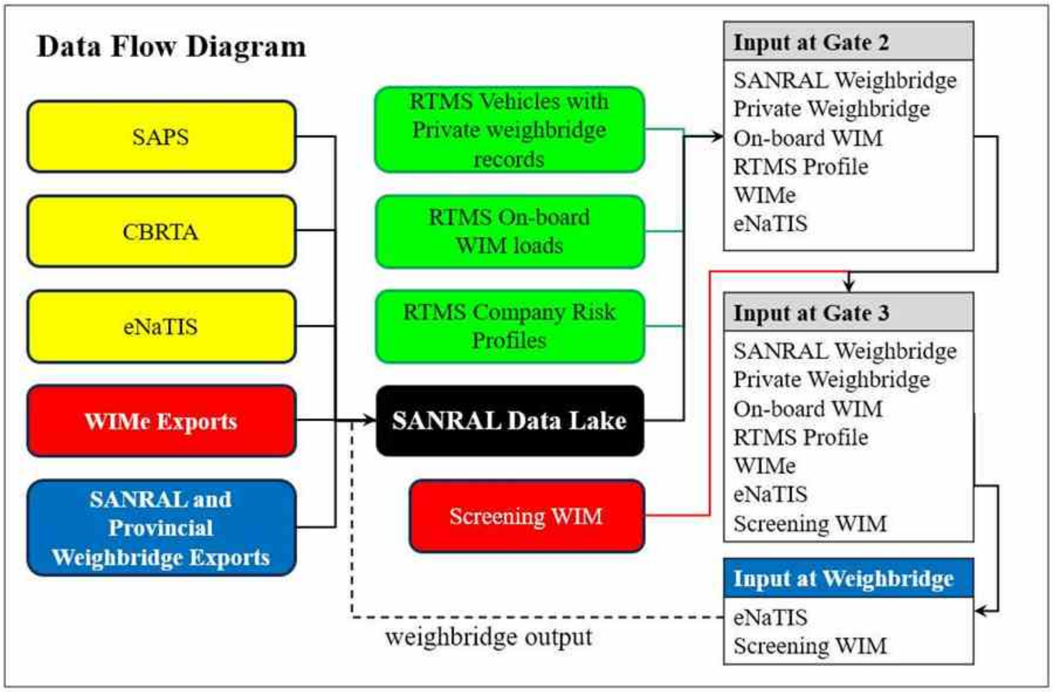


Figure 4 – Data Flow Diagram

5. The Way Forward

SANRAL is considering the implementation of a pilot project to put the developed theory to the test. If approved, the first step would be to conduct a WIM technology trial to test the performance of different WIM systems in the South African environment. These trials should commence during the first half of 2025. The following steps would be to implement a limited number of WIM enforcement stations as well as a pilot weighbridge bypass system at four TCCs to test their performance over a period of at least a year.

One of the aims of the strategy is to demonstrate that the operational benefits and time saving for transport operators would outweigh the benefits of overloading, and that freight operators would therefore largely eliminate overloading by choice. It is hoped that improved compliance and a desire for freight companies to participate in self-regulation and the weighbridge bypass system would already be evident from the pilot project.

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