A digital twin framework to support vehicle interaction risk management in the mining industry

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Abstract. In recent years, transport-related accidents, notably those involving trackless mobile machinery (TMM), have consistently ranked among the top three causes of fatalities and injuries in the South African mining industry (SAMI) [1]. These accidents arise from a combination of mechanical and technical malfunctions, environmental factors, and human or machine operator errors. Remarkably, these incidents persist despite the existence of specific regulations, standards, and codes of practice for transportation and machinery. This paper introduces a digital twin framework for TMM, which employs a systems engineering approach combined with software tools and computational analysis. This framework aims to enhance the current regulations by offering a continuous, quantitative risk assessment. By modelling and detecting non-conformance and adverse vehicle interaction events, the framework provides a quantitative risk analysis that complements the prevailing qualitative methods reliant on historical data and operational experience. A case study conducted at the CSIR main campus in Pretoria showcases the potential of the TMM Digital Twin.

1. Introduction

Transport-related accidents in the mining sector are a global concern. In the South African mining industry, they account for approximately 22% of accidents [2]. Internationally, vehicle interaction control failures contribute to 30-40% of mining fatalities annually, with pedestrians involved in about half of these incidents [3]. These accidents arise from a myriad of factors, including mechanical and technical malfunctions, environmental conditions, and human or machine operator errors. Human errors, for instance, can result from lapses in attention, procedural violations, or inadequate information provided to operators, which can compromise decision-making [4, 5]. External factors, such as equipment design, training quality, maintenance standards, infrastructure design, communication systems, and organisational safety culture, also play significant roles.

In South Africa, the Mine Health and Safety Act no. 29 of 1996 aims to protect the health and safety of mine employees [5]. Regulation 8.10 of the Act outlines the requirements for

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Trackless Mobile Machinery (TMM). The accompanying guideline delineates minimum requirements for mining operations to ensure worker safety [6]. Recently, the guidelines were updated to include requirements for preventing collisions between TMMs and pedestrians and collisions between diesel-powered trackless mobile machines. Despite these regulations and the introduction of the Zero Harm initiative in 2014, which has reduced overall mining fatalities, transport-related accidents remain a significant issue.

While South Africa has implemented various legislative measures and initiatives for mining safety, transport-related accidents remain a concern. This paper explores the TMM Digital Twin as a potential tool for addressing this issue. The TMM Digital Twin integrates various data sources, providing mine operators with a more comprehensive view of potential risks. This research aims to understand how such a tool can complement existing regulations and contribute to a safer and more efficient mining environment.

In the context of mining safety, vehicle interactions and non-conformance to the traffic management plan (TMP) pose a great risk to the safety of a mining environment. The potential risks can be mitigated by addressing three key areas:

- **Reducing Vehicle Interactions**: A high frequency of vehicle interactions presents a significant risk, especially in areas with intricate operations, or where large haul trucks operate in proximity to light-duty vehicles. Presently vehicle interaction frequency is typically dictated by fleet management software that is focused on increasing throughput.
- **Evaluating Control Effectiveness**: Mining sites utilise the Earth Moving Equipment Safety Round Table (EMESRT) Nine Layer Control Effectiveness model [3] to mitigate vehicle interactions and ensure safety throughout the mining site. It's important to assess the effectiveness of the control model in practice. As detailed in section 2.1, Levels 8 and 9 necessitate the deployment of dedicated hardware. However, not every mining operation possesses the resources for such hardware implementation. For Levels 1 through 7, software-based techniques can be employed to quantitively evaluate a mine's TMM related risk.
- **Traffic Management Plan Adaptation:** As mining operations evolve, TMPs require updates to stay relevant. At present mining entities rely on the experience of their engineers and reporting of accidents to bring about changes to their TMPs. A data-driven, simulation-based tool that aids decision makers in producing preventative solutions could add significant value in de-risking mining operations.

In September 2022, the Council for Scientific and Industrial Research (CSIR) team initiated a pilot at one of South Africa's prominent coal mines, using real-world data to test and assess the platform's performance. Due to data privacy constraints, specific details like real data, mine layout images, or analytical results from the pilot site cannot be disclosed. Consequently, this paper utilises public domain data in conjunction with dedicated experimental data to demonstrate the platform's capabilities.

The objective of this paper is to illustrate, through the use of a case study, the application of the TMM Digital Twin for the evaluation of Levels 1 to 7 of the EMESRT Nine Layer Control Effectiveness model and identify areas of high vehicle interaction through simulation.

2. Literature review

2.1. Existing regulations and controls

Internationally, one of the measures to reduce transport and mobile equipment-related accidents was the development of the Nine Layer Control Effectiveness Model, also referred to as the Vehicle Interaction Defensive Controls Model, by the Earth Moving Equipment Safety Round Table (EMESRT) [3, 7]. The goal of the model is to improve the reliability of vehicle interaction controls in preventing unwanted events such as collisions of equipment with other equipment, pedestrians and the environment, or loss of control of a piece of equipment. The model was developed on the basis that vehicle interaction controls are systemic, multi-level, interconnected, and dynamic and that many rely on human decisions and actions [3, 7]. The process controls of differing levels (1 to 9) and their interdependence in terms of type (design, operational, reactional) are shown in Fig. ***1***. Levels 1 to 3 form the design-related category of controls. These controls influence to a large degree the planning, layout, and strategic traffic control measures that the mine sets in place to govern TMM mining operations. The next level of controls, Levels 4 to 7, addresses issues related to the TMM operators' competence, fitness, and awareness during the normal operation of the vehicles. These controls ensure that vehicle operators, prior to using mine equipment, are well-trained (and continuously refreshed), qualified, inducted, and given the correct access control rights. Vehicle operators are also required to undergo medical examinations and are tested periodically (usually per shift) for drugs and substance use. Furthermore, some controls include the monitoring of drivers for fatigue as they carry out their duties.

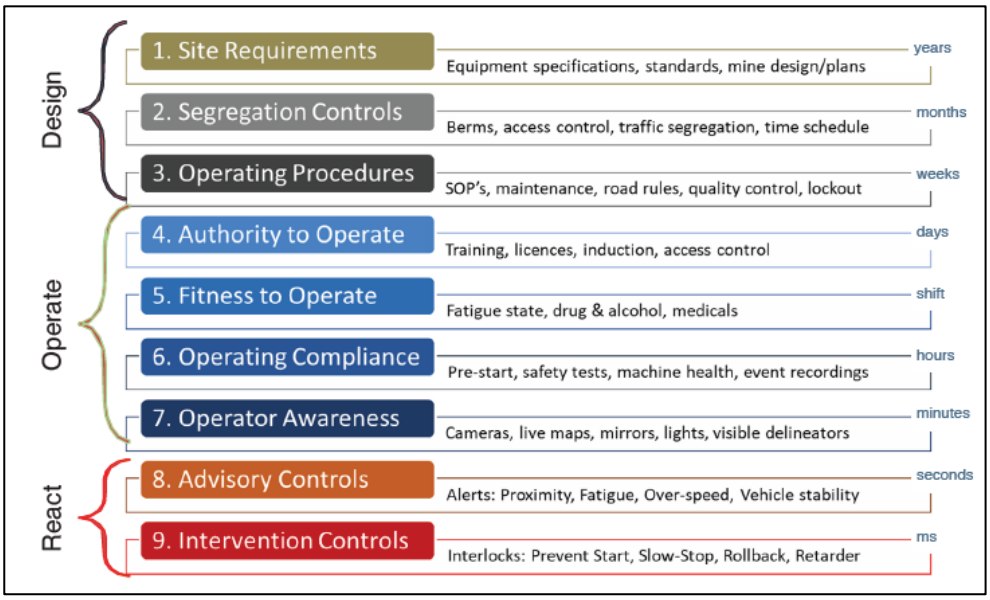


Fig. 1. The EMESRT Nine Layer Control Effectiveness model [3].

Level 7 or operator awareness controls equip vehicle operators and pedestrians with information that helps them identify and monitor potential hazards in the vicinity of their working environment. This information includes what the hazard is, its position, direction of movement, or the speed of travel of the hazard. Level 8 and Level 9 controls belong to the "react" category, which is made up of systems that manage residual interaction risk [3]. Level 8 – advisory controls – provide alerts, alarms, or instructions to vehicle operators, informing

them of potential unsafe interactions and the associated corrective actions required. The onus is on the vehicle operator to assess the instruction relative to other contributing factors and then act or intervene [3]. In contrast, for Level 9 controls, the vehicle subsequently examines the perceived environment relative to other contributing factors and then acts or intervenes, independent of the operator, for example, reducing speed to prevent a possible collision. The vehicle returns control to the operator if the operator acts to avoid an unsafe interaction or allows for a system reset after a collision intervention scenario. Levels 7 to 9 controls are consistent with the three levels of situational awareness described by [8]. These three levels form a hierarchy in which each stage is a necessary (but inadequate) precursor to the subsequent higher level [8, 9]. The three hierarchical levels are: perception of the elements in the environment, comprehension of the current situation, and prediction of future status. Fig. ***2*** shows a model that incorporates Levels 7 to 9 controls into the situational awareness model developed by Mica Endsley in 1995.

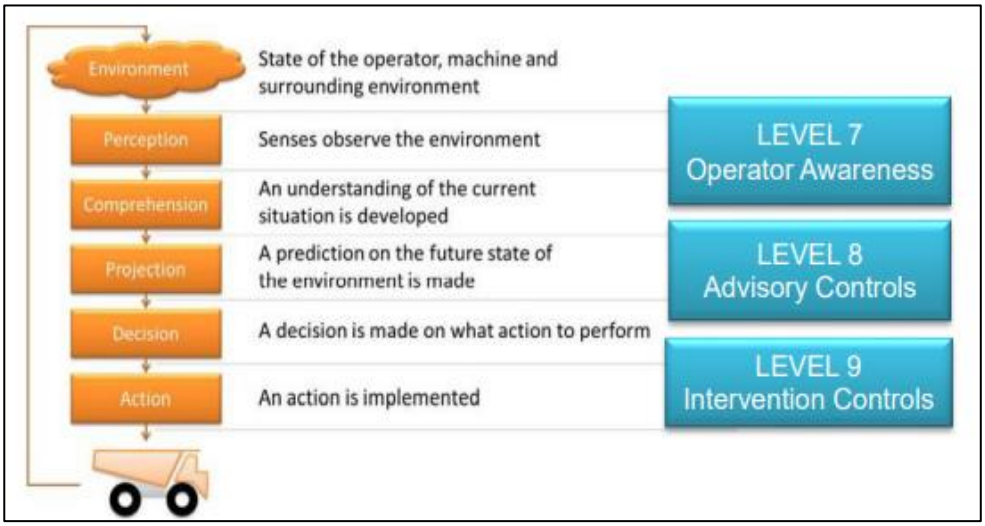


Fig. 2. A combined model of Level 7 to 9 controls and Mica Endsley's 1995 situational awareness model [7]

The South African mining industry has adopted the vehicle interaction defensive controls model by EMESRT for traffic management [10]. Even with the adoption of various practices and the introduction of pertinent measures, transport-related accidents continue to be a pressing issue. Nevertheless, there exists an opportunity to further reduce these incidents. By continuously developing and implementing innovative solutions, the industry can aim to achieve production targets without compromising worker safety or causing damage to equipment and infrastructure.

2.2. Traffic management plan

The TMP is employed by open-cast mines to address Levels 1, 2 and 3 of the EMESRT Nine Layer Control Effectiveness model. The development and implementation of a TMP is critical for the effective management of operations within an open-cast mine [11]. It helps to establish the requirements for creating a productive environment consisting of standard occupational safety practices. The implementation of leading practices in traffic management is intended to address the following unwanted events:

- Vehicle-to-pedestrian collisions.
- Vehicle-to-vehicle collisions (where operators are also brought to harm).
- Injury to pedestrians in restricted or hazardous zones.

With a TMP in place, maintenance and improvement strategies can be established to comply with leading practices in traffic management affecting both pedestrians and mobile equipment. TMP audits and inspections are scheduled on a regular basis within a mine to maintain compliance with the standard practices [12]. Therefore, the changing dynamics within a mine are always considered during the review process.

The TMP is a specification for the design of mine haul roads, internal mine roads, intersections, parking areas, traffic signage and rules of the road [12]. It is also a specification for all areas of the mine where vehicles operate to ensure that operations can be conducted safely and efficiently. Achieving a good safety performance is reliant on the skill and experience of the individuals responsible for the design and implementation for the TMP. Design aspects of the TMP such as risk analyses, road and infrastructure designs and traffic flow are generally done manually through various independent platforms and often only make use of qualitative measures. Therefore, there is an opportunity to improve safety performance by making use of a digitally enabled holistic TMP analysis tool.

2.3. Existing solutions

A comprehensive solution is needed to effectively address transport-related accidents within mining operations. Some systems provide methods for collision warning and risk management, while other systems provide methods and algorithms for traffic violation detection. The integration of non-conformance analysis, which assesses vehicle performance with respect to both traffic management rules and collision prevention systems, has not been implemented.

2.3.1. Collision avoidance and risk management systems

Vehicular Ad-Hoc Network (VANET) comprises four major components: vehicles, devices/sensors such as Global Positioning System (GPS)-enabled devices, roadside units (RSUs), and the Traffic Management Centre [13, 14]. Three prediction models are considered for vehicle collision prevention [13].

Firstly, the physical-based model focuses on analysing the dynamic trajectories of moving vehicles to predict the probability of collision, although it does not consider the broader traffic environment. Secondly, the intersection avoidance system employs sensors to monitor intersections and analyse vehicle movement data, aiming to predict and provide warnings about potential collisions at intersections to ensure safety. Lastly, the cooperative collision avoidance system analyses VANET data and driver behaviour to offer insights and warnings with the goal of enhancing road safety. The effectiveness of this system depends on the deployment of VANET [14] and other data systems, considering the entire traffic environment.

As seen in [15], a collision avoidance framework was developed for connected vehicles using a digital behavioural twin. This involves retrofitting relevant electronic, control, and communication systems into the actual vehicle, referred to as the 'Ego vehicle,' and creating a digital twin of the vehicle, known as the 'remote vehicle.' These vehicles continuously exchange information. The system utilises recorded digital data of the driving pattern and behaviour of both the vehicle and its digital twin to assess collision risks. The Ego vehicle is

equipped with an electronic display that provides augmented reality (AR) visualisations of identified risks. Additionally, the method includes adjustments to the vehicle's operation based on identified risks. It's important to note that this approach is exclusively designed for Toyota vehicles.

Similarly in [16], a real-time traffic risk prediction method and system based on driving behaviour using artificial intelligence (AI) is presented. This method involves modelling urban roads, establishing a traffic risk level model based on either simulated or actual vehicle positioning data, and predicting the risk level using the measured or simulated data. Its primary applications include enhancing traffic monitoring, optimising road construction, promoting safe driving practices, and potentially incorporating weather conditions into the prediction model.

These systems are primarily used for urban roadways and not necessarily developed for mining applications. However, the approaches in terms of real-time analysis, digital twinning, data considerations and holistic approaches, similar to VANET are all contextualised in the development of the TMM Digital Twin for mining operations, considering the vehicle types and harsh environment.

2.3.2. Traffic violations detection methods

Road traffic accidents have multiple causes, including external factors like weather and road conditions, as well as human factors such as driver violations or negligence [17]. A correlation between the traffic accidents and road user violations has been established, highlighting the significance of monitoring and addressing violations promptly to prevent catastrophic accidents.

Several systems have been proposed and implemented to detect traffic violations on urban roadways. Some of these systems utilise YOLOv3 algorithms [18] as part of Convolutional Neural Networks (CNNs) for analysing digital images or videos to detect violations. CNNs effectively process data in a grid-like format, learning all object parameters at each location and position. When processing a digital image, CNNs provide outputs that include objects with boundary boxes. This detection encompasses parameters like height, width, and boundary coordinates [18]. Additional processing is carried out through the detector algorithm to accurately evaluate the bounding box against the detection parameters, a technique commonly applied in traffic violation applications.

Other systems make use of Binary Large Object (BLOB) method to identify vehicle contours for detection, and thereafter use Mean Shift algorithm in tracking vehicles [19]. BLOB provides the capability to detect objects that have been processed with Convex Hull to be able to be considered as a vehicle. The Convex Hull method provides a computational geometry of an image in a two-dimensional plane, which results in a polygon. This is to ensure that excessive threshold results are not considered objects. BLOB has features to detect objects based on colour, size, and shape. The detected BLOB is tracked using the Mean Shift algorithm to ensure that when a collision occurs it does not reduce the accuracy of the object [19]. This object is therefore processed to be able to detect violations.

These systems are used in the following applications: signal jump violation detection; lane jump violation detection; road marking detection; speeding violation detection; parking violation detection; and missing car detection.

Common traffic violation detection systems, such as the IoT-based smart traffic signal violation monitoring system using edge computing [20], predominantly rely on vision

systems utilising cameras. However, in mining operations, camera-based detection is suboptimal in challenging conditions, notably dust. Therefore, a fit-for-purpose solution for mining operations is needed, one that leverages vehicle tracking, detection parameters, and computational analysis to monitor traffic violations.

3. System overview

The TMM Digital Twin is a cloud-based platform that has been developed to interactively conduct various analyses and simulations that are directly linked to the activities of vehicles in the mining site, both moving and stationary. Such simulations include non-compliance events, average braking, average speed, and vehicle movement tracking. To produce the simulation outputs, the platform requires vehicle logs, vehicle type for differentiation purposes, a drone image of the mining operation, and TMP (Fig. ***3***). The vehicle logs consist of Global Positioning System (GPS) data and optionally EMESRT Level 8 or 9 systems' data, if available. The drone image is geo-referenced so that GPS data coincides with the mine layout.

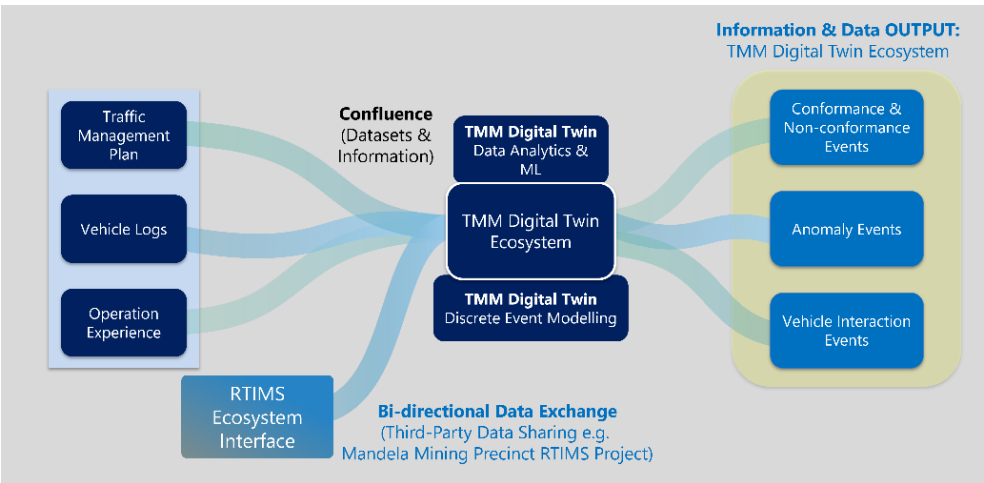


Fig. 3. Data flow model for the TMM digital twin platform.

The user interface allows users to upload vehicle log files. The user specifies the columns of interest (date, time, latitude, longitude, heading and speed), and the log files are processed by the back-end compute instance. The data or log files undergo a pre-processing phase to be configured into the correct format that can be read and correctly interpreted by the backend models and algorithms used (Fig. ***4***). Further post-processing is required to generate outputs and insights based on the provided data. (Fig. ***3***).

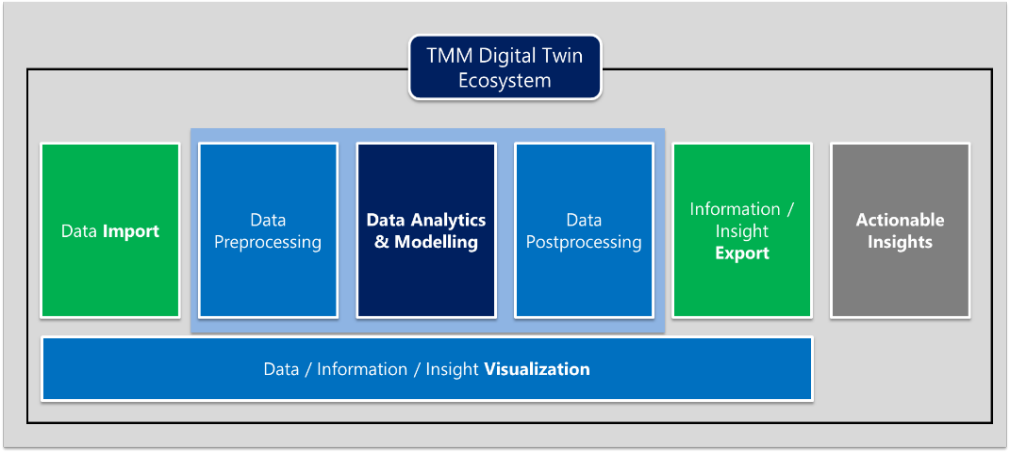


Fig. 4. Software ecosystem.

3.1. Digitisation of TMP

The TMM Digital Twin platform allows a user to configure their TMP in the software (Fig. ***5***). Once the latest layout of the mine is uploaded, the traffic management elements such as stop signs, berms, speed zones and loading/unloading areas can be configured with GPS coordinates or by visually referencing a TMP layout document.

After the TMP has been configured a 'Compliance Event' analysis can be conducted, where the adherence to road rules is determined for a vehicle set using their GPS data. Infringements of the TMP are visually overlaid on the map (Fig. ***6***) and statistical reports are also generated for the datasets.

Statistical evidence from the platform provides insights into the type of violations that occur, frequency of occurrence, and relative vicinity of the violation events. This helps to identify issues at various geographical locations in the mine that potentially require re-work of the TMP.

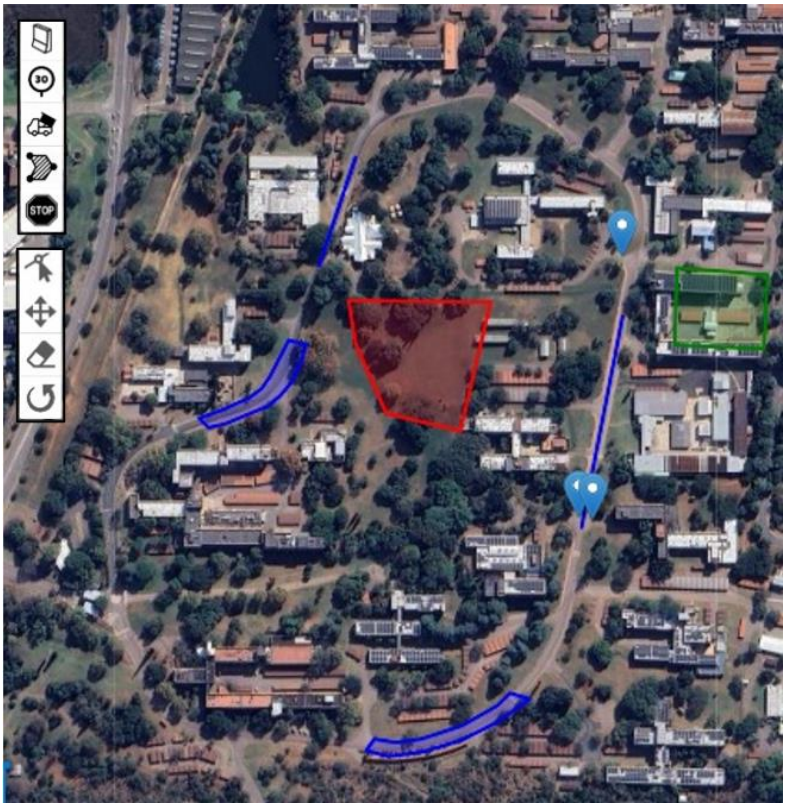


Fig. 5. Placement of traffic elements for TMP simulations.

3.2. Data cleaning and pre-processing

Real-world GPS data first needs to be 'cleaned' and pre-processed before it can be analysed. The data is first cleaned by removing duplicate entries, impossible GPS coordinates and stationary points. Finally, trajectory data is smoothed by removing noisy GPS points caused by poor GPS signal. Two primary methods used for smoothing are, a Kalman filter [21] that models vehicle motion and/or a Savitzky–Golay filter [22] that employs a least squares procedure.

To pre-process the data the trajectory is first simplified. Trajectory simplification is applied to improve processing speed and reduce the data storage overhead. A well-known compression algorithm, called Ramer-Douglas-Peucker [23] is used to approximate the original trajectory using significant fewer data points without a loss in data accuracy. General data calculations steps are then applied, for example point-to-point distances, acceleration from speed, etc. A final pre-processing step is route segmentation, where trajectory data is grouped into segments of certain distances to allow the calculation of segment-based statistics (for example to create average braking plots).

3.3. Route and event visualisation

Once the data have been cleaned and pre-processed it can be effectively visualised. Several visualisation methods are employed:

- **Route animation**: Routes are animated and plotted on hypertext markup language (HTML)-based maps (which are uploaded to cloud and viewed in the user interface). The movement of the vehicle over the map can be seen as a function of time.
- **Segment averaging**: Average speed or braking intensities can also be visualised as static plots.
- **Non-conformances**: Vehicle trajectory data is checked for compliance against the TMP. Violations or infringements of the TMP rules can be visualised on a map as shown where dashed lines indicate speed zone, stop sign and berms, exclusion zones, unloading zones and rule violations are clearly marked with the various coloured dots as depicted in Fig. ***6***.

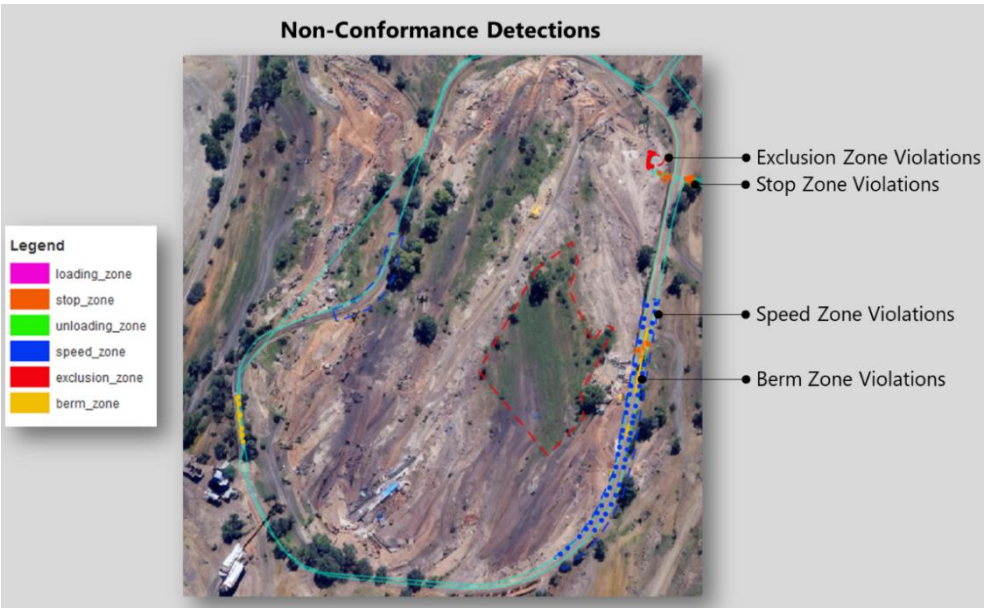


Fig. 6. Non-conformance detections.

3.4. Route simulation

The system allows users to create custom routes for which they do not have actual vehicle data. A synthetic route can be created, for example, between new planned loading and unloading sites. The user interface allows a user to select a few points along the map (shown with white x's) and the system will generate a smooth route along the selected points (in blue) as illustrated in Fig. *7*.

Fig. 7. Synthetic route creation

This synthetic route can then be amplified by adding statistical variance to generate realistic trips between loading and unloading sites. As many synthetic trips can be generated as required. Fig. ***8*** shows an example of variance trips (in blue) generated for a route (white dashed line).

Fig. 8. Generated synthetic dataset.

3.5. Vehicle interaction analysis

Synthetic (or real) vehicle trajectory data can be transformed into a format that can be ingested by Siemens Tecnomatix Plant Simulation (PlantSim) for simulation purposes. A PlantSim simulation can be set up to match real-world vehicle dynamics, including loading and unloading times as well as mean loaded and unloaded travel speeds. The simulation can be adapted by adding multiple vehicles to the route to simulate congestion and potential collisions. The output from such a simulation is valuable for route planning and developing

the TMP in mining operations. One such output is a heatmap – where the frequency of vehicle-to-vehicle interactions are visually represented as hotspots (high frequency events are depicted in warm colours) – shown in Fig. ***9***.

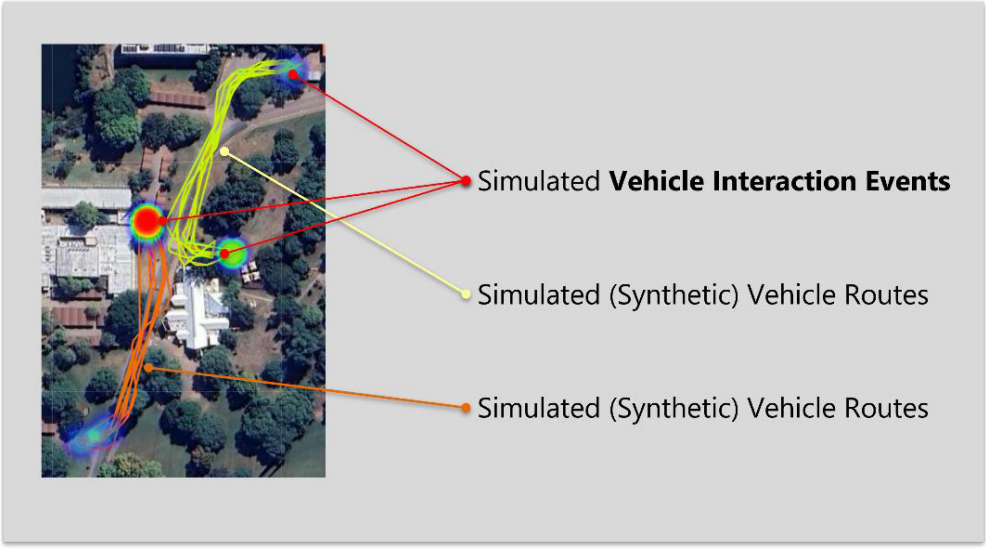


Fig. 9. Vehicle interaction heatmap of synthetic routes.

4. Analysis and report

The case study was conducted at the CSIR Main Campus in Pretoria (Fig. ***10***). The road network of the CSIR's Main Campus shares some similarities to that of an open-cast mine. The Northern section of campus consist of an outer loop, with roads stemming towards the centre. For this study, the campus layout served as a representative model of a basic open-cast mine for the analysis.

Fig. 10. Satellite view of CSIR Main Campus.

Analyses on the experimental vehicle data aim to provide insight into potential behavioural non-conformances using the software platform. The results section details the findings from these analyses.

4.1. Methodology

To evaluate the operation of the case study mine the following actions were be performed:

1. Driver fitness check and briefing. (Level 4 and Level 5 controls).
2. Collect GPS vehicle data (Level 6 and Level 7 controls).
3. Import vehicle data into software platform.
4. Create TMP layout document to address requirements of the test site (Level 1 to Level 3):
    a. Virtual berms to check segregation.
    b. Stop signage (as located on the CSIR campus)
    c. Speed monitoring zones where speed traps or speed bumps are not present.
    d. Exclusion zones where vehicles are not supposed to travel.
    e. Loading/unloading zone.
5. Configure the digital version of the TMP on the software platform.
6. Create a dataset to be used for analysis.
7. Perform conformance analysis of the dataset.
8. Update the digital TMP to purposely force non-conformance events.
    a. Change the speed zone threshold to a low value.
    b. Place stop signs where the vehicle travelled.
    c. Place a virtual berm where the vehicle travelled.
    d. Place the exclusion zone where the vehicle travelled.
9. Perform conformance analysis of the initial dataset but apply it to updated TMP.

10. Synthetic route creation to simulate possible vehicle interactions.

4.2. Experimental setup

Vehicle tracking data was generated by employing a Booyco Electronics CXS Collision Prevention System (Fig. ***11***).

Fig. 11. Booyco Electronics CXS Collision Prevention System *[24]*.

The GPS tracking system was installed on a light duty vehicle. A driver was instructed to drive a prescribed route along the outer loop in a clockwise manner, while adhering to the national traffic regulations. The designated maximum speed limit on campus is 40 km/h.

With the real-world experimental data captured, synthetic data was also created to simulate vehicle interactions. The real-world data consisted of the GPS data that was imported into the software by accessing an Application Programming Interface (API) endpoint. The synthetic data consisted of multiple routes created with the route creator tool.

4.3. Configuration process

To perform the analyses described in steps 7 and 9 of section 4.1, a set of specific actions must be completed. The sections to follow describes the processes to set up the analysis framework, define a dataset, and interpret the various analysis outputs.

4.3.1. Digital TMP configuration.

At the core of the analysis and simulation functionality lies the TMP, therefore the first step is to configure a digital version of the TMP. The TMP consists of all the traffic management elements that a mine implements to govern the flow of vehicles and pedestrians in the mining environment. The TMP consists of similar elements that can be found on public roads but are tailored to fit into mining operations.

The TMP is configured from a document outlining the planned layout. The mine layout is typically divided into sectors to allow traceability and placement of traffic elements. Fig. ***12*** shows the case study TMP specification overlain on a satellite image of a portion of the CSIR's Main Campus. The layout is divided into sectors A1 to C3. These sectors were, later in the process, used to visually illustrate the conformance/non-conformance statistics.

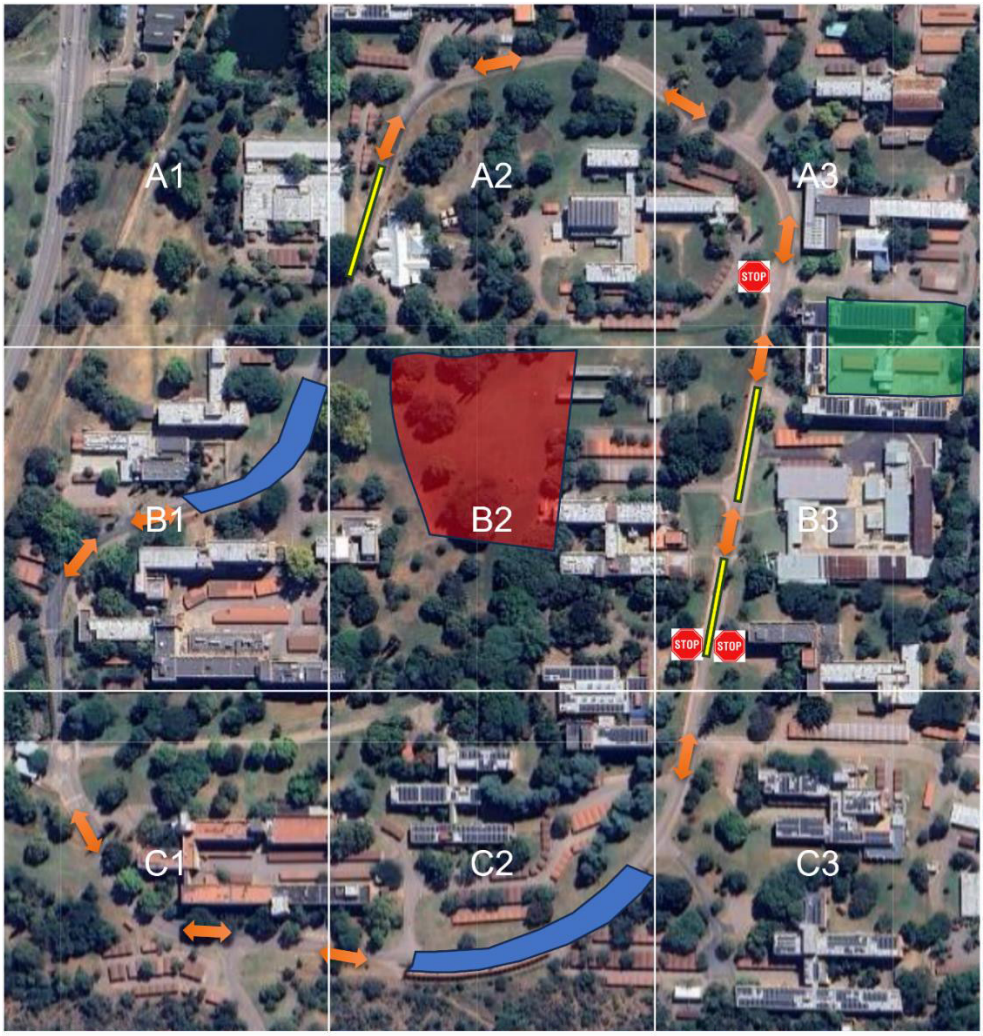
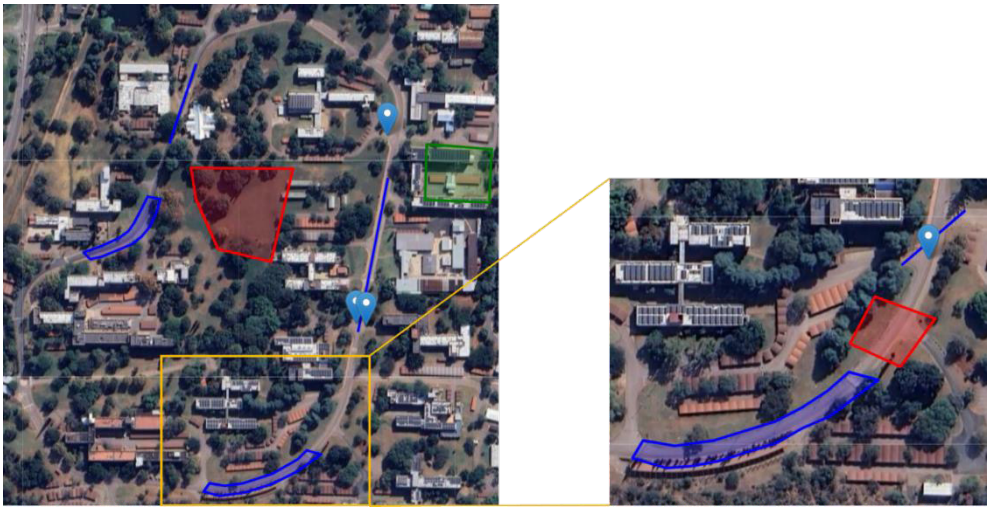


Fig. 12. Case study TMP layout document.

The planned layout considers the road layout, the required traffic management elements and traffic policies on the CSIR campus to ensure safe and efficient traversal on the road network. These traffic management elements include traffic flow (orange arrows), speed detection zones (blue zones, located in B1 and C2), segregation berms (slender yellow rectangles located in B3 and A2), loading/unloading zones (green zone spanning across A3 and B3) and exclusion zone (red zone located in and B2). Stop signs and exclusion zone correspond to their real-world positions. The speed detection zones are placed where no speed trap or nearby speed bump is located to monitor the adherence to the speed limits in these areas.

In the South African mining industry, there are leading practices for traffic management, however, there is no prescribed standard format or representation of the TMP. Fig. ***13*** and shows the digitised case study TMP with a digital version of the traffic management elements such as stop signs (blue location pins), speed zone (blue transparent block polygons), berms

(single blue line), unloading zone (green polygon) and exclusion zone (red polygon).



(a) (b)

Fig. 13. Creation of digital TMP: (a) campus TMP; (b) adapted TMP.

There are ten traffic management elements implemented for this case study. Each of the digitised TMP elements have a specific function and analyse the relevant input data. Berms monitor the segregation of the traffic, for example, if the vehicles stay in the road lanes. Stop signs monitor if a vehicle comes to a stop at the indicated intersections. Speed zones have a maximum allowed speed linked to it and monitors that all the vehicles that enter the zone maintain a speed below the set maximum. The unloading zone is a special variant of a speed zone as it monitors the maximum speed of the vehicles in the unloading areas but also logs data that is used to calculate throughput. Exclusion zones are used to define areas where no vehicle is allowed to enter. Fig. ***13***.a represents the campus TMP, which is the digital TMP as required by the layout in figure 11. Fig. ***13***.b purposefully adapts the campus TMP by adding traffic management elements to force violations. The speed detection threshold has been adjusted to 35 km/h, and a stop sign, berm, and exclusion zone have been positioned along the vehicle's path.

4.3.2. Dataset creation

To perform the analytical actions and conformance evaluation of the vehicle data, the user must define a dataset. The dataset is created from the imported GPS data. Datasets can be configured based on the following criteria:

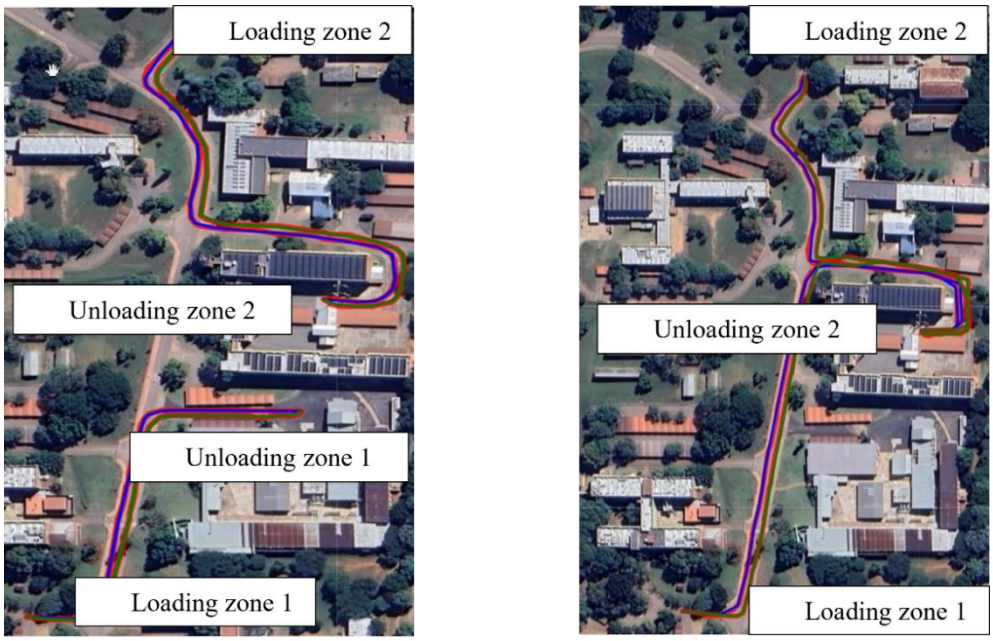
- Start and end dates and time.
- Specific vehicle to include in the dataset.
- Which analysis results to generate:
    - Average speed.
    - Average braking.
    - Vehicle movement visualisation.
    - Conformance analysis.

The analyses that are conducted by the platform each pertain only to the vehicles used in defining the dataset. The statistical report generation functionality of the platform can, however, combine the results from multiple datasets.

4.3.3. Route creation

To do simulations on new routes, for which there are no GPS data, a synthetic dataset can be created. The synthetic routes created for the case study are shown in Fig. ***14***. Firstly, a user must define the loaded route (after the haul truck has collected its load, shown in blue) and the unloaded route (after the haul truck has offloaded its load, shown in green). The vehicles' average speed is defined, and statistical variance can then be added to the route. The variance parameter introduces a small positional offset to the generated data points. Ultimately this creates a route that deviates slightly from the original spline. The variance-routes more closely mimic human operator driving behaviour. The speeds and route variance can independently be customised for each route.

In this case study two possible route layouts are evaluated. Both layouts create two independent loading and unloading routes. In the first case (Fig. ***14***.a), the loading and unloading routes are separated from each other. The second case (Fig. ***14***.b) sets up two separate loading zones that have a common unloading zone that can only be accessed via a single road.



(a) (b)

Fig. 14. Simulated route creation: (a) separated loading and unloading routes; (b) separate routes leading to a common unloading zone.

These routes are created to showcase the capabilities of the platform to simulate vehicle interaction for different scenarios using synthetic data. As previously mentioned, it is valuable to analyse vehicle interactions for existing operations and planning purposes.

4.4. Results

This section presents the results obtained from the case study, highlighting the detected conformance analysis and the simulation results of the synthetic datasets.

4.4.1. TMP validation

The conformance analysis leverages real-world GPS data to scrutinise whether the driver adheres to all stipulated TMP control elements. The real-world dataset and the campus TMP (Fig. ***13***.a) served as input to the software platform 's conformance analysis. The result of the conformance analysis is shown in Fig. ***15***.

Fig. 15. Conformance analysis of case study's real dataset.

As indicated in section 3.3, non-conformance events are shown as coloured dots corresponding to the colour of the traffic management element. The TMP consisted of 10 traffic management elements, none of which detected a non-conformance event. The absence

of non-conformance events serves as a clear indication that the driver adhered to the entire TMP.

4.4.2. Simulated TMP violations

In the preceding section, validity of the TMP was established by observing that the driver did not cause any non-conformance events. In order to illustrate the functionality of the software platform to identify non-conformance events the an adapted TMP was configured as shown in Fig. ***13***.b. The adapted TMP purposefully introduced fictitious traffic control elements in order to force non-conformance events to be detected. The results of the conformance analysis is shown in Fig. ***16***.

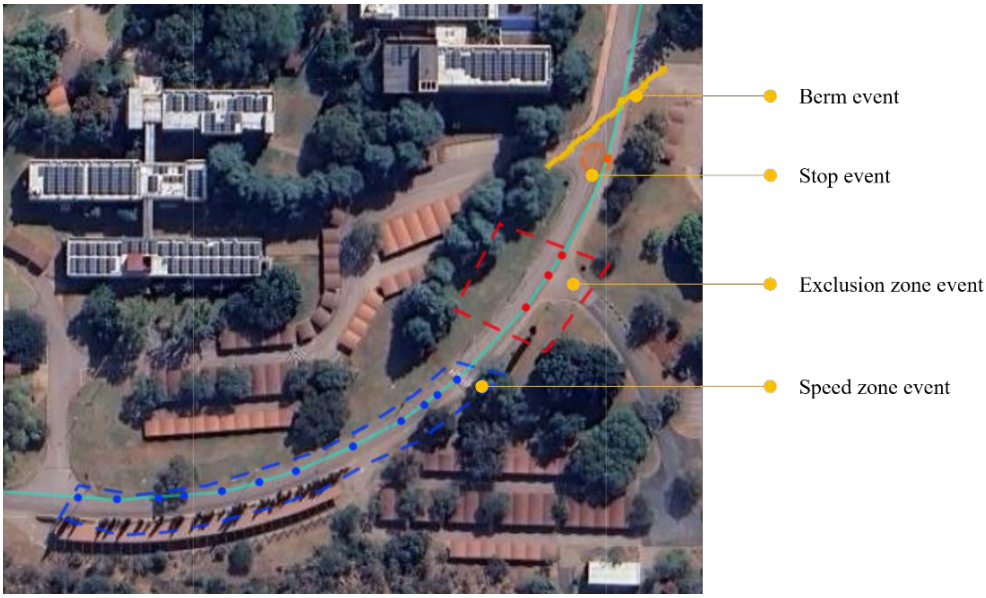


Fig. 16. Conformance analysis showing forced non-conformance events.

The software platform represents each event as a coloured dot along the vehicle path, corresponding to the colour associated with the respective TMP element. Specifically, the berm is denoted by yellow, the stop sign by orange, the exclusion zone by red, and the speed zone by blue.

The conformance analysis can also be visualised as statistical data. The conformance statistics are displayed on the TMP grid as seen in section 4.3.1. The conformance statistics of the analysis can be seen in Fig. ***17***. The detected non-conformance events are grouped according to the TMP element evaluated. The sectors that do not have the relevant TMP element simply has the colour and percentage value omitted.

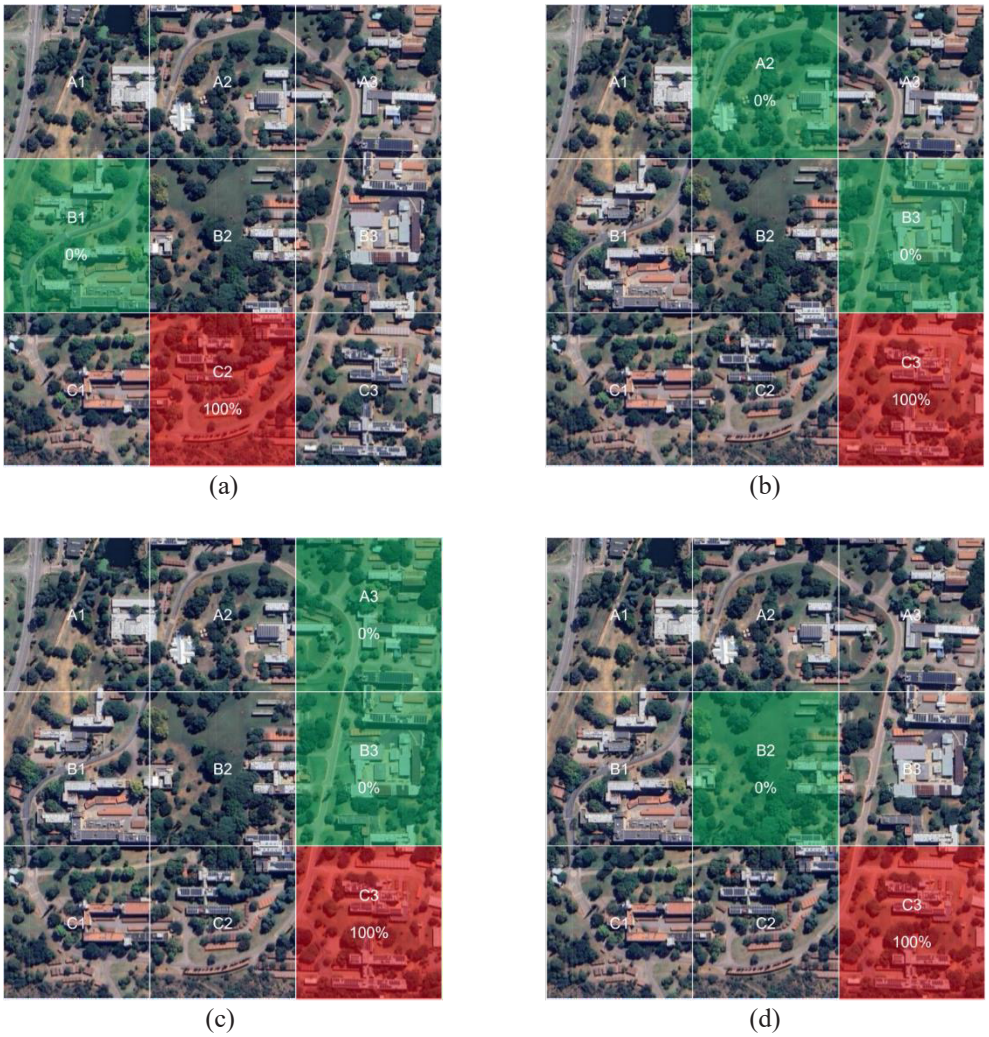


Fig. 17. Conformance analysis statistics visualisation: (a) speed violations; (b) berm violations; (c) stop sign violations; (d) exclusion zone violations.

In Fig. ***17***.a, all speed violations occurred in sector C2 and thus zero speed violations have been detected in B1. Similarly, berm and stop sign and exclusion zone violation statistics are shown in Fig. ***17***.b, Fig. ***17***.c and Fig. ***17***.d respectively.

The visual representation of the conformance analysis provides the user with a consolidated view of the conformance to the TMP and highlights the areas that need to be investigated to ascertain the causes of non-conformances. There are several possible contributing factors to non-conformances, such as poor road infrastructure, low visibility of signages and substandard driver behaviour.

4.4.3. Simulated vehicle interaction heatmaps

The synthetic datasets are used to simulate vehicle interaction. The vehicle interaction density is displayed in the form of a heatmap. The results of the two routes are shown in

Fig. **18**.

Fig. 18. Simulated vehicle interaction heatmap for synthetic routes: (a) separated loading and unloading routes; (b) separate routes leading to a common unloading zone.

In

Fig**. 18**.a, the two loading and unloading routes were physically separated. As can be expected, no hot spots are detected on the routes as the traffic operated on dedicated routes. The only interaction hot spots were at the designated loading and unloading locations.

The layout in

Fig**. 18**.b illustrates the separate loading routes which have a common unloading zone. As was the case with the first scenario, the loading and unloading zones show high vehicle interaction density. Additionally, it shows that the intersection leading to the unloading zone (location 'a') becomes an area where there is increased vehicle interaction. This highlights the area of interest to investigate the effectiveness of segregation controls and possible risks.

5. Conclusions

Experimental data was generated by tracking a vehicle, equipped with a GPS system. The data was analysed with the TMM Digital Twin software platform. The dataset was validated by comparing the software results to the experimental setup parameters – no traffic violations were found in the analysis as expected. The lack of violations indicated that the campus TMP was configured properly. Based on the dataset from the designated route, the TMP adequately addressed requirements for Levels 1 to 3. Furthermore, the driver complied with Levels 4 through 7, underscoring the platform's capability in accurately capturing and analysing the data.

Subsequently the campus TMP was adapted to simulate traffic violations for the experimental dataset. The speed limit was reduced to 35 km/h and fictitious traffic elements were added to force infringements. The adapted campus TMP analysis demonstrated that the platform detected the non-conformance events on the berm, stop sign, exclusion zone, and speed zone elements. The statistical visualisation of the non-conformance events were also shown. Green to red colour ranges indicated the number of infringements in each sector.

Furthermore, an investigation of vehicle interactions frequency was conducted by making use of synthetic routes. The analysis identified high interaction density areas and is reported on using heat maps. Two scenarios were considered. For the first scenario, separate loading and unloading routes resulted in high vehicle interaction densities at those zones. For the second scenario, where the loading and unloading routes shared a common road section, an additional high interaction area appeared at the intersection. By identifying the additional vehicle interaction hotspot via simulation, intervention controls can be implemented before the route is put into service.

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