BEYOND SPREADSHEETS: NEXT-GENERATION EVACUATION MODELLING AT KOEBERG NUCLEAR POWER STATION

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ABSTRACT

The Koeberg Nuclear Power Station (KNPS) Traffic Evacuation Model (TEM) plays a crucial role in ensuring the safety and efficiency of emergency responses, as well as evaluating the effectivity of the transport network to accommodate further development, in the effective evacuation area of the KNPS located near Cape Town, South Africa. The purpose of the overall study was to evaluate the City of Cape Town's documented emergency procedures for testing and estimating evacuation times, of which the TEM is a key component. The existing spreadsheet-based methodology which employs a simplified road capacity evaluation has indicated that the time for full evacuation of the evacuation area is approaching the 16-hour limit stipulated by the National Nuclear Regulator (NNR). With the simplified methodology and input estimates, it has become necessary to bring the evaluation methodologies in line with the state of the art and to update input information while developing a streamlined approach to updating input data. Additionally, the evaluation of expected evacuation time required extension to multiple scenarios representing different incident, population, infrastructure and traffic management scenarios.

In its latest redevelopment, modern transport modelling software was used to transform the TEM from a basic spreadsheet-based tool to a cutting-edge, integrated traffic and land use model. This advanced model employs a simulation-based assignment algorithm, enabling enhanced traffic flow analysis and evacuation route optimization. The integration of a user-friendly graphical user interface (GUI) is a notable advancement, allowing real-time user interaction with the model for proposing changes and simulating evacuation scenarios. This innovative tool is pivotal for evacuation planning and regulatory compliance. The intention moving forward is that the utility of the streamlined methodology is extended to urban planning and development assessment in the study area. The approach adopted exemplifies the successful application of technology in addressing complex transportation and land use challenges, setting new standards in evacuation modelling and urban planning.

This paper outlines the methodology employed in creating the state-of-the-art model, including the lessons learnt in acquisition, processing and ongoing maintenance of the

required input data. It demonstrates the model output and evacuation scenario evaluation and details the way forward in incorporating the model into existing statutory processes.

1. INTRODUCTION

1.1 Background

The Koeberg Nuclear Power Station (KNPS), located near Cape Town, South Africa, serves as a pivotal component in the nation's energy infrastructure. The National Nuclear Regulator (NNR) requires the City of Cape Town (CCT) and the Western Cape Provincial Government (WCPG) to assess if the existing and future transport infrastructure and services are adequate to effectively evacuate the surrounding area of the KNPS in the case of a radiological emergency. The National Nuclear Regulator Act (Act No.47 of 1999) and the supporting regulations states that no development that results in an increase of population should be considered within the five-kilometre Precautionary Action Zone (PAZ) radius of a nuclear facility's centroid location. Secondly, developments may only be considered in the five-to-16-kilometer Urgent Protective Action Planning Zone (UPZ), if the public can be evacuated in any 67.5-degree sector from the facility's centroid in a 16-hour period. The Precautionary Action Zone (PAZ) and Urgent Protective Action Planning Zone (UPZ) are shown in Figure 1.

The City of Cape Town Municipal planning By Law further defines the relationship between development and the disaster risk management procedures relating to evacuation:

"a development application shall only be approved by the City where it is satisfied that the disaster management infrastructure necessary to ensure effective implementation of the approved traffic evacuation model and associated disaster risk management procedures, is adequate."

The existing spreadsheet-based Traffic Evacuation Model (TEM) was developed to estimate the total evacuation time based on static evacuation volumes and theoretical evacuation route hourly vehicle capacity. Since 2008/09 concerns have been expressed by the City's Disaster Risk Management Department as well as ESKOM, about the ability of the spreadsheet-based TEM and its associated methodology to effectively predict the evacuation times for each region. Between 2010 and 2012, in response to these concerns, a City of Cape Town interdepartmental project management team updated the TEM baseline information. During mid-2013, additional sensitivity testing was performed, and capacity amendments made to the model in response to requests from the NNR. The NNR indicated that although the TEM is credible under the current level of spatial development near Koeberg, the longer-term use of the TEM was conditional to, amongst others, the development of a new, more detailed evacuation simulation model.

The result of these developments was the commissioning by the CCT of a comprehensive multimodal traffic simulation model. The purpose of this TEM was to validate and refine the results obtained from the existing spreadsheet-based model and expand the range of evacuation scenarios and strategies. The aim of the evacuation model is to be utilized to optimize evacuation routes and associated strategies, as well as identify infrastructural mitigation measures that adhere to the requirements of the NNR while maximizing the area's development and economic potential. The terms of reference required the development of a dynamic assignment, mesoscopic model with several microscopic models. Instead, the project team developed and integrated Meso- and Microscopic

Model, making use of a specialized simulation-based assignment technique. This integrated model contains sufficient network and intersection details to derive the benefits of a single integrated model with microscopic-level results for any intersection or area of the model. The integrated model simulates individual vehicles and the interaction of vehicles at conflict areas in detail.

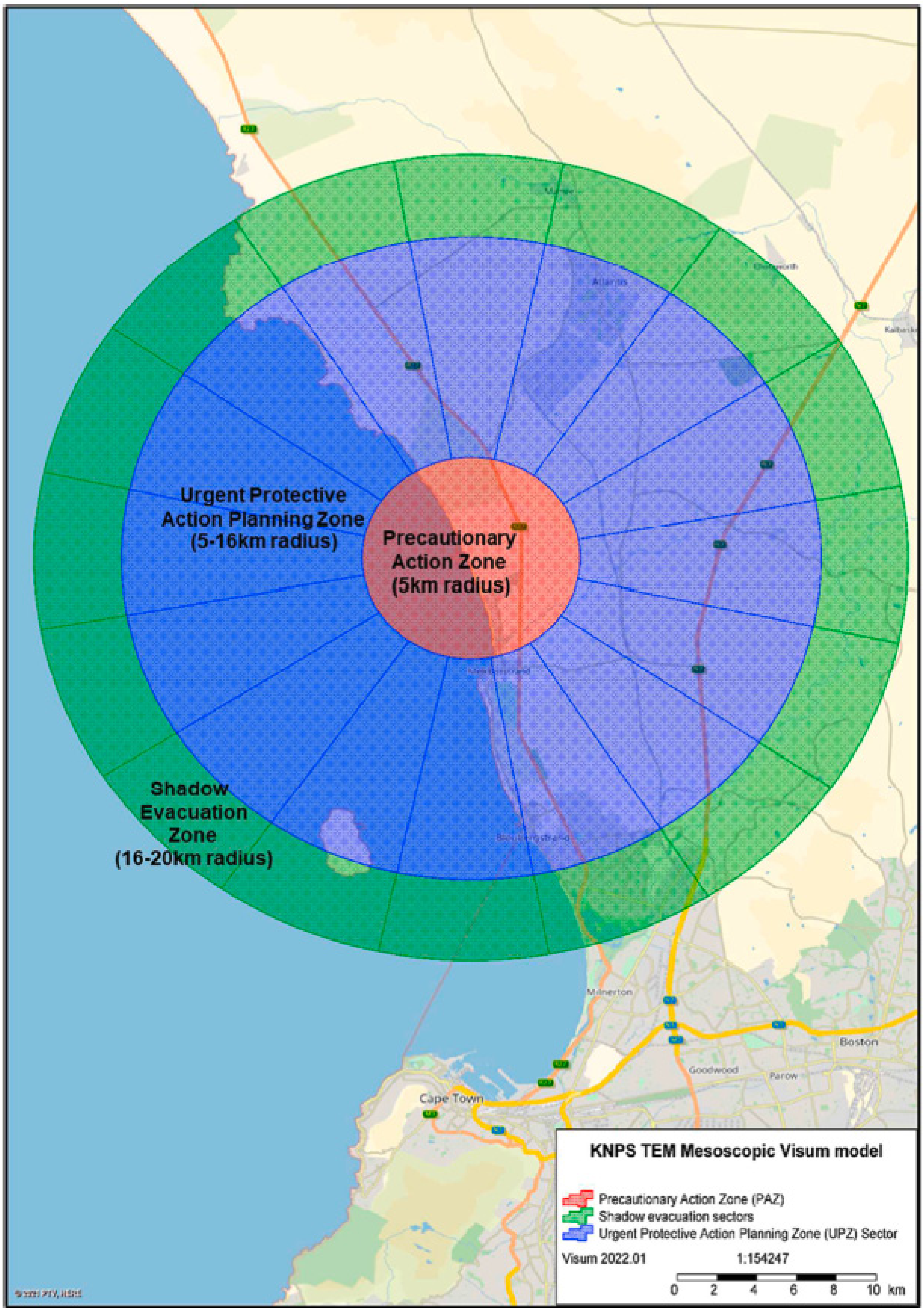

Figure 1: Koeberg Nuclear Power Station (KNPS) Evacuation Sectors, with KNPS being the centre of the concentric circles

1.2 Aim of Paper

This paper aims to present an overview of the advancements made in the field of evacuation modelling for the KNPS, indicating the transition from traditional spreadsheet-based methodologies to a state-of-the-art, integrated traffic and land use model. This evolution marks a significant step forward in the precision, reliability, and applicability of evacuation planning tools, setting new benchmarks for safety, efficiency, and regulatory compliance. The increased functionality allows for more realistic modelling of real-world transport dynamics, as well as the testing of driving or operational conditions for varied evacuation scenarios.

1.2.1 Problem Statement

The existing spreadsheet-based TEM, while serving as a foundational tool for evacuation planning, revealed limitations in scalability, flexibility, and the ability to accurately simulate complex traffic dynamics and land use interactions. These limitations prompted the need for a more advanced approach to adequately address the evolving infrastructure, population, and regulatory requirements within the KNPS effective evacuation area.

1.2.2 Scope of Paper

The scope of this paper encompasses the methodology employed in the development of the new TEM, including insights gained throughout the process of data acquisition, model construction, international evacuation expertise, and the ongoing maintenance of the system. It further explores the model's outputs and scenario evaluations (although results cannot be published currently), illustrating the potential for this tool to not only enhance evacuation planning but also contribute to urban planning in terms of land use (development assessment within the study area), transport and infrastructure.

2. OBJECTIVES OF THE STUDY

The objectives of this study are listed below which guided the development of the new TEM:

1. **Evaluate the City of Cape Town's documented emergency procedures** for testing and estimating evacuation times, with the TEM being a critical component.
2. **Update and streamline the evacuation evaluation methodologies to align with state-of-the-art practices** and to ensure that they remain relevant and effective with the current and future development scenarios.
3. **Develop a streamlined approach for updating input data**, ensuring that the TEM remains accurate and reflective of the current transportation and infrastructure conditions.
4. **Extend the evaluation of expected evacuation time to include multiple scenarios** representing different incident, population, infrastructure, and traffic management conditions.
5. Transform the TEM from a basic spreadsheet-based tool to a cutting-edge integrated traffic and land use model, employing modern transport modelling software.
6. **Ensure the model can integrate all elements of the existing transport network**, including all modes of land transport, especially focusing on public transport fleet logistics for evacuation purposes.
7. **Enable dynamic modelling** to accurately replicate the propagation of traffic flows through a network using appropriate dynamic simulation assignment techniques.

8. **Optimise evacuation routes for various scenarios** and provide recommendations for alternative route selection under severely congested traffic conditions.
9. **Confirm current evacuation time estimates** using the new model by testing certain evacuation scenarios for which the existing spreadsheet-based model produced evacuation times that were approaching the acceptable limits.
10. **Expand the scope of the evacuation scenarios** by incorporating the impact of shadow evacuations on evacuation performance in a 4km range from the UPZ boundary, whereas the current evacuation model considers a limited set of evacuation scenarios.
11. **The new model should be flexible** enough to assess the impacts and outcomes of a range of events and scenarios.
12. **Identify infrastructural, developmental, and logistical constraints** that could improve evacuation times or impact evacuation performance.
13. **Manage risks and uncertainties** by including scenarios with variations on inputs most sensitive to evacuation times in the event of a radiological disaster at Koeberg.
14. **Regularly update the model** to establish development thresholds, using it as a critical development evaluation tool.
15. **Draw from and integrate existing work and information from the City**, using the recently updated EMME model as a basis for the KNPS TEM development.

3. THE NEED FOR MODERNISATION

The modernisation of the Traffic Evacuation Model (TEM) for Koeberg Nuclear Power Station (KNPS) directly confronts the shortcomings of the existing spreadsheet-based model, marked by its limited scalability, flexibility, and precision in simulating complex evacuation dynamics. The existing model is limited to the evacuation routes shown in Figure 2, although in reality all routes could be utilised. This evolution is necessitated by the model's idealised and simplified approach to road capacity evaluation and its static homogenous nature, which inadequately captures the intricacies of real-world traffic flow and fails to adapt to changing conditions – issues that become increasingly critical as urban development progresses and evacuation scenarios approach the 16-hour limit set by the National Nuclear Regulator (NNR). The existing model's deficiencies in dynamically simulating traffic flows and optimizing evacuation routes have highlighted significant safety concerns, especially as evacuation time estimates near regulatory thresholds. By transitioning to a more sophisticated, integrated model that leverages advanced transport modelling software, this modernisation initiative not only seeks to address these critical safety concerns but also aims to ensure the model's continued relevance and effectiveness amidst evolving urban landscapes. The upgraded TEM represents a commitment to enhancing public safety in the event of radiological emergencies, offering a more reliable, adaptable solution that reflects both current conditions and future development scenarios, thereby reinforcing the safety, efficiency, and adaptability of evacuation planning at KNPS. Although the focus of the TEM model, especially in its current form has been the evaluation of development within the evacuation zones, the new model typology has the additional capability for use in evaluation and optimisation of the associated disaster risk management procedures and evacuation plan.

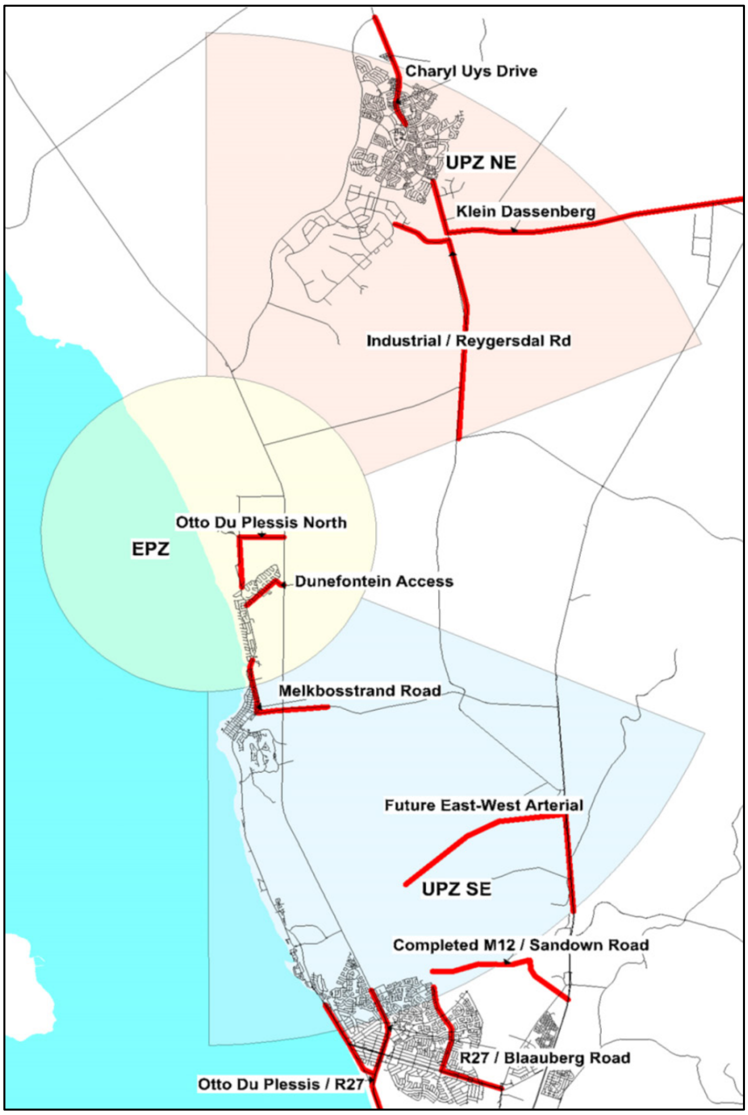

Figure 2: Existing spreadsheet model evacuation routes

4. THE TRAFFIC EVACUATION MODEL (TEM)

Dynamic modelling techniques are employed to accurately simulate the movement of traffic through the network. This approach allows for the consideration of various factors affecting evacuation, including incident specifics, population density, infrastructure capacity, and traffic management strategies. The model can now dynamically adjust to real-time conditions, offering more precise evacuation time estimates. Additionally, dynamic modelling enables the new TEM to conduct comprehensive traffic flow analyses. This includes the evaluation of evacuation scenarios under different conditions, such as varying times of day, incident types, and infrastructure disruptions. The model's capability to simulate traffic flow dynamics enhances the understanding of potential bottlenecks and areas of concern during an evacuation.

The new TEM employs a Simulation-based dynamic assignment (SBA) algorithm, enabling a detailed analysis of traffic flows and interactions. This approach allows for real-time simulation of evacuation scenarios, taking into account various factors such as traffic density, road capacity, and changes in traffic conditions. The algorithm provides a more accurate representation of how traffic moves and reacts in emergencies.

SBA represents a method of dynamic assignment that considers the effects of node impedances and enables the simulation of queue formation and dissolution over time, with the flexibility to adjust supply and demand dynamically. Unlike other dynamic assignment methods, an SBA employs a simulation-based approach to load the network with traffic, where each vehicle is individually simulated. The assignment implements a basic car following model to ensure that vehicles adhere to their assigned routes. The foundational algorithms of this approach draw from M. Mahut's research, as detailed in his dissertation, "A discrete flow model for dynamic network loading" (PhD thesis, University of Montreal, Canada, 2001).

The model was developed for the 16-kilometer radius around the KNPS and an additional 4 kilometres for a shadow evacuation area. However, during the inception, the CCT requested that the model be extended to a 25-kilometer radius. In the 16-kilometer radius area there are approximately 910 junctions for which detailed junction coding was done. The expanding, or shadow evacuation area, inclusive of the radius area from 16 to 25 kilometres, included another 3 657 junctions. The extent of the road network and zonal system included in the TEM are shown in Figure 2 and Figure 3 in the Annexure. The location of traffic signal-controlled junctions in the TEM is shown in Figure 3 in the Annexure.

The TEM was calibrated for the weekday morning and afternoon peak hour and includes car, taxi, bus and heavy vehicle modes and demand matrices. The model allows for a simulation-based assignment whereby the optimum routes are selected based on link- and intersection-based travel times. Intersection-based travel times are based on lane selection, queueing, signal settings, saturation flows, gap acceptance and priority movements. Intersection layouts contain not only the control measure (signalized vs stop-controlled), but also geometric layouts such as short lanes, slip lanes and medians. It should be noted that every road in the network may be utilised as an evacuation route, which is more representative of reality, as opposed to the spreadsheet model which only considered some of the main routes (as shown in Figure 2). Also, the TEM allows the user to constrain the evacuation routes to a specified set of road classes. The demand is dynamically assigned in 15-minute increments in the form of simulated vehicles travelling from the origin zone to the destination zone, selecting the optimum routes based on network conditions. A bottleneck intersection will thus have upstream effects in the form of delays and queues of vehicles waiting to pass through the intersection, while the downstream effects will be in the form of filtered demand. A person-based assignment was only used to compare and verify the extent of the public transport supply network in the TEM with the original EMME model. For the TEM, a vehicular interaction-based assignment was used. The vehicular interaction-based assignment allowed for an integrated assignment procedure whereby the simulated conditions on road links and junctions, like delays, speeds, and queues, will affect both private and public transport vehicles similarly.

5. SCENARIOS

The NNR’s Prescribed Evacuation Criteria are listed in Table 1.

Table 1: Prescribed Evacuation Criteria

Zone	Requirement
0-5km (PAZ)	Within the PAZ, evacuation of the public in all sectors, i.e. 360° within 4 hours.
5-16km (UPZ)	Within the UPZ area (or intersecting this area), an evacuation time of 16 hours of the projected population, within any 67.5° sector

5.1 Multiple Scenario Representations

The TEM is designed to simulate a wide range of evacuation scenarios, each reflecting different potential incidents, population distributions, infrastructure conditions, and traffic management strategies. This breadth of scenarios ensures that the model can assess evacuation plans across a spectrum of realistic emergency situations, including but not limited to radiological threats, natural disasters, and infrastructure failures.

5.1.1 Primary Evacuation Scenarios

The following evacuation scenarios were evaluated as part the primary evacuation scenarios:

- Evacuation during normal weekday daytime operating conditions.
- Evacuation during normal weekday night-time operating conditions.
- Evacuation during normal weekend daytime operating conditions.

These scenarios were evaluated with and without the effects of a 9km shadow evacuation area and were evaluated separately for the UPZ South East (SE) sector with the PAZ and the UPZ North East (NE) sector with the PAZ. The scenarios were also evaluated for both 2022 and forecasted 2040 demand.

The normal weekday daytime scenarios represent a typical normal summer weather daytime period when residents are generally dispersed within the UPZ performing daily activities. Workplaces, schools and other facilities are at typical daytime levels. This scenario includes assumptions that residents will evacuate from their place of residence, students will evacuate directly from the schools, hotel and motel facilities are occupied at average summer levels; and recreational facilities are at average summer daytime levels.

The normal weekend daytime scenario reflects a typical normal weekend period when residents are both at home and dispersed within the UPZ, and the work force is at a weekend level. This scenario includes assumptions that residents will evacuate from their place of residence; schools are closed, and students are at home; work places are staffed at typical weekend levels; hotel and motel facilities are occupied at average summer levels; and recreational facilities are at summer evening levels.

The normal weekday night-time scenario reflects a typical normal midweek and weekend evening period when residents are home, and the work force is at a night-time level. This scenario includes assumptions that permanent residents will evacuate from their place of residence; schools are closed, and students are at home; workplaces are staffed at typical night-time levels; hotel and motel facilities are occupied at average summer levels; and recreational facilities are at summer evening levels.

Figure 3 shows an example of evaluation data generated from model runs for various evacuation scenarios. In this case, the total number of vehicles within the evacuation area for any given 15-minute increment throughout the 16-hour evacuation period is shown for the base scenarios.

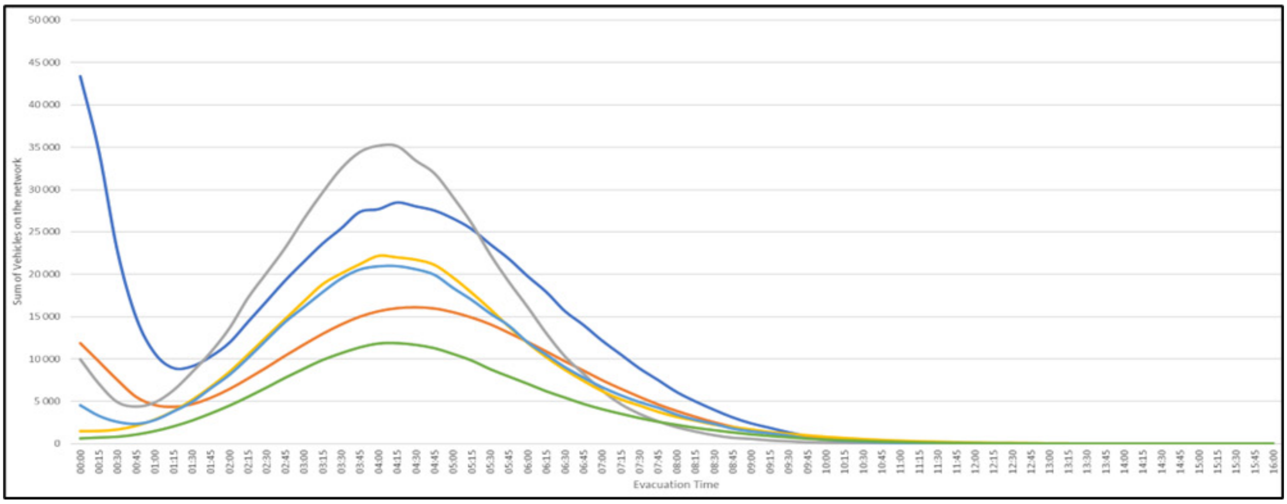

Figure 3: Example of dynamic results from new TEM model

5.1.2 Secondary Evacuation Scenarios

The secondary evacuation scenarios allowed for "worst case" scenarios, by applying worsening conditions to the worst performing scenario from the primary scenarios. The worsening conditions added the effects of inclement weather and traffic incidents.

Although numerous scenarios could be modelled, like major road closures and flooding, the following three (3) possible worsening conditions were selected to be evaluated:

- A – **Inclement weather**: The free-flow speeds on all the links in the model were reduced by 50% to represent bad weather and poor visibility;
- B – **Electricity failure**: All the traffic signal-controlled junctions in the model was converted to all-way stop controlled junctions to represent load shedding or electricity disruption; and
- C – **Traffic incident**: Sandown/Malibongwe Drive (M12) was closed in both directions where it crosses the Diep River to represent an incident on a critical evacuation route.

6. EVACUATION OPTIMISATION STRATEGIES

The KNPS TEM allows the option to evaluate optimisation strategies to improve the evacuation performance. The following range of interventions and strategies can be considered when improvements are investigated:

- Developing optimised evacuation routes to mass care centre locations.
- Investigating the impacts of using contraflow arrangements on higher order links.
- Investigating the impact of shoulder utilization on higher order links.
- Defining the best use of the available public transport vehicle fleet.
- Investigating the impact of phased evacuation strategies.

Based on the results of the primary evacuation scenarios and the base-year optimisation strategies, infrastructural and logistical intervention options were identified to improve evacuation times. The aim was to identify which, if any, single or combination of network elements (intersections, road links and structures) can be feasibly upgraded to improve the evacuation performance, and what the expected improvements are likely to be for the base year and forecasted land use scenarios. Since the Secondary Evacuation Scenarios experienced evacuation times in excess of the minimum required for the PAZ, an intervention in the form of intelligent transportation system (ITS) measures was evaluated. The effect of possible ITS measures were tested by removing certain model assignment restrictions, for example people not having access to perfect information, thereby limiting people to use one of the five most optimal routes, which is comparable to using one of the five most well-known routes available. This constraint was lifted in the assessment of possible ITS options, whereby people can be informed of unusual alternative routes via live transport models, Smart GPS devices, SMS, broadcasts, variable message signs, and intercoms.

7. INTEGRATING URBAN PLANNING AND DEVELOPMENT ASSESSMENT

7.1 Streamlined Methodology for Urban Planning

The TEM's advanced simulation capabilities enable a detailed analysis of how population growth, infrastructure development, and land use changes impact evacuation dynamics. This insight is invaluable for urban planners, offering a data-driven basis for making informed decisions about zoning, development approvals, and infrastructure investments. By simulating future development scenarios, the TEM helps ensure that urban growth does not compromise evacuation efficiency or safety.

7.2 Contribution to Development Assessments

The model's flexibility and detailed output make it an essential tool for assessing the potential impacts of new developments within the Koeberg evacuation area. It allows planners to evaluate how proposed projects might affect evacuation times and traffic flow, ensuring that development plans align with safety requirements and do not hinder emergency responses. This is particularly important in rapidly growing urban areas where development pressure is intense.

7.3 Policy Formation and Regulatory Compliance

Integrating evacuation planning with urban development assessment aids in the formulation of policies that balance growth with safety. The TEM's outputs can inform regulatory frameworks, guiding the location and density of new developments to maintain or improve evacuation performance. This ensures that urban expansion is managed in a way that is compliant with national safety standards and regulations set by bodies such as the National Nuclear Regulator (NNR).

7.4 Facilitating Stakeholder Collaboration

The model also serves as a platform for collaboration among various stakeholders involved in urban planning, emergency management, and community safety. By providing a clear visualisation of evacuation scenarios and development impacts, the TEM facilitates constructive dialogue between city planners, emergency services, developers, and the community. This collaborative approach fosters a shared understanding of the challenges and opportunities in integrating evacuation planning with urban development.

7.5 Future Directions

The integration of the TEM into urban planning and development assessment processes highlights the model's role as not just a tool for emergency preparedness but as a cornerstone of sustainable urban development. As the model continues to evolve, its contributions to enhancing the safety, efficiency, and resilience of urban areas surrounding nuclear facilities will remain critical.

7.6 User-Friendly Graphical User Interface (GUI)

A Graphical User Interface has been developed that allows users to engage with the model and analyse land-use applications in terms of the KNPS TEM. This is currently under review and more detail will be provided after referee report and final article format.

8. INCORPORATION INTO STATUTORY PROCESSES

8.1 Regulatory Compliance and Planning Integration

The updated TEM ensures that evacuation planning for the Koeberg area is in strict compliance with national safety standards and guidelines set by the National Nuclear Regulator (NNR). By providing accurate and dynamic evacuation time estimates, the model facilitates the adherence to regulatory requirements concerning evacuation safety. Its outputs are instrumental in the revision of emergency procedures, making them more robust and responsive to potential incidents.

8.2 Development Control and Zoning Adjustments

The TEM’s ability to assess the impact of urban development on evacuation efficiency has been integrated into the development control and zoning adjustment processes. Urban planners and local government authorities now have the capacity to evaluate proposed developments for their impact on evacuation times. This ensures that new projects within the evacuation area do not compromise the community's safety or hinder evacuation efforts.

8.3 Infrastructure Planning and Improvement Initiatives

Findings from the TEM regarding optimal evacuation routes and infrastructure improvements have been incorporated into infrastructure planning initiatives. Recommendations for road capacity upgrades, new evacuation routes, and public transport enhancements are considered in the allocation of municipal and national infrastructure budgets. This alignment ensures that infrastructure development supports efficient evacuation and meets the evolving needs of the community.

8.4 Emergency Response Planning

Emergency response plans are being updated to incorporate TEM findings, particularly those related to route optimization and traffic management strategies. These updates enhance the operational effectiveness of emergency services during an evacuation, ensuring that resources are allocated efficiently, and evacuation orders are executed smoothly.

8.5 Training and Capacity Building

The incorporation of the TEM into statutory processes extends to training and capacity building for relevant stakeholders, including emergency services personnel, urban planners, and local government officials. Training programs focus on understanding the TEM's functionality, interpreting its outputs, and applying its findings in real-world scenarios. This ensures that all parties involved in evacuation planning and urban development are equipped with the knowledge to make informed decisions.

8.6 Future Policy Formation

The insights provided by the TEM are influencing the formation of future policies related to urban development, emergency preparedness, and public safety. By embedding the model's outputs into the policy-making process, authorities can ensure that future regulations reflect the latest understanding of evacuation dynamics and urban development impacts.

9. DISCUSSION

The original spreadsheet-based TEM was a deterministic model (in other words using simple functions) with simplified demand and supply assumptions. The new PTV Visum simulation-based evacuation model offers several advantages over the deterministic spreadsheet-based model. The new PTV Visum-Based evacuation model provides a better realistic representation of the evacuation process. The specialised software considers factors like *vehicle dynamics, traffic flow, and driver behaviour*, resulting in a more accurate simulation and estimation of evacuation times.

9.1 Key Outcomes

This section summarises the key outcomes of the model's implementation.

9.1.1 Transition to Integrated Traffic and Land Use Model

The new TEM transitions from a spreadsheet-based model to an integrated traffic and land use model. This change involves the use of modern transport modelling software, enabling a more detailed and dynamic simulation of evacuation scenarios. The integration of traffic flow and land use data allows for a nuanced understanding of evacuation dynamics under various conditions.

9.1.2 Enhanced Evacuation Time Estimates

The TEM has provided more accurate and detailed evacuation time estimates across a variety of scenarios. These improved estimates are critical for emergency planning, offering a clearer picture of potential evacuation dynamics and enabling the identification of strategies to reduce evacuation times.

9.1.3 Evacuation Route Optimisation

A key feature of the new model is its ability to optimise evacuation routes. By analysing traffic flows and infrastructure constraints, the model identifies the most efficient paths for evacuation. This optimisation process considers alternative routes and strategies to alleviate congestion, ensuring the quickest possible evacuation times. This capability is crucial in developing effective evacuation strategies and recommendations for alternative routes in case of severe congestion.

9.1.4 Identification of Optimal Evacuation Routes
A major output of the model is the identification of optimal evacuation routes. The model's dynamic simulation capabilities have allowed for the analysis of traffic flows under different conditions, leading to recommendations for route selection that minimise congestion and maximise efficiency.

9.1.5 Scenario Evaluation and Recommendations
The model evaluates multiple evacuation scenarios, each representing different challenges and conditions. This evaluation process allows for the identification of optimal evacuation strategies for various scenarios, providing critical insights for emergency planning. Recommendations are made for alternative route selections and traffic management strategies to improve evacuation efficiency under severely congested conditions.

9.1.6 Impact of Development on Evacuation Performance
The model has evaluated the impact of current and future urban development within the evacuation area on evacuation performance. This analysis has highlighted areas where development could potentially affect evacuation times, informing urban planning decisions to ensure that safety is maintained as the region grows.

9.1.7 Recommendations for Infrastructure Improvements
By simulating various evacuation scenarios, the TEM has identified key infrastructure improvements that could enhance evacuation efficiency. These recommendations include upgrades to road capacity, enhancements to public transport options, and the introduction of new evacuation routes.

9.1.8 Flexibility and Scenario Expansion
The model's flexibility and expanded scenario capability have proven invaluable for testing a wide range of evacuation strategies. This includes assessing the effectiveness of contraflow systems, temporary road closures, and the use of public transport in evacuation scenarios, providing a comprehensive understanding of potential evacuation strategies.

9.1.9 Regulatory Compliance and Safety Enhancements
The detailed outputs of the TEM have ensured regulatory compliance with national safety standards, particularly those set by the National Nuclear Regulator (NNR). The model's findings have contributed to the development of evacuation plans that meet or exceed safety requirements, enhancing the overall preparedness of the Koeberg Nuclear Power Station and the surrounding areas.

9.1.10 Contributions to Urban Planning and Policy
Beyond emergency evacuation planning, the TEM's outputs have contributed to broader discussions on urban planning and policy formation. By integrating evacuation considerations into urban development assessments, the model has influenced policy decisions aimed at balancing growth with safety and efficiency.

9.2 Future Applications and Continuous Improvement

This section lists future applications and continuous improvement opportunities for the TEM.

9.2.1 Expanding Scope to Other Hazards

Future applications of the TEM could include its adaptation to model evacuation scenarios for a variety of hazards beyond radiological emergencies, such as natural disasters. This expansion would enhance the region's preparedness across a broader spectrum of potential incidents.

9.2.2 Integration With Smart City Initiatives

Leveraging emerging technologies and smart city initiatives presents an opportunity to further enhance the TEM. Real-time data integration could improve the accuracy of evacuation simulations, offering more responsive and adaptable evacuation strategies.

9.2.3 Public Engagement and Education

The model could also play a crucial role in public engagement and education efforts. By simulating evacuation scenarios and outcomes, it can raise awareness about the importance of emergency preparedness and encourage community involvement in safety planning.

9.2.4 Continuous Data Update and Model Refinement

The commitment to regularly updating the TEM with new data and refining its algorithms ensures that the model remains relevant and effective. This process of continuous improvement will incorporate lessons learned from actual emergencies, feedback from stakeholders, and advancements in modelling technology.

9.2.5 Operationalisation of TEM

The TEM may be used to support simulating live evacuations (evacuation trial runs). The model also has the potential to be adapted as an operational tool for disaster risk management.

9.3 The Way Forward

The way forward involves a multi-faceted approach to leverage the model's capabilities fully while pushing the boundaries of what it can achieve, as mentioned in this subsection.

9.3.1 Strengthening Collaboration

Enhanced collaboration between government agencies, emergency services, urban planners, and the community is essential. A unified approach ensures that all parties are aligned in their efforts to enhance public safety and urban resilience.

9.3.2 Integration With Existing City Planning Tools

The methodology behind the new TEM leverages and integrates with existing work and information from the City of Cape Town, including the EMME model. This integration ensures that the TEM is not only a tool for emergency evacuation planning but also contributes to broader urban planning and development assessments.

9.3.3 Leveraging Technological Advances

Embracing new technologies and data sources will be key to enhancing the TEM’s accuracy and functionality. Innovations in artificial intelligence, machine learning, and geographic information systems offer promising avenues for further development.

9.3.4 Fostering a Culture of Preparedness

Ultimately, the model's success will depend on fostering a culture of preparedness within the community. By engaging with residents, businesses, and institutions, the TEM can be a tool not just for planners and emergency responders but for everyone invested in the safety of the Koeberg area.

9.3.5 Regular Model Updates and Scenario Expansion

The new TEM is designed for flexibility and ease of updating. Regular updates ensure that the model reflects current transportation and infrastructure conditions. Additionally, the model expands the scope of evacuation scenarios, including the consideration of shadow evacuations and the impact of various incident types on evacuation performance.

10. CONCLUSION

The development of a state-of-the-art TEM for the KNPS marks a pivotal advancement in the field of emergency evacuation planning and urban development assessment. This paper has outlined the transition from a traditional spreadsheet-based approach to a sophisticated, integrated traffic and land-use model, underscoring the critical role of modernisation in enhancing evacuation efficiency, safety, and regulatory compliance.

One significant contribution is that the new TEM has the ability to measure the sufficiency of the current routes, and at what level it becomes necessary to upgrade or build new roads and infrastructure to ensure the evacuation time remains sufficient. This becomes a helpful tool in knowing when it is the appropriate time to upgrade or build new roads, or approve certain land use applications, as to avoid spending when it is not yet required, and knowing when that spending would be warranted, and similarly avoid approving land use applications that would not be able to be absorbed by the transport network in light of an evacuation.

10.1 Key Findings

The integration of modern transport modelling software has significantly improved the accuracy of evacuation time estimates, allowing for dynamic adjustments to real-time conditions and offering a more realistic simulation of traffic flows and interactions.

Scenario evaluations have highlighted the TEM's ability to accommodate a wide range of evacuation scenarios, thereby providing invaluable insights into optimising evacuation strategies under diverse and challenging conditions. The model's flexibility and expanded scenario capability underline its potential as a robust tool for future-proofing evacuation planning against an evolving urban landscape and increasing population densities around nuclear facilities.

10.2 Implications for the Future

The incorporation of the TEM into urban planning and development assessments signifies a leap forward in ensuring that future developments within the evacuation area are conducted with a keen understanding of their impact on evacuation performance. This is instrumental in safeguarding community safety while fostering sustainable urban growth.

The collaboration between government agencies, emergency services, urban planners, and the community, facilitated by the TEM, enhances the collective capacity to manage and mitigate evacuation-related challenges efficiently. The ongoing integration of technological advances and data sources into the TEM promises to elevate its accuracy and functionality further, setting new standards for evacuation planning in the context of nuclear safety and urban resilience.

The KNPS TEM stands as a pioneer of next generation technological innovation in addressing complex challenges at the intersection of urban planning, emergency preparedness, and public safety. Its continuous development and refinement will undoubtedly contribute to the creation of safer, more resilient communities around nuclear facilities, ensuring that the lessons learned today will pave the way for a safer tomorrow.

11. ACKNOWLEDGEMENTS

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ANNEXURE

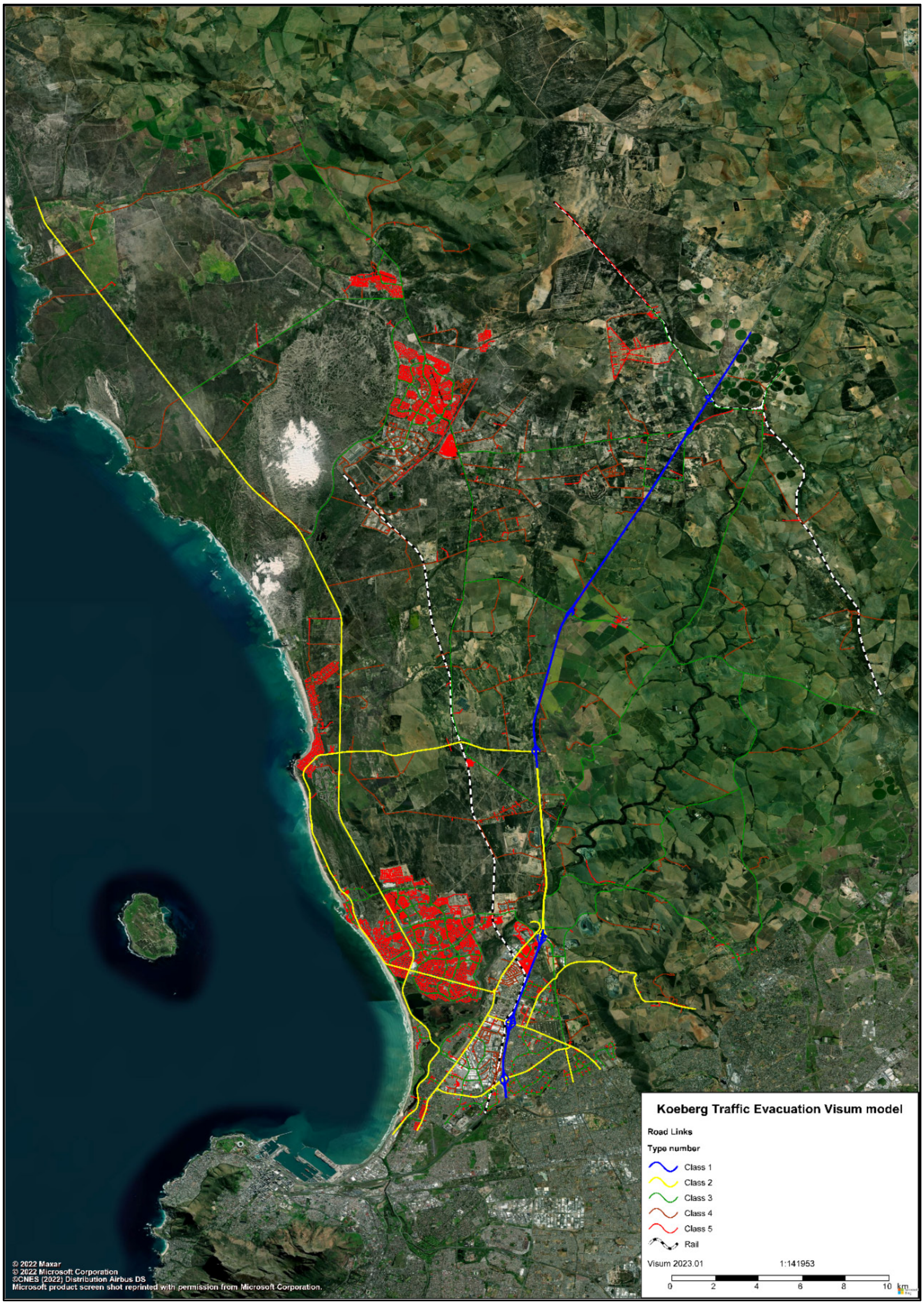

Figure 1: Extent of the Road Network Included in the TEM, where the entire road network is utilised for evacuation purposes and can also be specified per road class.

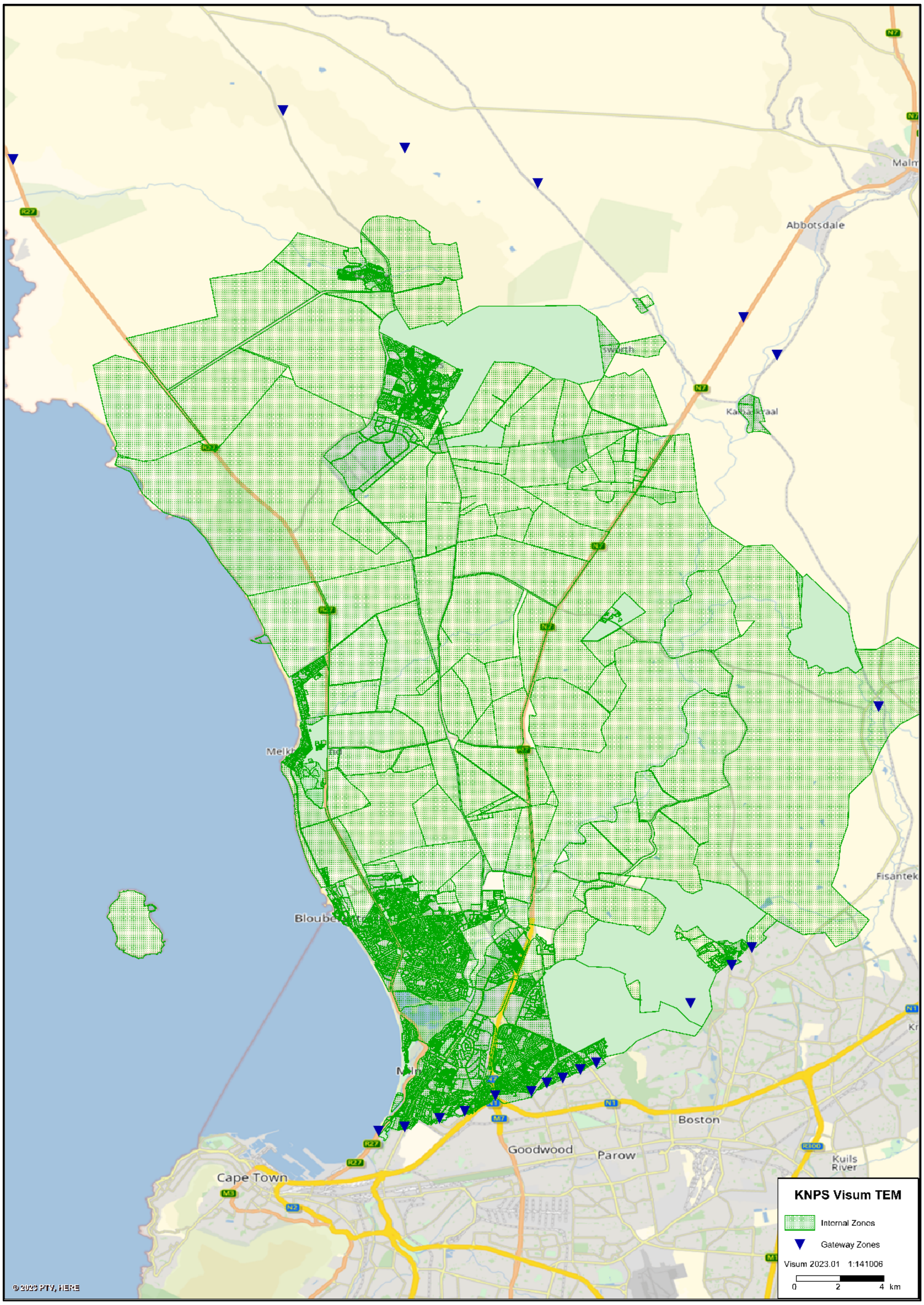

Figure 2: Zonal System in the TEM

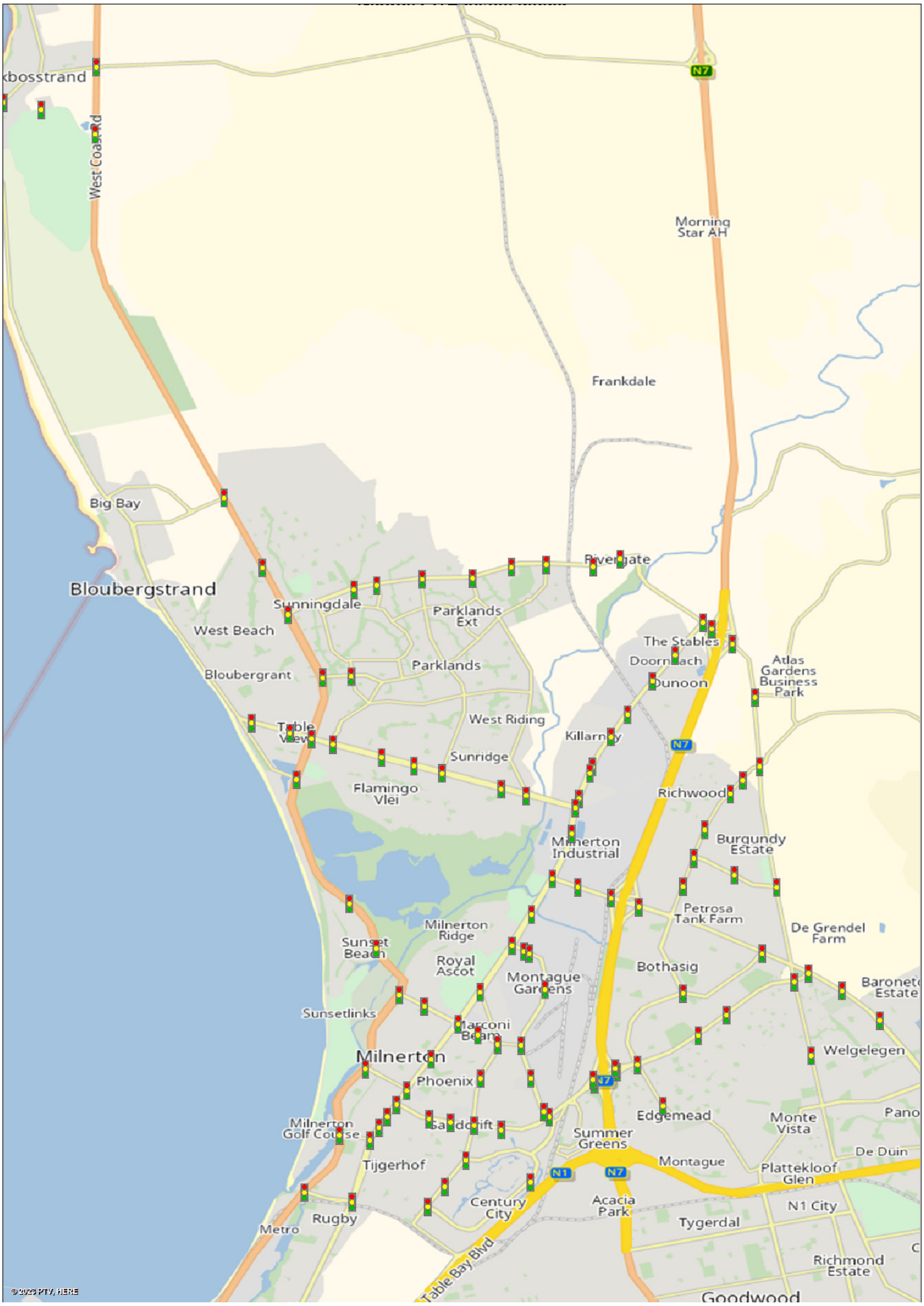

Figure 3: Location of Traffic Signal-Controlled Intersections in the TEM