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Land-Use Conflict and Traffic Congestion on the N12: Evaluating Planning Responses at the Moroka Bypass, South Africa

Nkosinathi Dube, Thembani Moyo, Retsepile Charity Kalaoane, Thulisile Ncamsile Mphambukeli

(Nkosinathi Dube, Department of Urban and Regional Planning, University of Johannesburg. Cnr Siemert & Beit Streets, Doornfontein 0184 Johannesburg, South Africa, ndube@uj.ac.za)

(Dr Thembani Moyo, Department of Urban and Regional Planning, University of Johannesburg. Cnr Siemert & Beit Streets, Doornfontein 0184 Johannesburg, South Africa, tmoyo@uj.ac.za)

(Dr Retsepile Charity Kalaoane, Department of Urban and Regional Planning, University of Johannesburg. Cnr Siemert & Beit Streets, Doornfontein 0184 Johannesburg, South Africa, retsepilek@uj.ac.za)

(Prof Thulisile Ncamsile Mphambukeli, Department of Urban and Regional Planning, University of Johannesburg. Cnr Siemert & Beit Streets, Doornfontein 0184 Johannesburg, South Africa, tmphambukeli@uj.ac.za)

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1 ABSTRACT

Rapid urbanisation and an increasing demand for housing in land-constrained areas often intensify land-use conflicts and place significant strain on existing transport infrastructure. In South Africa, national road corridors are critical connectors between towns, cities, and provinces. The integration of well-designed on- and off-ramps is essential to sustain efficient mobility. However, stop-controlled intersections on these corridors, as opposed to grade-separated interchanges, cause significant disruptions to traffic flow, accessibility, and safety, uncovering weaknesses in integrated and sustainable planning. This study examines the R558 stop-controlled intersection along the N12 at the Moroka bypass and compares its performance with four on-and-off ramps serving Soweto and surrounding neighbourhoods along the same corridor. Using quantitative methods, it is possible to confirm or disprove a hypothesis, as the formulae can be tested repeatedly. Spatial data was also consequently used to visualise these trends. Findings indicate that the four ramped interchanges effectively support traffic flow, access, and movement along the N12, demonstrating resilience against increased development pressures. In contrast, the R558 stop-sign intersection performs poorly, characterised by congestion, increased travel times, and heightened safety risks. The study also reveals that inadequate integration of transport planning into rezoning and residential development decisions exacerbates these problems, undermining mobility and regional sustainability. It concludes that sustainable and resilient infrastructure planning, particularly the timely provision of grade-separated interchanges, is essential to mitigate traffic conflicts arising from new developments in land-constrained areas.

Keywords: Sustainable planning, National road corridors, Mobility and accessibility, Land scarcity, Moroka bypass

2 INTRODUCTION

Urban growth often affects environmental and socio-economic dynamics, leading to improper land use in rezoned areas due to exponential population growth and housing demand. Zare et al. (2025) noted that according to World Bank data, currently about 56% of the world population is urban dwellers, and by 2050, it would have risen to nearly 70%. The expansion process of urban growth dominates in existing core areas as well as within other periphery core areas, as emergence (Perveen et al., 2017). In South Africa, emerging urban areas are common within the road corridors that normally connect towns, cities, and provinces. Breški and Maljković (2025) asserted that urban land use and quality of life are affected by the efficiency of road infrastructure and sustainable mobility. Hence, Xu et al. (2023) pointed out that planners and policymakers need to take advantage of advanced information and communication technologies to improve urban mobility paradigms and transportation system networks.

Transportation systems are vital for urban economic activities and social development through road infrastructure networks for the movement of people and goods between different locations (Marian et al., 2024; Bayata et al., 2025). Reliability and safety of transportation systems have been over-researched through exploring the well-being and safety of both passengers and drivers on the roadways (Ulak et al., 2019; Siebke et al., 2023). However, these dynamics in transportation are essential and received attention. According to the World Health Organisation (WHO), approximately 50 million non-fatal injuries and more than a million road traffic deaths occur worldwide each year (Brunner et al., 2019; Riedmaier et al., 2020; Karbasi & O'Hern, 2022). Khashayarfard and Nassiri (2021) argued that accidents resulting in road traffic deaths and injuries are mostly caused by driver errors, such as speeding, poor visibility, fatigue, and distractions. Less has been researched on the impact of infrastructure on road traffic accidents compared to road traffic congestion caused by infrastructure (Islam, 2025; Syla et al., 2025).

Commuters' well-being, economic activities, and environmental sustainability are significantly affected by the critical challenge of urban traffic congestion caused by transportation infrastructure (Islam, 2025). In South Africa, national road corridors are vital transportation infrastructure that feature separate interchanges with properly designed on- and off-ramps and stop-controlled intersections. Osman (2023) stated that frequent sites of traffic congestion are within the intersections but worse within the four-leg intersections. This study intended to explore the significant disruption to traffic flow, accessibility, and safety at the four-leg intersection of R558 and N12. Breški and Maljković (2025) claimed that smartly planned road infrastructure improves traffic flow, which minimizes traffic delay and reduces fuel consumption and emissions, which significantly contribute to a sustainable environment and urban mobility.

According to the World Health Organisation (WHO), road traffic accidents cause over a million deaths and 50 million non-fatal injuries worldwide each year (Brunner et al., 2019; Riedmaier et al., 2020; Karbasi & O'Hern, 2022). Most accidents result from human error, including speeding, poor visibility, fatigue, and distractions (Khashayarfard & Nassiri, 2021). However, the role of infrastructure in influencing these incidents, especially congestion caused by infrastructural shortcomings, has received comparatively less attention (Islam, 2025; Syla et al., 2025).

In South Africa, national road corridors feature various intersection types, including grade-separated interchanges and stop-controlled intersections. The latter, particularly four-leg intersections such as the R558 and N12 junction, often experience significant traffic congestion and safety issues (Osman, 2023). Smartly planned road infrastructure can improve traffic flow, reduce delays, fuel consumption, and emissions, contributing to sustainable urban mobility (Breški and Maljković, 2025). Intersections are critical nodes in transport networks where traffic conflicts arise due to opposing and converging vehicle flows (Bayata et al., 2025). Traffic congestion at intersections contributes significantly to environmental pollution and escalates transport costs (Li et al., 2024).

3 LITERATURE REVIEW

The Transport Impact Assessments (TIA) in the road network provides essential insight into traffic flow through the assessment outcome on the evaluation of the impact of controlled intersections and uncontrolled/free-flow highway segments (Marian et al., 2024). This includes roadway design, accessibility, and traffic congestion that reflects the traffic demand, network performance, safety, and environmental sustainability. In the capital city of Albania, Tirana, TIA was conducted using the fixed-time traffic systems that impact the traffic flow and compromise safety and environmental sustainability, as well as stress drivers with time delays (Syla et al., 2025). On the other hand, TIA mostly integrates human intervention into the traffic flow or congestion. For instance, Ulak et al.'s (2019) TIA in the city of Tallahassee, Florida, United States of America, was based on human behaviour in relation to the T-intersections, focusing on the experience and age of the driver.

There is intensive literature on TIA using traffic and network performance, which evaluates how land use development and infrastructure changes affect traffic flow. Cakici and Murat (2019) argued that conflict in traffic flow persists due to a lack of optimisation-based traffic management approach consideration in the traffic volume and network. These are determinant factors in the TIA when utilising the traffic demand and road network performance for new development settlement with the periphery core areas that have attracted high working households within the road corridors. Osman (2023) emphasises that there is an exceeding capacity on the road network due to rapid urbanisation and population growth in Sweden, which increases traffic demand because of more trips taken within limited spaces. Ultimately, the expansion of urbanisation results in traffic congestion due to the increasing number of vehicles that transport the growing number of passengers and drivers on unchanged road networks, such as the Moroka bypass N12.

Safety and pollution as main factors in the TIA are common in the evaluation of traffic congestion within various intersections. According to Xu et al. (2025), crash frequency and severity are usual measurements in the TIA when considering traffic safety, which is critical in urban planning. Particularly for intersections that experience rapid increases of vehicles affected by the continuation of residential development. Many scholars have concentrated on the introduction of autonomous vehicles since human error was identified as the main factor that compromises road safety (Riedmaier et al., 2020; Khashayarfard & Nassiri, 2021; Ploeg et al., 2021; Karbasi & O'Herns, 2022) rather than the effect of land use change influenced by population growth. Instead, Siebke et al. (2023) considered the impact of autonomous emergency braking systems in different modes of transport on road safety at intersections. Additionally, traffic congestion within the intersection causes vehicles to emit a lot of carbon monoxide (Bayata et al., 2025; Syla et al., 2025). Zare et al. (2025) advocate for the integration of efficiency and resilience into urban transportation system assessment to limit air pollution at road intersections.

3.1 Intersection Performance Evaluation

The intersections on urban road networks are very vulnerable points of traffic congestion, particularly on controlled intersections where there are opposite direction traffic patterns (Marian et al., 2024). Intersection performance plays a huge role in the quality of road services for users by evaluating using metrics as an indicator for the efficiency of the volume-to-capacity ratio as well as control time (Zare et al., 2025). Islam (2025), under urban road traffic management, adopted the Travel Time Index (TTI) and Planning Time Index (PTI) as performance indicators to quantify the time penalty incurred by travellers during free-flow conditions and congestion periods. According to Islam (2025), higher values indicate severe delay in the ratio of peak-period travel time, meaning when the value of TTI is greater than 1.0, it indicates high congestion, and when it is much lower than 1.0, it resembles the free-flow travel time. For the observed intersection, Shirazi et al. (2023) stated that a comprehensive performance evaluation done at a downtown Las Vegas intersection was through traffic measurement that directly estimates any of the trajectories, such as turning movement count or speed, to mimic a realistic traffic flow.

3.2 Scenario-Based Traffic Simulation

Scenario-based traffic simulation utilises various computational models to examine infrastructure upgrades, policy interventions, future traffic growth, or the scenario of 'do-nothing' in urban road management (Perveen et al., 2017; Bayata et al., 2025). Various models such as AIMSUN, TOPSIS, VISSIM, YOLO, etc., are utilised to determine broader traffic pattern analysis over a larger area or provision of detailed traffic behaviour. Xu et al. (2025) claimed that many studies commonly use AIMSUN and VISSIM that efficiently handle scenarios because of their friendly interfaces and versatility abilities to switch between simulations. The three simulations are predictive and exploratory tools explored based on the researcher's comparison scenarios, especially for robust planning that considers the calibration and validation of traffic challenges (Ulak et al., 2019; Li et al., 2024; Breški & Maljković, 2025). Varga et al. (2023) believe that at a network level, a macroscopic approach is preferred for traffic demand and assignment, such as space mean speed, traffic density, and traffic flow volume in regions. Bayata et al. (2025) noted that mesoscopic is good to describe traffic flow as a homogeneous continuum employing equations for both vehicle clusters and networks. While microscopic, concentrate on vehicle routes when describing traffic flow (Xu et al., 2025).

3.2.1 Traffic Volume Analysis

In transportation planning applications, traffic volume analysis is one of the paramount parameters (Apronti et al., 2016). Khan et al. (2018) stated that analysis is critical for efficient management and control of congestion levels that are magnified in urban intersections where there is a high number of conflicts when there is extreme traffic volume. Transportation analysis and management systems mostly utilise traffic volume forecasts to adequately characterise traffic patterns and reaction towards variability (Wagner-Muns et al., 2017). For instance, Khan et al. (2018) advocate for the use of Unmanned Aerial Vehicles (UAVs) in dense, inaccessible, or hazardous areas to generate matrices for analysing traffic volume. Additionally, area scale affects the traffic volume measurement and analysis in both network base and nodes, which are covered over different periods (Macioszek & Kurek, 2021). However, Macioszek and Kurek (2021) argue that most Global South countries, which are not equipped with tolling systems, automated traffic counters, or other technologies, make use of systematic observation for analysing traffic volume. The volume of traffic flow in the past decades since the 1980s has been analysed by applying various non-parametric (supervised machine learning) and parametric methods (Janković et al., 2021).

3.3 Queueing Theory on Transport Impact Assessment

Regarding TIA, there is a wide spectrum of research on understanding queueing theory to determine the traffic flow through applying various traffic-queue modelling (Gunes et al., 2020; Wang et al., 2020; Zhao & Gilbert, 2025). The theoretic approach is about collecting data using any form of system and technology to assess traffic flow and waiting time of vehicles in an intersection (Bui, 2018). According to Wang et al. (2020), using actuated traffic information, the mathematical traffic queue model usually analysis delays and queues by estimating the intersection traffic volume. Gunes et al. (2020) asserted that queuing theory provides performance calculations by mathematically examining traffic scenarios to derive results based on issues around waiting time or delay due to the structure of the infrastructure. Mostly the use of queuing theory is to have a broader range of applications as a canonical way to address complex traffic systems and elaborate on the dynamics that lead to traffic delay and congestion (Timmerman, 2022). Zhao and Gilbert (2025) claimed that the analytical study in queuing theory is about characteristics that delay the flow.

4 METHODOLOGY

A quantitative research approach was adopted, integrating numerical traffic data with spatial analysis to ensure objective measurement and replicability of results. The quantitative component enabled the testing of assumptions related to traffic growth, intersection performance, and the effectiveness of Transport Impact Assessments (TIAs). Traffic data were obtained from secondary sources, including municipal traffic count records, South African National Roads Agency Limited (SANRAL) datasets, and previously submitted TIA reports associated with residential developments in the study area. These datasets comprised Average Daily Traffic (ADT), peak-hour volumes, turning movement counts, and heavy vehicle percentages. Where necessary, historical counts were compared with more recent data to assess traffic growth trends.

The study area is located south of Johannesburg, focusing specifically on the R558 stop-controlled intersection along the N12 at the Moroka Bypass (see Figure 1). This intersection experiences recurring congestion and varying degrees of delay, particularly during peak periods, making it a suitable case study for evaluating the implementation and effectiveness of TIAs. The R558 intersection was selected due to its strategic function as a feeder route connecting residential developments to the regional road network and its documented traffic delays. For comparative purposes, four nearby ramped interchanges along the N12 corridor were included in the analysis to benchmark operational performance and assess whether alternative intersection configurations could better accommodate increasing traffic volumes.

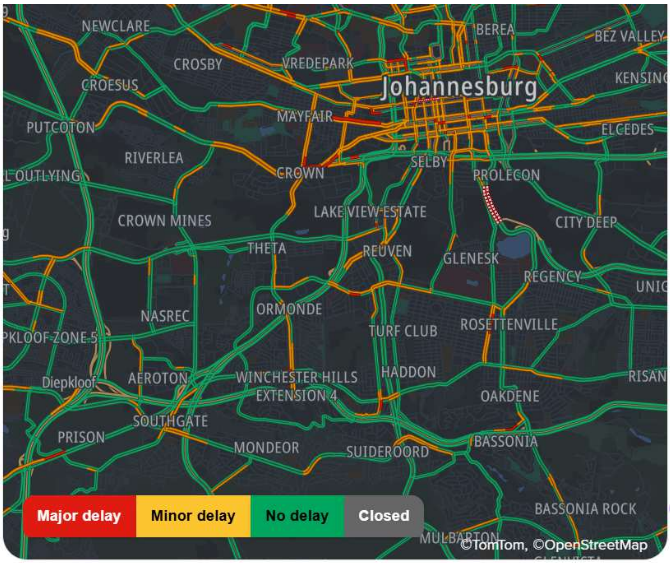

Fig. 1: Study Area

Spatial data were used to visualise traffic patterns, congestion levels, and network connectivity within the study area. Geographic Information System (GIS) software was employed to map traffic volumes, intersection layouts, surrounding land uses, and residential development patterns. Spatial layers included road network shapefiles, intersection control types, zoning data, and aerial imagery. These visualisations assisted in identifying spatial correlations between residential growth and traffic demand, as well as illustrating capacity constraints at critical nodes.

The methodology section further elaborates on the procedures for the traffic volume analysis. Peak-hour traffic volumes were extracted and analysed using standard traffic engineering formulae to calculate volume-to-capacity (v/c) ratios, Level of Service (LOS), and average control delay. Queuing theory principles were applied to estimate queue lengths and waiting times at the stop-controlled intersection under existing and projected traffic conditions. Scenario-based microsimulation tools such as AIMSUN and VISSIM were considered from Xu et al. (2025); however, due to limitations in detailed input data (such as signal phasing, driver behaviour parameters, and calibrated network models), the study prioritised traffic volume analysis supported by deterministic queuing models. This approach ensured methodological consistency and reliability given the available datasets, while still enabling a rigorous assessment of how TIAs accounted for projected traffic impacts associated with residential development in the corridor.

5 FINDINGS AND DISCUSSION

The findings illustrate clear temporal variations in congestion across both annual and weekly scales along the N12 corridor. Although the monthly congestion profiles for 2024 and 2025 follow comparable seasonal trends, suggesting that broader structural travel patterns remain relatively stable, important inter-annual differences are evident in cumulative delay and peak-period intensity (see figure 2).

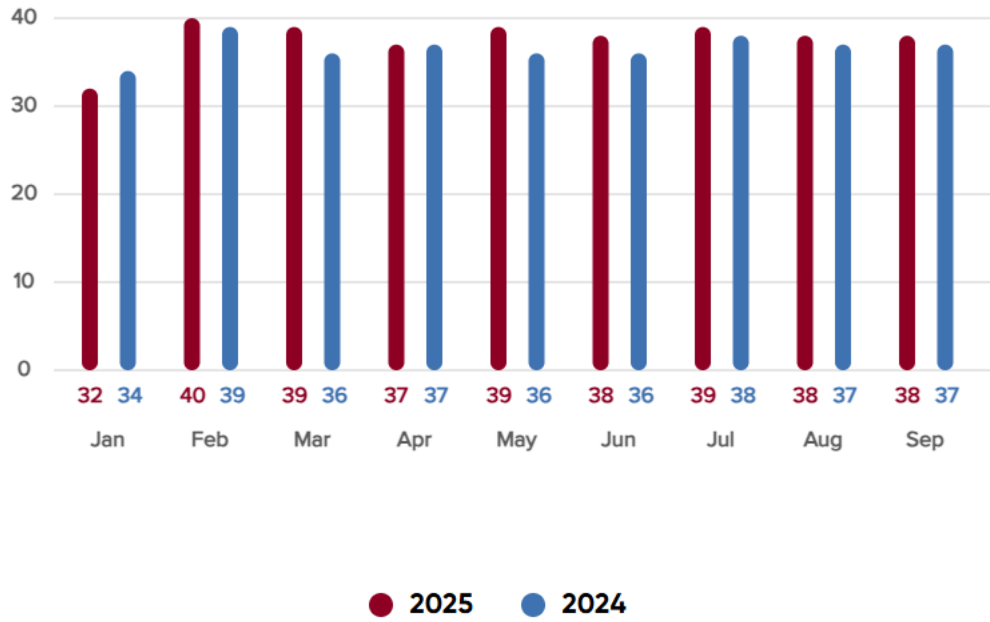

Fig. 2: 2024 vs 2025 congestion trend

At the annual scale, commuters in 2025 experienced approximately 65 hours of peak-period congestion, representing an increase of 3 hours and 50 minutes compared to 2024 during comparable peak observations. However, when cumulative annual delay is considered, total time lost decreased from 153 hours in 2024 (6 days and 9 hours) to 98 hours in 2025 (4 days and 2 hours), reflecting a net reduction of 55 hours. This apparent discrepancy suggests that while certain peak segments intensified in duration or intensity, overall congestion exposure across the year declined. Such a shift may reflect improved traffic distribution, adaptive commuter behaviour (e.g., peak spreading), minor operational adjustments, or localized network improvements.

5.1 Temporal Variations in Congestion

Weekly and diurnal analyses reveal more pronounced temporal dynamics (see figure 3). Mondays consistently recorded the highest congestion levels, particularly during the morning peak period (07:00–08:00). This pattern aligns with typical post-weekend demand surges, where work-related commuting is at its highest. The finding that travelling before 07:00 on Mondays could save up to four hours annually for a commuter undertaking a 30-minute trip highlights the sensitivity of congestion to relatively small temporal shifts in departure time. This reflects a network operating near capacity, where marginal increases in flow result in disproportionate increases in delay.

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06:00am	17 min 50 s	17 min 50 s	17 min 40 s	17 min 30 s	17 min	15 min 10 s	15 min 30 s
	23 min	23 min	22 min 40 s	22 min	20 min 50 s	16 min	16 min 10 s
08:00am	22 min 20 s	22 min 30 s	22 min 10 s	21 min 10 s	19 min 50 s	17 min 10 s	17 min
	19 min 40 s	20 min	20 min	19 min 30 s	19 min 10 s	18 min 10 s	17 min 40 s
10:00am	19 min 10 s	19 min 30 s	19 min 30 s	19 min 20 s	19 min 30 s	19 min	18 min 10 s
	19 min 20 s	19 min 50 s	19 min 40 s	19 min 40 s	20 min	19 min 30 s	18 min 30 s
12:00pm	19 min 30 s	20 min	19 min 50 s	20 min	20 min 30 s	19 min 50 s	18 min 20 s
	19 min 30 s	20 min	20 min	20 min 10 s	20 min 30 s	19 min 50 s	18 min 20 s
02:00pm	19 min 40 s	20 min 10 s	20 min 10 s	20 min 20 s	20 min 50 s	19 min 20 s	18 min 10 s
	20 min 40 s	21 min 30 s	21 min 30 s	21 min 30 s	21 min 50 s	18 min 50 s	18 min
04:00pm	23 min 20 s	24 min 10 s	23 min 50 s	23 min 40 s	22 min 50 s	18 min 30 s	17 min 50 s
	23 min	24 min 10 s	23 min 40 s	23 min 30 s	21 min 50 s	18 min 10 s	17 min 40 s
06:00pm	20 min 20 s	20 min 50 s	20 min 40 s	20 min 50 s	20 min 10 s	18 min 30 s	18 min 10 s
	18 min 50 s	19 min	19 min	19 min 20 s	19 min 10 s	18 min 40 s	18 min 10 s
08:00pm	18 min 10 s	18 min 20 s	18 min 20 s	18 min 20 s	18 min 30 s	18 min 20 s	17 min 50 s

Fig. 3: Weekly congestion

Peak-period comparisons further indicate that, in 2024, commuters experienced more than 20 minutes of congestion delay per 30-minute trip during both morning and evening peaks. While for 2025, congestion intensity declined to over 13 minutes (morning peak) and 12 minutes (evening peak) per 30-minute trip. Despite this improvement, the morning peak consistently exhibited higher congestion levels than the evening peak in both years. This asymmetry reflects directional commuter flows toward employment nodes during the morning, resulting in concentrated demand over shorter time intervals. Evening travel tends to be more dispersed in departure times and destinations, reducing peak intensity. The spatiotemporal assessment confirms that congestion is not uniformly distributed but concentrated at specific nodes and corridors. Delays were particularly pronounced near off-ramps, intersections, and high-access-density zones, where friction between through-movements and local access traffic reduces effective capacity.

5.2 Impact of Land-Use Types on Traffic Flow

The spatial analysis demonstrates a strong association between congestion intensity and surrounding land-use patterns. High-density residential developments, mixed-use corridors, and commercial activity zones were consistently linked to elevated traffic volumes and longer delays. These land-use types generate high trip production and attraction rates, particularly during peak commuter periods.

Key observations include:

- High-density residential areas contribute significantly to morning outbound flows and evening inbound flows, amplifying directional congestion.
- Nearby commercial and retail corridors increase midday and evening traffic, extending congestion beyond traditional peak periods.
- Activity nodes along major arterial corridors intensify turning movements and reduce intersection efficiency, particularly at stop-controlled and ramp-adjacent intersections.

Where land-use intensification occurred without proportional upgrades to road capacity or intersection control, congestion levels were notably higher. This finding suggests that, in some instances, TIAs may have underestimated cumulative impacts or that mitigation measures were insufficient relative to actual development uptake and traffic growth.

6 IMPLICATIONS FOR TRANSPORT PLANNING

The temporal and spatial patterns observed have several implications for transport planning along the corridor. Firstly, the clear relationship between high-density land uses and congestion intensity underscores the necessity of aligning development approvals with network capacity assessments. TIAs should incorporate cumulative impact modelling rather than evaluating developments in isolation. Seondly, given the concentration of congestion during the Monday morning peak, demand management measures such as flexible work hours, staggered school start times, and remote work incentives could significantly reduce peak intensity.

Since congestion clusters around off-ramps and intersections, targeted geometric improvements (e.g., additional turning lanes, improved channelisation, or signalisation where appropriate) may yield greater benefits than corridor-wide widening. Additionally, sustained land-use intensification without parallel investment in public transport will likely reverse the 2025 congestion improvements. Enhancing public transport accessibility along high-density corridors could mitigate further traffic growth. The year-to-year variation demonstrates that congestion is dynamic and responsive to both behavioural and infrastructural factors. Continuous traffic monitoring and periodic reassessment of TIAs are therefore essential to ensure that mitigation measures remain effective under evolving demand conditions. Overall, the findings indicate that while congestion levels in 2025 were lower than in 2024 on a cumulative basis, traffic pressure along the corridor remains structurally high and closely linked to land-use intensity. Without coordinated spatial and transport planning interventions, future development is likely to erode the observed improvements and reintroduce escalating congestion trends.

7 CONCLUSION

This study provides an empirical assessment of transport infrastructure performance within the context of accelerating residential development, making a key contribution by quantitatively linking land-use change, traffic growth, and intersection performance within a constrained corridor environment. By integrating traffic volume analysis, queuing theory, and spatiotemporal congestion assessment, the research moves beyond descriptive evaluation and demonstrates measurable operational disparities between grade-separated interchanges and at-grade control.

The findings confirm that the R558 stop-controlled intersection along the N12 corridor operates inefficiently as traffic demand increases. Persistent congestion, extended peak-period delays, and elevated conflict exposure underscore the structural limitations of stop-control in a high-growth, high-volume environment. In contrast, ramped interchanges along the same corridor exhibit comparatively stable performance, highlighting the operational resilience afforded by grade separation under similar demand conditions. This comparative analysis constitutes a central contribution of the study, providing evidence-based justification for selecting an infrastructure typology in rapidly developing peri-urban contexts.

Furthermore, the study demonstrates that inadequate integration of transport planning into rezoning approvals and residential development processes significantly amplifies congestion pressures. Where land-use intensification proceeded without proportional infrastructure upgrades, volume-to-capacity ratios increased, queue lengths extended, and system reliability declined. By quantifying cumulative delay and identifying spatiotemporal congestion patterns, the research illustrates how incremental development decisions can collectively compromise corridor-level functionality. A further contribution lies in the methodological approach. In the absence of detailed simulation inputs for microsimulation platforms, the study demonstrates the robustness of traffic volume analysis supported by deterministic queuing theory as a practical, replicable evaluation tool in data-constrained environments. This provides a transferable framework for similar corridors where comprehensive simulation modelling is not feasible.

The study therefore concludes that sustainable and resilient transport systems require proactive alignment between land-use planning and infrastructure provision. Timely implementation of grade-separated interchanges, rigorous cumulative impact assessment within Transport Impact Assessments (TIAs), and continuous traffic performance monitoring are essential to safeguarding mobility, safety, and long-term regional efficiency. Without such alignment, infrastructure lag will continue to undermine network performance and erode the functional sustainability of rapidly urbanising corridors.

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