Passenger flow analysis & peak congestion management in metro stations: risks, strategies and system-based modelling

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SUMMARY

In metro and urban rail systems, commuter flows consistently cause bottlenecks, extended dwell times, and train queuing which result in significant congestion (Zhang et al., 2024). Existing approaches often emphasise quantitative assessments while overlooking human decision-making, organisational constraints, and systemic interactions. To address this gap, the study adopted a qualitative case study design incorporating expert interviews and document analysis. Interviews were conducted with senior practitioners and safety experts from four stakeholders, coupled with extensive operational documentation analysis, accident analysis and an observation session. Results reveal that passenger congestion in metro systems is governed by a combination of infrastructural, behavioural and organisational factors. Work Domain Analysis (WDA) and Control Task Analysis (ConTA) was then applied to develop a systems-based approach to crowd management and further outlines the requirements of AI in crowd management at metro stations. Present management strategies rely on timed controlled entry, strategic station closures, one-way flows and manual crowd direction. Evidence suggests that AI can support predictive crowd monitoring; however, feasibility depends on data integration and organisational readiness, with stakeholders viewing AI as a gradual decision-support enhancement rather than full automation.

KEYWORDS

Rail human factors; crowd management; cognitive work analysis; artificial intelligence

Introduction

Metro systems continue to play a vital part in urban transportation as they are effective and high-capacity transportation solutions in urban communities. In the UK, public transport, including urban rails, has a major share in daily commutes. In one single year between April 2024 to March 2025, 1,730 million journeys were made by Passenger Rail in UK (ORR, 2025). The commuter morning and evening surges have persistently created bottlenecks, extended dwell times, train queuing creating significant delays (J Zhang et al., 2024). Recent analyses support the idea that peak-hour congestion creates challenges to operations and safety in terms of overcrowded platforms, extended queues at entry points to the system, and propagating consequent delays (Seriani et al., 2023). Similar situations may also occur for specific events, such as sporting fixtures, music concerts, carnivals and festivals, and during planned maintenance work.

Studies indicate that congestion is the result of complicated interactions between passenger behaviour, station design, and operational factors. Passenger activities such as pushing, rushing to the doors, and unwillingness to wait for subsequent trains often amplify densities at various points of bottlenecks. The nature of station design, such as narrow staircases, poorly located ticket barriers and limited access on platforms, still makes passenger movement challenging and multiplies overcrowding at the main interchange areas (Seriani et al., 2023). Traditional crowd management measures mostly rely on reactive measures that leave systems vulnerable during peak surges (Seriani & Fujiyama, 2020). Despite significant reliance on metro systems to manage urban mobility, peak-hour passenger congestion remains a safety and operational challenge. Existing research is dominated by quantitative models which do not take fully into account human, organizational, and systemic factors. To address this gap, this study adopts a qualitative, multi-case approach, engaging directly with key stakeholders responsible for metro operations and safety. Guided by systems thinking and Cognitive Work Analysis (CWA), specifically Work Domain Analysis (WDA) and Control Task Analysis (ConTA) the study builds a holistic framework for congestion and risk management in metro stations and examines the requirements of AI in crowd management by assessing whether operators have the right data, structures, and readiness to implement AI.

Approach

Congestion affecting metro systems is not the result of isolated issues, but is due to complex, interdependent factors involving physical infrastructure, passenger behaviour, operational protocols, and institutional policies. Systems thinking provides a methodology for examining these interactions holistically. Among systems thinking methodologies, Cognitive Work Analysis (CWA) stands out for its ability to model socio-technical systems under conditions of uncertainty and variability (Vicente, 1999). CWA has been widely applied in safety-critical domains such as aviation, nuclear power, and military command systems, but the application of CWA to metro congestion management, particularly in the UK, remains minimal despite the clear potential benefits (Naweed & Golightly, 2022).

Work Domain Analysis (WDA) defines the system's functional structure through an abstraction pyramid, mapping the relationships between high-level purposes, values, functions, processes, and physical components. Control Task Analysis (ConTA) identifies the tasks necessary that can achieve system goals under varying operational contexts. Work Domain Analysis (WDA) is particularly relevant to metro crowd management because it provides a structured means of linking what the system is designed to achieve with how it operates. Literature suggests that international metro systems such as the Sydney Metro and Hong Kong MTR have applied WDA to assess crowding and passenger safety (Peftitsi et al., 2020; Read et al., 2022), whereas UK metro applications remain limited. The future integration of CWA with Artificial Intelligence (AI) presents a potential research avenue. However, adoption of AI raises privacy concerns over surveillance and data protection (Potoglou et al., 2017), interoperability issues across legacy and new systems, risk of algorithm bias, and the need for validation and safety assurance in sensitive environments such as metro stations. The comprehensive review of existing literature reveals significant limitations in current approaches to managing crowd congestion in metro systems. This study responds directly to these gaps by positioning Cognitive Work Analysis as the systemic backbone for AI-enhanced crowd management in metro systems.

Metro crowding has been widely studied through quantitative modelling and simulation. However, there is limited understanding of how systems are managed in practice, particularly regarding organisational constraints and staff decision-making. To address this, qualitative methods were selected over quantitative approaches due to the study's focus on process understanding. A qualitative case study approach enabled the collection of context-rich, expert-driven insights that reveal operational realities beyond what numerical data alone can capture. This approach also allows assessment of AI feasibility by capturing whether operators have the data, organisational structures, and readiness needed for real-time crowd management. Figure 1 indicates the methodological framework of the research study.

Method

Stakeholders were selected to reflect different levels of responsibility and expertise within the transport ecosystem of the UK and the Republic of Ireland. The case study involves four key stakeholders representing different scales of the transport system – including a small regional city (<1 million), medium-sized capital city (1 – 5 million) and an extremely large (>10m population) city. Standards and human factors experts were also involved in the study. Semi-structured interviews enabled the collection of in-depth insights while allowing participants the flexibility to highlight issues specific to their contexts. Ethical (verbal) approval was obtained prior to interview. Notes and recordings were transcribed and thematically analysed using manual coding aligned with WDA's abstraction levels.

Organisational documents including Rail Accident Investigation Branch reports (eg RAIB, 2016), standards. business plans, annual reports, operational plans, and passenger rail usage statistics were analysed to understand formal protocols and risk structures behind crowd control. The study also involved one site visit to understand the physical context of crowd management.

Work Domain Analysis (WDA) was applied to map the metro station environment across five abstraction levels: Functional Purpose; Values and Priority Measures; Purpose-Related Functions; Object-Related Processes; and Physical Objects. Control Task Analysis (ConTA) examined the critical decisions undertaken during periods of peak congestion.

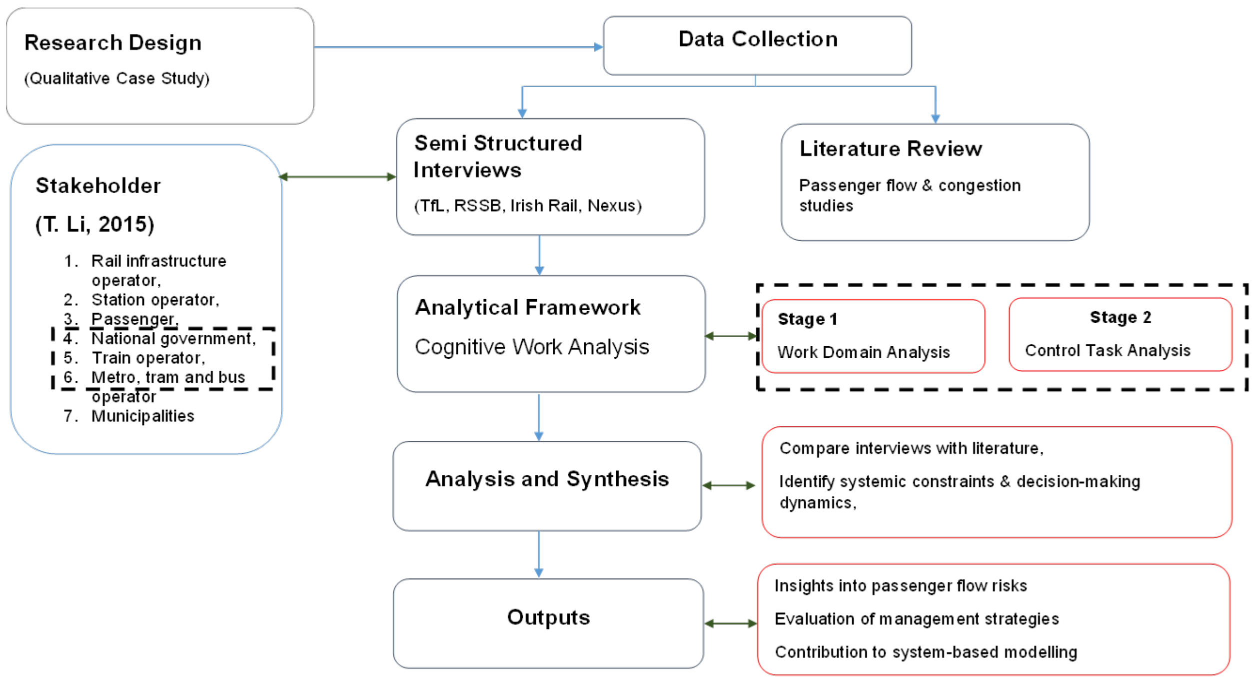

Figure 1 Research Design and Methodological Framework

Results

Results from comparative assessment of interviews confirm prior work that passenger congestion in metro systems is governed by a combination of infrastructural, behavioural and organisational factors. Narrow platforms, escalators and the platform–train interface are main physical bottlenecks (Seriani and Fujiyama, 2018). Behavioural elements such as unfamiliarity, non-compliance, and sudden inflows from events or transfers, while organisational issues such as dispersed responsibilities make it hard to manage metro crowding.

Present management strategies often rely on timed controlled entry, strategic station closures, one-way flows and manual crowd direction. These measures are effective during normal operations but remain predominantly reactive and dependent on staff situation awareness. Differences in technological readiness were observed across stakeholders, with one operator demonstrating selective predictive monitoring and dashboard integration, while other stakeholders rely primarily on CCTV and manual coordination systems.

Work Domain Analysis enabled the mapping of congestion management across five abstraction levels: functional purposes, values and priority measures, purpose-related functions, object-related processes, and physical objects. Passenger safety, service reliability and congestion reduction were identified as dominant system purposes. Infrastructure constraints such as ticket barriers, escalators and platform layouts interact with operational processes including gate control, staff deployment and communication protocols.

Figure 2 illustrates the WDA model developed from interview and document analysis, showing the structural relationships between system purposes, operational functions and physical infrastructure. Control Task Analysis describes multiple tasks which can be grouped under 4 key areas – monitoring, controlling, communicating and responding. Figure 3 provides a schematic of these tasks.

Discussion

The findings confirm that passenger congestion in metro systems is not merely a result of increased passenger volumes but emerges from systemic interactions between infrastructural, behavioural, and organisational factors. Narrow platforms, escalators and ticket barriers act as physical bottlenecks; however, these constraints are amplified by passenger behaviour and operational decisions. Congestion therefore cannot be attributed to isolated design flaws but must be understood as a socio-technical phenomenon shaped by interacting system elements.

Current management strategies rely heavily on staff-led interventions such as timed entry, one-way flow systems, temporary gate closures and manual crowd direction. While these measures are effective in maintaining safety during routine operations, they remain predominantly reactive during peak conditions. This reinforces the central role of human adaptability in congestion management, where situational awareness and professional judgement determine whether crowding escalates into safety risks.

The application of Work Domain Analysis (WDA) revealed how high-level system purposes such as passenger safety and service reliability are translated into operational functions constrained by infrastructure and technology. Control Task Analysis (ConTA) further illustrated how operators continuously balance safety, uninterrupted service and passenger throughput under time pressure.

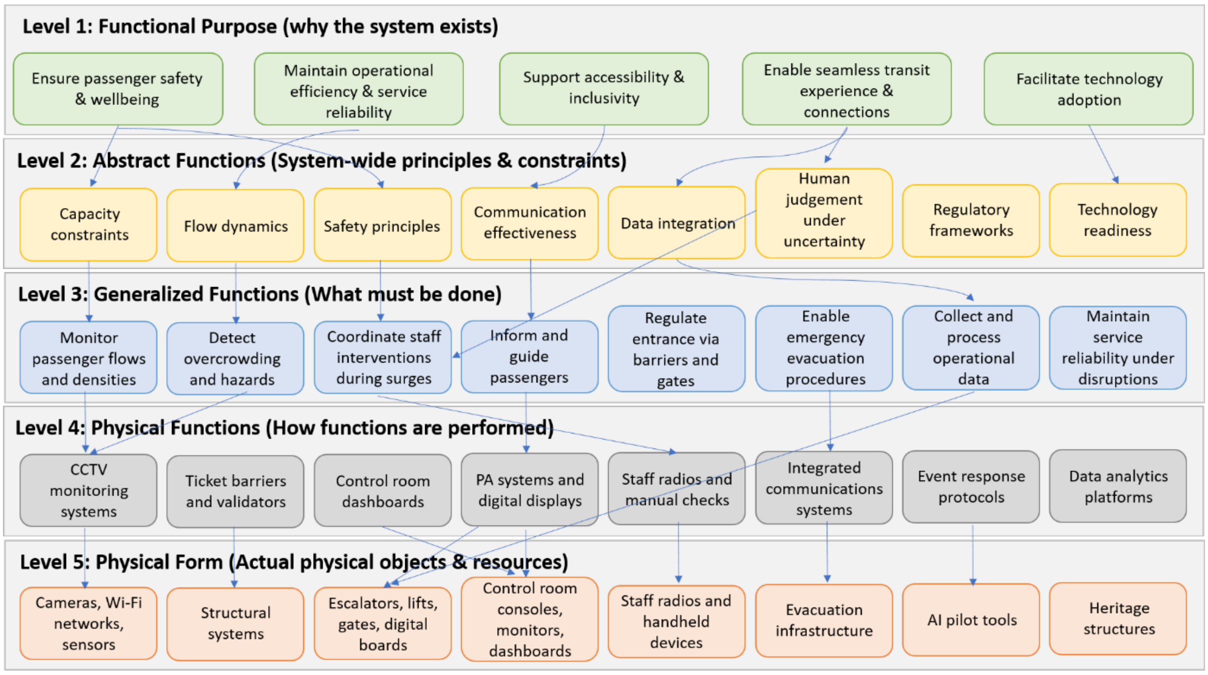

Figure 2: WDA analysis on crowd management based on interviews

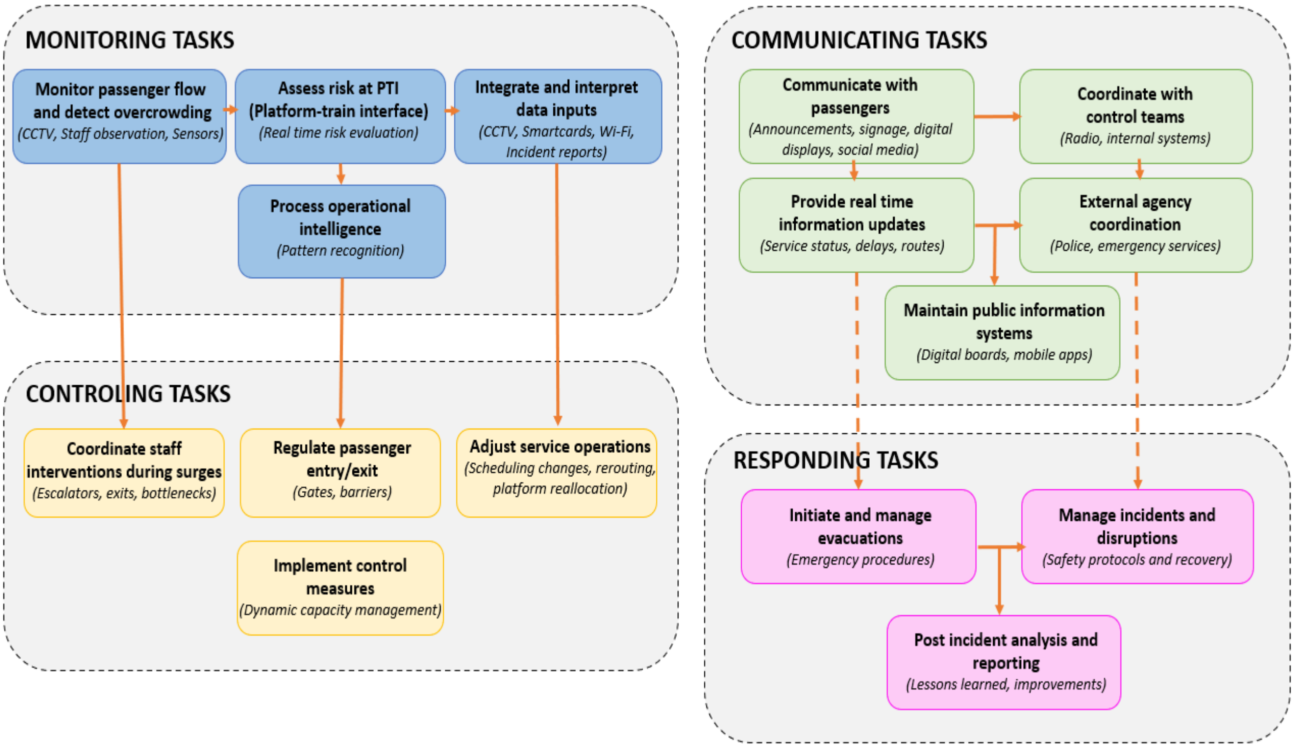

Figure 3: Control Task Analysis on Crowd Management based on Interviews

These modelling approaches demonstrate that congestion management involves layered decision-making across multiple abstraction levels rather than isolated operational responses. The study also highlights that Artificial Intelligence (AI) tools, while promising, cannot operate effectively without organisational alignment and data integration. Stakeholders consistently viewed AI as a decision-support mechanism rather than full automation. Integrating AI within a CWA framework provides a pathway for proactive congestion management, but only where organisational readiness and governance structures are aligned.

Feasibility of AI in Crowd Management

Different operators have different capacities of AI deployment in crowd management. Based on interviews and studying the documentation an assessment has been made and shown in Table 1.

Table 1: Feasibility of AI in metro Crowd Management

Sr #	Agency	Current Use of AI	Perceived Benefits	Barriers / Concerns	Overall Feasibility
1.	Metro operator 1	Piloting AI video analytics for monitoring PTI and crowd flows	Early detection of congestion; improved staff deployment; proactive interventions.	Data privacy, validation, integration with legacy systems.	High – Leading adopter with short-term scalability.
2.	Standards body	Focused on research and assurance, not operational use.	Supports improved safety standards and data for risk frameworks.	Emphasizes need for validation, cautious rollout.	N/A in Operations & Supportive in principle, but cautious.
3.	Metro operator 2	No active AI, manual crowd management dominates.	Potential for congestion prediction at small stations.	Funding and resource constraints; limited technical staff.	Low–Medium – Feasible with investment.
4.	Metro operator 3	No AI adoption, manual interventions only.	Could help with platform crowding and event-based surges.	Manual operations dominate; tech adoption not a priority.	Low – Currently reactive; requires long-term investment.

Based on the literature findings and interview insights, two scenarios have been discussed. Figure 4 shows how metro system can use AI in managing overcrowding issue event. Moreover, a detailed roadmap for AI adoption has been illustrated in Figure 5, which indicates how AI can be adopted by operators to improve crowd prediction and management.

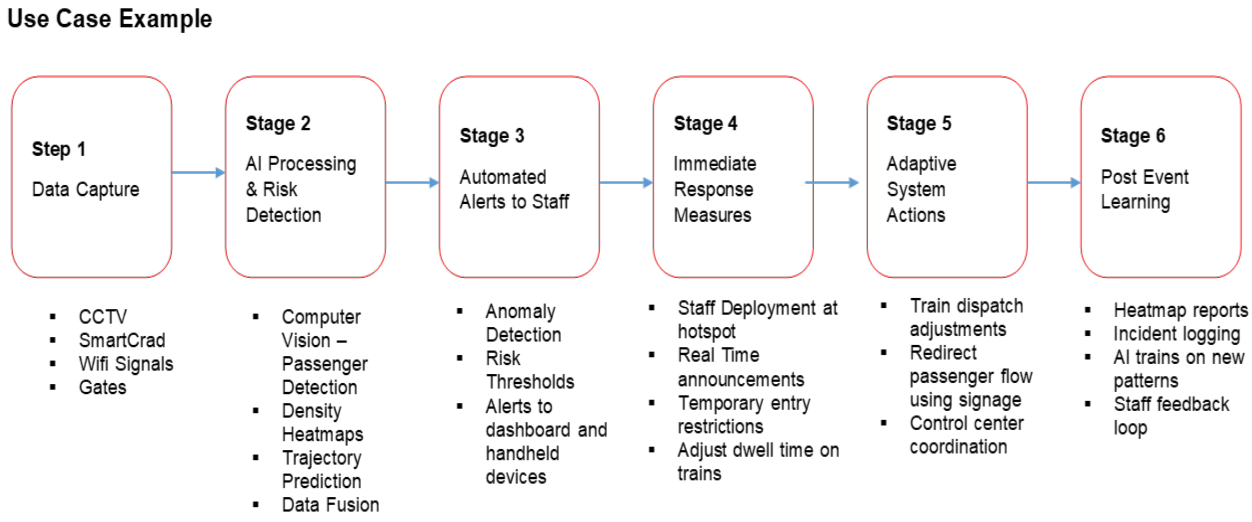

Figure 4: Use of AI in Event based Crowd Management

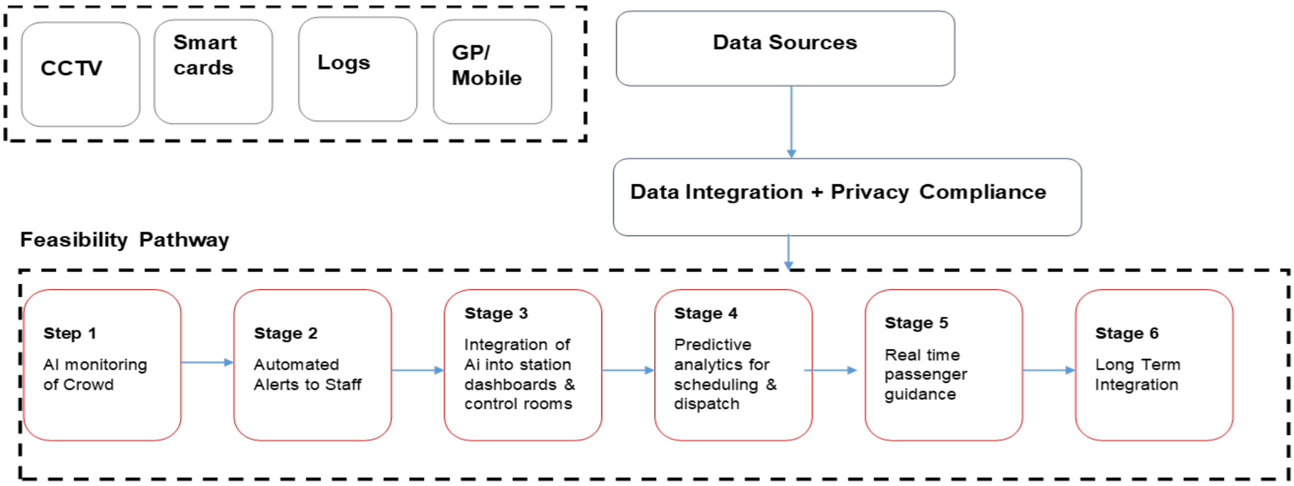

Figure 5: Adaptability approach of AI in Metro Train Operations

The following three limitations of methodology are the small sample size, which suggests future work should involve a broader range of operators to capture more comparative diversity. Secondly, self-report bias. Subsequent studies could relate interviews with observational or passenger-based data to enhance these viewpoints. Lastly, Technology limitations, future research may assess a pilot study of AI tools or simulation-based evaluations to validate perceived opportunities and risks.

Conclusions

Passenger congestion in metro systems remains a persistent operational and safety challenge shaped by the interaction of infrastructure design, operational practices, passenger behaviour, and organisational capacity. This study demonstrates that congestion is not solely a physical or operational issue, but a systemic challenge embedded within socio-technical structures.

Current management strategies rely heavily on staff-led interventions and remain predominantly reactive during peak surges. By applying Cognitive Work Analysis (CWA), particularly Work Domain Analysis (WDA) and Control Task Analysis (ConTA), this research provides a structured understanding of how high-level safety and reliability goals are translated into operational decision-making under constraints. The study advances knowledge by demonstrating that human adaptability remains central to managing congestion risks. Artificial Intelligence (AI) tools offer potential to enhance predictive monitoring and decision-support capabilities; however, feasibility depends on data integration, organisational readiness, regulatory assurance, and stakeholder trust. Future research should extend these findings through cross-operator studies, mixed-method approaches, and evaluation of AI pilot implementations within live metro environments

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