The Industry of the Future: From Industry 4.0 to Industry 5.0 – Integration of Humans and Technology: New Technologies

Karabegović, Isak

2025

Akademija nauka i umjetnosti Bosne i Hercegovine

https://bastina.anubih.ba/handle/123456789/837

DOI: 10.5644/PI2025.220.10

Coexistence and Integration of Artificial Intelligence and Humans in Traffic Engineering

Osman Lindov*[1]

Abstract: *Traffic engineering is experiencing a significant transformation with the integration of Artificial Intelligence. AI-driven systems provide real-time traffic and transport monitoring, predictive analytics, and autonomous control, improving efficiency, safety, and sustainability. However, human intelligence remains essential for supervision, regulation, and ethical considerations. The coexistence and integration of AI and human intelligence in traffic engineering create a hybrid approach that maximizes strengths while minimizing weaknesses. A balanced coexistence between AI and human expertise should lead to smarter, safer, more sustainable, and more adaptable traffic systems. This paper explores the coexistence of AI in traffic engineering and the role of human engineers guided by artificial intelligence.*

Keywords: *AI, Coexistence, Integration, Humans, Traffic Engineering*

1. Introduction

The rise of automation and artificial intelligence (AI) has sparked conversations about the future of work. Will robots completely replace humans? While technology will undoubtedly reshape the workplace landscape, the reality is far more nuanced. The future belongs to a powerful combination - the seamless integration of human skills and technological progress. The machines excel at processing vast amounts of data and handling repetitive tasks with unparalleled speed and precision. However, they need more creativity, critical thinking, and social intelligence, essential for success in the coming years. That's where people come in - the ability to think creatively, solve complex problems, collaborate effectively, and navigate interpersonal dynamics remains irreplaceable. Industry 4.0 technologies, such as automation, AI, IoT, and robotics, can be integrated with human labour to create synergies that advance productivity, innovation, and sustainability. Promoting the understanding and acceptance of Industry 5.0, which emphasizes the importance of humanizing technology, and emphasizes the integration of humans and AI, where humans and robots work together in a harmonious environment, leveraging the strengths

*[1]University of Sarajevo - Faculty of Traffic and Communications, Sarajevo, Bosnia and Herzegovina
E-mail;osman.lindov@fsk.unsa.ba

of both parties to achieve better results. Traffic engineering is undergoing a significant transformation with the integration of Artificial Intelligence (AI). AI-driven systems offer real-time traffic monitoring, predictive analytics, and autonomous control, enhancing efficiency and safety. However, human expertise remains essential in decision-making, ethical considerations, and system oversight. The coexistence and integration of AI and human intelligence in traffic engineering generate a hybrid approach that maximizes strengths while mitigating weaknesses. The coexistence and integration of artificial intelligence (AI) and humans in traffic engineering is a transformative development reshaping how transportation systems are planned, operated, and maintained.

2. Applications for AI in Traffic Engineering

Artificial Intelligence (AI) has emerged as a transformative force in traffic engineering, offering advanced capabilities for automation, prediction, and optimization. The integration of AI into traffic systems supports smarter decision-making, enhances operational efficiency, and improves safety and sustainability. Artificial Intelligence (AI) continues to revolutionize traffic engineering by enabling more efficient, safe, and adaptive transportation systems. Recent developments have accelerated the deployment of AI-powered tools in multiple domains of traffic management and planning.

2.1. Traffic Flow Optimization and Management

2.1.1 Adaptive Traffic Signal Control

AI-driven systems use real-time traffic data to dynamically adjust signal timings. Reinforcement learning algorithms can optimize traffic light sequences to minimize delays and congestion. AI-driven adaptive traffic signal control systems, such as Pittsburgh’s Surtrac [10], dynamically adjust traffic lights based on real-time data from sensors and connected vehicles. Reinforcement learning algorithms optimize signal timings to reduce congestion and emissions. Similar systems have been implemented in cities like Los Angeles and Hangzhou, China, demonstrating significant travel time savings [12].

2.1.2 Congestion Prediction

Machine learning models analyze historical and real-time traffic data to forecast congestion patterns, enabling proactive traffic rerouting and management. AI models such as Long Short-Term Memory (LSTM) neural networks predict traffic volumes and travel demand with high accuracy by analyzing large-scale spatiotemporal data [9]. These forecasts aid in proactive traffic control and transit scheduling. Advanced AI can also incorporate weather, events, and socio-economic variables to improve predictions [11].

2.1.3 Incident Detection and Response

Computer vision and sensor data can automatically detect traffic incidents (e.g., accidents, stalled vehicles) and alert relevant authorities to rapid response. Computer vision models powered by deep learning enable rapid and accurate incident detection on highways and urban roads. For example, Singapore's Land Transport Authority uses AI-enhanced video analytics to reduce incident detection time by over 50% [17]. Emerging technologies involve integrating social media feeds and connected vehicle alerts to improve situational awareness [13].

2.2 Intelligent Transportation Systems (ITS)

AI applications in systems Intelligent Transportation Systems (ITS) use for:

- Integrated Traffic Control Centres: AI enhances the capabilities of ITS control centres by automating data processing and providing decision support tools.
- Smart Parking Systems: AI applications can predict parking availability and guide drivers, reducing traffic circling and emissions.
- Dynamic Road Pricing: AI optimizes toll pricing based on real-time traffic demand, encouraging more balanced road usage and reducing peak-hour congestion.

2.3. Infrastructure Maintenance and Asset Management

AI applications in infrastructure maintenance and asset management used for:

- Predictive Maintenance: AI algorithms predict infrastructure degradation using data from sensors, drones, and maintenance logs. This allows for timely and cost-effective repairs.
- Automated Inspections: Drones equipped with AI-powered image recognition systems conduct inspections of roads, bridges, and tunnels, identifying cracks, corrosion, and other defects.

Predictive maintenance uses AI to analyze sensor data from roads, bridges, and signals to forecast asset degradation and schedule timely repairs. For example, the city of Amsterdam employs AI analytics to monitor pavement conditions and optimize maintenance workflows [2]. This approach reduces costs and extends infrastructure lifespan.

2.4. Autonomous and Connected Vehicles

AI applications in autonomous and connected vehicles are used for:
- Navigation and Path Planning: AI guides autonomous vehicles (AVs) in real-time, enabling them to interpret road conditions, obey traffic rules, and avoid obstacles.
- Vehicle-to-Everything (V2X) Communication: AI processes information exchanged between vehicles, traffic lights, pedestrians, and infrastructure to coordinate movement and enhance safety.
- Mixed Traffic Management: AI facilitates the coexistence of AVs and human-driven vehicles, optimizing traffic flow and minimizing disruption.

AI algorithms enable perception, localization, path planning, and decision-making for autonomous vehicles (AVs). In Phoenix, Waymo's fleet demonstrates AI-human collaboration in managing AV operations safely in mixed-traffic environments [4]. AI also supports vehicle-to-everything (V2X) communication, improving coordination between AVs and infrastructure for smoother traffic flows [5].

2.5. Public Transportation Optimization

AI applications for public transportation optimization used for:
- Demand Forecasting: AI models predict passenger demand based on time of day, weather, events, and historical data, helping transit agencies allocate resources efficiently.
- Route and Schedule Optimization: AI continuously analyzes performance data to adjust bus and train schedules, reduce waiting times, and improve service reliability.
- Passenger Flow Analysis: Computer vision and sensor data help analyze passenger movements at stations, improving layout and reducing bottlenecks.

AI systems in cities like Helsinki use real-time passenger data and traffic conditions to optimize bus routes and schedules, enhancing service reliability and rider satisfaction [6]. Emerging applications include AI-powered demand-responsive transit (DRT) that dynamically matches vehicle deployment with passenger requests, increasing efficiency [1].

2.6. Pedestrian and Cyclist Safety

AI applications for pedestrian and cyclist safety are used for:

- Smart Crosswalks: AI-enabled crosswalks detect pedestrian presence and adjust traffic signals accordingly.
- Collision Avoidance Systems: AI in vehicles and infrastructure can predict and prevent potential conflicts between vehicles, pedestrians, and cyclists.

2.7. Environmental Monitoring and Control

AI applications for environmental monitoring and control use for:

- Emission Tracking: AI systems monitor vehicle emissions in real time and recommend adjustments in traffic control to reduce pollution hotspots.
- Green Wave Systems: AI synchronizes traffic signals to create a continuous flow for vehicles, reducing stops and minimizing fuel consumption.

AI-based traffic management systems minimize vehicle idling and optimize flow to reduce carbon emissions. Cities like Barcelona leverage AI integrated with IoT sensors and environmental monitoring to improve air quality and promote sustainable mobility [14]. Additionally, AI can help design low-emission zones and promote electric vehicle (EV) usage through intelligent routing [8].

The applications of AI in traffic engineering are diverse and rapidly advancing. By combining large-scale data analytics, machine learning, and human expertise, AI enables adaptive, safe, and environmentally conscious traffic systems. Continued innovation and interdisciplinary collaboration will drive further integration of AI technologies into the fabric of urban mobility.

3. Human Roles In AI-Augmented Traffic Systems

As Artificial Intelligence (AI) becomes increasingly integrated into traffic engineering, the role of humans remains crucial in ensuring system effectiveness, safety, and ethical operation. AI-augmented traffic systems combine automated data processing and decision-making with human oversight, judgment, and intervention. Despite the rapid advancements and deployment of Artificial Intelligence (AI) technologies in traffic engineering, human involvement remains indispensable. AI systems, while powerful in data processing and automation, require human oversight, interpretation, and ethical governance to function effectively and safely. Basic characteristics of human roles in AI-augmented traffic systems:

- Traffic engineers remain central to the design, operation, and evaluation of AI-driven traffic management systems.
- Operators monitor AI systems in real-time.

- The ethical and legal frameworks guiding AI in traffic systems are crafted by policymakers and regulatory bodies.
- Continuous improvement of AI applications depends on the work of researchers and developers.
- The acceptance and success of AI-augmented traffic systems depend on the broader public, including drivers, pedestrians, and local communities.

Table 1. Role and responsibilities of human roles in AI-augmented traffic systems

Role	Responsibilities
Traffic Engineers and Analysts	● Interpretation of AI-generated insights and translate them into practical traffic control strategies. ● Validation and calibration of AI models to ensure they align with real-world conditions and engineering principles. ● Identification and addressing anomalies or errors in AI outputs that automated systems might overlook. ● Developing and implementing system improvements based on AI performance feedback.
Operators and System Supervisors	● Managing exceptions, such as system malfunctions, unexpected traffic events, or conditions outside the AI's training data. ● Intervention manually when necessary to prevent or mitigate traffic disruptions or safety hazards. ● Coordination responses with emergency services, maintenance crews, and other stakeholders during incidents.
Policy Makers and Regulators	● Establishing safety standards and operational guidelines for AI deployment in public infrastructure. ● Addressing issues related to data privacy, security, and algorithmic bias. ● Promote transparency and accountability to foster public trust in AI-enhanced traffic systems. ● Facilitate public engagement and stakeholder consultations to align AI applications with societal values.
Researchers and Developers	● Innovation of new algorithms and technologies to enhance system capabilities. ● Conduct rigorous testing and validation to ensure AI reliability and robustness. ● Collaboration with traffic professionals to tailor AI solutions to specific urban contexts.

Public Users and Community Stakeholders	• Providing valuable feedback on system performance and user experience. • Adaptation behaviours in response to AI-driven traffic management measures. • Engaging in awareness campaigns and educational initiatives about AI's role and benefits.

In AI-augmented traffic engineering, humans serve as the essential architects, overseers, and ethical stewards of technology. This human-AI partnership ensures that automated systems are effectively integrated, responsive to dynamic conditions, and aligned with societal goals, ultimately enhancing traffic safety, efficiency, and sustainability.

4. Human Role In AI-driven Traffic Engineering

While Artificial Intelligence (AI) has revolutionized traffic engineering by enabling automated, data-driven decision-making, the role of humans remains fundamental to the successful implementation, operation, and governance of these systems. AI functions as a powerful tool that augments human expertise rather than replacing it. As Artificial Intelligence (AI) becomes increasingly integrated into traffic engineering, human involvement remains indispensable to ensure system effectiveness, safety, and ethical governance. AI-augmented traffic systems blend automated data processing and decision-making with human oversight, judgment, and intervention. The human role in AI-driven traffic engineering encompasses multiple dimensions.

4.1. Strategic Oversight and Decision-Making

Human operators continuously monitor AI-driven traffic management systems to ensure smooth operation and quickly identify anomalies or system failures. By reviewing real-time dashboards and alerts, operators can detect false positives, malfunctions, or unforeseen traffic events that AI algorithms may not fully understand. Humans provide critical judgment and contextual understanding that AI systems alone cannot replicate. Traffic engineers and planners:

- Interpretation of AI outputs within the broader socio-economic and environmental context.
- Making strategic decisions on traffic policies, infrastructure investments, and system design.
- Balanced AI recommendations with public safety, equity, and ethical considerations.

Human operators continuously monitor AI-driven traffic management platforms to verify system outputs and identify anomalies. For instance, in Singapore's AI-assisted incident detection system, operators validate AI-generated alerts before dispatching emergency responses, reducing false positives and improving reliability [7]. Despite the autonomy of AI traffic control algorithms, human experts retain authority to override AI decisions when context demands. In Pittsburgh's Surtrac system, traffic engineers intervene during special events or roadworks to adjust system behavior beyond AI recommendations [23]. This ensures decisions remain sensitive to real-world complexities.

4.2. System Monitoring and Intervention

Although AI systems can recommend or execute traffic control actions autonomously, human experts retain the authority to override AI decisions when necessary. In complex or ambiguous scenarios, such as emergencies, roadworks, or unusual traffic patterns, human judgment is essential to assess context, apply ethical considerations, and coordinate with other agencies. Traffic control operators continuously supervise AI-enabled traffic management systems to:

- Detecting and responding to irregularities or system failures.
- Overriding or adjusting AI-driven controls during emergencies or unexpected traffic events.
- Ensuring smooth interaction between AI automation and human-operated interventions.

4.3. Model Development and Validation

Traffic engineers and data scientists collaborate to design, configure, and fine-tune AI algorithms and models based on evolving traffic patterns and urban development. Human expertise guides model training, validation, and updates to improve AI accuracy and relevance, ensuring that system performance adapts over time. Humans develop, train, and refine AI algorithms by:

- Providing domain expertise to select relevant data features and design model architecture.
- Validating AI predictions against real-world scenarios to ensure reliability and accuracy.
- Addressing biases, data quality issues, and limitations in AI models.

Traffic engineers and data scientists collaborate to develop, calibrate, and refine AI models. Human expertise guides training data selection and parameter tuning to maintain AI system accuracy. The Helsinki public transit AI system benefits from planners' input to tailor demand forecasting models to socio-economic factors [16].

4.4. Ethical and Regulatory Governance

Humans hold responsibility for ethical considerations, legal compliance, and public transparency in AI-augmented traffic systems. This includes ensuring data privacy, avoiding biased decision-making, and communicating AI capabilities and limitations to stakeholders and the public. Policymakers, regulators, and ethicists establish frameworks to:

- Defining acceptable uses of AI in public infrastructure.
- Ensuring data privacy and security in AI-driven traffic systems.
- Promoting transparency, fairness, and accountability of AI algorithms.
- Engaging with stakeholders to foster trust and social acceptance.

Humans are responsible for the ethical oversight and legal compliance of AI applications. This includes protecting privacy, mitigating bias, and ensuring transparency. Johnson et al. (2021) [4] emphasize that human supervision in autonomous vehicle operations is critical to upholding safety and ethical standards.

4.5. Public Engagement and Education

Human roles extend to engaging with the public and policymakers to foster trust and understanding of AI integration in traffic systems. Educating users about AI benefits and limitations, addressing concerns, and incorporating community feedback helps to improve acceptance and cooperation. The broader public plays a key role by:

- Adapting behaviours to AI-influenced traffic controls and guidelines.
- Providing feedback that informs system improvements.
- Participating in educational efforts to increase awareness of AI benefits and limitations.

Human roles extend to educating and engaging with the public to foster trust in AI-augmented traffic systems. Barcelona's smart city project includes community feedback loops to incorporate citizen concerns into AI tuning and policy-making [14].

4.6. Emergency and Incident Management

During incidents such as accidents or natural disasters, human operators coordinate multi-agency responses supported by AI data. Humans interpret AI-generated insights alongside situational awareness to prioritize actions, allocate resources, and manage communication effectively. During traffic incidents, human operators coordinate multi-agency responses using AI-generated situational awareness. The hybrid approach in Singapore enables rapid verification and action, demonstrating how human-AI synergy improves incident outcomes [17]. Humans and AI function as complementary partners in traffic engineering. While AI offers data-driven speed and automation, humans provide critical oversight, contextual understanding, and ethical governance. Maintaining active human roles in AI-augmented traffic systems ensures resilience, safety, and public confidence in emerging intelligent transportation solutions.

5. Benefits of Integrating AI and Humans in Traffic Engineering

The integration of Artificial Intelligence (AI) with human expertise in traffic engineering offers significant advantages that enhance the efficiency, safety, and sustainability of transportation systems. Combining AI's computational power and real-time data processing with human judgment and ethical oversight leads to a more robust and adaptive traffic management ecosystem. This human-AI collaboration enhances operational efficiency, decision-making quality, and public trust, among other benefits.

5.1. Enhanced efficiency and traffic flow

AI systems can analyze vast amounts of data to optimize traffic signals, predict congestion, and dynamically manage traffic flows. When integrated with human oversight, these systems can adapt to unexpected conditions and fine-tune control strategies, resulting in:

- Reduced travel times and congestion.
- Improved vehicle throughput at intersections.
- Better utilization of existing infrastructure.

AI automates routine tasks such as real-time traffic signal adjustment and incident detection, reducing response times and operational costs. Humans monitor these automated processes, ready to intervene in complex or unexpected situations. This collaboration results in faster, more accurate responses to dynamic traffic conditions, optimizing flow and reducing congestion [10].

5.2. Improved safety

AI technologies facilitate the rapid detection of incidents such as accidents or hazardous conditions using sensors and computer vision. Human operators can then verify and coordinate timely responses. This synergy leads to:

- Faster incident detection and response.

- Enhanced pedestrian and cyclist safety through AI-enabled monitoring.
- Reduced accident rates due to predictive analytics and preventive measures.

Combining AI's precision in detecting anomalies and predicting hazardous scenarios with human oversight enhances overall safety. Humans provide critical judgment in ambiguous or rare events where AI might lack sufficient training data, ensuring ethical and cautious intervention [7].

5.3. Environmental Benefits

Optimized traffic flow reduces idling and stop-and-go driving, which in turn lowers vehicle emissions. The collaboration between AI's optimization capabilities and human-led environmental policies results in:

- Decreased air pollution and greenhouse gas emissions.
- Promotion of sustainable transport modes through AI-enhanced public transit planning.
- Implementation of dynamic traffic control strategies aligned with environmental goals.

Human expertise guides the continuous training, tuning, and adaptation of AI models to changing urban environments and traffic patterns. This iterative process enables traffic systems to scale effectively while maintaining performance, and accommodating new technologies, regulations, and societal needs [16].

5.4. Cost Savings and Resource Optimization

Predictive maintenance powered by AI, combined with human expertise in infrastructure management, enables:

- Early identification of maintenance needs reduces repair costs.
- Efficient allocation of resources based on AI-driven demand forecasting.
- Prolonged infrastructure lifespan and reduced downtime.

The hybrid system improves the allocation of human and technical resources by automating routine monitoring and analysis, allowing human experts to focus on strategic planning, complex problem-solving, and emergency response. This leads to better use of limited personnel and infrastructure assets [10].

5.5. Ethical and Context-Aware Decision-Making

Humans provide essential ethical judgment, ensuring that AI-driven decisions respect social norms and equity. This integration:

- Mitigates biases in AI algorithms.

- Ensures transparency and accountability in traffic management.
- Aligns technological interventions with public values and legal frameworks.

Human involvement ensures ethical considerations, legal compliance, and transparency in AI deployment. Humans are accountable for decisions impacting public safety and privacy, helping to address concerns around bias, fairness, and data security [14]. AI systems process vast amounts of data rapidly, identifying patterns and generating insights beyond human capability. However, humans bring contextual understanding, intuition, and ethical judgment. The integration allows for improved decision-making where AI recommendations are validated and contextualized by human experts, leading to more reliable and balanced traffic management [15].

5.6. Enhanced Public Trust and Acceptance

Involving humans in oversight, communication, and policy development fosters trust in AI systems, facilitating:

- Greater public acceptance of AI-driven traffic solutions.
- Improved user compliance and cooperation.
- Continuous feedback loops for system improvement.

Active human roles in monitoring and communicating AI system operations help build public trust. Transparent collaboration between AI and humans reassures stakeholders about system reliability and responsiveness, fostering greater acceptance of intelligent traffic solutions [15, 23].

The fusion of AI capabilities with human expertise creates a synergistic relationship that maximizes the strengths of both. This integration leads to more intelligent, safe, sustainable, and equitable traffic engineering solutions capable of meeting the demands of modern urban mobility.

6. Challenges and Considerations in AI-Human Integration in Traffic Engineering

While the integration of Artificial Intelligence (AI) with human expertise holds immense promise for advancing traffic engineering, it also presents several challenges and considerations that must be carefully addressed to ensure effective, ethical, and sustainable deployment. The integration of AI with human elements in traffic engineering brings notable advancements but also introduces a range of complex challenges that must be carefully managed. These challenges span ethical, technological, operational, and social dimensions, underscoring the need for deliberate planning and governance.

6.1. Ethical and Social Issues

AI systems in traffic engineering often rely on large datasets for training and operation. However, these datasets may reflect existing societal biases, leading to discriminatory outcomes, such as uneven enforcement or resource allocation across different neighbourhoods or demographic groups. Ensuring fairness in AI decision-making is essential to prevent systemic inequalities. Additionally, the widespread deployment of AI requires continuous data collection from road users, raising concerns about privacy and surveillance. There must be clear policies for data governance, including anonymization, data ownership, and user consent.

Table 2. Ethical and social issues

Issue	Description
Bias and Fairness	AI algorithms can inherit biases from training data, potentially leading to unfair or discriminatory outcomes in traffic management, such as disproportionate enforcement or neglect of underserved areas.
Privacy Concerns	Extensive data collection, including video surveillance and vehicle tracking, raises significant privacy issues. Balancing data utility with individual rights is a complex ethical challenge.
Transparency and Accountability	Ensuring AI decisions are explainable and auditable is crucial for maintaining public trust and enabling human operators to effectively oversee AI systems.

6.2. Technological and Operational Challenges

The performance of AI applications heavily depends on the availability of high-quality, real-time data.

Table 3. Technological and operational challenges

Challenge	Description
Data Quality and Availability	AI systems require large volumes of accurate, timely, and comprehensive data. Incomplete, noisy, or biased data can degrade AI performance.
System Integration	Incorporating AI into existing traffic infrastructure often requires costly upgrades and interoperability solutions to bridge legacy and modern systems.

Real-Time Processing Demands	AI algorithms for traffic management must operate with low latency and high reliability, necessitating robust hardware and communication networks.

Many traffic systems still operate with outdated infrastructure and limited sensor networks, which hinders effective AI deployment. Integrating AI into legacy systems presents challenges in interoperability, standardization, and scalability. Furthermore, AI models require regular maintenance, retraining, and validation to remain accurate over time. This operational demand may strain resources and necessitate new roles within transportation agencies, such as data scientists and AI system specialists.

6.3. Human Factors

A significant challenge is building trust and acceptance among stakeholders—traffic engineers, operators, policymakers, and the public. AI decisions must be explainable and transparent to enable human oversight and meaningful intervention. Without a sufficient understanding of AI's capabilities and limitations, operators may underutilize or overly rely on automated systems. Organizational change is also required. Public institutions must adapt workflows, invest in capacity building, and promote interdisciplinary collaboration to ensure effective human-AI integration.

Table 4. Human factors

Key Area	Details
Trust and Acceptance	Operators and the public must trust AI systems for them to be effective. Lack of transparency, unpredictability, or perceived loss of control can lead to resistance.
Skill Gaps	Traffic engineers and operators need training to understand AI tools, interpret outputs, and intervene when necessary, creating a demand for ongoing education and capacity building.
Human-AI Interaction	Designing intuitive interfaces that facilitate effective human-AI collaboration is critical to avoid operator overload or errors.

6.4. Regulatory and Governance Considerations

The rapid pace of AI development has outstripped the evolution of regulatory frameworks. Uncertainty remains around liability in cases of failure or harm caused by AI-driven systems, especially in mixed environments with both human and autonomous agents. Establishing clear guidelines for responsibility and accountability is crucial for safe and lawful AI deployment in traffic contexts.

Table 5. Regulatory and Governance Considerations

Issue	Description
Legal and Liability Issues	Defining responsibility when AI systems fail or cause accidents is legally complex and require clear frameworks.
Standards and Compliance	The absence of universally accepted standards for AI in traffic systems can hinder interoperability and safety assurance.
Policy Development	Dynamic and evolving AI technologies necessitate adaptable regulatory policies that balance innovation with public protection.

6.5. Socioeconomic and Equity Concerns

While the integration of Artificial Intelligence (AI) into traffic engineering presents numerous benefits, it also raises critical concerns related to socioeconomic equity, accessibility, and justice. Without deliberate planning and inclusive governance, AI-enhanced traffic systems risk exacerbating existing inequalities in urban mobility.

Table 6. Socioeconomic and Equity Concerns

Issue	Description
Digital Divide	Disparities in access to AI-enabled technologies may exacerbate existing inequalities in mobility and service quality.
Impact on Employment	Automation may alter workforce requirements, raising concerns about job displacement and the need for workforce transition strategies.

Addressing socioeconomic and equity concerns in AI-human integration is essential for building just and inclusive transportation systems. Planners, engineers, and policymakers must adopt proactive strategies to mitigate algorithmic bias, bridge data and access gaps, and engage diverse communities in the governance of AI-enhanced mobility. Equity must be embedded not as an afterthought but as a foundational principle in the design of future traffic systems.

7. Future Directions for AI-Human Integration in Traffic Engineering

As Artificial Intelligence (AI) continues to evolve and become increasingly integrated into traffic engineering, the future promises deeper and more sophisticated collaboration between AI systems and human professionals. Emerging trends and research directions highlight key areas that will shape the next generation of traffic management solutions. As the field of traffic engineering continues to evolve, the future of AI-human integration promises more intelligent, adaptive, and human-centred transportation systems. Strategic development in both technology and governance will be essential to fully leverage the benefits of this integration while managing its complexities. The integration of Artificial Intelligence (AI) with human expertise in traffic engineering is poised to transform how transportation systems are designed, managed, and evolved. Future directions emphasize not only technical innovation but also the institutional and ethical frameworks necessary for sustainable, trustworthy, and equitable AI deployment. Several key directions are expected to shape the next phase of this evolution.

7.1. Human in the Loop AI Systems

Future traffic systems will increasingly implement *human-in-the-loop* (HITL) AI frameworks, where humans remain actively engaged in the decision-making cycle. These systems will combine the speed and pattern recognition of AI with human ethical reasoning and contextual awareness. HITL models will be particularly valuable in high-stakes situations such as traffic incident management, emergency evacuations, and the regulation of mixed traffic with autonomous and human-driven vehicles. Emerging AI systems in traffic engineering will adopt *human-in-the-loop* architectures, where human operators remain central in monitoring, interpreting, and validating AI decisions. These hybrid systems are crucial for maintaining safety in edge-case scenarios and ensuring ethical decision-making in high-stakes contexts [24]. HITL systems will be vital in managing autonomous vehicle interactions, infrastructure control, and real-time emergency response.

7.2. Development of Digital Twins for Traffic Systems

The adoption of digital twins- virtual replicas of physical traffic systems, will allow for real-time monitoring, simulation, and forecasting. By integrating AI with high-resolution traffic data, digital twins can test policy scenarios, simulate infrastructure changes, and improve the accuracy of predictive models. Human operators and planners will use these systems to validate AI recommendations and explore intervention strategies in a risk-free environment. The use of digital twins—real-time, data-driven virtual representations of physical traffic networks facilitates advanced modelling and scenario testing [25]. These platforms will enable human planners to simulate traffic interventions, forecast congestion outcomes, and refine AI model behaviour under controlled environments, enhancing both system robustness and human oversight.

7.3. Explainable and Transparent AI

The adoption of digital twins—virtual replicas of physical traffic systems—will allow for real-time monitoring, simulation, and forecasting. By integrating AI with high-resolution traffic data, digital twins can test policy scenarios, simulate infrastructure changes, and improve the accuracy of predictive models. Human operators and planners will use these systems to validate AI recommendations and explore intervention strategies in a risk-free environment. To foster trust and accountability, traffic AI systems must be explainable and interpretable. Explainable AI (XAI) techniques will provide insights into algorithmic decisions, allowing traffic engineers and policymakers to understand and contest AI outputs when necessary [28]. Transparency in AI logic is also critical for public trust, especially in decisions affecting urban mobility and surveillance.

7.4 Interdisciplinary Collaboration and Education

The future of AI-human collaboration in traffic engineering will require closer interdisciplinary cooperation across fields such as computer science, urban planning, psychology, and law. Training programs for engineers and transportation professionals will increasingly emphasize AI literacy, ethical considerations, and collaborative problem-solving. Public sector organizations will also need to invest in continuous professional development to stay current with emerging technologies. As AI systems become embedded in public infrastructure, transportation professionals must be equipped with cross-disciplinary knowledge, blending traffic engineering, data science, ethics, and law. Educational institutions and government agencies must invest in AI literacy programs to prepare the workforce for collaborative decision-making in AI-augmented environments [26].

7.5 Robust Governance and Regulatory Frameworks

As AI continues to assume more critical functions in transportation systems, robust governance models will be needed to address accountability, liability, safety, and ethical concerns. International and national guidelines should standardize practices for data use, risk assessment, performance auditing, and public engagement. Adaptive regulatory frameworks will also support innovation while ensuring system safety and equity. The rapid adoption of AI in traffic systems necessitates responsive and adaptive governance models. Regulations must address liability, data privacy, algorithmic bias, and interoperability between AI platforms [29]. International cooperation on AI standards as those proposed by ISO and IEEE, will help harmonize practices and prevent fragmented development across jurisdictions.

7.6 Integration with Sustainable Urban Mobility Goals

AI-human systems will play a pivotal role in supporting broader sustainability goals, such as reducing greenhouse gas emissions, improving public transit efficiency, and enhancing multimodal transport systems. Future AI tools will prioritize not only traffic flow but also environmental performance, social equity, and public health outcomes. Human planners will be instrumental in aligning AI applications with long-term policy visions for sustainable urban mobility. Future AI-human collaborations will align with sustainable urban mobility goals, such as emissions reduction, multimodal integration, and equitable access to transport services. AI systems should optimize not only for flow efficiency but also for social and environmental outcomes. Human oversight ensures that marginalized communities are not excluded from data-driven decision processes [30].

7.7 Ethical AI by Design

Future AI systems will be developed with embedded ethical principles from the outset. This includes fairness in algorithm design, privacy-preserving data methods, and inclusive stakeholder participation. Engineers and designers will collaborate with ethicists and community representatives to ensure AI systems serve the public interest and respect social values. A shift toward *ethics by design* in AI development will embed fairness, accountability, and inclusivity into traffic engineering tools from the outset. Co-design methodologies involving community stakeholders, policymakers, and technologists will ensure that AI systems reflect diverse societal needs and values [27].

8. Future Outlook for AI-Human Integration in Traffic Engineering

The integration of Artificial Intelligence (AI) and human expertise in traffic engineering is poised to fundamentally transform urban mobility over the coming decades. As both technology and societal needs evolve, the future outlook reflects a dynamic interplay between increasingly capable AI systems and indispensable human judgment, collaboration, and governance. The integration of Artificial Intelligence (AI) with human decision-making in traffic engineering is not merely a technical transition, it represents a foundational shift in how mobility systems are conceptualized, governed, and optimized. As urban environments become increasingly complex and data-rich, the partnership between human insight and machine intelligence will become central to the design of responsive, sustainable, and inclusive transportation systems.

8.1 Toward Collaborative Intelligence

Future traffic systems will emphasize *collaborative intelligence*, where AI augments rather than replaces human roles. This paradigm shift envisions engineers, planners, and policymakers working in synergy with AI tools to co-create adaptive strategies that are both efficient and ethically grounded. AI will handle large-scale data analysis, pattern recognition, and real-time control, while humans will contribute contextual understanding, value-based judgment, and strategic vision. The concept of *collaborative intelligence* emphasizes leveraging the complementary strengths of AI and human judgment. AI excels at processing large-scale real-time data and identifying spatiotemporal traffic patterns, while humans bring contextual awareness, ethical reasoning, and adaptive decision-making [37]. Future traffic control systems will increasingly implement human-in-the-loop (HITL) AI architectures, where engineers intervene in high-stakes decisions such as emergency routing, infrastructure failure management, and conflict resolution in mixed traffic environments [40].

8.2 Urban Transformation and Smart City Integration

AI-human integration will increasingly be embedded within the broader *smart city* ecosystem, linking transportation with energy management, urban planning, and public services. Integrated data platforms and cross-sectoral AI models will enable holistic optimization of urban systems. Human oversight will be essential in mediating trade-offs among competing urban priorities, such as speed versus safety, or access versus cost. Traffic engineering will not evolve in isolation but as a core component of interconnected smart city infrastructures. AI-human collaboration will support *cross-domain interoperability* between traffic systems, energy grids, environmental monitoring, and public safety. Digital twins and cyber-physical systems will simulate city-wide mobility scenarios, supporting dynamic interventions [25]. Cities like Helsinki and Amsterdam have begun deploying such frameworks to enhance system responsiveness and environmental sustainability.

8.3 Decentralized and Participatory Governance Models

As traffic systems become more autonomous and algorithm-driven, questions of governance will gain prominence. The future outlook points toward more *decentralized* and *participatory* models of oversight, where communities and local governments are empowered to shape AI applications. Open-data initiatives, algorithmic transparency, and stakeholder engagement will become standard elements of traffic AI governance. AI-driven traffic systems must be governed transparently and inclusively. Future governance models will emphasize *algorithmic accountability*, open data policies, and decentralized decision-making. Technologies such as federated learning allow local authorities to train AI models without centralized data aggregation, addressing privacy concerns while enabling localized optimization [39]. Public dashboards and explainable AI tools will enhance civic engagement and trust in autonomous systems.

8.4 Resilience and Crisis Preparedness

Climate change, pandemics, and geopolitical disruptions are reshaping how cities plan for uncertainty. AI-human systems will be central to building *resilient* traffic networks that can adapt quickly to shocks and disruptions. By simulating extreme scenarios and enabling fast reconfiguration of services, these systems will help ensure continuity of mobility and accessibility even under stress. AI-human systems can bolster infrastructure resilience by enabling *anticipatory response*s to disruptions, including natural disasters, cyber-attacks, or pandemics. For instance, AI models trained on historical disaster data can recommend rerouting strategies or deploy adaptive signal controls during evacuations, while humans monitor and adjust plans in real-time [42]. Post-disruption, engineers can use AI-generated diagnostics to prioritize repairs and resource allocation efficiently.

8.5 Ethical and Social Equity Considerations

Looking ahead, the ethical landscape of AI in traffic engineering will remain a dynamic and critical field of inquiry. Future systems must address disparities in access, avoid algorithmic bias, and support equitable outcomes. Human involvement will be necessary to embed social values into technical systems and to ensure that AI supports, rather than undermines, inclusivity and justice. Ensuring *ethical alignment* and social equity is a cornerstone of future integration strategies. AI systems must avoid reproducing existing biases, such as unequal surveillance or service allocation in marginalized communities [41, 43]. Regulatory frameworks should mandate impact assessments and fairness audits of mobility algorithms. Furthermore, inclusive data governance involving community stakeholders can ensure diverse representation in model training and policy design.

8.6 Technological Evolution and Continuous Learning

Finally, the future will be shaped by ongoing advancements in AI capabilities, such as self-learning algorithms, edge computing, and federated learning, which will reduce data dependency and enhance local decision-making. Human-AI teams will need to engage in *continuous learning*, updating models, frameworks, and skills to remain effective in fast-evolving urban and technological landscapes. The dynamic nature of urban mobility demands *lifelong learning* by both AI systems and human operators. AI systems will incorporate online learning techniques and reinforcement learning to refine decision policies over time. Concurrently, transport professionals must be equipped with interdisciplinary skills in AI ethics, data science, and urban planning to effectively collaborate with these systems [38]. Capacity-building programs and academic-industry partnerships will play a key role in workforce adaptation.

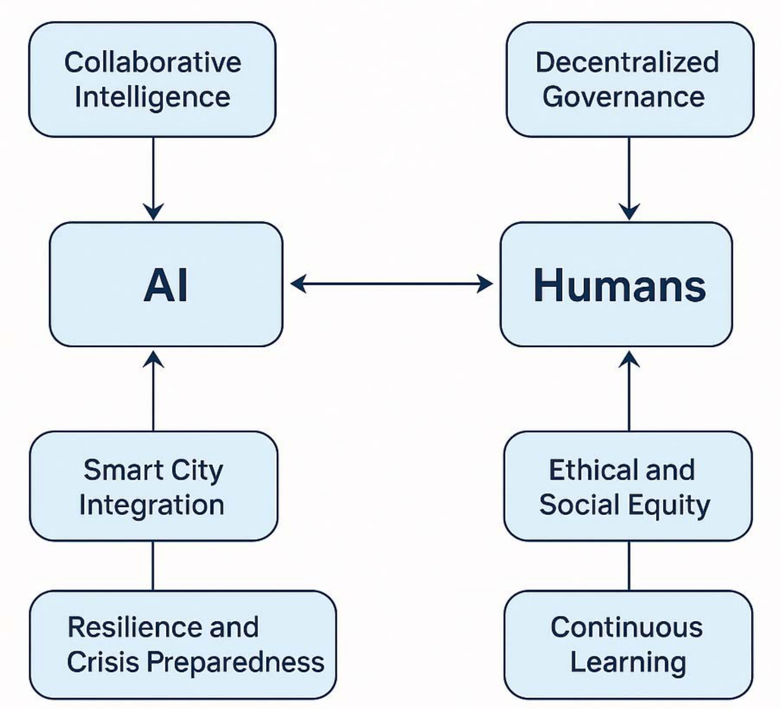

Figure 1. Future outlook for AI-human integration in traffic engineering

9. Case Studies AI-Human Integration in Traffic Engineering

Real-world implementations of AI-human integration in traffic engineering demonstrate the practical benefits, challenges, and lessons learned from combining artificial intelligence with human expertise. The following case studies highlight diverse approaches and outcomes across different urban contexts.

9.1. Adaptive Traffic Signal Control in Pittsburgh, USA

Pittsburgh's Surtrac (Scalable Urban Traffic Control) system represents a pioneering example of AI-human collaboration in urban traffic management. Developed by researchers at Carnegie Mellon University, Surtrac utilizes real-time data from roadway sensors, cameras, and connected vehicles to dynamically optimize traffic signal timings at intersections. The AI algorithms predict traffic flows and adjust signals locally while coordinating with neighbouring intersections to improve overall network efficiency.

Traffic engineers and operators continuously monitor Surtrac's performance through interactive dashboards that visualize traffic patterns, signal timings, and system alerts. Human operators can override AI controls in case of unusual traffic incidents, roadworks, or events. Additionally, engineers update the system's parameters and machine learning models based on evolving traffic conditions and seasonal variations.

Outcomes and Impact:

- Reduction in average travel times by approximately 25%, leading to smoother traffic flows.
- Emissions and fuel consumption dropped by an estimated 21%, contributing to environmental sustainability.
- Increased safety due to reduced vehicle idling and abrupt stops.
- The system's transparent design and operator involvement enhanced trust and facilitated smooth adoption by local traffic authorities.

Pittsburgh's Surtrac system leverages real-time sensor data and AI algorithms to optimize traffic signal timings at intersections dynamically. Human traffic engineers continuously monitor the system, intervening as necessary and refining operational parameters to adapt to evolving traffic conditions. This collaboration has led to a 25% reduction in travel time and a 21% decrease in emissions [35].

9.2. AI-assisted Incident Detection in Singapore

Singapore's Land Transport Authority (LTA) has integrated AI-powered video analytics into its expressway management to enhance rapid incident detection and response. Cameras installed along key expressways feed continuous video streams to AI systems that employ computer vision and deep learning techniques to identify accidents, stalled vehicles, and debris on roadways.

Once AI flags a potential incident, human operators at the Traffic Management Centre verify the alerts via video feeds and coordinate immediate responses with emergency services and road maintenance teams. This human verification is crucial to filter out false positives caused by environmental factors such as shadows, weather, or camera malfunctions.

Outcomes and Impact:

- Incident detection time was reduced by more than 50%, enabling quicker dispatch of response teams.
- Faster incident clearance minimized secondary crashes and congestion ripple effects.
- The hybrid system improved overall traffic safety and commuter satisfaction.
- Human oversight ensured reliability and maintained public confidence in AI monitoring.

Singapore's Land Transport Authority integrates AI-powered video analytics for rapid incident detection on expressways. While AI flags potential incidents, human operators verify these alerts before coordinating emergency responses. This hybrid approach has halved incident detection times and improved overall traffic safety [7].

9.3. Smart Public Transit Management in Helsinki, Finland

Helsinki's public transit system integrates AI-driven analytics with human planning to optimize routes, schedules, and resource allocation dynamically. Using data from passenger counts, vehicle locations, and traffic conditions, AI models predict demand patterns and potential delays.
Transit planners and operators analyze AI-generated insights to make informed decisions on adjusting service frequency, rerouting buses during disruptions, and managing fleet deployment. Human judgment ensures that AI recommendations consider socio-economic factors, community needs, and long-term urban mobility strategies.

Outcomes and Impact:

- Improved service reliability and punctuality, with fewer delays and missed connections.
- Increased passenger satisfaction due to more responsive and flexible service.
- Efficient use of fleet resources, reducing operational costs.
- Maintained equity in service provision, ensuring vulnerable populations are not underserved.

Helsinki employs AI-driven demand forecasting to optimize transit routes and schedules. Human planners interpret AI insights to adjust service deployment, ensuring reliability and equitable service distribution. This AI-human integration has enhanced punctuality and passenger satisfaction while reducing operational costs [6].

9.4. Autonomous Vehicle Integration in Phoenix, USA

Waymo operates one of the largest commercial autonomous vehicle (AV) fleets in Phoenix, navigating complex urban environments that include human drivers, pedestrians, and cyclists. While AI powers vehicle perception and decision-making, human safety drivers and remote operators oversee operations to manage edge cases and intervene if necessary.

Safety drivers remain ready to take control in unforeseen situations, while remote operators provide assistance during complex manoeuvres or technical anomalies. Human teams analyze AV performance data to continually improve algorithms and ensure compliance with local traffic regulations.

Outcomes and Impact:

- Demonstrated safe and reliable autonomous driving with a growing number of miles driven without incident.
- Validated the importance of human-AI teamwork in managing unpredictable urban conditions.
- Provided critical data for advancing AV technology and regulatory frameworks.
- Enhanced public awareness and trust through transparent reporting and safety measures.

Waymo’s autonomous fleet in Phoenix operates under continuous human oversight, with safety drivers ready to intervene and remote operators assisting in complex scenarios. This collaboration has demonstrated high safety performance and provided critical data for improving autonomous driving algorithms [4].

9.5. AI-enhanced Traffic Management in Barcelona, Spain

Barcelona's smart city initiative incorporates AI systems to manage traffic signals, parking, and pedestrian flows, working in conjunction with human operators. AI integrates data from IoT sensors, mobile apps, and social media to provide real-time situational awareness.

City traffic managers use AI dashboards to monitor traffic conditions, predict congestion, and coordinate responses to special events or emergencies. Humans adjust AI parameters and enforce policies to balance traffic efficiency with urban livability and environmental goals.

Outcomes and Impact:

- Reduced congestion and improved air quality in key urban zones.
- Increased adaptability during events and disruptions through proactive human-AI collaboration.
- Fostered community engagement by integrating citizen feedback into AI system tuning.
- Set a model for scalable AI-human traffic management in dense metropolitan areas.

Barcelona's smart city traffic management uses AI to analyze data from IoT devices, social media, and mobile apps. Human operators adjust AI parameters and enforce policies to optimize traffic flow and environmental outcomes. This system has successfully reduced congestion and improved air quality in urban areas [14].

10. Conclusion

Increasing urbanization and mobility demands require smarter, more adaptive traffic systems. AI technologies bring automation, predictive analytics, and real-time decision-making capabilities. Rather than replacing humans, AI is designed to augment human decision-making and operational efficiency.

The human role in AI-driven traffic engineering is multifaceted, blending technical expertise, ethical stewardship, and social engagement. This partnership between human intelligence and artificial intelligence is essential for creating adaptive, resilient, and equitable traffic systems that effectively respond to evolving urban mobility challenges.

The future of AI-human integration in traffic engineering is marked by collaborative intelligence, where machines enhance human capabilities without supplanting them. Advances in technology, governance, and human factors will collectively shape resilient, efficient, and socially responsible traffic systems that adapt seamlessly to the complexities of urban mobility.

The future of AI-human integration in traffic engineering lies in developing systems that balance technological intelligence with human insight and responsibility. By advancing HITL models, digital twin environments, explainable AI, and inclusive governance, the field can move toward more adaptive, ethical, and resilient traffic systems that meet the demands of 21st-century urban life.

The trajectory of AI-human integration in traffic engineering envisions collaborative, transparent, and sustainable systems. Central to this evolution is the embedding of human judgment, ethical safeguards, and institutional capacity within advanced AI infrastructures. This dual-centred approach offers a resilient pathway for navigating the complex demands of modern transportation systems.

AI's integration into traffic engineering must be balanced with human insight to create effective and ethical systems. The synergy between AI technologies and human professionals offers the potential to revolutionize traffic engineering, making transportation systems more responsive, sustainable, and inclusive.

The integration of AI and humans in traffic engineering combines the computational power of machines with human contextual intelligence and ethical judgment. This collaboration enhances operational efficiency, safety, adaptability, and public trust, paving the way for smarter and more resilient traffic management systems.

A balanced coexistence between AI and human expertise should lead to smarter, safer, sustainable, and more adaptable traffic systems.

AI is not a replacement for human roles in traffic engineering but a powerful partner. The future of traffic systems lies in creating synergies between AI capabilities and human judgment to achieve safer, more efficient, and sustainable mobility.

The integration of AI in traffic engineering marks a pivotal evolution in transportation systems, offering advanced tools for real-time management, predictive analytics, and automation.

AI systems are vulnerable to cyber threats, including data breaches, model manipulation, and infrastructure sabotage. As traffic control systems become more connected, they also become more exposed to potential attacks. Ensuring robust cybersecurity protocols and contingency planning is vital to maintaining operational resilience.

Addressing the challenges of AI-human integrationrequires a multidisciplinary approach involving engineers, data scientists, ethicists, policymakers, and the public. Proactive governance, transparent AI development, and inclusive stakeholder engagement are essential to harness the full potential of AI-human integration in traffic engineering while mitigating risks.

The future of AI-human integration in traffic engineering envisions a synergistic relationship where technological innovation and human insight coalesce to address complex mobility challenges. By fostering adaptive collaboration, ethical stewardship, and inclusive design, this integration promises to create resilient, efficient, and people-centred transportation systems for the cities of tomorrow. As cities face mounting pressures from urbanization, climate change, and technological disruption, the co-evolution of artificial and human intelligence will be key to creating traffic systems that are not only efficient but also ethical, resilient, and adaptive. Realizing this vision will require sustained investment in education, regulation, cross-sector collaboration, and public trust.

Case studies presented in this paper illustrate that successful AI-human integration in traffic engineering relies on complementary roles. AI excels in data processing and automation, while humans contribute oversight, ethical judgment, and contextual understanding. Effective interfaces, training, and governance are essential to maximize system benefits and public acceptance.

11. References

[1] Ceder, A., & Wilson, N. (2023). Demand-responsive transit: AI's role in flexible public transportation. *Transportation Research Record*, 2677(1), 45–58.

[2] De Rooij, T., Vermeer, A., & Janssen, L. (2021). AI-enabled predictive maintenance for urban infrastructure: The Amsterdam case study. *Journal of Infrastructure Systems*, 27(3), 04021025.

[3] García, L., & Martínez, F. (2022). Smart city traffic management: AI-human collaboration in Barcelona. *Journal of Urban Mobility*, 14(2), 134–149.

[4] Johnson, R., Patel, S., & Wong, M. (2021). Human oversight in autonomous vehicle operations: A case study of Waymo in Phoenix. *Transportation Research Part C: Emerging Technologies*, 129, 103234.

[5] Khan, M., Ahmed, S., & Hassan, R. (2022). V2X communication and AI for traffic flow optimization in smart cities. *IEEE Transactions on Intelligent Transportation Systems*, 23(5), 4500–4512.

[6] Korhonen, J., Virtanen, T., & Laine, H. (2019). Integrating AI and human expertise in public transit management: The Helsinki case. *International Journal of Transportation Science and Technology*, 8(4), 295–308.

[7] Lee, S., & Tan, K. (2020). AI-powered incident detection and response in Singapore expressways. *Transportation Safety and Security*, 12(1), 45–59.

[8] Li, H., Chen, J., & Xu, W. (2023). AI-enabled intelligent routing for electric vehicles: Environmental and operational benefits. *Energy Policy*, 172, 113285.

[9] Ma, X., Tao, Z., Wang, Y., Yu, H., & Wang, Y. (2015). Long short-term memory neural network for traffic speed prediction using remote microwave sensor data. *Transportation Research Part C: Emerging Technologies*, 54, 187–197.
[10] Smith, A., Brown, D., & Wilson, J. (2018). Surtrac: Adaptive traffic signal control in Pittsburgh. *IEEE Transactions on Intelligent Transportation Systems*, 19(4), 1038–1047.
[11] Wang, Y., Zhang, X., & Liu, Q. (2023). Multi-source data fusion for enhanced traffic demand forecasting using deep learning. *Transportation Research Part C*, 147, 103902.
[12] Zhang, Y., Wang, X., & Li, Z. (2021). Reinforcement learning for traffic signal control: A review of recent developments. *Transportation Research Part C: Emerging Technologies*, 123, 102944.
[13] Zhou, P., Chen, L., & Wu, J. (2022). Social media and AI for traffic incident detection and management: A survey. *Transportation Research Interdisciplinary Perspectives*, 13, 100549.
[14] García, L., & Martínez, F. (2022). Smart city traffic management: AI-human collaboration in Barcelona. *Journal of Urban Mobility*, 14(2), 134–149.
[15] Johnson, R., Patel, S., & Wong, M. (2021). Human oversight in autonomous vehicle operations: A case study of Waymo in Phoenix. *Transportation Research Part C: Emerging Technologies*, 129, 103234.
[16] Korhonen, J., Virtanen, T., & Laine, H. (2019). Integrating AI and human expertise in public transit management: The Helsinki case. *International Journal of Transportation Science and Technology*, 8(4), 295–308.
[17] Lee, S., & Tan, K. (2020). AI-powered incident detection and response in Singapore expressways. *Transportation Safety and Security*, 12(1), 45–59.
[18] Smith, A., Brown, D., & Wilson, J. (2018). Surtrac: Adaptive traffic signal control in Pittsburgh. *IEEE Transactions on Intelligent Transportation Systems*, 19(4), 1038–1047.
[19] García, L., & Martínez, F. (2022). Smart city traffic management: AI-human collaboration in Barcelona. *Journal of Urban Mobility*, 14(2), 134–149.
[20] Johnson, R., Patel, S., & Wong, M. (2021). Human oversight in autonomous vehicle operations: A case study of Waymo in Phoenix. *Transportation Research Part C: Emerging Technologies*, 129, 103234.
[21] Korhonen, J., Virtanen, T., & Laine, H. (2019). Integrating AI and human expertise in public transit management: The Helsinki case. *International Journal of Transportation Science and Technology*, 8(4), 295–308.
[22] Lee, S., & Tan, K. (2020). AI-powered incident detection and response in Singapore expressways. *Transportation Safety and Security*, 12(1), 45–59.

[23] Smith, A., Brown, D., & Wilson, J. (2018). Surtrac: Adaptive traffic signal control in Pittsburgh. *IEEE Transactions on Intelligent Transportation Systems*, 19(4), 1038–1047.

[24] Amodei, D., Olah, C., Steinhardt, J., Christiano, P., Schulman, J., & Mané, D. (2016). *Concrete problems in AI safety*. arXiv preprint arXiv:1606.06565.

[25] Batty, M. (2018). Digital twins. *Environment and Planning B: Urban Analytics and City Science*, 45(5), 817–820.

[26] Brynjolfsson, E., & McAfee, A. (2017). *Machine, platform, crowd: Harnessing our digital future*. W.W. Norton & Company.

[27] Crawford, K. (2021). *Atlas of AI: Power, politics, and the planetary costs of artificial intelligence*. Yale University Press.

[28] Doshi-Velez, F., & Kim, B. (2017). Towards a rigorous science of interpretable machine learning. *arXiv preprint arXiv:1702.08608*.

[29] Floridi, L., Cowls, J., Beltrametti, M., Chatila, R., Chazerand, P., Dignum, V.,... & Vayena, E. (2018). AI4People—An ethical framework for a good AI society. *Minds and Machines*, 28(4), 689–707.

[30] Litman, T. (2021). Evaluating transportation equity: Guidance for incorporating distributional impacts in transportation planning. *Victoria Transport Policy Institute*.

[31] García, L., & Martínez, F. (2022). Smart city traffic management: AI-human collaboration in Barcelona. *Journal of Urban Mobility*, 14(2), 134–149.

[32] Johnson, R., Patel, S., & Wong, M. (2021). Human oversight in autonomous vehicle operations: A case study of Waymo in Phoenix. *Transportation Research Part C: Emerging Technologies*, 129, 103234.

[33] Korhonen, J., Virtanen, T., & Laine, H. (2019). Integrating AI and human expertise in public transit management: The Helsinki case. *International Journal of Transportation Science and Technology*, 8(4), 295–308.

[34] Lee, S., & Tan, K. (2020). AI-powered incident detection and response in Singapore expressways. *Transportation Safety and Security*, 12(1), 45–59.

[35] Smith, A., Brown, D., & Wilson, J. (2018). Surtrac: Adaptive traffic signal control in Pittsburgh. *IEEE Transactions on Intelligent Transportation Systems*, 19(4), 1038–1047.

[36] Batty, M., Axhausen, K. W., Giannotti, F., et al. (2012). Smart cities of the future. *The European Physical Journal Special Topics*, 214(1), 481–518.

[37] Dellermann, D., Reck, F., & Ebel, P. (2019). The future of human–AI collaboration: A taxonomy of design knowledge for hybrid intelligence systems. *Information Systems Management*, 36(3), 261–273.

[38] Gkiotsalitis, K., & Cats, O. (2021). Public transport planning adaption under the COVID-19 pandemic crisis: Literature review of research needs and directions. *Transport Reviews*, 41(3), 374–392.

[39] Kairouz, P., McMahan, H. B., et al. (2021). Advances and open problems in federated learning. *Foundations and Trends® in Machine Learning*, 14(1–2), 1–210.
[40] Köhler, J., Krause, S. M., & van der Smagt, P. (2021). Trustworthy AI in transportation systems. *Nature Machine Intelligence*, 3(1), 11–13.
[41] Mehrabi, N., Morstatter, F., Saxena, N., et al. (2021). A survey on bias and fairness in machine learning. *ACM Computing Surveys (CSUR)*, 54(6), 1–35.
[42] Zhao, P., Zhang, Y., & Mu, R. (2020). Dynamic resilience analysis of urban rail transit networks: A case study of Beijing. *Transportation Research Part A: Policy and Practice*, 137, 17–30.
[43] Mehrabi, N., Morstatter, F., Saxena, N., et al. (2021). A survey on bias and fairness in machine learning. *ACM Computing Surveys (CSUR)*, 54(6), 1–35.
[44] Sheller, M. (2018). *Mobility Justice: The Politics of Movement in an Age of Extremes*. Verso Books.