

Theoretical Implications of Connected and Automated Vehicles for Urban Traffic Planning

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Abstract: Rapid advances in connected and automated vehicles (CAVs) are reshaping travel behaviours, road capacity characteristics and urban mobility systems. Classical urban traffic planning theories are developed for human-driven traffic flows and cannot fully capture the operational features of CAVs. This paper explores the theoretical implications of CAVs for urban traffic planning. It first reviews core assumptions embedded within classical traffic planning theories from traffic flow, travel demand modelling and network equilibrium perspectives. Next, the study identifies key transformations introduced by CAV technology, including improved flow stability, coordinated vehicle scheduling, altered travel demand patterns and revised parking requirements. This work further analyses theoretical challenges raised by mixed traffic environments and cooperative vehicle operations, and proposes potential extensions to existing planning paradigms. The results provide theoretical support for revising urban traffic layout, road resource allocation and mobility governance under CAV deployment.

Keywords: connected and automated vehicles; urban traffic planning; traffic flow; travel demand; planning theory

1. INTRODUCTION

Deployment of connected and automated vehicles (CAVs) brings transformative changes to urban transportation. Supported by vehicle-to-everything (V2X) communication and autonomous driving technologies, CAVs modify microscopic traffic flow characteristics, reshape travel choices of residents, and restructure supply-demand relationships within urban transport systems. Classical urban traffic planning theories are established under the assumption of human-driven vehicles (HDVs). Their preset parameters related to reaction time, driving behaviour and travel decision-making become less applicable in CAV operating environments.

Existing literature largely focuses on CAV technical performance, traffic capacity gains and safety improvements. Few studies systematically investigate how fundamental planning paradigms need to evolve when CAVs enter real road networks (Guerrieri, 2021; Hu et al., 2026). Against this research gap, this paper examines the theoretical implications of CAVs for urban traffic planning and re-evaluates the validity, boundary and extension directions of traditional planning theories.

The remainder of this paper is organised as follows. Section 2 reviews core assumptions of classical urban traffic planning theories. Section 3 describes four major transformations induced by CAVs. Section 4 discusses challenges to conventional theories in mixed traffic scenarios. Section 5 proposes extended theoretical frameworks adapted for the CAV era. Section 6 concludes the study and highlights future research directions.

2. CORE ASSUMPTIONS OF CLASSICAL URBAN TRAFFIC PLANNING THEORIES

2.1 Traffic Flow Theory: Human-Centric Car-Following and Stability

Classical traffic flow theory, from the Lighthill-Whitham-Richards (LWR) model to modern car-following models such as the Intelligent Driver Model (IDM) and Gipps' model, is built on empirical observations of human driving behaviour. A core assumption is finite driver reaction time, generally ranging from 0.7 to 2.5 seconds depending on traffic and driver conditions (Treiber et al., 2006; Sipahi et al., 2006). Such reaction delays create platoon string instability: minor perturbations propagate upstream and amplify, forming stop-and-go waves and capacity drop.

Road capacity values in the Highway Capacity Manual (HCM) and engineering practice are calibrated for HDVs, with typical lane capacity between 2000 and 2400 passenger cars per hour per lane (pcphpl). Saturation flow at signalised intersections also relies on human acceleration and gap acceptance behaviour. The fundamental diagram of flow, density and speed is derived from human driving data, where capacity represents the maximum throughput constrained by human driving limits.

2.2 Travel Demand Modelling: The Four-Step Framework and Rational Choice

The conventional four-step travel demand model, consisting of trip generation, trip distribution, mode choice and route assignment, relies on human behavioural assumptions. Trip generation assumes travel demand arises from daily human activities, and the value of travel time savings (VTTS) quantifies the disutility of travel time. Mode choice treats private vehicle ownership as a binary state and assumes travellers make independent decisions with limited real-time traffic information. Parking demand is geographically tied to trip destinations, requiring parking supply near activity locations.

The VTTS concept underpins cost-benefit analysis, infrastructure investment and network design. Traditional models assume driving time carries disutility because drivers must continuously focus on vehicle control. Induced demand

is understood as new trips generated when road capacity expands, attracting travellers from alternative routes, modes or departure times.

2.3 Network Equilibrium: Wardrop's Principles and Selfish Routing

Traffic assignment theory follows Wardrop's (1952) first principle of User Equilibrium (UE). Individual drivers seek to minimise personal travel cost, so no traveller can reduce travel time by changing routes unilaterally. This principle rests on two assumptions: drivers obtain network information through travel experience, and route decisions follow self-interest. The "price of anarchy" measures efficiency loss relative to the System Optimum (SO), where total network travel cost is minimised (Roughgarden and Tardos, 2002).

Traditional network design adopts bi-level programming. The upper level represents planner objectives while the lower level captures UE route selection. Link performance functions such as the Bureau of Public Roads (BPR) function are calibrated for HDV congestion, with speed declining as flow approaches capacity due to human car-following and merging friction.

3. KEY TRANSFORMATIVE CHANGES INDUCED BY CAVs

3.1 Enhanced Traffic Flow Stability and Increased Road Capacity

CAVs equipped with Cooperative Adaptive Cruise Control (CACC) change car-following dynamics fundamentally. Sensor and communication response times at millisecond levels replace human reaction delays of 0.7–2.5 seconds. Vehicle-to-vehicle (V2V) communication allows CAVs to receive acceleration data from multiple preceding vehicles, rather than only the immediate lead vehicle as human drivers do. This enables string-stable platooning and suppresses upstream amplification of disturbances, removing stop-and-go oscillations at high traffic density.

Simulation and empirical tests confirm considerable capacity improvements. Under full CACC CAV penetration, highway lane capacity may rise by 80%–100% relative to HDV baselines, reaching 4000–5000 pcphpl (Guerrieri, 2021; Virginia DOT, 2020). Partial penetration also yields measurable benefits. The upcoming 7th HCM edition estimates a 13% capacity gain for basic freeway segments at 60% CAV penetration and a 21% rise in saturation flow at intersections under 80% penetration (McTrans, 2021). Hu et al. (2026) further confirm that higher CAV penetration improves flow stability, revises fundamental diagram relationships and slows congestion spread in mixed traffic.

3.2 Centralized Scheduling and Cooperative Vehicle Operations

Unlike human drivers making independent, decentralised decisions, CAVs can be coordinated using centralised or distributed control algorithms. At intersections, reservation-based management and cooperative signal control can eliminate traffic signals at high penetration, supporting continuous vehicle movement through trajectory planning. CAV platoons enable coordinated merging, lane changing and speed harmonisation impossible for uncoordinated HDVs.

Shared automated vehicle (SAV) fleets support fleet-level scheduling. Operators can dynamically assign routes, match ride-sharing passengers and rebalance empty vehicles network-wide. Operations shift from individual utility maximisation toward system-level optimisation, bringing

Wardrop's SO from a theoretical benchmark toward practical implementation. Zhang and Nie (2018) show that controlling a portion of vehicles under SO routing can reduce total network travel cost significantly.

3.3 Transformed Travel Demand and Value of Time

Full automation reduces travel time disutility because passengers no longer need to control vehicles; travel time may be used for work, rest or leisure. Studies indicate VTTS may drop by 30%–80%, depending on automation level and in-vehicle amenities. Lower VTTS increases acceptable commute distances and may encourage suburban sprawl for private CAV users, reshaping trade-offs between travel time and travel cost.

Shared mobility introduces further demand-side changes. A single SAV may replace 5–11 private vehicles with appropriate fleet management and occupancy (Fagnant and Kockelman, 2015). However, empty repositioning trips and longer trip distances may offset some efficiency gains. Travel demand redistributes spatially as commuters accept longer trips and temporally as congestion eases, flattening peak-hour demand profiles.

3.4 Decoupled Parking Requirements and Curb Space Reallocation

One major spatial effect of CAVs is decoupling parking from trip destinations. After dropping passengers, automated vehicles can relocate to cheaper peripheral parking, and SAVs may proceed directly to the next trip without parking. Optimised parking allocation reduces system costs and releases parking capacity in urban road networks. Under high SAV penetration, urban parking demand may fall by 50%–70%, freeing large land areas previously dedicated to parking.

Curb spaces formerly reserved for on-street parking can be converted to pick-up/drop-off zones, bicycle lanes, pedestrian space, green infrastructure or travel lanes. This breaks the traditional land-use-transport feedback loop that has shaped urban form over decades.

4. CHALLENGES TO EXISTING PLANNING THEORIES

4.1 Validity of Fundamental Traffic Flow Parameters

Road capacity, speed-flow-density curves and saturation flow values defined in planning manuals lose validity as CAV penetration grows. Throughput no longer depends purely on infrastructure geometry but also on CAV penetration, communication reliability, platoon rules and cooperation protocols. Guo et al. (2023) note many existing works overestimate mixed-traffic capacity. When platoons exceed six vehicles or penetration lies between 60% and 80%, human drivers keep longer following distances behind CAV platoons, lowering real capacity.

Road design standards based on human perception-reaction time, sight distance and lane width become conservative for CAV operation. Meanwhile, dedicated CAV lanes and intelligent infrastructure lack mature design specifications. The long transition period of mixed HDV-CAV traffic creates heavy modelling difficulty: capacity becomes dynamic with fleet composition rather than a static infrastructure attribute. Hao et al. (2022) find CAVs improve network reliability and reduce Braess paradox occurrences substantially under full penetration.

4.2 Instability of Travel Demand Forecasting

The four-step model faces structural limitations for CAV scenarios. Shared fleets separate vehicle ownership from mobility access, destabilising trip generation rates. Declining VTTS and extended acceptable travel distances alter trip distribution patterns. New service types including SAVs and pooled rides blur traditional boundaries among private cars, taxis and public transit, making old mode-choice models less applicable. Parking generation standards embedded in zoning rules become obsolete once parking is disconnected from destinations.

CAV-induced demand differs from conventional induced demand. Increased capacity may create longer trips, empty vehicle travel and reduce demand for alternative transport modes. Expanded commuting ranges reshape land use and urban rent gradients. Correia et al. (2026) report roughly 87% of urban road segments have basic infrastructure unsuitable for CAV deployment. Heterogeneous road conditions increase uncertainty in demand forecasting.

4.3 Equilibrium Paradoxes in Mixed Cooperative-Selfish Traffic

Mixed traffic with both cooperative CAVs and selfish HDVs generates hybrid equilibrium states that cannot be fully captured by pure UE or SO theory. HDVs follow selfish routing, while coordinated CAVs follow system-oriented routing, forming mixed equilibrium (Harker, 1988). Controlling too few cooperative vehicles yields limited system benefits, while over-control may create unfair cost distribution among traveller groups. Sharon et al. (2018) identify a threshold number of cooperative vehicles needed to approach SO performance; this threshold varies nonlinearly with network topology and demand.

V2X communication also changes information environments assumed in classic route-choice models. CAVs obtain complete real-time network data and adjust routing instantly. This weakens the assumption of static stable equilibrium because traffic flows continuously adapt rather than converge to fixed flow patterns.

4.4 Equilibrium Paradoxes in Mixed Cooperative-Selfish Traffic

Traditional road space allocation divides right-of-way among general lanes, parking, sidewalks, bicycle facilities and transit lanes based on HDV characteristics and static parking demand. CAVs introduce new trade-offs: dedicated CAV lanes versus mixed traffic, pick-up/drop-off zones versus through lanes, V2X communication infrastructure versus conventional signage. Geometric standards for lane width, turning radius, intersection spacing and ramp metering require re-evaluation.

Governance frameworks also need revision. Traditional traffic management separates infrastructure control by public agencies and vehicle operation by individual drivers. The

CAV era distributes trajectory-level control among vehicle manufacturers, fleet operators and road authorities. This multi-agent coordination challenge exceeds the scope of existing planning institutions.

5. EXTENSIONS OF THEORETICAL PARADIGMS

5.1 Penetration-Dependent Traffic Flow Theory

Updated traffic flow theory for CAVs should treat capacity and fundamental diagram parameters as endogenous variables determined by CAV penetration, communication quality and cooperation protocols, instead of fixed infrastructure constants. Multi-class car-following models may integrate IDM for HDVs, ACC for unconnected automated vehicles and CACC for connected vehicles. Microscopic vehicle interaction rules should be coupled with macroscopic network planning models (Hu et al., 2026). Penetration-adjusted capacity factors proposed in the updated HCM provide a practical intermediate solution toward fully dynamic capacity models.

Stability analysis must extend beyond string stability of homogeneous platoons to mixed multi-class traffic. Vehicle composition determines whether perturbations amplify or dissipate. New capacity paradoxes and Braess-type phenomena specific to mixed traffic require dedicated investigation. Hao et al. (2022) demonstrate that adding links may reduce network capacity under low CAV penetration, although this effect disappears at high automation levels.

5.2 Activity-Based Demand Models with Endogenous Value of Time

The four-step framework should evolve toward activity-based demand models incorporating CAV features: the relation between in-vehicle productivity and VTTS under different automation tiers; traveller trade-offs between private CAV purchase and SAV subscriptions; empty trips for fleet rebalancing and parking relocation; and land-use feedback from reduced travel disutility. New induced demand models should distinguish demand sources: new person trips, extended trip lengths, modal shifts and empty vehicle movements.

Parking modelling must shift from destination-fixed static requirements toward network-wide dynamic parking optimisation. Optimisation should account for empty travel cost, spatial land value differences and SAV fleet operations. Bi-level parking planning frameworks integrate traveller behaviour, CAV operational expenses and land opportunity cost into a unified tool.

5.3 Multi-Class Network Equilibrium and Cooperative Control Theory

Traffic assignment theory needs extension into multi-class hybrid equilibrium for mixed traffic. HDVs follow bounded-rational UE based on limited experience; cooperative CAVs adopt SO or constrained-SO routing; SAV fleets optimise routes balancing operator cost and passenger service quality. The concept of information-aware equilibrium describes heterogeneous route decisions under different information availability.

Network design should treat CAV routing controllability as a design variable alongside physical infrastructure investment. Classic bi-level models may be upgraded into three-level

frameworks: top-level infrastructure planning, middle-level CAV cooperative routing control, bottom-level HDV user equilibrium response. Integrated algorithms combining dedicated CAV lane layout, trajectory planning and dynamic traffic assignment illustrate the need for joint optimisation of infrastructure and vehicle control (Ngo, 2023).

5.4 Integrated Space-Mobility Planning Framework

Urban traffic planning should integrate land-use planning and curb management. This unified framework optimises: multi-functional road space allocation for CAV lanes, HDV lanes, pick-up/drop-off zones and non-motorised facilities; parking location and pricing considering vehicle repositioning; V2X infrastructure deployment; SAV operating regulations and zones; land-use patterns that capture mobility gains while mitigating sprawl.

Traditional road classification based on mobility-access trade-offs for human drivers should be reconsidered. A new classification can be built on CAV readiness, permitted traffic types and communication infrastructure level. The data-driven road CAV-readiness classification developed by Correia et al. (2026) offers an empirical foundation. Temporal road management allows lanes to switch dynamically between CAV-only and mixed operation according to time-of-day and real-time traffic states.

6. CONCLUSIONS AND DISCUSSION

This paper systematically analyses theoretical implications of CAV deployment for classical urban traffic planning theories. By reviewing core behavioural and operational assumptions of traditional planning frameworks and summarising CAV-driven transformations, this study confirms that CAV technology challenges not merely individual parameter values but the foundational assumptions governing traffic flow, travel choice and network equilibrium.

Four main theoretical outcomes emerge. First, traffic flow theory shifts from static human-calibrated parameter models to penetration-sensitive multi-class models, defining road capacity as an emergent property of vehicle-infrastructure cooperation rather than a fixed infrastructure metric. Second, travel demand modelling moves past four-step limitations by incorporating endogenous VTTS, shared mobility, empty trips and decoupled parking behaviour. Third, network equilibrium theory is extended for mixed traffic where cooperative system optimisation and selfish user routing coexist. Fourth, road design and space allocation become adaptive, multi-functional and jointly optimised with vehicle control strategies.

Several research directions remain open. The long mixed-traffic transition period calls for adaptive planning frameworks suitable for continuously changing fleet composition, rather than only full-automation end states. Governance mechanisms for multiple stakeholders and equity issues deserve deeper research, including fair distribution of CAV benefits and service gaps in areas lacking automation-ready infrastructure. Environmental and urban form impacts also require integrated assessment, including sprawl risks from lower travel disutility and urban ecological gains from repurposed parking land.

CAV deployment represents a paradigm shift in urban mobility instead of simple vehicle technical upgrade,

requiring corresponding evolution in planning theory. This paper identifies limitations of conventional theories and outlines pathways for theoretical extension, supporting the development of CAV-era traffic planning frameworks. Future work should conduct empirical validation, model refinement and practical case studies to realise sustainable, equitable and efficient urban intelligent transport systems.

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