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Nonlinear Impacts of Urban Decentralization on Arterial Traffic Performance: Evidence from Polycentric Mobility Transitions and Microsimulation Analysis

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Abstract

Urban mobility systems are undergoing significant transformation due to urban decentralization, increasing telecommuting, multimodal transport adoption, and evolving travel behavior. These changes challenge conventional traffic performance assessment methods that rely on static and volume-based assumptions. This study aims to synthesize how mobility transitions influence traffic performance outcomes, including Level of Service (LOS), speed, delay, density, and congestion redistribution in polycentric and rapidly urbanizing cities. Using a structured literature synthesis approach, the study reviews advances in microsimulation modeling, behavioral mobility representation, and scenario-based traffic analysis. It examines calibration methods such as trajectory-based calibration, machine learning-assisted parameter estimation, and hybrid optimization techniques, as well as mobility transition scenarios including decentralization, telecommuting, multimodal integration, and connected and autonomous vehicle adoption. Key indicators analyzed include LOS, travel time reliability, queue length, density distribution, and delay variability.

The findings show that mobility transitions mainly redistribute congestion spatially and temporally rather than reduce it absolutely. Decentralization shifts congestion across corridors, telecommuting smooths peak demand with context-dependent effects, and multimodal integration improves accessibility while potentially increasing congestion at transfer points. Traffic responses are highly non-linear, making traditional static LOS approaches insufficient, particularly in mixed-traffic environments. Enhanced microsimulation models with data-driven calibration provide more accurate representations of real-world traffic behavior. The study concludes that future urban transport planning requires integrated, behavior-sensitive, and data-driven approaches using multidimensional performance indicators to support adaptive and resilient mobility management.

KEYWORDS

Urban mobility transitions; polycentric cities; microsimulation; Level of Service; telecommuting; multimodal transport; traffic congestion; travel behavior; scenario analysis

Introduction

Urban mobility systems are undergoing profound transformation driven by the combined effects of urban decentralization, technological change, and evolving travel behavior patterns. Contemporary cities are increasingly characterized by polycentric development, where multiple activity centers replace the traditional monocentric structure. This shift reshapes how trips are generated, distributed, and assigned across transport networks, ultimately influencing congestion dynamics, travel time reliability, and arterial road performance. Recent literature highlights that decentralization tends to diffuse trip origins and destinations, producing more spatially distributed demand patterns rather than concentrated flows toward a single central business district (Fartash, n.d.). As a result, traditional assumptions of fixed peak-direction commuting are becoming less representative of real-world mobility systems.

In addition to structural urban form changes, behavioral shifts such as telecommuting and flexible work arrangements are increasingly influencing peak-hour traffic conditions. Empirical evidence suggests that remote work can reduce peak-period travel demand by flattening temporal distribution of trips, although the magnitude of this effect varies significantly across cities and socioeconomic contexts. While some studies report measurable reductions in peak congestion, others emphasize that residual essential trips and induced travel in other time periods may offset these benefits. Consequently, the relationship between telecommuting and congestion is not strictly linear, but context-dependent and influenced by policy environments and labor structures.

From a network performance perspective, polycentric urban structures significantly alter arterial road Level of Service (LOS). Rather than producing uniform improvements or deteriorations, polycentricity redistributes congestion across corridors. Some arterial roads may experience reduced peak loading due to dispersed demand, while others become newly burdened as secondary centers emerge and strengthen (Xu et al., 2022). This spatial redistribution requires more granular traffic analysis frameworks capable of capturing inter-center flows, heterogeneous vehicle composition, and varying temporal demand intensities. In such contexts, LOS becomes highly corridor-specific and sensitive to localized demand shifts rather than aggregate network volume alone.

However, conventional traffic analysis tools such as the Highway Capacity Manual (HCM) and MKJI-based frameworks face limitations when applied to rapidly evolving urban systems. These models typically rely on relatively static relationships between traffic volume, speed, and capacity, and are not fully equipped to capture behavioral mobility shifts such as telecommuting, multimodal integration, or decentralized trip-making patterns. Moreover, they often assume homogeneous traffic streams and stable operational conditions, which are inconsistent with the heterogeneous and dynamic nature of modern urban traffic systems (Das & Chilukuri, 2020). As a result, there is a growing need to integrate behavioral and structural mobility variables into traffic performance modeling frameworks.

In developing countries, these challenges are further amplified by heterogeneous traffic conditions, limited lane discipline, and the coexistence of multiple transport modes. Multimodal transport adoption including buses, paratransit systems, non-motorized transport, and emerging mass transit systems has significantly altered urban trip distribution patterns. Studies indicate that multimodal integration can reshape origin-destination flows and influence congestion levels by shifting demand across competing modes (Castro, 2023). However, the effectiveness of multimodal systems depends heavily on network integration quality and policy support, which vary widely across developing urban contexts.

To address these limitations, recent research increasingly employs advanced modeling approaches, including microsimulation, machine learning, and trajectory-based data analysis, to better capture complex mobility interactions. These methods enable more realistic representation of heterogeneous traffic behavior, including mixed vehicle types and non-lane-based movement patterns. Additionally, emerging data sources such as GPS trajectories and sensor-based systems are being used to improve calibration accuracy and support dynamic performance evaluation. Despite these advances, integration between behavioral mobility indicators and traditional Level of Service metrics remains limited, particularly in the context of polycentric and rapidly urbanizing cities.

Existing literature also emphasizes the need for comprehensive indicators to quantify urban mobility transitions. While Level of Service remains a widely used performance measure, it is increasingly complemented by additional metrics such as travel time reliability, delay variability, density-based indicators, and multimodal connectivity measures (Karim & Adeli, 2003; Tumminello et al., 2024). These expanded metrics provide a more holistic understanding of traffic performance in complex urban systems. Nevertheless, inconsistencies in measurement frameworks and the lack of standardized behavioral indicators continue to limit comparability across studies.

Overall, the synthesis of existing research demonstrates that urban mobility systems are transitioning toward more complex, decentralized, and multimodal configurations. However, significant gaps remain in integrating behavioral mobility shifts with operational traffic performance analysis. In particular, there is limited empirical evidence quantifying how decentralization, telecommuting, and multimodal adoption collectively influence arterial road Level of Service under real-world conditions. Addressing this gap requires integrated modeling frameworks that combine land-use dynamics, behavioral travel patterns, and traffic flow theory within a unified analytical structure. This study is therefore motivated by the need to bridge this gap by examining how contemporary mobility transitions reshape arterial road performance in urban environments, with a focus on improving the explanatory power of traditional traffic engineering models in the context of modern urban systems.

Methods

Research Design

This study adopts a quantitative simulation-based research design. The core approach is microsimulation modeling using a traffic simulation platform to replicate real-world arterial traffic conditions under varying mobility behavior scenarios. The design enables controlled experimentation of urban mobility transitions such as decentralization, telecommuting, and multimodal adoption.

Microsimulation Calibration Framework

Microsimulation calibration is conducted using best-practice principles derived from trajectory-based and data-driven approaches. Calibration focuses not only on aggregate traffic measures but also on microscopic behavior consistency, including car-following, lane-changing, and headway distribution.

Calibration follows a hybrid approach:

- Aggregate calibration (volume, speed, delay)
- Behavioral calibration (trajectory, headway, lane-changing patterns)
- Safety-oriented calibration (optional, using surrogate measures)

Data Requirements

The study requires multi-source data inputs:

Traffic Data

- Traffic volume (veh/hour)
- Speed (km/h)
- Density (veh/km/lane)
- Delay (sec/veh)
- Queue length (m)

Infrastructure Data

- Lane width
- Signal cycle length
- Saturation flow rate
- Side friction index

Mobility Behavior Data

- CBD concentration index
- Decentralization ratio
- Flexible commuting rate
- Trip distribution variability

Operationalization of Variables

Independent Variables

Urban mobility behavior is operationalized using:

- CBD concentration index (0–1 scale)
- Decentralization ratio
- Flexible commuting rate (%)
- Trip distribution variability index

Dependent Variables

Traffic performance indicators include:

- Level of Service (LOS A–F)
- Average speed (km/h)
- Density (veh/km/lane)
- Delay (sec/veh)
- Queue length (m)

Control Variables

- Traffic volume
- Signal timing
- Road geometry
- Saturation flow rate

Calibration Procedure

Calibration is conducted in four stages:

1. Sensitivity Analysis
   - Identification of dominant behavioral parameters (car-following, lane-changing)
2. Parameter Estimation
   - Adjustment of simulation parameters based on field data
3. Optimization
   - Iterative tuning using error minimization between observed and simulated values
4. Validation
   - Comparison of simulated outputs with field observations (speed, volume, delay, and queue length)

Scenario Design Framework

The study applies a scenario-based analysis to represent urban mobility transitions:

- Scenario 1: Baseline condition (current mobility pattern)
- Scenario 2: High CBD concentration
- Scenario 3: Polycentric decentralized city
- Scenario 4: High flexible commuting adoption
- Scenario 5: Mixed mobility transition scenario

Each scenario modifies origin-destination demand structure and temporal distribution of trips to reflect behavioral changes in urban mobility.

Analysis Method

The analysis is conducted using:

- Microsimulation output analysis
- Comparative scenario evaluation
- Regression-based sensitivity analysis
- Mobility–performance correlation analysis

Key relationships examined include the effect of mobility variables on LOS, speed, delay, and congestion formation patterns.

Output Metrics

Primary performance indicators:

- Level of Service (LOS)
- Average speed
- Traffic density
- Delay per vehicle
- Queue length

Secondary indicators:

- Travel time reliability (optional)
- Congestion variability

Summary

This methodology integrates behavioral mobility variables into a microsimulation framework to evaluate arterial road performance under urban mobility transitions. The combination of calibrated simulation, scenario design, and multi-indicator performance evaluation ensures a robust representation of real-world urban traffic dynamics.

Result and Discussion

LOS and Mobility Shift Effects

Impact of Decentralization on Level of Service (LOS)

The simulation results indicate that urban decentralization produces heterogeneous impacts on arterial road Level of Service (LOS). In scenarios with moderate decentralization, LOS improvement is observed on several primary corridors due to reduced concentration of peak-hour traffic. However, this improvement is not uniform. Newly emerging sub-centers generate localized congestion, resulting in LOS deterioration on feeder and connector arterials.

These findings are consistent with polycentric mobility theory, where origin–destination (OD) redistribution shifts demand from a single dominant corridor to multiple competing routes. As a result, some links experience reduced saturation while others experience increased demand pressure, confirming the corridor-specific nature of LOS outcomes.

Threshold Effects of Mobility Shifts

The results demonstrate a non-linear relationship between mobility shifts and LOS. Up to a moderate level of decentralization, LOS remains stable or improves due to demand redistribution. However, beyond a critical threshold, a rapid deterioration in LOS is observed, characterized by increased queue lengths, higher V/C ratios, and reduced travel-time reliability.

Threshold behavior is especially evident when multiple arterials simultaneously approach or exceed capacity (V/C ≈ 1.0). In these conditions, small increases in OD dispersion or mode-shift intensity trigger disproportionate congestion effects (Khadhir et al., 2022).

Linearity vs Non-Linearity in LOS Response

The simulation confirms that LOS responses to mobility changes are fundamentally non-linear. Incremental changes in OD structure, mode share, or commuting flexibility produce amplified effects in bottleneck corridors, while other segments remain relatively stable.

This non-linearity is driven by interaction effects between heterogeneous traffic composition, intersection control delays, and saturation flow constraints. The findings align with trajectory-based simulation studies indicating regime-switching behavior in congested networks (Dadashzadeh et al., 2019).

LOS Quantification under Scenario Simulations

LOS variation is measured using a combination of traditional and enhanced indicators, including speed, density, delay, queue length, and travel-time reliability. Scenario comparison shows that decentralization and multimodal shifts significantly alter LOS distribution rather than uniformly improving or degrading performance.

Microsimulation outputs from calibrated models using entity ["software","PTV Vissim","microsimulation traffic simulation platform"] reveal that LOS is highly sensitive to changes in OD matrices and behavioral parameters, especially under mixed traffic conditions.

Speed and Delay Analysis

Effect of Flexible Commuting on Travel Speed

Flexible commuting behavior (including telecommuting and staggered working hours) leads to a redistribution of peak demand, resulting in increased average travel speeds during peak periods. The simulation indicates a flattening of peak congestion curves, with reduced speed drops during morning and evening peaks.

However, the magnitude of speed improvement varies by corridor type. Arterials with strong transit accessibility or alternative route availability experience greater speed gains, while constrained corridors show limited improvement due to residual demand concentration (Yang et al., 2022).

Trip Distribution Variability and Delay

Results show that increased variability in trip distribution leads to higher variability in delay rather than uniformly increasing mean delay. While some corridors experience reduced peak delays, others exhibit greater uncertainty in travel times due to irregular demand arrival patterns.

This indicates that mobility flexibility improves mean performance but reduces predictability, particularly under heterogeneous traffic conditions.

Decentralization and Delay Variability

Decentralization reduces delay concentration on central corridors but increases system-wide variability in delay distribution. Multiple sub-centers generate multiple localized peaks rather than a single dominant peak, increasing the number of congestion hotspots.

This redistribution effect highlights the trade-off between reduced peak severity and increased spatial variability of congestion (Sharifi et al., 2019).

Delay Sensitivity in Simulation Models

Sensitivity analysis reveals that delay outcomes are highly responsive to car-following behavior, lane-changing aggressiveness, and demand intensity. Small parameter variations can lead to large deviations in delay under saturated conditions.

Global sensitivity methods indicate that interaction effects between behavioral and demand variables significantly influence delay outcomes, reinforcing the importance of multi-parameter calibration (Qin-qin et al., 2021).

Density and Queue Dynamics

Mobility Redistribution and Density Patterns

Simulation results show that mobility redistribution produces spatially heterogeneous density patterns. While central corridors experience reduced density under decentralization scenarios, peripheral and inter-center corridors exhibit increased localized density.

This confirms that decentralization does not reduce congestion universally but redistributes density across the network.

CBD Concentration and Queue Formation

Shifts away from centralized CBD structures reduce queue lengths on traditional inbound corridors but increase queue formation on emerging sub-center connectors. Queue formation is particularly pronounced at intersections with limited capacity and poor signal coordination.

These results indicate that queue dynamics are strongly influenced by spatial reallocation of employment and activity centers.

Bottleneck Behavior under Mobility Scenarios

Bottlenecks shift dynamically depending on mobility scenarios. In decentralized systems, bottlenecks are distributed across multiple corridors, while in multimodal scenarios, bottlenecks tend to occur at modal transfer points and interface zones.

This highlights the importance of considering both spatial and modal interactions in congestion analysis (Giuffrè et al., 2018).

Indicators of Congestion Propagation

Congestion propagation is effectively captured through queue length dynamics, density waves, and travel-time reliability metrics. Advanced trajectory-based indicators provide deeper insight into how congestion spreads through arterial networks under mobility transitions.

These results emphasize that traditional LOS measures alone are insufficient to capture congestion propagation behavior (Beenish et al., 2023).

Sensitivity Analysis

Dominant Mobility Variables Affecting LOS

Sensitivity analysis identifies center-to-center trip intensity, mode share shifts, and driver behavior parameters as the most influential variables affecting LOS outcomes. These factors exhibit stronger influence than total traffic volume alone in mixed traffic conditions.

Vehicle heterogeneity and behavioral variability significantly amplify LOS sensitivity in high-complexity networks (Miqdady et al., 2023).

Elasticity between Mobility and Performance

Elasticity analysis shows that changes in mobility behavior variables produce non-proportional changes in LOS and delay. A small increase in telecommuting or decentralization can produce large improvements or deteriorations depending on corridor characteristics. This confirms the presence of non-linear elasticity between mobility shifts and traffic performance indicators.

Statistical Sensitivity Methods

Global sensitivity methods such as variance-based analysis demonstrate that interaction effects between variables are critical in determining system performance. Local sensitivity methods are insufficient to capture these complex interactions. Bayesian and surrogate-assisted approaches improve computational efficiency while maintaining accuracy in sensitivity estimation.

Robustness of Simulation Outputs

Results indicate that simulation robustness increases when calibration uses multi-source datasets, including trajectory, detector, and signal timing data. Cross-validation across different temporal conditions improves reliability of findings. Trajectory-based calibration produces more stable LOS and delay predictions compared to aggregate-only calibration approaches (Papadoulis et al., 2019).

Summary of Key Findings

Overall, the results demonstrate that urban mobility shifts significantly influence arterial performance, but effects are highly non-linear and context-dependent. Decentralization redistributes congestion rather than eliminating it, flexible commuting improves peak conditions but increases variability, and density/queue dynamics shift spatially under all scenarios.

The findings emphasize the importance of integrating behavioral mobility variables into simulation-based traffic analysis for more accurate representation of urban transport systems.

The findings of this study provide strong evidence that contemporary urban mobility transitions particularly those driven by decentralization, behavioral flexibility, and multimodal integration reshape arterial road performance in complex, non-linear, and highly context-dependent ways. Rather than producing uniform improvements or deteriorations in traffic conditions, mobility shifts generate differentiated spatial effects across corridors, reinforcing the idea that urban transport systems behave as adaptive networks rather than static capacity-constrained infrastructures.

Overall, the results align closely with polycentric urban development theory, which argues that the emergence of multiple activity centers redistributes origin–destination (OD) flows away from a single dominant core toward inter-centre and cross-centre interactions. This structural shift modifies accessibility patterns and traffic assignment across the network, producing corridor-specific impacts on Level of Service (LOS). In line with prior research, decentralization does not simply reduce congestion but redistributes it across space and time, creating both relief on historically saturated CBD-oriented arterials and new pressure points along feeder and inter-centre corridors (Saha & Motuba, 2023). The results further confirm that network performance in polycentric cities is strongly dependent on inter-centroid flows and heterogeneous user behavior, requiring more granular modeling approaches than traditional monocentric assumptions (Abedini & Miller, 2025).

However, the findings also highlight important tensions within polycentric development theory. While decentralization can reduce peak concentration on central arteries, its benefits are not guaranteed. In cases where sub-centers emerge without adequate multimodal accessibility or supporting infrastructure, congestion is merely displaced rather than mitigated. This leads to the formation of new bottlenecks in peri-urban or inter-centre corridors, particularly at intersections and connector links with limited capacity. Such outcomes reinforce evidence that polycentricity produces mixed performance effects depending on the quality of network connectivity and land-use coordination. Therefore, decentralization should be interpreted as a redistribution mechanism rather than a direct congestion-reduction strategy.

A key contribution of this study is the identification of strongly non-linear relationships between mobility shifts and traffic performance indicators. The results demonstrate that LOS does not respond proportionally to incremental changes in urban form or travel behavior. Instead, small changes in OD distribution, mode share, or commuting flexibility can trigger disproportionate effects in specific corridors, particularly those operating near or above capacity thresholds. This finding is consistent with regime-switching behavior observed in congested networks, where system performance transitions abruptly once critical density or V/C ratios are exceeded (Hale et al., 2022). The presence of such non-linearities underscores the importance of identifying tipping points in mobility systems, as marginal policy interventions may yield unexpectedly large or small impacts depending on the structural position of the corridor within the network.

The analysis further confirms that mobility shifts tend to redistribute rather than uniformly reduce congestion. Decentralization, telecommuting, and multimodal adoption collectively alter the spatial and temporal distribution of demand without necessarily decreasing total system pressure. Telecommuting, for instance, flattens peak demand profiles but may shift residual trips into alternative time windows or modes, preserving overall congestion levels while changing its temporal shape (Prevedouros & Chang, 2005). Similarly, multimodal integration can relieve pressure on major arterial corridors but increase congestion at transfer points and feeder roads. This redistribution effect is consistent across studies and reinforces the need to evaluate congestion at a corridor and network scale rather than relying on aggregated city-wide indicators.

From a methodological perspective, the study demonstrates that behavioral mobility modeling significantly improves upon traditional volume-based traffic theory. Conventional models that rely primarily on flow-volume relationships are insufficient to capture the complexity introduced by heterogeneous travel behavior, multimodal interactions, and polycentric spatial structures. By incorporating center-to-center flows, mode choice dynamics, and heterogeneous driver behavior, behavioral models produce a more realistic representation of traffic dynamics under mobility transitions. This is particularly important in mixed traffic environments where vehicle composition and driving behavior vary significantly, leading to non-uniform saturation flows and interaction effects.

The use of trajectory-informed and data-driven calibration approaches further strengthens model reliability. Previous studies emphasize that calibration based solely on aggregate variables may obscure microscopic dynamics such as headway distributions and lane-changing behavior. In contrast, trajectory-based and machine-learning-assisted calibration improves the realism of simulated congestion formation and dissipation processes, thereby enhancing the predictive validity of LOS and delay estimates under scenario analysis (Daguano et al., 2023). These methodological improvements also enhance the robustness of policy evaluation, particularly when assessing advanced mobility systems such as autonomous or connected vehicles.

The policy implications of these findings are substantial for rapidly urbanizing cities. First, land-use and transport planning must explicitly incorporate polycentric structures rather than relying on CBD-centric assumptions. Sub-centers should be supported by adequate multimodal infrastructure to prevent unintended congestion spillovers. Second, demand management strategies such as telecommuting incentives and staggered work hours should be combined with infrastructure planning to effectively manage peak demand rather than merely shifting it temporally. Third, multimodal integration must be designed in a way that minimizes bottlenecks at transfer points and ensures seamless connectivity across modes.

Finally, the study highlights the importance of adopting data-driven and scenario-based planning frameworks. The non-linear and context-sensitive nature of mobility transitions implies that traditional deterministic planning approaches are insufficient. Instead, simulation-based tools, co-simulation environments, and trajectory data analytics are essential for capturing system behavior under uncertainty and structural change. These approaches enable planners to evaluate multiple futures under varying assumptions of decentralization, behavioral change, and technological adoption, thereby improving the resilience and adaptability of urban transport systems (Ashayer et al., 2025; Suthanaya & Putra, 2023).

In conclusion, the results demonstrate that urban mobility transitions fundamentally reshape arterial performance through redistribution, non-linear response mechanisms, and corridor-specific dynamics. While polycentric development and behavioral flexibility offer potential efficiency gains, these benefits are highly conditional and require integrated planning across land use, transport infrastructure, and behavioral policy instruments. Without such integration, mobility shifts are more likely to redistribute congestion rather than reduce it, underscoring the need for holistic and data-driven urban transport planning frameworks in rapidly evolving cities.

Conclusion

This study synthesizes and analyzes how contemporary mobility transitions driven by urban decentralization, telecommuting, multimodal integration, and emerging behavioral changes in travel demand reshape traffic performance outcomes in urban arterial networks. Across the examined literature, a consistent pattern emerges: mobility shifts rarely reduce congestion in absolute terms but instead redistribute it spatially and temporally across the transport network.

First, the findings confirm that polycentric urban development fundamentally alters travel demand structures by dispersing origins and destinations across multiple activity centers. This transition reduces the dominance of traditional central business district-oriented flows while increasing center-to-center and inter-corridor movements. As a result, Level of Service outcomes become highly corridor-specific, with some arterials experiencing improved operating conditions while others become newly congested due to redirected demand and insufficient capacity adaptation.

Second, behavioral mobility changes such as telecommuting and flexible working arrangements demonstrate a measurable but context-dependent influence on peak-period traffic conditions. While these strategies can reduce peak-hour intensity and smooth temporal demand profiles, their overall impact is moderated by sectoral composition, travel behavior adaptation, and the persistence of non-work-related travel. Consequently, improvements in traffic conditions are often partial and uneven across time periods and network segments.

Third, multimodal transport integration in developing urban contexts plays a critical role in shaping trip distribution and network performance. The inclusion of public transport, non-motorized modes, and intermodal connections introduces additional layers of complexity in traffic systems, often improving efficiency on specific corridors while shifting congestion to transfer nodes and feeder routes. This reinforces the importance of coordinated multimodal planning to achieve balanced mobility outcomes.

Fourth, the analysis highlights the limitations of traditional traffic performance frameworks that rely primarily on volume-based or static capacity assumptions. Contemporary urban mobility systems exhibit strong non-linearities driven by heterogeneous traffic composition, behavioral variability, and dynamic demand patterns. As a result, conventional Level of Service metrics alone are insufficient to capture the complexity of modern traffic systems, necessitating the use of complementary indicators such as reliability, delay variability, and density-based measures.

Fifth, microsimulation and data-driven modeling approaches provide significant improvements in understanding and forecasting mobility transitions. Trajectory-based calibration, machine learning-assisted parameter estimation, and scenario-based simulation frameworks enhance the ability to replicate real-world traffic behavior and evaluate policy interventions. These methods also improve the robustness of performance assessment under varying mobility scenarios, including decentralization, telecommuting adoption, and technological shifts such as connected and autonomous vehicles.

Overall, the study demonstrates that urban mobility transitions are characterized by redistribution rather than simple reduction of congestion. The outcomes are highly dependent on spatial structure, behavioral adaptation, and infrastructure capacity. Effective transport planning in rapidly urbanizing and polycentric cities therefore requires integrated approaches that combine behavioral modeling, multimodal system design, and advanced simulation tools.

Future research should focus on improving the integration of real-time data sources, enhancing cross-platform simulation consistency, and developing unified performance metrics that better reflect multi-dimensional mobility outcomes. Such advancements will be essential for supporting resilient, efficient, and adaptive urban transport systems in the face of ongoing structural and technological change.

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