Four integrated approaches in order to set consistent strategy to solve saturated mobility areas

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***Abstract*— The critical challenges posed by saturated urban mobility, where population and vehicle densities exceed infrastructure capacity, resulting in chronic congestion and the degradation of public space. These bottlenecks generate systemic negative impacts, including diminished economic productivity, heightened environmental pollution, and the exacerbation of social inequalities—particularly in metropolises like São Paulo. To mitigate these issues, this study evaluates established three approaches from literature review in order to propose a novel integrated model that synthesizes three existing literature-based approaches with a fourth original methodology, aiming to harmonize the efforts of diverse urban stakeholders and restore fluidity to the urban fabric.**

Keywords—Saturated Urban Mobility, Mobility Bottlenecks, Mobility Noise and Pollution

I. INTRODUCTION

Areas with saturated mobility are characterized by population and vehicle densities that drastically exceed the designed capacity of existing urban infrastructure. These geographic “bottlenecks” manifest at points where the flow of people and goods converges in a disorderly manner, resulting in chronic congestion, overcrowded transit terminals, and sidewalks that are insufficient for the volume of pedestrians. Saturation is often visible through the degradation of public space, where the struggle for every square inch between cars, buses, cyclists, and pedestrians creates an environment of constant friction, lack of fluidity, and stagnation of movement.

The problem these areas pose for large cities lies in the systemic impact they have on quality of life and the local economy. Congestion undermines the predictability of travel, resulting in significant losses of time and productivity, while also drastically increasing levels of air and noise pollution, which worsens public health. In metropolises like São Paulo, these bottlenecks isolate outlying neighborhoods and overload the health and transportation systems, exacerbating social inequality, since the most vulnerable populations are the ones who suffer the most from delays and precarious access to centers of opportunity.

To solve or alleviate congestion, the implementation of Sustainable Transport-Oriented Development (DOTS) strategies is essential. This involves prioritizing high-capacity public transit, such as dedicated lanes and subways, combined with the creation of micromobility infrastructure that discourages the use of private cars. In addition, tactical urban planning solutions—such as widening sidewalks, creating low-emission zones, and decentralizing public services to reduce the need for long commutes—can transform congested areas into shared spaces. The use of real-time traffic management technologies and incentives for staggered work schedules have also proven to be effective tools for smoothing out demand peaks and restoring fluidity to the urban fabric.

Although there is a vast body of research on solving problems related to urban areas with congested mobility, it is evident that the application of these techniques has not yet led to integrated strategies; this is the objective of this article, which proposes the integration of three approaches from the literature and a fourth, suggested by the authors of this article, in order to bring together the efforts of various stakeholders in a city.

II. LITERATURE REVIEW: THE THREE APPROACHES

A. First approach by (Phil. Trans. R. Soc. A, 2024) [1]

Based on the research paper "Addressing the urban congestion challenge based on traffic bottlenecks" (Phil. Trans. R. Soc. A, 2024) [1], the current approach to traffic bottlenecks has shifted from simple road widening to a sophisticated, data-driven "Decentralized Traffic Management" framework.

Instead of viewing congestion as a city-wide problem, these techniques isolate the specific "root" of the delay.

- Jam Trees (JT) Analysis: A method used to track the evolution of congestion in real-time. By treating a traffic jam like a "tree" that grows and branches across a network, planners can identify the "seed" or the exact link where the bottleneck originates.

- Spatiotemporal Meso-Dynamics: Research highlights that bottlenecks are rarely static. By analyzing meso-scale dynamics, planners can see how bottleneck locations shift throughout the day, allowing for interventions that move in sync with the traffic flow.

- Big Data Integration: Leveraging real-time data from navigation apps and IoT sensors to move beyond historical "averages" toward predictive, momentary snapshots of traffic cost. [2]

The study argues for a shift away from top-down, rigid urban hierarchies toward a flexible, decentralized system.

- Early Detection & Prediction: By identifying the formation of a bottleneck in its infancy, authorities can implement preventative measures (e.g., altering signal timings or pushing app alerts) before a "jam tree" becomes unmanageable.

- Congestion Cost Calculation: Techniques now exist to calculate the "cumulative cost" of a specific bottleneck—including time lost and environmental impact—helping planners prioritize which intersections or road links require the most urgent infrastructure investment.

The papers [1] and [2] emphasizes "reasserting the role of urban planning" by combining physical layouts with digital tools.

- Complex Systems Science: Using mathematical models of complex systems to understand how a single bottleneck can trigger a "cascade failure" across the entire city grid.

- Dynamic Zoning: Using bottleneck data to define temporary "Low Emission Zones" or "Restricted Access Zones" in real-time during peak congestion periods.

Modern techniques must account for the "App Effect," where navigation software unintentionally creates new bottlenecks by routing thousands of cars onto small residential streets. [1] and [2]

- System-Centric Routing: Working with navigation providers to ensure that route selection factors in the city's network hierarchy, rather than just the shortest individual travel time.

- Macro-Scale Scaling Laws: Applying universal scaling laws to predict how city size and population growth will naturally increase the frequency of bottlenecks, allowing for "future-proof" road designs.

B. *Second approach by (Land 2024, 13(2), 255) [3]*

The study "Analysis of Urban Congestion Traceability: The Role of the Built Environment" (Land 2024, 13(2), 255) [3] shifts the focus from simple traffic volume to the built environment's role in creating bottlenecks. It argues that physical urban characteristics—like building density and road network design—are the root causes of congestion.

The papers [3] and [4] introduce "Traceability" as a core technique. Instead of just treating the symptom (the traffic jam), planners identify the originating factors in the built environment.

- Built Environment Profiling: Identifying how factors like building density, land-use diversity, and floor area ratios contribute to traffic "black spots."

- Spatiotemporal Correlation: Using big data to trace how congestion "propagates" from specific complex crossings or high-density blocks to the rest of the city network.

The researches [3] and [4] emphasize that traditional "top-down" construction is often too slow, favoring more flexible structural interventions:

- Complexity Reduction of Crossings: Simplifying "complicated crossings" (identified via geodata like OpenStreetMap) where merging traffic and multiple signal phases create natural bottlenecks.

- Strategic Road-Width Tweaking: Instead of massive expansion, localized widening or narrowing (road diets) is used to balance flow and prevent "bottlenecking" at entry ramps.

- Multi-Agent Reinforcement Learning (MARL): Implementing AI-driven systems that coordinate multiple entrance ramps simultaneously, ensuring that one ramp's relief doesn't create a bottleneck further downstream.

The studies [3], [4] and [5] advocate for "proactive" rather than "reactive" management through Intelligent Transportation Systems (ITS):

- Variable Speed Limits (VSL): Dynamically adjusting upstream speed limits to prevent a "shockwave" of braking when vehicles approach a bottleneck.

- Lane Change Control (LCC): Using digital signage or connected vehicle data to issue mandatory lane-change instructions well before a merge point, reducing the "weaving" behavior that often triggers jams.

- Combined VSL-LCC Systems: Using these two techniques synergistically to homogenize traffic flow and stabilize vehicle density in heavy traffic regions.

Since infrastructure has physical limits, the paper discusses "soft" techniques to manage the load on bottlenecks:

- Congestion Pricing: Implementing fees for entering specific high-density zones or using bottleneck-prone bridges/tunnels during peak hours.

- Public Travel Guidance: Using real-time data to "nudge" commuters toward alternative routes or transit modes before they enter a known bottleneck region.

- Subway & Public Transport Boosting: Expanding high-capacity rail lines as a "structural" relief valve for the road network's bottlenecks.

The research highlights that structural bottlenecks (caused by road design) and functional bottlenecks (caused by high-density land use) must be treated together. The goal is a "feedback loop" where real-time data informs flexible urban planning, moving away from rigid, permanent road structures.

C. *Third approach by (Montenegro et. al., 2024) [6]*

Based on the research detailed in the study (Montenegro et. al., 2024) [6], classifying urban areas into specific "city blocks" or regions based on their environmental and structural characteristics is a transformative tool for managing mobility.

Classifying city blocks allows planners to understand how urban form (the shape and arrangement of buildings) interacts with traffic.

- Acoustic Shielding: By identifying "closed" vs. "open" block structures, cities can route heavy traffic away from blocks that naturally amplify noise (canyon effects) and toward those that can better dissipate or shield residential interiors from sound.

- Pollutant Trapping: Classification identifies "street canyons" where high-rise buildings prevent air circulation. This allows for mobility interventions—such as congestion pricing or vehicle restrictions—specifically in blocks where pollutants reach dangerous concentrations.

The research [6] supports the "Superblock" model, which uses region classification to reorganize traffic flow.

- Traffic Filtering: By classifying a 3x3 grid of blocks as a single unit, "through-traffic" is pushed to the perimeter. This reduces the number of vehicles in "inner" heavy traffic areas, drastically lowering local noise and air pollution.

- Modal Shift: Identifying blocks with high pedestrian potential allows cities to convert those specific regions into low-emission zones (LEZs), encouraging a shift from private cars to active mobility (walking/cycling).

Rather than applying city-wide rules that may be inefficient, block-level classification allows for surgical precision in heavy traffic management:

- Dynamic Speed Limits: Lowering speeds in blocks classified as "noise-sensitive" or "poorly ventilated" can reduce noise by several decibels and decrease the "stop-and-go" emissions typical of heavy traffic.

- Electrification Priority: Classification helps identify "Hotspot Regions." Cities can then prioritize these specific regions for electric bus routes or EV-only delivery zones, maximizing the health ROI of infrastructure spending.

The studies [6] and [7] highlight that certain block shapes (like rectangular grids) promote more fluid traffic than others (triangular or irregular).

- Reducing "Cruising" and Idle Time: Proper classification informs the placement of smart parking and delivery hubs, reducing the 30% of traffic typically caused by drivers looking for parking in congested regions.

- Environmental Benchmarking: By classifying regions, cities can set specific "Environmental Capacity" limits—once a block reaches its noise or pollution threshold, smart traffic management systems can re-route incoming vehicles to alternative paths.

Classifying the city at the block level transforms "mobility" from a simple task of moving cars into a sophisticated strategy for enhancing urban livability. It moves us away from generic traffic management toward Environmental Traffic Management (ETM).

III. DISCUSSION ON THREE REFERENCE APPROACHES

The synthesis of these three previously described approaches reveals a shift in urban management: moving away from simply "building more roads" toward a precision-engineered, data-driven ecosystem where the physical environment and digital intelligence work in tandem.

By merging these insights, is possible to plan a three-pivoted conclusion on the future of urban mobility:

The integration of these approaches shows that traffic bottlenecks are rarely random; they are the physical manifestation of urban morphology.

- The first approach provides the "where" (classifying blocks by shape and environmental sensitivity).

- The second approach the "how" (tracking the "Jam Tree" evolution of a bottleneck).

- The third approach the "why" (linking congestion to building density and land-use).

Modern cities must use Traceability Analysis to determine if a bottleneck is a structural failure (bad road design) or a functional failure (over-dense land use) before applying a solution.

There is no longer possibility to rely solely on physical infrastructure. The most effective way to handle heavy traffic and pollution is a "hybrid" approach:

- Hard Interventions: Reorganizing city blocks into Superblocks to physically filter through-traffic and creating "acoustic shields" through building arrangement.

- Soft Interventions: Utilizing AI-driven decentralized management, such as Variable Speed Limits (VSL) and Lane Change Control (LCC), to "smooth" the flow of traffic before it hits a known bottleneck.

The most critical takeaway is that mobility and environmental health are now inseparable. The studies collectively suggest that managing a bottleneck is no longer just about "saving time"—it is about:

- Air Quality: Reducing the "stop-and-go" emissions in "street canyons."

- Noise Control: Routing heavy loads away from "noise-sensitive" block classifications.

- Health ROI: Prioritizing interventions in "Hotspot Regions" where the built environment naturally traps pollutants.

IV. FOURTH APPROACH AND ITS INTEGRATION TO ONES PREVIOUSLY PRESENTED

The integration of drones, high-definition cameras, and IoT sensors creates a multi-layered monitoring ecosystem that can be segmented into high-resolution grids, such as a three-block radius. At the ground level, stationary sensors embedded in pavement, streetlights, and waste bins collect granular data on localized environmental conditions and physical occupancy. These sensors monitor real-time variables like parking space availability, air quality indices, and seismic vibrations from heavy transit, providing the continuous "baseline" data necessary to understand the unique metabolic pulse of those specific blocks.

To complement this static data, AI-powered cameras mounted at key intersections provide the visual intelligence required for flow management. By utilizing edge computing, these cameras can categorize traffic—distinguishing between cyclists, pedestrians, and emergency vehicles—without compromising individual privacy through anonymization protocols. Within a three-block grid, this allows the city's central nervous system to identify immediate bottlenecks or safety hazards, such as an illegal double-parking incident that might be invisible to ground sensors but is clearly captured by a wide-angle lens.

Autonomous drones act as the dynamic layer of this infrastructure, serving as rapid-response aerial nodes that can be deployed to any point within the three-block grid in seconds. While cameras are fixed, drones provide "on-demand" perspective, offering vertical inspection of building facades or overhead views of unfolding emergency situations. In a smart city framework, drones can also function as mobile signal boosters or data relays, ensuring that the information gathered by ground sensors in "dead zones" is successfully transmitted to the cloud during high-interference periods.

Such triad lies in data fusion, where information from all three sources is synthesized into a digital twin of the urban environment. In this model, a sensor might detect a sudden spike in acoustic noise, triggering a nearby camera to pivot toward the sound, while a drone is automatically dispatched to provide an aerial assessment for first responders. By confining this high-density integration to a three-block grid, city planners can manage the "micro-mobility" of the neighborhood with extreme precision, ensuring that the infrastructure is not just reactive, but predictive in its maintenance and service delivery.

To implement a sophisticated sensor-drone network, the logical starting point is a comprehensive diagnostic assessment that identifies "hotspots" based on saturated mobility and environmental degradation. By cross-referencing traffic density data with air quality indices, city planners can rank three-block grids by their level of "urban stress." This data-driven prioritization ensures that the initial capital investment is directed toward areas where the return on quality of life—such as the reduction of nitrogen dioxide levels or the alleviation of chronic transit delays—will be most immediate and measurable.

The integration of Programmatic Digital Out-of-Home (pDOOH) advertising into the smart city grid offers a powerful mechanism for real-time communication and behavioral nudging. By synchronizing digital billboards and transit displays with the data harvested from the three-block sensor network, the city can transform static advertisements into context-aware public service tools. For instance, if ground sensors and cameras detect a sudden spike in congestion or a critical drop in air quality within a specific grid, the pDOOH platform can instantly override scheduled commercial content to display alternative route suggestions or public health alerts. This creates a responsive communication loop where the "voice" of the city reacts dynamically to the physical state of the block, ensuring that the information is relevant to the immediate audience.

Beyond emergency alerts, pDOOH can be leveraged to incentivize sustainable mobility shifts through data-driven triggers. By linking the pollution ranking of a specific three-block radius to the advertising algorithm, the system can promote micromobility services—such as nearby bike-sharing or electric scooters—precisely when traffic saturation begins to peak. This synchronization allows for "hyper-local" marketing that supports urban fluidity; for example, offering a discount code for public transit on a digital screen only when the local sensors indicate that the street is reaching its designed vehicle capacity. This transforms pDOOH from a purely commercial asset into a vital component of the city's demand management strategy, aligning private sector infrastructure with the public goal of reducing urban stress.

Following the ranking process, the implementation should move into a micro-infrastructure audit of the selected grids. This involves evaluating existing physical assets, such as the height and spacing of streetlights for camera mounting and the availability of secure "nesting" stations for drones on public building rooftops. Instead of an expensive overhaul, this phase focuses on retrofitting. For instance, a grid identified as a high-pollution zone might be equipped with specialized electrochemical sensors first, creating a "modular" deployment strategy that can be scaled according to the specific needs of that neighborhood.

The third stage focuses on the integration of a localized Digital Twin, a virtual representation of the three-block area. Before the full network goes live, the data feeds from the newly installed sensors and cameras are calibrated within a digital model to simulate various scenarios. This allows stakeholders to test how the system reacts to a simulated emergency or a sudden surge in pedestrian traffic. By starting with a digital-first approach for each grid, the city can fine-tune the AI algorithms responsible for data fusion, ensuring that the automated responses—like drone dispatches—are accurate and do not create unnecessary "noise" or privacy concerns for residents.

Finally, the rollout culminates in a community-centric pilot phase, where the technological benefits are made transparent to the local population. Since these three-block grids are the primary living spaces for thousands, implementation must include public dashboards or mobile apps that share real-time insights—such as the cleanest walking route or the quietest time to visit a local park. By proving the system's value at the block level through tangible improvements in daily convenience and health, the city builds the social trust necessary to expand the network from a few high-priority "cells" into a unified, city-wide smart organism.

V. CONCLUSION

Traditional urban approaches to saturated mobility have largely failed because they often treat symptoms rather than systemic causes, frequently falling into the trap of induced demand. Historically, city planning has relied on expanding road infrastructure to alleviate congestion, a strategy that paradoxically attracts more vehicular traffic and reinforces a cycle of car dependency. Furthermore, these efforts are often fragmented; transport policies frequently operate in "silos," detached from housing or environmental strategies, which prevents the formation of a cohesive, multi-modal network. This lack of integration—combined with a failure to utilize real-time, localized data—means that interventions remain too static and slow to keep pace with the rapid, "disorderly" growth of modern metropolises.

Linking the study of saturated mobility directly to its environmental externalities—specifically air and noise pollution—is essential because these elements exist in a vicious feedback loop that compounds urban decay. When mobility reaches a state of saturation, the resulting "stop-and-go" traffic patterns cause vehicles to operate at their least efficient levels, leading to disproportionately higher emissions of particulate matter and nitrogen oxides compared to free-flowing traffic. By treating congestion and pollution as a singular, integrated metric, city planners can move beyond mere traffic management and toward comprehensive public health protection. This holistic view reveals that a geographic bottleneck is not just a source of lost time, but a localized "toxic cell" where high decibel levels and poor air quality converge to diminish the cognitive and physical well-being of the surrounding population. Furthermore, joining these datasets allows for a more accurate socio-economic impact analysis, ensuring that interventions like Low Emission Zones are placed where they can provide the maximum dual benefit: restoring movement while simultaneously lowering the environmental burden on the city's most vulnerable residents.

The integration of drones, cameras, and IoT sensors within a decentralized three-block grid framework represents a transformative leap from reactive urban management to proactive, data-driven governance. by synthesizing ground-level environmental data with aerial perspectives, cities can move beyond the "bottlenecks" of saturated mobility and address the systemic inequalities that arise from infrastructure failure. This "bottom-up" technological layer ensures that the most congested and polluted areas receive targeted, real-time interventions, effectively turning chaotic urban friction into a streamlined, digital twin of the neighborhood.

A digital twin built from this "micro-grid" approach scales sustainably by utilizing a modular, bottom-up architecture that avoids the prohibitive costs and data silos of traditional, city-wide implementations. By perfecting the digital replica of a three-block radius first, planners can establish a standardized "template" for data interoperability—ensuring that drones, sensors, and pDOOH systems communicate through a unified language. As new grids are added, the digital twin expands like a biological tissue rather than a rigid machine, allowing for distributed processing where data is managed locally to reduce energy consumption and bandwidth strain on central servers. This incremental scalability ensures that the system remains financially viable and technologically adaptable, permitting the city to integrate future innovations without discarding existing infrastructure, thus maintaining a long-term balance between technological growth and resource conservation.

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