Dynamic Road-Space Allocation: A Critical Review of Data, Methods and Readiness for Resilient Urban Transport Systems

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Abstract: Dynamic Road-Space Allocation (DRSA) has emerged as a promising approach for creating flexible, multimodal, and people-centred urban streets. While traditional Dynamic Lane Allocation (DLA) focuses primarily on motor-vehicle lanes, DRSA extends the concept to the entire street cross-section – sidewalks, bike lanes, curb space, and transit facilities – allowing infrastructure to adapt to temporal and spatial variations in demand. This study reviews and synthesizes existing DRSA tools and frameworks to assess their scope, capabilities, and operational readiness. Five tools were recorded using a structured form and systematically examined. Findings reveal that although DRSA shows strong conceptual potential, practical tools remain limited and vary widely in their methodological sophistication. Only one of the tools demonstrates the highest level of maturity, having been tested across multiple European cities. The remaining tools offer valuable modelling approaches but are constrained by simplification assumptions. Across all tools, common gaps relate to governance acceptance and regulatory constraints. The review highlights the need for next-generation DRSA tools that integrate real-time sensing, digital twin environments, and machine-learning techniques, while also embedding equity and accessibility considerations. Advancing these tools will be essential for scaling DRSA from research applications to common practice in urban street redesign.

1 INTRODUCTION

Cities worldwide face growing competition for limited street space due to rapid urbanization and the change in mobility patterns. Cars, public transit, micromobility, pedestrians, and parking now all contend for space within fixed geometries, leading to congestion and inefficiency. Traditional static lane configurations often leave capacity underused in certain directions or modes, especially during off-peak periods (Zheng & Geroliminis, 2013).

Dynamic Road-Space Allocation (DRSA) offers a way to optimize the use of existing infrastructure by adjusting space distribution according to temporal demand patterns (Valença, 2023). Recent technological advancements, such as real-time data collection and automated control, now can enable cities to monitor and reassign road space safely and efficiently (Sayarshad & Oliver Gao, 2018; Valença et al., 2023).

This shift from static infrastructure to an adaptive, multimodal, and demand-responsive network can enhance network performance and resilience (ITF, 2022), maximize the efficiency of limited space (Valença et al., 2023; Zheng & Geroliminis, 2013), and improve multimodal integration (Zhang et al., 2018).

Following the introduction of "dynamic" concepts in the literature, some applications focused on Dynamic Lane Allocation (DLA) while others extended the idea to DRSA. In DLA, traffic lanes are reassigned to different uses or directions in different periods of the day (e.g., peak and non-peak periods) according to multimodal demands (Valença et al., 2023). Applications of the DLA include integrated lane allocation and signal timing at intersections

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(European Commission, 2019; Huang et al., 2025), improvements and prioritization of bus transit (Hu et al., 2024; Xie et al., 2012), temporary access for ride-sharing vehicles to dedicated bus lanes during selected periods (Jin et al., 2024), and dynamic reversal strategies in which the reversible lane shifts direction based on vehicle density (Li et al., 2023).

However, DLA considers only the traffic lanes as part of the allocable urban space, overlooking crucial elements such as curbs, sidewalks, land use and interactions with active transportation (Valença, 2023). In contrast, DRSA takes into account the entire urban street space and is defined as a planning and management approach that adaptively reallocates road-space over time based on changing multimodal and multifunctional demands (Valença et al., 2021). By enabling the flexible redistribution of street space across modes, DRSA tools are increasingly viewed as a mechanism to enhance the resilience of urban transport systems in the face of disruptions, demand fluctuations, and changing policy priorities.

This study aims to review existing tools designed for DRSA applications, assess the gaps that constrain their deployment, and provide directions for future research. Ultimately, the objective is to support the evolution of DRSA solutions from experimental or simulation-based concepts toward integrated, and practice-ready systems capable of informing real-world decision-making in urban environments.

Based on the authors' review of the literature, there is currently no comprehensive study that lists and compares existing DRSA tools. This paper addresses that gap by offering a structured overview and comparative assessment of tools designed to support DRSA.

The remainder of this paper is organized as follows. Section 2 outlines the methodology used to identify and document existing tools for DRSA. Section 3 presents the results, while Section 4 discusses the findings with a focus on gaps and opportunities for improvement. Finally, Section 5 provides the conclusions.

2 METHODOLOGY

The identification of DRSA tools followed a structured search across academic and grey literature. Searches in Scopus, TRID, and Google Scholar used keywords related to DRSA, dynamic street management, and reallocation strategies. Complementary sources such as project reports, international guidelines, and documentation from transport agencies were reviewed to capture operational tools not fully covered in academic publications. The aim was to identify tools that support the data-driven assessment, monitoring, or management of dynamically allocated road space.

The identified tools were then screened using inclusion criteria. Tools were retained when they supported DRSA and were sufficiently documented to allow detailed characterization. Tools that were conceptual, insufficiently documented, or unrelated to DRSA were excluded.

To systematically gather information on existing tools, solutions, practices, methodologies, and standards relevant to the application of DRSA, a structured data-collection form was developed. The purpose of this form was to ensure uniform documentation across sources and to allow for comparisons between different tools and approaches. The form consisted of six major sections (Sections A – F), each containing several subsections designed to capture key attributes of DRSA-related tools.

Section A: Record identity and fit collected essential information about each tool, including its name, a short open-ended description, and its classification into primary and secondary groups. Respondents also specified the main goal of the tool (chosen from a set of options) and indicated the transport modes or assets considered. Section B: Evidence and maturity documented the tool's Technology Readiness Level (TRL), details on deployments or implementations (city or site and timing), and the scale of implementation, e.g. the number of coordinated modes, the area of dynamically managed assets, or the number of trips analysed. When available, evidence of achieved impacts across key performance indicators (KPIs) was recorded, including safety, efficiency, environment, user satisfaction or acceptance, accessibility or inclusivity, and other (open response). For each KPI, the form requested the corresponding unit of measurement (% or Δ), the period of assessment, and the sample size.

Section C: Data and analytics profile captured information on the data modalities used (selected from predefined options), the spatial granularity of the tool (i.e., the spatial unit of analysis or implementation), and the algorithms supporting the tool's operation. Section D: Gap analysis focused on identifying barriers to broader adoption or transferability. Respondents could select up to three of the most critical gaps from a predefined list and had the option to identify the single most critical barrier. They were also asked to provide brief descriptions of mitigation actions or future development plans. Section E: Social context documented the tool's target user groups, selected from a predefined set of possible users and finally section F: bibliography and URLs gathered reference material, including relevant URLs, links to associated pilots or projects, and the reference type.

The predefined lists used in the data-collection form were designed to ensure consistency and comparability across tools, rather than to exhaustively capture all possible attributes. Similarly to other studies on simulation tools (Auld & Mohammadian, 2009; Stavropoulou et al., 2023) the selected dimensions reflect commonly used evaluation criteria in DRSA, transport planning, and ITS-related research, including tool objectives, modal scope, data modalities, algorithmic approaches, maturity level, and deployment context. These categories correspond to key stages in the lifecycle of DRSA solutions – from data inputs and analytical methods to implementation readiness and governance constraints – and are widely referenced in the literature on DRSA, intelligent transport systems, and urban mobility management. Open-ended fields were included alongside predefined options to allow respondents to report additional characteristics not covered by the lists.

The selected tools represent the most mature and well-documented DRSA implementations, allowing for a focused yet representative assessment of the current state of the field. The final set was intentionally limited to a small number of tools to enable an in-depth and comparable assessment. The intended respondents for this form are researchers in the transportation field, practitioners, and representatives of transportation agencies.

3 RESULTS

Following the dissemination of the structured form, the completed responses were collected and reviewed. The recorded data included five tools relevant to the concept of DRSA. These include the MORE Road-space reallocation toolkit and street-design packages (European Commission, 2022); STREETS4ALL, a framework for dynamic and equitable reallocation of urban street space (Moura & Antunes, n.d.); an automated road-space reallocation model (Ballo & Axhausen, 2023); an optimization framework for exclusive bus lane allocation in multimodal networks with dynamic congestion (Tsitsokas et al., 2019); and a multimodal road-space allocation optimization (Zheng & Geroliminis, 2013). These tools represent the current landscape of DRSA-related methodologies identified through the data-collection process.

The MORE toolkit (European Commission, 2022; *Streets as Ecosystems*, 2022) provides the most practical support for DRSA applied on major urban corridors in five European cities. It combines policy/guidance documents, a decision-support appraisal tool, co-creation processes, design option generation to reallocate lanes, curb space and time-use of street space in favour of sustainable modes, and enhanced output measures of performance. By contrast, STREETS4ALL (CERIS, 2024; Moura et al., 2024; Moura & Antunes, n.d.) proposes an equitable and dynamic allocation of urban street space, accommodating future multi-modal and multi-functional street uses. The automated road-space reallocation model (Ballo & Axhausen, 2023) shifts perspective toward modelling and testing radical mobility futures by reallocating street space to maximize cycling infrastructure while still preserving access for motorized traffic and transit. Meanwhile, the two optimization-based models, the exclusive bus lane allocation (Tsitsokas et al., 2019) and the multimodal macro-level allocation (Zheng & Geroliminis, 2013), focus primarily on operational performance and congestion mitigation rather than full urban space reallocation. Table 1 presents short descriptions of each identified tool.

Table 1: Summary of identified tools.

Tool	Description
MORE (European Commission, 2022)	A suite of guidance, tools, and design packages. It supports dynamic reallocation of urban road and curb space along TEN-T corridors in favor of sustainable modes.
STREETS 4ALL (Moura & Antunes, n.d.)	Methods, designs, and technologies to dynamically reallocate street space over time, identifying high-potential zones, proposing flexible interventions, and evaluating impacts.
Reallocation model (Ballo & Axhausen, 2023)	An algorithmic method to reallocate Zurich's road space by prioritizing cycling while preserving motorized and transit access.
Optimization framework (bus lane) (Tsitsokas et al., 2019)	A modeling-optimization framework that, using a Store-and-Forward traffic model and combinatorial optimization, allocates exclusive bus lanes in congested multimodal networks to minimize total passenger-hours traveled.
Optimization framework (bus-car) (Zheng & Geroliminis, 2013)	A multimodal macroscopic fundamental diagram to optimize car–bus road space in city center and periphery, minimizing passenger-hours traveled.

The tools differ in their modal scope. MORE and STREETS4ALL encompass all major road assets/modes, including active modes (micromobility and pedestrians), transit, private vehicles, curb side, and urban space. The optimization models, however, consider narrower subsets, bus versus car, while the automated model incorporates private vehicles, transit and micromobility.

Data requirements and analytical needs also vary across the five identified tools (Table 2 and Table 3). MORE rely on various data inputs including imaging and positioning data, spatial aspects, curbside stopping, pedestrian flows, street users and activities, etc. (McArthur et al., 2022). These inputs allow the tool to operate at the corridor level, supported by web-based and traditional planning tools, simulation models (e.g., Vissim) and demand-forecasting tools for the assessment of alternative reallocation scenarios. STREETS4ALL uses user, network, and land-use data at the urban scale to delineate zones considered in dynamic street-space reallocation analyses. Operating at the zone level, it leverages behavioural models, spatial analytics and demand forecasting algorithms to develop and evaluate solutions for equitable and dynamic street space reallocation (Moura et al., 2024).

The remaining three tools rely primarily on optimization-oriented data inputs and algorithmic formulations. The automated model draws primarily on public transit network data and digital elevation models, using optimization algorithms at the network scale to generate a reconfigured network and assess benefits. The optimization framework for bus lane allocation also operates at the network level, requiring network and demand data and employing simulation combined with optimization to test bus lane assignments under dynamic congestion and minimize the total passenger-hours travelled across all modes. Finally, the multimodal road-space allocation model (bus-car) uses demand data, along with pricing data to optimize the allocation of limited road space among modes. Functioning at the zone or regional scale, it integrates optimization, macroscopic modelling, and pricing algorithms to examine how pricing can shift demand to more efficient modes.

Across the reviewed tools, deployments vary in maturity, and real-world integration (Table 4). MORE, the most tested tool, was deployed between 2019 and 2021 in five partner cities (Budapest, Constanta, London, Lisbon, and Malmö) along the Trans-European Transport Network (TEN-T) multimodal corridors (European Commission, n.d.). Its implementation across European contexts and its pilot testing in real-world environments has led to a TRL of 7, indicating a system prototype demonstrated in an operational environment. In contrast, STREETS 4ALL has been used primarily for methodological development and case studies: a site-selection application in Lisbon and an adaptation for small-city contexts in Coimbra (2022-2025). While applied at the city level, it does not yet function as a city-wide real-time control system. This tool has been classified as TRL 5 which means that the tool has been validated in a relevant environment.

Table 2: Data modalities of identified tools.

Data modalities	MORE	STREETS 4ALL	Reallocation model	Optimization framework (bus lane)	Optimization framework (bus-car)
Administrative and operational data (parking, ticketing, occupancy)	✓				
Demand data				✓	✓
Digital elevation model			✓		
Land use data		✓			
Network data/feeds (GTFS, APIs, ticketing)		✓	✓	✓	✓
Positioning/navigation and motion sensors (GPS, GNSS, mobile traces)	✓				
Pricing/cost data					✓
Public transit network data			✓		
User and crowd-sourced data (apps, surveys)		✓			
Visual and imaging data (CCTV, street cameras)	✓				

Table 3: Algorithms used by each tool.

Algorithms used	MORE	STREETS 4ALL	Reallocation model	Optimization framework (bus lane)	Optimization framework (bus-car)
Behavioral models (discrete choice, hybrid choice, social learning)		✓			
Demand forecasting models (statistical, ML, hybrid)	✓	✓			
Macroscopic modeling					✓
Pricing modeling					✓
Routing algorithms / optimization			✓	✓	✓
Simulation / agent-based models	✓			✓	
Spatial analysis		✓			

The other tools remain primarily in the research or simulation phase. The Reallocation Model was applied to a large subset of urban street network of Zurich, but without a live deployment, keeping its TRL to 5, validated in a relevant environment that mimics real-world conditions. The bus-lane optimization framework was tested through simulation in the 6.5 km² downtown area of San Francisco (Financial District and South of Market Area), involving 156 intersections and 426 links, capturing realistic geometric and operational complexity while still operating as an offline experiment. Finally, the bus-car optimization framework has not been deployed in a real-world setting and has only been applied to a simulated two-region city consisting of an inner bus-dedicated core and a mixed-traffic periphery (radii 1.6 km and 3.2 km, respectively). Both optimization tools are classified at TRL 5, corresponding to validation in relevant but controlled environments.

Across all five tools, several common gaps emerged (Table 5). A dominant issue is the dependency on local governance structures and regulations, which affects the transferability and applicability in real-world of MORE, STREETS4ALL, the Reallocation Model, and the bus-lane optimization framework. MORE is additionally constrained by the lack of open APIs and data-sharing protocols, limiting interoperability with existing planning systems. The Reallocation Model and the bus-car optimization framework exhibit simplification-related limitations, which restrict their ability to capture real-world behavioural and operational complexities. Data availability also emerged as a barrier for two of the tools: the bus-lane optimization framework requires network and transit data that may not exist in many cities, while the bus-car optimization framework requires data not only for input but also for calibration. Finally, the bus lane optimization tool is noted to be also computationally demanding, posing challenges for real-time or large-scale applications.

Table 4: Deployment sites and scales of application for each tool.

Tool	Deployment	Scale
MORE	Budapest, Constanta, London, Lisbon, Malmö (2019-2021)	5 partner cities. Corridors of TEN-T (multimodal corridors)
STREETS 4ALL	Lisbon, Portugal: site selection case study; Coimbra, Portugal: small-city methodology adaptation (2022-2025)	City-level but not a city-wide real-time control system
Reallocation model	Zurich: case-study network, not a live deployment (2023)	A large subset of urban street network (graph)
Optimization framework (bus lane)	Downtown area of San Francisco, in California, USA: Simulation experiments for a real urban network with several bus lines	Test site: 6.5 km^2 urban area (156 intersections, 426 links; 1-6 lanes/ link; 70-400 m links' length; 50 km/h free flow speed).
Optimization framework (bus-car)	Not deployed in a real city. An application performed with a case study of a simulated two-region city.	An urban network with 2 concentric regions: mixed bus-car traffic in the periphery, bus-dedicated space in the center.

Table 5: Main gaps per tool.

Tool	Main gaps
MORE	Dependent on local governance or regulation; Lack of open APIs or data-sharing protocols
STREETS 4ALL	Dependent on local governance or regulation
Reallocation model	Dependent on local governance or regulation; Modeling limitations due to simplification
Optimization framework (bus lane)	Dependent on local governance or regulation; Data may not be available for other cities; Computationally demanding
Optimization framework (bus-car)	Modeling limitations due to simplification; Data requirements

4 DISCUSSION

The review highlights that tools supporting DRSA remain at a relatively early stage, with significant variation in their deployment scale. The results indicate that existing DRSA tools primarily support planning and scenario-based analyses rather than operational or real-time road-space management. Although several tools incorporate advanced modelling and optimisation techniques, their reliance on static datasets and offline evaluation frameworks limits their applicability in adaptive or real-time contexts. This distinction between analytical capability and operational readiness represents a key challenge in transitioning DRSA from research-oriented tools to deployable urban mobility systems. Among the five tools examined, the MORE toolkit is the only one that has been tested in multiple real-world environments. However, its application still supports planning and design rather than real-time road-space management. MORE helps the planning process through advanced co-creation consultation, online generation of design options and iterative refinement based on multimodal impact assessments. It is a dynamic and flexible street-space management approach supported by co-creation, multimodal analysis, and configurable design elements. The remaining tools – STREETS4ALL, the reallocation model, and the two optimization frameworks – provide valuable methodological foundations but operate mainly within simulated or conceptual settings. This gap between analytical models and operational deployment remains one of the central challenges in moving DRSA from research to practice.

Advancing DRSA toward real-world implementation requires the introduction of smart and advanced technologies that will detect transport and urban dynamics and communicate to the infrastructure. These include Internet of Things (IoT), machine-learning techniques, digital twin architectures, smart sensors, big data, etc. The detection of multimodal fluctuations of demand in real-time is important to allow for real-time DRSA solutions to be feasible and efficient (Valença et al., 2023).

Furthermore, DRSA solutions should not only focus on more efficient use of space in terms of performance, i.e., travel times and emissions, but also reflect contemporary objectives of equity, transport justice and people-centric street design (Valença et al., 2023). Future tools should account for the needs of all user groups, including pedestrians, cyclists, persons with reduced mobility, micromobility users, transit passengers, etc.

As emerged from the review, a couple of tools omit crucial components of street-space such as sidewalks and curbs. Future DRSA solutions should consider redesigning the entire street cross-section, adjacent land uses, access and place functions, and the broader socio-spatial context of urban environments (McArthur et al., 2022).

Finally, the review showed that governance acceptance is a critical gap for DRSA tools. Despite demonstrating promising performance in simulation, DRSA tools can only be adopted if they align with political priorities, regulatory frameworks, and community expectations. This underscores the need for tools that better integrate governance processes, behavioural responses, and social acceptance. While optimization and simulation tools can identify theoretically optimal reallocations, their real-world adoption depends on political feasibility, community acceptance, and the adaptability of regulatory frameworks. Combining technical optimization with participatory design, behavioural modelling, and institutional readiness assessments represents a promising direction for future research.

Practical mitigation pathways for governance barriers may include the introduction of regulatory sandboxes (OECD, 2025) allowing cities to pilot temporary road-space reallocations, the development of standardized evaluation frameworks for DRSA impacts, and the integration of DRSA tools into existing traffic management and planning workflows. Demonstration projects and living labs can further support institutional learning and stakeholder confidence by allowing municipalities to test DRSA interventions in controlled environments before large-scale deployment. These staged pilot implementations can serve as an intermediate step between research-oriented DRSA tools and their operational use in urban traffic management.From a resilience perspective, the reviewed gaps – particularly the lack of real-time data integration, limited operational readiness, and strong governance dependency – directly constrain the ability of DRSA tools to support adaptive and robust transport system responses.

These findings have direct implications for Intelligent Transportation Systems (ITS) and vehicle–infrastructure integration. The absence of real-time multimodal sensing, interoperable data pipelines, and dynamic control mechanisms in existing DRSA tools limits their ability to interface with V2X-enabled urban management systems. As cities increasingly deploy connected infrastructure and cooperative ITS architectures, DRSA solutions will need to evolve from offline planning tools toward systems capable of interacting with vehicle, infrastructure, and traffic management platforms in real time. In this context, DRSA platforms could integrate with connected vehicle ecosystems through V2X communication, enabling real-time interaction between vehicles, infrastructure, and traffic control systems. Coupling DRSA with urban digital twins and adaptive control platforms would support continuous monitoring and dynamic adjustment of street configurations.

5 CONCLUSIONS

This review demonstrates that DRSA holds great potential for supporting more sustainable, efficient, and people-centered urban mobility systems. By moving beyond DLA, DRSA encompasses the entire street cross-section, including sidewalks, curbs, transit space, and multifunctional uses, allowing cities to adapt their infrastructure to changing multimodal and temporal demands. Although the concept has gained traction in recent years, the practical tools supporting DRSA remain limited in number, scope, and maturity.

Among the five tools examined, the MORE toolkit stands out as the most advanced, having been piloted across multiple cities and demonstrating higher operational readiness. The other tools – STREETS4ALL, the reallocation model, and the two optimization frameworks – offer important methodological insights but remain to research and simulation environments. Across all tools, common gaps emerged: dependence on governance frameworks, data limitations, simplification-related modelling constraints, and in some cases computational demands. These collectively highlight the challenges of transitioning DRSA from experimental settings to common urban practice.

To advance DRSA into broader real-world deployment, three priority research directions emerge for next-generation DRSA tools. First, they must integrate advanced sensing, real-time data, digital twin architectures, stronger integration with cooperative ITS and connected infrastructure, and machine-learning capabilities to detect multimodal dynamics as they grow and enable system-wide coordination. Second, equally important is the incorporation of equity, accessibility, and user-centred design principles to secure that reallocation strategies benefit all street users, including the vulnerable road users (VRUs).

Finally, governance acceptance remains a decisive factor: successful DRSA implementation requires alignment with political priorities, regulations, and strong community engagement. Integrating technical innovation with institutional readiness and participatory approaches is a critical next step for applying DRSA as a typical planning and management strategy. DRSA solutions support sustainable mobility and promote liveability and place-making instead of car-dominated urban planning approach. As urban transport systems become increasingly connected and data-driven, DRSA has the potential to evolve into a key component of next-generation intelligent mobility management platforms.

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