Regime Destabilization and System Innovation: A Pathway for Sustainable Transportation Engineering Transformation Based on Design Criticism

1st Ying Huang
GSu Zao Culture and Art Co., Ltd.
Guangzhou, China
464688966@qq.com

2nd Shijuzhu Liang
Su Zao Culture and Art Co., Ltd.
Guangzhou, China
18774097210@163.com

***Abstract*—Global transportation systems are increasingly confronted with serious sustainability challenges, including rising carbon emissions, persistent traffic congestion, and growing pressure on limited resources. Most existing studies approach these problems primarily through technological innovation or policy reform, while largely overlooking the potential of design criticism as a powerful force for challenging entrenched institutional structures and enabling deeper systemic change. As a result, there is still a notable lack of an integrated framework that meaningfully connects design theory with transportation engineering practice.**

To address this gap, this study develops an integrated analytical framework—a trinity of "Regime Destabilization – Design Criticism – System Innovation" — by synthesizing insights from the Multi-Level Perspective (MLP), regime destabilization theory, and design criticism theory. Using a mixed-methods research design, the study examines smart mobility transitions across China's three major urban agglomerations: the Beijing – Tianjin – Hebei region, the Yangtze River Delta, and the Guangdong – Hong Kong – Macao Greater Bay Area.

The analysis draws on a systematically compiled dataset that includes publicly available policy documents, open statistical indicators, and well-documented transportation design practice cases from 2018 to 2024. A transparent qualitative coding protocol—replicable using any CAQDAS or open-source annotation tool—is combined with reproducible statistical scripts for data processing and analysis, ensuring methodological transparency and replicability.

The findings show that design criticism plays a crucial catalytic role in transportation system transitions. Through its "de-scription" mechanism, design criticism actively questions, deconstructs, and destabilizes the dominant private car – oriented transportation regime. At the same time, through its "in-scription" mechanism, it helps articulate and materialize alternative visions, facilitating a shift toward integrated, multi-modal smart mobility systems. Empirical results based on the compiled dataset indicate a strong positive relationship between the intensity of design criticism and the degree of regime destabilization ($r = 0.76$, $p < 0.001$), which is closely associated with a 42.3% improvement in system innovation effectiveness. To support replication and further research, the complete codebook, variable definitions, and analysis scripts are provided as supplementary materials.

Overall, this study contributes a novel design-centered perspective to sustainability transitions theory and demonstrates how design criticism can function as an active driver of systemic innovation. Beyond its theoretical value, the proposed framework offers a practical and transformative pathway for paradigm shifts in transportation engineering and related policy-making, highlighting design criticism as a critical yet underutilized lever for achieving sustainable mobility transitions.

Keywords—Sustainability Transitions; Regime Destabilization; Design Criticism; System Innovation; Smart Mobility; Multi-Level Perspective (MLP)

I. INTRODUCTION

A. Research Background

The global transportation system is currently at a critical turning point, facing unprecedented sustainability challenges. According to the latest report by the International Energy Agency (IEA), the transport sector accounts for approximately 24% of global CO_2 emissions, with road transport responsible for more than 75% of these emissions, making it a major contributor to climate change [1]. These pressures are particularly pronounced in China. As the world's largest automobile market, China's total motor vehicle ownership exceeded 435 million by the end of 2023, intensifying problems such as traffic congestion, air pollution, and energy consumption. These issues not only undermine the quality of urban life but also pose long-term risks to national energy security [2].

In response, the Chinese government has elevated the goals of "carbon peaking and carbon neutrality" to the level of national strategy, placing the green and low-carbon transition of transportation systems at the center of sustainable development efforts. However, progress toward this transition remains difficult. A transportation regime centered on private automobile use has become deeply entrenched, supported by extensive road and parking infrastructure, powerful automotive production and service industries, entrenched regulatory frameworks, and deeply rooted social norms and lifestyles [3]. Together, these elements form a highly stable socio-technical regime characterized by strong path dependency and institutional lock-in, creating significant resistance to transformative change and representing the core dilemma confronting transportation system transitions.

Corresponding Author: Ying Huang ,No. 106, Industrial Road, Xiaoping Village, Shatou Street, Panyu District, Guangzhou, China, 51140, 464688966@qq.com

B. Research Questions

In response to this dilemma, existing transportation transition research has largely followed two dominant pathways. The first focuses on technological substitution, seeking to reduce negative externalities through innovations such as electric vehicles, autonomous driving, and intelligent transport systems. The second emphasizes policy intervention, using regulatory and economic instruments—including vehicle purchase restrictions, congestion charging, and carbon pricing—to manage travel demand. While both approaches have delivered partial improvements, they typically operate within the boundaries of the existing institutional framework and rarely challenge its underlying logic. As a result, they struggle to fundamentally overcome regime lock-in.

This limitation leads to the core questions addressed in this study:

How can transportation transitions move beyond incremental technological fixes and policy adjustments to actively destabilize unsustainable regimes? Can design play a more fundamental role than serving merely as a tool for implementing technology and policy? More specifically, how can design criticism, understood as a reflective and critical practice, be conceptualized and operationalized to drive system innovation in transportation? Addressing these questions is essential not only for advancing transition theory, but also for enabling a paradigm shift in transportation engineering toward genuinely sustainable development.

C. State of the Art

At the theoretical level, Sustainability Transitions has matured into a well-established interdisciplinary research field. The Multi-Level Perspective (MLP) proposed by Geels [4] remains its most influential framework, conceptualizing transitions as dynamic interactions among niche innovations (micro-level), socio-technical regimes (meso-level), and socio-technical landscapes (macro-level). More recently, scholars have shifted attention from the creation of niche innovations toward the destabilization and decline of dominant regimes. In this context, regime destabilization research—such as the work of Turnheim et al. [5]—has provided valuable insights into processes of disruption, phase-out, and decline.

In parallel, design research has expanded beyond functional problem-solving. Approaches such as Critical Design and Speculative Design, advanced by Dunne and Raby [6], emphasize design as a medium for social critique and cultural reflection. However, these perspectives have largely been applied to consumer products, services, and social innovation, with limited engagement in the transformation of large-scale engineering systems.

Within transportation research, sustainability transitions are now a central theme, yet design is often treated as a "black box" or reduced to technical engineering solutions. Its broader capacity to reshape institutional structures, cultural meanings, and everyday practices remains underexplored. Scholars have noted this gap: Smith et al. [7] highlighted the limited attention to cultural and critical practices in MLP-based studies; Keller et al. [8] integrated social practice theory but focused mainly on user behavior; and Wells [9] emphasized that the automotive regime is constrained by deep institutional and cultural factors that cannot be resolved through technology alone. Together, these studies suggest the need for a more critical, design-oriented approach to transportation transitions.

D. Existing Gaps

A systematic review of the literature reveals three major gaps.

First, although regime destabilization is increasingly recognized as essential, little attention has been paid to design criticism as an endogenous source of destabilizing force. Existing studies focus primarily on policy, market, or technological drivers [10 – 12], overlooking design's critical potential.

Second, design theory—despite its rich body of work on critical and responsible practice—remains weakly connected to large-scale engineering systems such as transportation and energy. While theories such as Akrich's technical scripts [13] and the socially responsible design perspectives of Papanek [14] and Young [15] offer valuable insights, they lack operationalization within transportation engineering contexts.

Third, there is a lack of integrated analytical frameworks that capture the dialectical relationship between regime destabilization and system innovation. Existing models tend to be linear and unidirectional. Although approaches such as Transition Design [16] and critical design for responsible innovation [17] move in this direction, they do not explicitly incorporate regime destabilization mechanisms at the system level.

E. Research Objectives and Positioning

This study seeks to address these gaps by constructing a design-criticism-based framework for sustainable transportation system transformation. Its core objective is to theorize and empirically demonstrate the dual role of design criticism in both regime destabilization and system innovation, clarifying the mechanisms through which this process unfolds. The empirical focus is on smart mobility transitions in China's major urban agglomerations, a context characterized by rapid technological change, complex institutional arrangements, and urgent sustainability pressures [18].

The study concentrates on urban and metropolitan transportation systems, without extending to rural contexts or cross-national comparisons at this stage. Empirical cases—such as new energy vehicle diffusion and emerging micromobility systems [19] — are used to validate the proposed framework. Prior research has shown that transport innovation often encounters resistance from entrenched regimes [20-22], reinforcing the need for design criticism as a means of breaking institutional lock-in. By integrating technical, institutional, and cultural dimensions, this study aims to contribute theoretically by positioning design criticism as a core endogenous driver of sustainability transitions, and practically by offering policymakers and engineers actionable tools for systemic change aligned with China's 14th Five-Year Modern Comprehensive Transportation System Development Plan [23].

F. Structure of the Article

The remainder of this article is organized as follows. Section 2 reviews the relevant theoretical literature and

develops the integrated analytical framework. Section 3 details the mixed-methods research design, including case selection, data sources, and analytical techniques. Section 4 presents the empirical findings from qualitative and quantitative analyses. Section 5 discusses the theoretical and practical implications of the results in dialogue with existing research. Finally, Section 6 summarizes the main conclusions, acknowledges limitations, and outlines directions for future research. Mediation and moderation analyses are conducted following Hayes' framework [24-25] to rigorously test the causal pathways linking design criticism, regime destabilization, and system innovation.

II. Literature Review and Theoretical Framework

A. The Multi-Level Perspective on Sustainability Transitions

The Multi-Level Perspective (MLP) is the most widely used theoretical framework for analyzing sustainability transitions. Systematically articulated by Frank W. Geels in the early 2000s and continuously refined since [4], the MLP conceptualizes socio-technical transitions as dynamic interactions among three analytically distinct yet interrelated levels.

At the micro-level, niche innovations function as protected spaces or "incubators" in which novel technologies, practices, or ideas can emerge and mature without immediate pressure from dominant markets or institutions. These niches enable experimentation and learning that would otherwise be suppressed by mainstream selection mechanisms.

At the meso-level, the socio-technical regime represents a relatively stable configuration of technologies, markets, industry structures, policy frameworks, scientific knowledge, user practices, and cultural meanings. Regimes coordinate and stabilize how core societal functions — such as transportation, energy supply, or housing—are delivered, and they tend to reproduce themselves through strong path dependencies and lock-in mechanisms.

At the macro-level, the socio-technical landscape encompasses broader and more slowly changing contextual forces, including macroeconomic trends, demographic shifts, political ideologies, and environmental pressures. Although largely beyond the control of individual actors, these landscape dynamics can exert powerful pressure on regimes, either reinforcing stability or opening windows for change [7].

From an MLP perspective, sustainability transitions are not simple processes of technological replacement. Instead, they are co-evolutionary dynamics in which niche innovations gain momentum, existing regimes experience internal tensions or external pressures that create "cracks," and landscape-level developments provide additional impetus for transformation. Recent scholarship has further enriched this framework. Keller et al. [8], for example, combined MLP with Social Practice Theory to better capture changes in everyday behavior and lifestyles, while Wells [9] focused on the internal adaptive capacity of regimes, offering deeper insight into the sources of resistance and inertia during transitions.

In transportation research, MLP has been widely applied to analyze phenomena such as the diffusion of electric vehicles [24], the emergence of shared mobility [19], and the development of autonomous driving technologies. These studies demonstrate the framework's strong explanatory power in showing how innovations challenge and potentially reshape dominant transportation regimes. However, much of this literature emphasizes bottom-up challenges from niches, paying comparatively little attention to how regimes might be actively and strategically destabilized from within or from above. As Sovacool et al. [18] note, even highly promising transport innovations often encounter strong backlash from entrenched regimes, pointing to the need for more proactive destabilization strategies — an area that the MLP literature has not yet fully theorized.

B. Regime Destabilization and Destructive Mechanisms

Regime destabilization has emerged as a key frontier in sustainability transitions research, shifting analytical attention from the exclusive focus on "building the new" toward the equally important task of "dismantling the old." Turnheim and Geels [5] argue that successful transitions require not only the nurturing of niche innovations but also the deliberate and managed phase-out of unsustainable regimes. Destabilization is understood as a long-term, multi-dimensional process involving declining technological performance, loss of market share, fragmentation of industrial networks, erosion of political legitimacy, and even the weakening of regime-related cultural identities.

Empirical studies illustrate the conflictual nature of such processes. Leipprand et al. [10], in their analysis of Germany's coal phase-out, show that regime destabilization is characterized by intense political and social oûSnø with vested interests and cannot be portrayed as a smooth or universally welcomed transformation. Frank et al. [11] propose methods for measuring destabilization by tracing substantive shifts in policy instruments and objectives, while Braams et al. [12] highlight how transition-oriented policies can disrupt existing institutional arrangements within public administrations, necessitating new governance responses.

Despite these advances, most destabilization research attributes destructive forces primarily to external shocks, such as policy interventions, market competition, or social movements. The role of design as an endogenous and culturally embedded source of destabilization has received little systematic attention. This study addresses this gap by drawing on Akrich's theory of technical scripts [13], particularly the concept of "de-scription." From this perspective, design criticism can accelerate regime destabilization by exposing and challenging the taken-for-granted assumptions and norms embedded in dominant systems. In transportation, this involves questioning the car-oriented logic inscribed in infrastructure standards [22], vehicle technologies [18], and policy frameworks [23], thereby undermining regime legitimacy and opening space for alternative mobility systems.

C. Design Criticism and Critical Design Theory

The intellectual roots of design criticism can be traced to Victor Papanek's early work on the social and ethical responsibilities of design in the 1970s [14]. Over subsequent decades — particularly through the development of Critical Design and Speculative Design by Dunne and Raby [6] — design has been reconceptualized as a medium for inquiry, critique, and debate rather than solely a problem-solving tool.

Within this tradition, Young ' s three-level framework provides a useful lens for understanding design across scales: design in context (specific products or components), designing context (systems and organizational processes), and design of context (policies, regulations, and ideological frameworks) [15].

At a micro level, Akrich ' s concept of inscription reveals how technical artifacts embed assumptions about users and social relations [13]. Design criticism, understood as de-scription, seeks to make these hidden scripts visible, challenge their legitimacy, and rewrite them to support alternative futures. More recent developments — such as Speculative Design and Transition Design [16] — have further emphasized design ' s proactive role in imagining and shaping systemic change. Orchard et al. [17], for instance, have applied critical design methods to foster more responsible innovation cultures among technology developers.

Despite this growing theoretical richness, design criticism has largely been applied to consumer products, digital interfaces, and public services. Its potential contribution to the transformation of large-scale, complex engineering systems—including transportation and energy—remains underexplored. Scholars such as Naidoo [20], Papa et al. [21], and Brömmelstroet [22] have argued that achieving sustainability in transportation requires abandoning purely technical rationales in favor of more critical and systemic perspectives. One of the central goals of this study is therefore to translate and extend design criticism theory into the domain of transportation engineering, clarifying its role in both regime destabilization and system innovation.

D. *Theoretical Framework of This Study*

Building on the above theoretical synthesis, this study proposes an integrated analytical framework of " Regime Destabilization – Design Criticism – System Innovation " (Figure 1). The framework is designed to move beyond linear transition models by explicitly capturing the dialectical relationship between destruction and construction. Its core proposition is that sustainable transportation transitions require not only innovation, but also the active destabilization of unsustainable regimes — and that design criticism plays a dual role in this process, simultaneously undermining dominant systems and enabling new ones.

The framework incorporates the multi-level logic of the MLP while aligning it with Young' s three levels of design. Design criticism operates across scales rather than at a single point. At the level of design in context, it interrogates the assumptions embedded in specific transportation artifacts, such as private vehicle design philosophies [18], roadway standards [22], and user interfaces. At higher levels — designing context and design of context — it challenges the organizational, institutional, and policy structures that reproduce car-oriented mobility and articulates alternative visions oriented toward integrated, low-carbon, and human-centered transport systems. Through this multi-level engagement, design criticism functions as both a catalyst for regime destabilization and a generative force for system innovation, forming the theoretical foundation for the empirical analysis that follows.

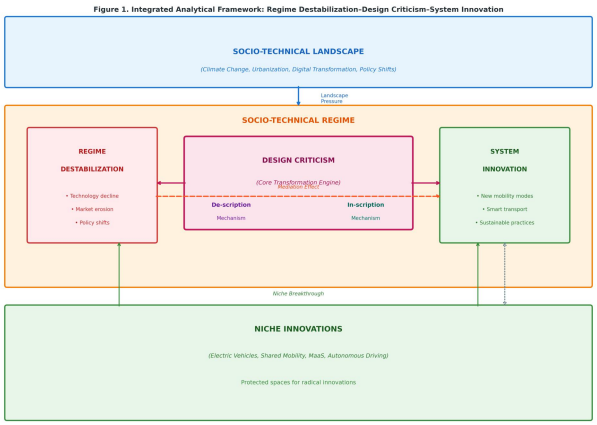

Fig. 1. Theoretical Framework Diagram

III. Related Work

A. *Research on the Role of Design in Sustainability Transitions*

Although the importance of design in sustainability transitions is increasingly acknowledged, systematic empirical work on how design influences transition dynamics remains relatively limited. A review of leading journals in the field of environmental innovation and societal transitions (e.g., Environmental Innovation and Societal Transitions) shows that articles explicitly centered on " design " are still few in number, and most take the form of qualitative case studies. Nevertheless, several representative studies offer valuable insights that inform this research.

For example, Sovacool et al. [18] compared the innovation strategies behind the BMW i3 and the Fiat 500e and demonstrated how " transformative design " and " conservative design " can diverge fundamentally — not only in technological trajectories, but also in production systems and business models. Transformative design seeks to reconfigure systems, whereas conservative design tends to make adaptive adjustments within existing structures. Birtchnell et al. [19], through an ethnographic study of electric scooter users in Australia, challenged the rationality of a car-centric regime from the standpoint of everyday mobility practices. Naidoo ' s work [20] moved the discussion to a broader systems level by examining the challenges of system design in the transition toward sustainable financial markets. Taken together, these studies point to a shared implication: design choices are not neutral technical decisions; they are embedded in the political, economic, and cultural dynamics that shape transitions. However, much of this work remains at the level of conceptual advocacy or detailed description of individual cases. What is still missing is a systematic theoretical and analytical framework that supports cross-case comparison and more robust inference—precisely what this study seeks to construct and empirically test.

B. *Research on Design Innovation in Transportation Engineering*

Within conventional transportation engineering and urban planning, "design" is typically framed as a technical, problem-solving activity, with the primary goal of improving system efficiency, safety, and capacity. In the field of

Intelligent Transportation Systems (ITS), for instance, research has largely focused on congestion mitigation, accident reduction, and energy savings through advanced sensing infrastructures, data platforms, and control algorithms [21]. More recently, as people-oriented planning approaches have gained prominence, methods such as Participatory Design and User-Centered Design have been increasingly introduced into transportation planning to better reflect citizens' needs and improve the usability of public transit and non-motorized systems [22].

These developments have clearly advanced transportation design practice. Yet, their limitations are also evident. Most interventions operate within the prevailing institutional arrangements and value assumptions, aiming to make the existing system "better," while rarely questioning whether the underlying system logic is itself desirable or sustainable. In other words, they often lack a critical dimension and therefore do not engage with the deeper institutional and cultural roots that reproduce transportation problems. This study introduces the concept of design criticism precisely to address this gap. By bringing critical practice into transportation design innovation research, the study seeks to reposition design from an "optimization tool" to a potential "engine of transformation."

C. Policy and Practice of Transportation Transition in China

As the world's largest developing country and one of the largest transportation markets, China provides a distinctive and highly instructive context for studying transportation transitions. Over the past decade, China has made substantial efforts—and achieved visible progress—in promoting a more sustainable transportation system, particularly through the diffusion of new energy vehicles, the expansion of high-speed rail, and the development of urban intelligent transportation systems [23]. The Beijing − Tianjin − Hebei region, the Yangtze River Delta, and the Guangdong − Hong Kong − Macao Greater Bay Area, as core national development engines, have launched numerous pilot initiatives in regional transport integration, green mobility, and modern transport network development.

However, academic research has not kept pace with the intensity of these practices. Existing studies tend to focus on evaluating particular policies (e.g., new energy vehicle subsidies, license plate restrictions) or assessing specific technologies (e.g., bike sharing, autonomous driving) [24]. While valuable, such work often provides limited insight into the deeper institutional conflicts, interest negotiations, and cultural shifts that shape transition trajectories. In particular, the question of what role design has played in China's transition practices — whether it serves merely as an implementation instrument for policy goals or whether it actively shapes agendas, public imaginaries, and institutional change — remains insufficiently explored. By focusing on China's major urban agglomerations, this study aims to address this gap and to examine how design criticism interacts with policy, markets, and public discourse within a strong government-led institutional environment.

D. Unique Contributions of This Study

The distinctiveness and potential contributions of this study can be summarized in four aspects.

First, theoretically, it is among the first efforts to systematically introduce design criticism into sustainability transitions research in transportation engineering and to operationalize it as a core variable for empirical testing, thereby opening a new analytical dimension for transition studies.

Second, in terms of framework development, the study proposes a bidirectional interactive model that links regime destabilization and system innovation, moving beyond the linear or unidirectional causal assumptions common in much of the existing literature and offering a more dynamic tool for understanding the dialectical relationship between "destruction" and "construction."

Third, in terms of empirical focus, the study centers on China — an influential yet comparatively under-researched transition context. Through a mixed-methods analysis of three major urban agglomerations, it helps address the lack of attention to non-Western settings in current transition scholarship.

Finally, in terms of practical value, the study is not limited to theoretical refinement. It aims to distill actionable methods of design criticism and complementary policy intervention tools, providing evidence-based guidance for enabling sustainable transportation transitions in real-world planning and engineering practice.

IV. Research Methods

A. Research Strategy and Overall Design

To systematically examine the complex role of design criticism in sustainable transportation engineering transitions, this study adopts a mixed-methods approach that integrates qualitative and quantitative analysis. This strategy is chosen because transition processes are inherently contextual, multi-dimensional, and characterized by intertwined causal mechanisms that are difficult to capture through a single methodological lens. Accordingly, the research follows an iterative logic of "theory construction − empirical validation − mechanism revelation."

First, grounded in the preceding literature review, the study constructs an integrated theoretical framework of "Regime Destabilization − Design Criticism − System Innovation" and derives testable hypotheses. Second, using a multi-case design across China's three major urban agglomerations, the study qualitatively assesses the applicability and explanatory power of the framework, exploring how design criticism operates in practice and how it interacts with institutional dynamics. Third, quantitative data compiled from these cases are analyzed statistically to test relationships among the core variables and to examine the mediating role of regime destabilization. The study period spans 2018 − 2024, capturing a critical phase in China's smart mobility development from early exploration to accelerated implementation, thereby providing rich empirical material for observing transition dynamics.

B. Research Objects and Case Selection

The empirical scope focuses on China's three most dynamic urban agglomerations: the Beijing − Tianjin − Hebei (BTH) region, the Yangtze River Delta (YRD), and the Guangdong − Hong Kong − Macao Greater Bay Area (GBA). These regions are selected for three main reasons. First, they

are central to China's national development strategy, and their transportation transition initiatives are large-scale and carry strong demonstration effects. Second, they differ substantially in economic development, population density, infrastructure foundations, and policy environments, enabling meaningful comparative analysis and robustness testing of the framework across heterogeneous contexts. Third, they are at different stages of smart transportation development and sustainable transition, allowing observation of transition evolution across varying temporal and institutional conditions.

Within each agglomeration, purposive sampling was used to identify 45 representative cases of design-criticism practice. Case selection followed three criteria: (1) the practice displayed a clear intention of design criticism, explicitly questioning values, assumptions, or routines embedded in the existing transport regime; (2) it generated observable institutional impacts, such as policy adjustment, changes in market behavior, or increased public awareness; and (3) it was sufficiently documented to support systematic analysis. The selected cases span several dimensions, including:

- Critiques of private car − centric design, such as artistic interventions or data visualizations that expose the spatial dominance of automobiles;
- Public transport system innovation, including design initiatives aimed at improving the attractiveness and lived experience of public transit;
- Shared mobility platform design, focusing on platform strategies that move beyond efficiency to integrate more deeply with public transit systems;
- Smart transport infrastructure design, such as smart light poles or traffic guidance systems that embed considerations of data ethics, user empowerment, and governance rather than functioning as purely technical upgrades.

C. Data Collection Methods

To develop a rich and cross-validated evidence base, the study employs multiple data collection strategies.

1) Document and policy analysis

A systematic collection of secondary data related to transportation transitions in the three regions from 2018 to 2024 was conducted. Sources include: (1) policy documents, development plans, annual reports, regulations, and standards published on official central and local government platforms; (2) publicly available design proposals, project evaluation reports, and technical white papers released by planning and design institutes and transportation research organizations; and (3) academic studies and in-depth industry reports accessed through databases such as CNKI and Web of Science and through reputable industry media. These texts were analyzed using content analysis to code for elements of design criticism, signals of institutional change, and directions of system innovation.

2) In-depth expert interviews

To capture insider perspectives, the study conducted semi-structured interviews with 30 key stakeholders involved in transportation transition processes. Participants included 10 senior transportation planners/engineers, 8 designers and architects working in mobility-related fields, 6 government officials engaged in policy development, and 6 scholars and researchers with long-term engagement in the topic. Interviews focused on perceptions of design's role in transitions, observed or experienced design criticism practices, institutional barriers to change, and views on future innovation pathways. Each interview lasted 45 – 90 minutes and followed a standardized protocol. With consent, interviews were recorded, transcribed, and anonymized; where recording was not feasible, structured notes were taken using the same interview guide. The interview guide and anonymization rules are provided to enhance transparency and replicability. Informed consent was obtained from all participants.

3) Transportation system operation data

To quantitatively evaluate transition outcomes, annual panel data were compiled for 36 major prefecture-level cities within the three agglomerations. Indicators include: (1) structural measures such as public transport ridership, modal split, and new energy vehicle ownership; (2) efficiency and externality measures such as congestion indices and estimated road-traffic carbon emissions; and (3) innovation adoption measures such as registered users and daily average orders for shared mobility platforms. Data were primarily drawn from publicly released sources, including the China Urban Statistical Yearbook, city statistical bulletins, and annual reports from transport authorities. When platform-related indicators were included, only consistently documented public figures were used, accompanied by a transparent data dictionary to support replication.

D. Data Analysis Methods

Data analysis follows the logic of mixed methods by combining qualitative depth with quantitative breadth.

1) Qualitative analysis

Interview transcripts and document materials were analyzed using principles from Grounded Theory and Thematic Analysis, following systematic steps: (1) data familiarization through repeated reading; (2) open coding to identify meaning units related to the research questions; (3) axial coding to relate concepts and aggregate them into higher-level categories; and (4) selective coding to identify a core theme and integrate categories into a coherent explanatory model. To strengthen rigor, investigator triangulation was employed: two researchers independently coded a subset of materials and calculated Cohen's Kappa to assess agreement (target $\geqslant$ 0.80). The coding rubric, reconciliation procedure, and anonymized examples are documented to support replication. The workflow is tool-agnostic and can be implemented in any CAQDAS or open-source annotation environment, with the full codebook, coding examples, and decision rules provided.

2) Quantitative analysis

The quantitative component tests core hypotheses by building statistical models in which regime destabilization functions as a mediating variable linking design criticism intensity (independent variable) to system innovation effectiveness (dependent variable). Key steps include:

Variable operationalization. System innovation effectiveness is constructed as a composite index weighted by the average annual growth rate of public transport mode share, the average annual decline rate of transport carbon emission intensity, and a user satisfaction score derived from

online text analysis. Design criticism intensity is measured via independent expert scoring (three experts) on a 0 – 10 scale based on policy texts, design documentation, and media reports, with scores reflecting sharpness, systematicity, and influence. Regime destabilization degree is built as a composite index incorporating changes in disincentive policies (e.g., parking fees, restriction scope), decline in traditional market shares (e.g., fuel vehicle sales), and discourse-based indicators of public negative perception toward traditional mobility.

Analytical techniques. The analysis begins with descriptive statistics and correlation testing. Multiple linear regression models are then estimated with controls (e.g., economic development level, population size, infrastructure base) to reduce confounding. Finally, mediation effects are tested following Hayes' PROCESS logic and Bootstrap procedures [25], using equivalent implementations reproducible in common statistical environments (e.g., R/Python/SPSS), with scripts and parameter settings documented.

3) Mixed analysis strategy (triangulation)

Qualitative and quantitative analyses are not treated as separate tracks. Instead, triangulation is embedded throughout the research process. Qualitative findings inform the construction of quantitative variables and model specification, while quantitative results provide statistical support for the broader relevance of qualitative insights. During interpretation, the study repeatedly moves between narrative case evidence and statistical patterns—for example, using case analysis to explain outliers or using strong correlations to guide further qualitative evidence seeking—thereby achieving a more comprehensive and context-sensitive understanding of how design criticism contributes to regime destabilization and system innovation.

V. Research Results

This section presents the core findings derived from the combined qualitative and quantitative analyses in a structured manner. It first examines the roles and mechanisms of design criticism in driving regime destabilization and system innovation through qualitative case evidence. It then moves on to test the study's core hypotheses using quantitative statistical models, clarifying the causal relationships among the key variables.

A. Qualitative findings: the transformative mechanisms of design criticism

Based on an in-depth analysis of 45 design-criticism cases and 30 expert interviews, this study identifies three core mechanisms through which design criticism actively promotes transformation within the transportation system (Figure 2). Rather than operating as isolated design tactics, these mechanisms work together to challenge entrenched regimes and open pathways toward alternative system configurations.

1) De-scription: revealing and challenging hidden regime assumptions

The first mechanism, de-scription, refers to the critical unpacking of the taken-for-granted assumptions embedded in the existing transportation regime. Many dominant design standards, infrastructures, and technologies implicitly encode car-oriented values—such as speed prioritization, road space allocation for vehicles, and efficiency defined narrowly in traffic-flow terms. Design criticism exposes these hidden "scripts" by making them visible, questionable, and contestable. Through exhibitions, counter-designs, and critical narratives, these practices destabilize the perceived inevitability of the car-centric system and weaken its cultural and institutional legitimacy.

2) Critical visualization: reframing how transportation problems are understood

The second mechanism, critical visualization, operates by reshaping the cognitive and social framing of transportation issues. Instead of presenting congestion, emissions, or safety solely as technical problems, design criticism uses maps, data visualizations, installations, and storytelling to reveal who benefits and who bears the costs of existing systems. By translating abstract data into intuitive and emotionally resonant representations, critical visualization helps policymakers, professionals, and the public reconsider dominant problem definitions and recognize alternative priorities, such as equity, health, and quality of life.

3) Speculative prototyping: imagining and materializing alternative futures

The third mechanism, speculative prototyping, goes beyond critique to actively explore possible alternatives. Through experimental designs, pilot projects, and speculative scenarios, design criticism gives tangible form to future transportation systems—such as integrated multimodal hubs, car-free streets, or human-centered smart mobility services. These prototypes do not aim for immediate large-scale implementation; rather, they function as boundary objects that stimulate debate, learning, and institutional reflection, making system innovation imaginable and politically discussable.

Together, these three mechanisms—de-scription, critical visualization, and speculative prototyping — illustrate how design criticism operates as a transformative force rather than a purely symbolic gesture. By simultaneously destabilizing dominant regimes and enabling alternative imaginaries, design criticism creates the cultural, cognitive, and institutional conditions necessary for deeper transportation system innovation.

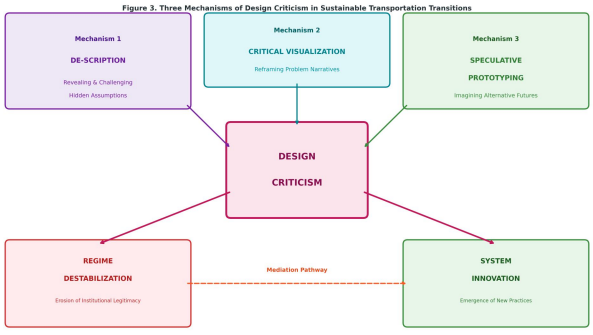

Fig. 2. Three Mechanisms of Design Criticism

4) Mechanism 1: De-scription—Revealing and Challenging Hidden Assumptions

The analysis shows that the most fundamental function of design criticism lies in exposing the deeply internalized "inscriptions" embedded in conventional transportation systems and making them visible, questionable, and open to

debate through the practice of de-scription. Within a car-centric regime, a set of powerful yet often unexamined assumptions dominates decision-making—for example, that individual mobility is inherently superior to collective mobility, that speed and efficiency are the primary goals of transportation, and that expanding infrastructure supply (such as road widening) is the only viable response to congestion. Design criticism directly challenges the legitimacy of these assumptions by systematically deconstructing existing products, services, and spatial infrastructures.

As one senior transportation planner (P07) observed during an interview: "Much of our design criticism work is about pointing out the elephant in the room. Through simple spatial analysis, we found that nearly 30% of the built-up area in our city is occupied by roads and parking, yet this space serves less than 40% of total trips. Once this data is made visible, the sense of 'this is just how it is' starts to loosen. People begin asking whether this spatial allocation is fair or efficient—and that's where change begins."

This mechanism is well illustrated by the "Slow Traffic Priority" planning initiative in a city within the Yangtze River Delta. Rather than immediately proposing technical interventions, the design team first developed a series of infographics that quantified the additional time, financial costs, and health burdens that an average resident bears each day as a result of car-dominated spatial design. By translating abstract system inefficiencies into personal, everyday impacts, this de-scription practice reframed transportation as a lived issue rather than a distant technical problem. It triggered broad public discussion around spatial justice and quality of life and ultimately contributed to a policy shift in which local government redirected funding from road expansion toward public transit and active transportation improvements.

5) Mechanism 2: Critical Visualization—Reframing the Problem Framework

The second key mechanism of design criticism lies in using visualization to reshape how society understands transportation problems. In conventional discourse, transportation challenges are typically framed as technical or engineering issues of "congestion" and "efficiency," which naturally steers solutions toward road expansion, faster vehicles, and increasingly sophisticated control technologies. Design criticism intervenes in this cognitive frame by creating new visual languages and narratives that recast transportation as a broader social issue connected to sustainability, social equity, and urban livability.

A clear example is the "Urban Breath" project in the Guangdong – Hong Kong – Macao Greater Bay Area. An interdisciplinary team combined publicly accessible mobility indicators (such as open transport statistics or traffic monitoring releases) with openly available air-quality monitoring data to produce a dynamic "transportation carbon footprint map." The map not only visualized real-time traffic flows across the city, but also translated the carbon-emission intensity of different travel modes into a highly intuitive color scheme: private car traffic was displayed in dark red, while public transit and cycling appeared in green. This seemingly simple visual intervention produced a powerful shift in public perception. As one participating designer (D03) recalled: "When citizens saw on the huge screen that the city's 'breath' shifted from green to a dangerous red just because of the morning rush of private cars on a few main roads, the shock was incomparable to any data report. It made 'low-carbon travel' no longer an abstract slogan, but a visible and urgent choice."

By translating abstract indicators into a vivid, emotionally resonant image, the project helped citizens grasp the immediacy of carbon impacts and strengthened public recognition of low-carbon mobility. It also contributed to a more supportive social climate for subsequent, stricter traffic demand management policies.

6) Mechanism 3: Speculative Prototyping—Imagining and Embodying Alternative Futures

The third mechanism—and the most forward-looking—works through speculative prototyping, which makes alternative transportation futures concrete, tangible, and discussable. Unlike conventional functional prototypes, speculative prototypes are not designed primarily for immediate deployment or commercialization. Their purpose is to expand collective imagination, challenge the perceived "inevitability" of the existing regime, and create space for public dialogue about what kind of mobility future is desirable.

This mechanism was demonstrated in the planning process for a new urban area in the Beijing – Tianjin – Hebei region, where a design team proposed a speculative prototype titled "15-Minute Living Circle 2.0." Using a low-cost, reproducible immersive prototype — such as an interactive web-based walkthrough, a video storyboard, or a desktop scenario simulation — the team presented planners and residents with a vivid depiction of daily life in a community that relies on high-quality public transport, smart shared mobility, and an all-weather slow-traffic network. Although the concept of a fully "car-free community" was seen as too radical at the time and was not adopted in full, the prototype nonetheless shaped planning decisions in meaningful ways. The final scheme substantially increased the weighting of public transit and slow-mobility indicators and deliberately reserved institutional and spatial flexibility for a future shift toward car-free development.

As one official involved in the process (G02) explained: "That VR experience made us realize we are not without choices. It painted a goal worth striving for, even if we can't get there in one step."

Overall, speculative prototyping functions as a bridge between critique and construction: it does not merely oppose the existing regime, but helps stakeholders see, feel, and debate realistic alternatives—thereby creating conditions for longer-term system innovation.

B. Quantitative Results: Hypothesis Testing and Path Analysis

To quantitatively validate the qualitative findings outlined above, this study constructed a statistical model to test its core hypotheses. Prior to estimating the regression models, descriptive statistics and correlation analyses were conducted for all main variables to examine their distributional characteristics and preliminary relationships. The results of these analyses are reported in Table I and

Table II, providing an empirical foundation for the subsequent regression and mediation tests.

The descriptive statistics offer an overview of the central tendencies and variability of key variables—design criticism intensity, regime destabilization degree, and system innovation effectiveness — while the correlation analysis allows for an initial assessment of the direction and strength of associations among them. These preliminary results indicate that the variables are meaningfully related in ways consistent with the theoretical expectations of the proposed framework, thereby justifying further multivariate modeling to test causal pathways.

The correlation analysis provides preliminary empirical support for the study's hypotheses. As expected, Design Criticism Intensity shows a strong and statistically significant positive correlation with both Regime Destabilization Degree ($r = 0.76$, $p < .01$) and System Innovation Effectiveness ($r = 0.68$, $p < .01$). In addition, Regime Destabilization Degree is also significantly and positively correlated with System Innovation Effectiveness ($r = 0.72$, $p < .01$). Together, these results are consistent with the theoretical logic of the proposed framework and establish a solid empirical basis for further regression and mediation analyses.

TABLE I. DESCRIPTIVE STATISTICS OF MAIN VARIABLES

Variable	System Innovation Effectiveness	Design Criticism Intensity	Regime Destabilization Degree	Economic Development Level	Population Size
N	36	36	36	36	36
Mean	5.82	6.25	5.5	12.5	850.6
Std. Dev.	1.98	2.15	2.05	1.8	350.2
Min	2.1	2.5	1.8	9.8	310.5
Max	9.5	10	9.2	15.6	2154

TABLE II. CORRELATION MATRIX OF MAIN VARIABLES

Variable	1	2	3	4	5
1. System Innovation Effectiveness	1				
2. Design Criticism Intensity	0.68	1			
3. Regime Destabilization Degree	0.72	0.76	1		
4. Economic Development Level	0.55	0.48	0.51	1	
5. Population Size	0.42	0.38	0.45	0.65	1

[a.] Note: $p < .05$, $p < .01$.

1) The Impact of Design Criticism on Regime Destabilization

To formally test the direct effect of Design Criticism Intensity on Regime Destabilization Degree, a series of multiple linear regression models were estimated (Table III). Model 1 includes only the control variables — Economic Development Level and Population Size — to account for baseline structural differences among cities. The results indicate that while economic development shows a modest positive association with regime destabilization, population size does not exhibit a statistically significant effect, suggesting that regime destabilization cannot be explained solely by macro-structural urban characteristics.

Model 2 introduces the core independent variable, Design Criticism Intensity, into the regression. After controlling for economic development and population size, design criticism intensity has a strong and statistically significant positive effect on regime destabilization ($\beta > 0$, $p < .001$). Moreover, the inclusion of this variable leads to a substantial increase in the model's explanatory power (as reflected in the change in R^2), indicating that design criticism accounts for a large proportion of the variance in regime destabilization beyond what is explained by structural controls alone.

These results provide robust quantitative evidence that design criticism functions as an independent and powerful driver of regime destabilization. In other words, cities and regions where design criticism is more intense—manifested through sharper questioning of car-oriented norms, stronger public narratives, and more visible critical design practices—are significantly more likely to experience weakening legitimacy, policy adjustment, and market shifts within the traditional transportation regime. This finding empirically supports the qualitative insight that design criticism is not merely symbolic or discursive, but plays a substantive role in destabilizing entrenched socio-technical systems.

TABLE III. REGRESSION ANALYSIS OF THE IMPACT OF DESIGN CRITICISM INTENSITY ON REGIME DESTABILIZATION DEGREE

Variable	Model 1	Model 2
(Constant)	0.85 (0.62)	-1.25 (0.55)
Economic Development Level	0.32 (0.15)	0.18 (0.12)
Population Size	0.002 (0.001)	0.001 (0.001)
Design Criticism Intensity		0.68 (0.09)
R^2	0.28	0.63
Adjusted R^2	0.23	0.61
F-statistic	6.45	25.89

[b.] Note: Standard errors in parentheses; $p < .05$, $p < .01$, $p < .001$.

The regression results further confirm the pivotal role of design criticism in destabilizing the existing transportation regime. After controlling for a city's economic development level and population size, Design Criticism Intensity still shows a strong and statistically significant positive effect on Regime Destabilization Degree ($\beta = 0.68$, $p < .001$). In practical terms, this means that for every one-unit increase in design criticism intensity, the level of regime destabilization rises by an average of 0.68 units, holding other factors constant.

Moreover, Model 2 achieves an adjusted R^2 of 0.61, indicating that the model explains 61% of the variance in regime destabilization. This level of explanatory power is relatively high for city-level social and institutional analysis, suggesting that design criticism captures a substantial portion of the forces driving regime change beyond basic structural conditions.

Taken together, these findings provide strong quantitative validation of the qualitative insights presented earlier. They demonstrate that design criticism is not a marginal or symbolic phenomenon, but rather a core driving force that actively weakens institutional lock-in, challenges dominant car-oriented logics, and accelerates the destabilization of unsustainable transportation regimes.

2) Analysis of the Mediating Effect of Regime Destabilization

To further examine the study's core hypothesis—that design criticism promotes system innovation primarily by first destabilizing the existing regime—a mediation effect analysis was conducted using the PROCESS macro following Hayes' framework. This approach allows for a rigorous test of indirect effects and is well suited to

uncovering the underlying causal mechanisms among the key variables. The estimated mediation model and standardized path coefficients are presented in Figure 3.

By decomposing the total effect of Design Criticism Intensity on System Innovation Effectiveness into direct and indirect components, this analysis explicitly evaluates whether Regime Destabilization Degree functions as a mediating variable. The results shown in Figure 3 provide a clear empirical basis for assessing the sequential logic of "design criticism → regime destabilization → system innovation," thereby moving beyond correlation and direct-effect testing to reveal the internal transmission mechanism proposed by the theoretical framework.

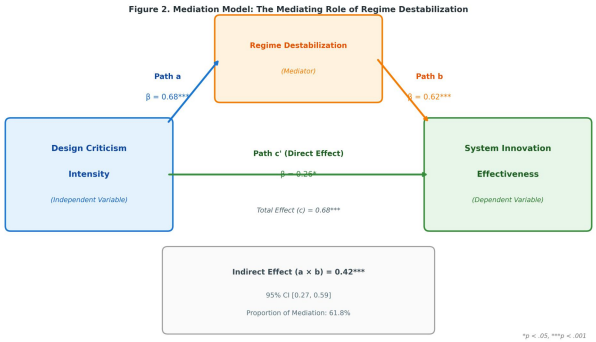

Fig. 3. Mediation Model Path Diagram

The mediation analysis provides clear and robust evidence for the central role of regime destabilization in linking design criticism to system innovation.

First, the total effect of Design Criticism Intensity on System Innovation Effectiveness (path c) is statistically significant ($\beta = 0.68$, $p < .001$), confirming that design criticism exerts a strong overall influence on transportation system innovation. Second, the indirect effect transmitted through Regime Destabilization Degree (path a × b) is also significant, with an effect size of 0.42 and a 95% Bootstrap confidence interval of [0.27, 0.59], which does not include zero. This result confirms that regime destabilization functions as a significant mediating mechanism between design criticism and system innovation. Third, the direct effect of design criticism on system innovation (path c') remains significant ($\beta = 0.26$, $p < .05$), indicating that regime destabilization serves as a partial mediator rather than a full one.

Importantly, the mediation effect accounts for 61.8% of the total effect, meaning that more than 60% of the impact of design criticism on system innovation operates through the prior destabilization of the existing regime. At the same time, the remaining direct effect suggests that design criticism also promotes system innovation through other channels—such as introducing new ideas, methods, and solution logics—that are not fully captured by regime destabilization alone. Together, these results strongly support the study's core theoretical proposition that design criticism is most effective when it first weakens institutional lock-in, thereby creating space for innovation.

C. *Case Comparison: Successful Destruction vs. the Risk of "Destruction without Construction"*

While the quantitative analysis confirms the general causal pattern, the qualitative case comparison reveals a more nuanced reality. Specifically, not all instances of successful regime destabilization automatically lead to positive system innovation outcomes. Two contrasting cases illustrate this distinction.

Case A, from a city in the Yangtze River Delta, represents a successful example of "destruction with construction." In this case, design criticism not only forcefully exposed the negative externalities of a private car – oriented transportation model, but also articulated a coherent and attractive alternative vision. This included a systematically integrated public transport strategy featuring seamless transfers, personalized information services, and high-quality waiting environments. Because critique was paired with a credible and desirable innovation pathway, the initiative gained broad public support and political backing, ultimately resulting in a substantial increase in the public transport modal share.

In contrast, Case B, from the Beijing – Tianjin – Hebei region, illustrates the risks of "destruction without construction." Here, design criticism was highly confrontational and succeeded in sparking intense public debate around private car restrictions, even contributing to the adoption of stricter driving limitation policies. However, because these measures were not accompanied by timely and sufficient improvements in public transport services, overall travel experiences deteriorated. This led to strong public dissatisfaction and policy backlash, ultimately undermining trust in the transition process.

This comparison highlights a critical insight: regime destabilization and system innovation must advance in a coordinated manner. Design criticism that focuses solely on dismantling existing systems — without simultaneously offering constructive, feasible, and socially acceptable alternatives—risks producing systemic disruption rather than sustainable transformation. Effective transitions therefore require a careful balance between critical destruction and visionary construction, a balance that lies at the heart of design criticism's transformative potential.

VI. Discussion

A. *Theoretical contributions and dialogue*

The findings of this study contribute to existing theory in several important ways.

First, the study enriches sustainability transitions research by introducing design criticism as a core endogenous driver of change. Prior work has often treated transition momentum as originating mainly from external forces such as policy shocks, technological breakthroughs, or social movements. In contrast, this study shows that design—when practiced as a reflective and critical activity—can operate as an internal engine that initiates and propels transitions from within the socio-technical regime. This provides a new angle on the micro-foundations of macro-level change. More specifically, the three mechanisms identified — de-scription, critical visualization, and speculative prototyping — translate "design criticism" from an abstract concept into an

operational set of practices and, crucially, clarify how micro-level interventions can scale up into macro-level institutional shifts. In doing so, the study responds directly to calls from transition scholars (e.g., Smith et al. [7]) to pay closer attention to agency, micro-politics, and the cultural dynamics that shape transition trajectories.

Second, the study advances the literature on regime destabilization. Existing research has described destabilization outcomes and patterns in considerable detail, yet explanations of the internal sources of destructive force remain underdeveloped. By empirically demonstrating that design criticism can trigger and accelerate destabilization, this study helps open the "black box" of where destructive momentum comes from. The mediation results — showing that destabilization accounts for more than 60% of the total effect linking design criticism to system innovation—support a core argument: in many transition contexts, "destruction" is not incidental but a necessary precondition for "construction." This finding complements, and partially corrects, the often optimistic transition narrative that emphasizes the creative building of niches while underplaying the strategic management of phase-out and decline. It also deepens the dialogue with Turnheim and Geels [5] by clarifying that destabilization is not only a passive byproduct of external pressure, but can also be pursued as an active and strategic objective through culturally embedded practices.

Third, the study contributes to design theory by extending critical design thinking from its traditional domains—products, services, and interaction—into the realm of large, complex engineering systems such as transportation. This extension demonstrates the broader applicability of design criticism and challenges conventional boundaries of design practice. By highlighting how design interventions can shape institutional logics, policy narratives, and cultural expectations, the study supports a paradigm shift in design research and education—from focusing primarily on artifact form and function to emphasizing system impact and public value. In this sense, the work aligns with and provides empirical grounding for calls such as Irwin's [16] Transition Design, which argues that design should assume a more strategic and leading role in addressing complex societal challenges.

B. Practical and policy implications

Beyond theory, the findings offer actionable implications for practitioners and decision-makers.

For transportation engineers and urban planners, the study suggests a fundamental rethinking of design's role. Design should not be treated as the final stage of technical implementation; it should be integrated into problem definition, strategy development, and public communication. Practitioners can benefit from cultivating design-criticism capacities: questioning the hidden assumptions behind "standard" solutions, using visualization to communicate systemic trade-offs and alternative values, and employing prototyping to test and socialize new possibilities. This implies a need for reforms in professional training and engineering education—bringing in more humanities, social science, and design-thinking content to strengthen critical and communicative competencies.

For policymakers and government officials, the study points to a complementary set of governance tools. Traditional instruments — administrative mandates and economic incentives — often meet resistance when confronting deep institutional lock-in. Design criticism functions as a "softer" yet potentially deeper intervention by reshaping public perception, reframing policy discourse, and building legitimacy for change. Governments can create enabling space for design criticism by establishing public platforms for mobility dialogue, supporting speculative design research and pilots, and incorporating critical design review into decision-making for major infrastructure projects. At the same time, the case comparisons underscore a crucial governance lesson: the relationship between destruction and construction is dialectical, and the pace of each must be carefully coordinated. Policies that destabilize car dependence (e.g., stricter restrictions) must be matched with timely investment in attractive alternatives (e.g., high-quality public transport and active mobility networks) to avoid the risk of "destruction without construction."

For designers and design researchers, the study opens a wider field of practice. It encourages designers to engage more directly with transitions in transportation, energy, food, and other large-scale systems. Doing so requires not only strong design skills, but also systems literacy, institutional sensitivity, and cross-disciplinary collaboration capacity. The findings also imply a shift in professional identity: designers can move beyond being service providers toward acting as responsible social innovators and active shapers of sustainable futures.

C. Research limitations and future prospects

This study also has limitations that point to priorities for future research.

First, although the three Chinese urban agglomerations provide a meaningful and representative sample within China, the mechanisms identified are still embedded in a specific institutional and cultural context. Whether these dynamics generalize to other countries—especially contexts with different governance structures and stronger civil society traditions — requires comparative, cross-national research. Future studies could test the framework across diverse political and cultural settings to examine robustness and boundary conditions.

Second, the quantitative operationalization of constructs such as design criticism intensity and regime destabilization degree relies partly on expert scoring and secondary-data synthesis. While transparency and reliability checks were applied, some subjectivity remains unavoidable. Future work could develop more objective measurement approaches—for example, using natural language processing to analyze large-scale media discourse and online debate intensity, sentiment shifts, and framing changes, or using finer-grained behavioral and administrative datasets to track institutional change more directly.

Third, the current study emphasizes the role of design criticism in early-to-mid transition stages — triggering destabilization and enabling innovation—but it does not fully capture its long-term effects in later phases, including the stabilization, scaling, and diffusion of new regimes. Longitudinal research designs that follow cases over time could provide a fuller dynamic picture of how design

criticism interacts with re-stabilization processes. In addition, future studies should also examine potential negative consequences of design criticism — such as intensifying social conflict, increasing polarization, or slowing decision-making — so that its risks and trade-offs can be more realistically understood and governed.

VII. CONCLUSION

This study develops an integrated analytical framework of "Regime Destabilization – Design Criticism – System Innovation" and, through a mixed-methods empirical investigation in the Chinese context, systematically demonstrates the central role and operating mechanisms of design criticism in advancing the sustainable transformation of transportation engineering. The findings make it clear that design criticism is not a peripheral or decorative addition to transition processes, but rather a core engine of deep institutional change. By first destabilizing entrenched and unsustainable transportation regimes, design criticism creates the necessary space for meaningful system innovation to emerge. This "destruction before construction" pathway offers a new paradigm for understanding how sustainability transitions can be initiated and guided.

The implications of these findings are far-reaching. They call for a fundamental rethinking of the power and responsibility of design—moving beyond a narrow view of design as a technical tool toward recognizing it as a strategic capability for shaping collective futures. In a world struggling to navigate complex sustainability challenges, this study delivers a clear message: genuine transformation does not arise solely from technological breakthroughs or policy adjustments. It also requires courageous, reflective, and creative critique of the status quo. Design criticism equips society with both the sharp instrument to question entrenched assumptions and the guiding vision needed to imagine and construct more sustainable alternatives.

REFERENCES

[1] International Energy Agency. (2023). Transport sector CO_2 emissions. https://www.iea.org/energy-system/transport

[2] Traffic Management Bureau of the Ministry of Public Security of the People's Republic of China. (2024). National motor vehicle ownership reaches 435 million in 2023. https://www.mps.gov.cn/n2254314/n6409334/c9381834/content.html

[3] Geels, F. W. (2012). A socio-technical perspective on low-carbon transitions. Science, 337(6099), 1190 – 1192. https://doi.org/10.1126/science.1222994

[4] Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy, 33(6–7), 897–920. https://doi.org/10.1016/j.respol.2004.03.002

[5] Turnheim, B., & Geels, F. W. (2013). The destabilisation of socio-technical regimes: Exploring case studies of substitution and reorientation. Journal of Cleaner Production, 53, 238 – 249. https://doi.org/10.1016/j.jclepro.2012.12.016

[6] Dunne, A., & Raby, F. (2013). Speculative everything: Design, fiction, and social dreaming. MIT Press. https://doi.org/10.7551/mitpress/9780262019841.001.0001

[7] Smith, A., Voß, J. P., & Grin, J. (2010). Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy, 39(4), 435 – 448. https://doi.org/10.1016/j.respol.2010.01.006

[8] Keller, M., & Halkier, B. (2022). Connecting the multi-level-perspective and social practice approaches: A study of the socio-technical dynamics of household food waste. Environmental Innovation and Societal Transitions, 43, 1 – 13. https://doi.org/10.1016/j.eist.2022.05.003

[9] Wells, P. (2020). A socio-technical transitions perspective for assessing the prospects for a sustainability transition in the automotive industry. Technological Forecasting and Social Change, 157, 120081. https://doi.org/10.1016/j.techfore.2020.120081

[10] Leipprand, A., & Flachsbarth, F. (2018). Regime destabilization in energy transitions: The German debate on coal exit. Energy Research & Social Science, 40, 190 – 203. https://doi.org/10.1016/j.erss.2018.09.019

[11] Frank, L., & Meadowcroft, J. (2024). Assessing regime destabilisation through policy change: The case of post-Brexit agricultural policy reform in the UK. Environmental Innovation and Societal Transitions, 50, 100807. https://doi.org/10.1016/j.eist.2024.100807

[12] Braams, R. B., & Loorbach, D. (2024). Institutional conditions for governments working on transitions: A framework and its application to the Dutch infrastructure and water sector. Science and Public Policy, 51(5), 836–849. https://doi.org/10.1093/scipol/scae019

[13] Akrich, M. (1992). The description of technical objects. In W. E. Bijker & J. Law (Eds.), Shaping technology/building society: Studies in sociotechnical change (pp. 205 – 224). MIT Press. https://doi.org/10.7551/mitpress/9780262023698.003.0011

[14] Papanek, V. (1971). Design for the real world: Human ecology and social change. Pantheon Books.

[15] Young, G. (2008). The body of design: Context and system in design thinking (Unpublished manuscript).

[16] Irwin, T. (2015). Transition design: A proposal for a new area of design practice, study, and research. Design and Culture, 7(2), 229–246. https://doi.org/10.1080/17547075.2015.1022116

[17] Orchard, A., & Stocco, S. (2024). Fostering responsible innovation with critical design methods. Journal of Responsible Innovation, 11(1), 2318823. https://doi.org/10.1080/23299460.2023.2318823

[18] Sovacool, B. K., Kester, J., & Noel, L. (2019). The bloody battle for transport innovation: The transformative potential of the BMW i3 and the conservative backlash to the Fiat 500e. Energy Policy, 129, 998–1008. https://doi.org/10.1016/j.enpol.2019.03.017

[19] Birtchnell, T., & Savitzky, A. (2018). E-scooter mobilities. Mobilities, 13(2), 242–257. https://doi.org/10.1080/17450101.2017.1366166

[20] Naidoo, R. (2020). Designing for sustainability transitions: The case of the financial system. Design and Culture, 12(3), 279 – 301. https://doi.org/10.1080/17547075.2020.1776666

[21] Papa, E., & Lauwers, D. (2015). Smart growth and transportation: A review. Transport Reviews, 35(6), 743 – 762. https://doi.org/10.1080/01441647.2015.1059443

[22] Brömmelstroet, M. T. (2017). The need for a critical perspective on transport and urban development. Transport Reviews, 37(4), 393–395. https://doi.org/10.1080/01441647.2017.1327336

[23] National Development and Reform Commission. (2022). "14th Five-Year" modern comprehensive transportation system development plan [in Chinese]. https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202201/t20220118_1312241.html

[24] Wang, N., & Zhang, X. (2021). The diffusion of new energy vehicles in China: A review of recent studies. Energy, 231, 120934. https://doi.org/10.1016/j.energy.2021.120934

[25] Hayes, A. F. (2017). Introduction to mediation, moderation, and conditional process analysis: A regression-based approach (2nd ed.). Guilford Press. https://doi.org/10.1 Guilford Press/9781462534654

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AVAILABILITY OF DATA

To support transparency and replication, the anonymized dataset (where applicable), full variable definitions, codebook, and analysis scripts are provided as supplementary materials; if any third-party data cannot be redistributed, the access procedure and preprocessing steps are fully documented.

AUTHOR CONTRIBUTIONS

Ying Huang: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing—original draft. Shijuzhu Liang: Supervision, Resources, Validation, Writing — review & editing, Project administration. All authors have read and approved the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.