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Divergent urban pathways to autonomous mobility across thirty Chinese cities

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Autonomous vehicles (AVs) are diffusing in cities worldwide, propelled by expectations for enhanced safety and sustainability. This study examines urban innovation mechanisms across 30 pilot cities in China, analyzing AV experimentation activities, policy mixes, and emphasized innovation system functions using a novel dataset of 116 pilot projects and 881 policy documents. Combining qualitative content analysis and K-means clustering, we identify three city archetypes: *Innovation Leaders, Specialized Developers*, and *Emerging Participants*. These groups reveal distinct configurations of innovation mechanisms and development trajectories shaped by local priorities and capacities. *Innovation Leaders* pursue end-use-focused AV innovation through forward-looking institutional arrangements facilitating market formation, whereas other cities focus on industrial manufacturing and infrastructure development. Empirically, this heterogeneity reflects diversified value-chain positioning across city archetypes. As a core theoretical and methodological contribution, our study reveals multiple, context-dependent urban pathways for building an AV innovation system, showing how municipal governments dynamically combine innovation mechanisms over time.

Autonomous vehicles (AVs) are poised to transform urban mobility worldwide. Self-driving technologies promise safer transport, reduced congestion, and improved energy efficiency, though uncertainty persists about whether these benefits can be achieved[1–4]. Recent commercial deployments by leading companies, including Waymo in the United States and Apollo Go in China, demonstrate AV technology's rapid progression from laboratory research to real-world applications. Yet accelerating socio-technical transitions around disruptive technologies like AVs requires systemic changes across multiple domains, including industrial supply chains, urban infrastructure, regulatory frameworks, business models, and traffic patterns[5–9].

Cities are critical hubs where such socio-technical transformations unfold, nurturing innovation through various mechanisms[10]. As centers of economic and social activity, cities function as incubators, aggregating key actors, resources, and infrastructure necessary for social and technological advancement[11,12]. They also function as testing grounds, allowing new technologies to be validated and deployed under real-world conditions[13–15]. Municipal governments play a particularly pivotal role by designing policy mixes that combine strategic vision, regulatory and financial instruments, and by establishing governance frameworks that foster the formation of innovation systems and the diffusion of novel technologies and business practices[16,17]. At the same time, it is necessary to recognize that cities are not isolated from the broader context and the multi-level governance system in which they are embedded[18–20]. Understanding how cities leverage these mechanisms is therefore essential for deepening knowledge of how they contribute to diffusing socio-technical innovations to address social and environmental issues at national and global scales[11,21,22].

China has rapidly emerged as a global leader in AV innovation. By mid-2024, 32,000 kilometers of roads were authorized for vehicle testing, with 16,000 licenses issued to over 70 companies[23]. Experimental introductions of robotaxi and robobus services have mushroomed across major cities, accelerating real-world deployment. China's prominence in AV development reflects technological progress as much as long-term, state-led planning. Intelligent vehicles were positioned as a strategic technological sector under the "Made in China 2025" plan in 2015, while the "Strategy for Innovation and Development of Intelligent Vehicles" published in 2020 set commercialization and mass-production targets for 2025. China's AV development is further embedded in the broader Intelligent Connected Vehicles (ICV) industrial strategy[24,25]. Formulated to guide the value chain reconfiguration of the automobility sectors through integration with the digital sector[26,27], this ICV strategy highlights vehicle-to-infrastructure connectivity and a vehicle-road-cloud development paradigm, positioning governments as central actors in infrastructure provision and smart mobility governance. This government-industry collaboration approach contrasts with the predominant innovation approach in Western countries, where firms such as Waymo, Tesla, and Cruise primarily emphasize individual vehicle autonomy and firm-driven technological development.

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Scores of cities across China are advancing national AV and ICV objectives by implementing a wide range of pilot and demonstration projects initiated by upper-level authorities. These sites of urban experimentation—involving exploratory trials of vehicles, regulatory arrangements, and business models—are crucial to accelerating China's technological progress. Not only do they allow testing across diverse use cases, generating large volumes of data to train autonomous-driving systems[28], they also help mobilize significant investments in AV-related sectors while building knowledge of effective governance approaches. Sites of pilot activities span diverse urban contexts, from prosperous global innovation hubs like Beijing and Shanghai to smaller manufacturing centers like Liuzhou and Shiyan. Amidst disparities in innovation capacity, socioeconomic conditions, and industrial development goals, cities vary widely in how they pursue AV development and foster local innovation systems[29]. This heterogeneity offers a valuable opportunity to understand how city-specific conditions shape urban mechanisms of AV innovation.

In transportation studies, AV development has rapidly gained traction, with much literature examining pilot project implementation across jurisdictions, along with implications for broader mobility systems[16,28,30]. However, these studies concentrate primarily on North American and European countries, devoting less attention to innovation practices in Asia[31,32]. In China, scholarship on AVs predominantly addresses technical aspects, while socio-technical perspectives remain comparatively less developed. Although Chinese scholars increasingly address social perspectives like governance[33,34], public acceptance[35], and economic or environmental impacts[36], analyses typically center on single cities or aggregate national and industrial trends[37,38]. Consequently, within both China and globally, comparative studies of urban innovation activities across diverse cities remain scarce. This limits systematic understanding of the diverse urban conditions that enable or constrain AV development and diffusion, as well as variations in governance approaches.

This study addresses these gaps by comparatively analyzing 30 Chinese cities implementing nationally authorized AV pilot projects. Guided by the question, "What mechanisms do different types of cities use to build AV innovation systems, and how do these evolve over time?", we created a novel dataset (Supplementary data 1 and 2) capturing the core features of 116 pilot projects and 881 policy documents from 2016 to 2024, upon which we performed a coding-based qualitative content analysis. The analysis encompasses a diversity of AV applications, from passenger mobility services, such as robotaxis, to specific industrial use cases, such as logistics and delivery. To identify trends across the 30 pilot cities in a structured fashion, we performed a K-means clustering analysis in accordance with AV-related innovation and economic indicators. Finally, we examined the mechanisms underpinning each city's governance strategies from three perspectives emphasized in the sustainability transitions and innovation literature: (1) AV experimentation activities, (2) policy mixes and targeted market segments, and (3) innovation system functions.

We collectively refer to these three perspectives as "urban innovation mechanisms" ("Methods" and Table 4). Each provides a distinct yet interlinked governance lever by which city actors seek to shape the formation and evolution of local AV innovation and adoption pathways. The articulation of these mechanisms is based on descriptions that we deductively identified in the interdisciplinary literature from the fields of urban experimentation and strategic niche management[29,39], policy mixes[20,40,41], and technological innovation systems[42,43], which we then aligned with our empirical observations. The first mechanism, experimentation activities, captures what is being enacted through pilot implementation and how cities utilize AVs in urban contexts, examining project purposes, testing stages, and end-use cases[28,29]. The second mechanism, policy mixes and targeted market segments, captures how governments bundle policy instruments to steer experimentation and position their innovation activities in industrial value chains[12,44]. The third mechanism, innovation system functions[41,43], examines how these pilot and policy practices contribute to innovation system formation and diffusion over time. While abundant literature exists in isolation on each of these perspectives[10,39,45], recent scholarship increasingly calls for more dynamic accounts of how policies interact with innovation processes and socio-technical transitions[41,46]. By conceptually integrating three strands of scholarship into a cohesive analytical procedure, our study advances sustainability transitions research with comparative empirical evidence on the translation of experimentation and policy mixes into innovation-system functions and the co-evolution of these governance mechanisms across divergent urban pathways—insights that are difficult to generate from single-lens or temporally static approaches.

Our analysis reveals three city types—*Innovation Leaders, Specialized Developers, and Emerging Participants*—each characterized by distinct urban conditions and capacities that shape divergent temporal journeys for building up AV innovation systems. Empirically, this heterogeneity reflects differentiated value-chain positioning within China's ICV agenda across city archetypes: *Innovation Leaders* pioneer downstream deployment and institutional experimentation, whereas the other cities concentrate more heavily on industrial manufacturing, infrastructure readiness, and passenger-free applications. These findings underscore the need to align national innovation agendas with city-specific conditions and capacities, as well as the importance of upper-level coordination to facilitate cross-city learning and exchange. Theoretically and methodologically, our study identifies multiple, context-dependent urban governance pathways to AV innovation, showing how municipal governments carry out experimentation, policy mixes, and system functions over time. This temporally dynamic, multi-dimensional perspective extends the innovation scholarship, which has predominantly conceptualized system dynamics at national or sectoral scales[45,47], to the city level, highlighting the plurality of innovation systems within a country. By using a comparative and longitudinal design through clustering cities in accordance with local conditions and capacities, we yield new insights into sustainability transitions and urban governance studies debates on contextualization and multi-scalar governance[19,42,48]. Particularly, our results reveal the proactive role of urban governance actors in steering technology-based urban development and the resulting heterogeneity of governance strategies across places.

Results

Three city archetypes reflecting heterogeneous local contexts and innovation capacities

To systematically examine heterogeneity in innovation mechanisms across different urban contexts, we used K-means clustering to group the 30 cities (Supplementary Tables 1 and 2) based on AV-related indicators covering four dimensions: AV implementation activity, government fiscal strength, innovation capacity, and industrial capacity (Supplementary Table 3). This analysis identified three distinct clusters of cities (Tables 1 and 2, Fig. 1), labeled as *Innovation Leaders, Specialized Developers*, and *Emerging Participants*.

Innovation Leaders ($n = 4$) are the most active in AV development, possessing the highest number of pilot projects, associated policies, and roads allocated for testing. Comprising Beijing, Shanghai, Guangzhou, and Shenzhen, these four Tier-1 megacities are China's political, financial, and innovation epicenters. Their elevated administrative status affords regulatory flexibility for forward-looking policy frameworks and institutional receptivity to disruptive technologies. They benefit from exceptional fiscal capacity, evidenced by extensive budget allocations and technology investments, and from thriving innovation ecosystems bolstered by comprehensive patent portfolios and a concentration of high-tech enterprises. These cities maintain preeminent positions in automotive and digital sectors while hosting the highest concentration of AV companies, corporate headquarters, and innovation hubs—critical resources for catalyzing the shift towards autonomous mobility. Meanwhile, urban conditions such as dense populations and intense traffic congestion due to large vehicle stocks generate substantial market demand for shared mobility services. This is evident in the heavy consumption of online ride-hailing and public

Table 1 | Results of K-means clustering analysis and indicator performance

Category	Indicator	Innovation leaders ($n = 4$)	Specialized developers ($n = 9$)	Emerging participants ($n = 17$)
AV implementation activity	1. Policy documents addressing AV innovation (count)	88	36	12
	2. Number of AV pilot projects (count)	6	4	2
	3. Open road for trials (km)	1621	1391	149
Fiscal strength of the government	4. Fixed asset investment (million yuan)	73,435	56,246	18,169
	5. Budget revenue (million yuan)	479,752	172,866	59,631
Innovation capacity	6. Science and technology expenditure (million yuan)	38,298	15,001	3148
	7. Patents (count)	200,913	90,272	26,811
	8. Number of AV-specialized small to medium enterprises (count)	7	5	1
Industrial capacity	9. Passenger vehicle production (1000 vehicles)	7030	4150	2710
	10. EV production (1000 vehicles)	1440	410	220

Note: Descriptions and data sources for all variables are provided in Supplementary Table 3.

transport, creating optimal environments for large-scale AV testing and deployment.

Specialized Developers ($n = 9$) share a strategic position as regional economic powerhouses with strong industrial capacity but comparatively limited administrative autonomy and fiscal resources. This cluster includes leading automotive manufacturing cities such as Wuhan and Chongqing, as well as Information and Communications Technology (ICT) and digital sector leaders like Hangzhou and Wuxi. These cities show significant AV development through project implementation and policy formulation, though overall performance across indicators is inferior to *Innovation Leader*s. Their industrial structures are focused on specialized upstream sectors, with fewer AV companies possessing cross-cutting or service-provision competencies. Similar to *Innovation Leaders*, growing populations attracted from surrounding regions to these economic centers, along with rising rates of car ownership, add a dual pressure on urban traffic.

Emerging Participants ($n = 17$) constitute the late majority selected for national AV pilot projects and perform substantially lower across all measured dimensions. Despite the moderate within-cluster variation in administrative level and economic volume, the industrial structures in these cities are closely tied to the automobility value chains, either as traditional automotive manufacturing bases or as transportation hubs for surrounding regions. Such conditions provide an ideal context for AV applications in downstream industries like logistics. Meanwhile, socio-demographic characteristics, notably weak public transport use, suggest lower potential for shared urban AV systems.

AV experimentation activities

To compare how cities utilize pilot projects for AV innovation, we examined project purposes, testing and deployment stages, and end-use applications (Fig. 2a–c). We find that *Innovation Leaders* place greater emphasis on market deployment and allowing AV companies to test technological applications at advanced innovation stages, including fully driverless commercial operations. By contrast, other cities primarily use pilot projects to establish digital infrastructure and end-use cases, aiming to attract AV applications and industrial development.

Innovation Leaders demonstrate the most comprehensive portfolio of AV pilot projects, spanning the full spectrum of innovation goals, from research, testing and licensing to market-oriented deployment, end-use application in downstream services, and digital infrastructure readiness (Fig. 2a). These projects have strengthened the technological and service-delivery capacity of AV companies by establishing experimentation pathways that progressively evolve from closed-field testing to driverless commercial operation (Fig. 2b). *Innovation Leaders* also exhibit the most diversified end-use applications, including driverless commercial operations with robotaxis and robobuses in addition to routine passenger-less vehicles for logistics, street sweepers, and patrols (Fig. 2c). Beijing's High-Level Autonomous Driving Demonstration Zone exemplifies this progress into passenger applications. Since 2021, city officials have leveraged the demonstration zone to support road testing and operation trials for Robotaxis with leading AV companies Apollo Go and Pony.ai. Until the end of 2024, Robotaxis were allowed to experiment in the capital's downtown areas surrounding major railway stations without on-board safety supervisors.

Specialized Developers primarily focus on cultivating specialist competencies in upstream manufacturing of intelligent and ICT technologies while developing digital infrastructure to attract experimentation and the establishment of specialized AV firms. Project-specific bonds are commonly employed to facilitate investment in digital infrastructure, such as the deployment of roadside sensing facilities and the building of cloud control platforms and data centers. Though municipal and district governments in *Specialized Developers* frequently establish demonstration areas for trial operation, these end-use applications are mostly government-driven, fragmentarily implemented across districts, and confined to industrial parks or high-tech zones distant from downtown areas, limiting their diffusion potential. The scarcity of projects aimed at market-oriented deployment reflects structural industrial characteristics: these cities lack AV companies with downstream service-delivery competencies and historically specialize in upstream automotive manufacturing and supply chains.

Emerging Participants have project portfolios similar to *Specialized Developers*, but lag substantially in end-use applications and commercial operation activity. These cities focus on deploying AVs in fixed-route buses and low-speed, passenger-free delivery applications with lower technical complexity, while prioritizing infrastructural readiness. Research, testing, and licensing projects remain at early stages—predominantly closed-field or road testing and trial operation—and primarily serve as collaborative platforms or industrial parks to attract high-tech companies and investment. The high proportion of government-driven projects for digital infrastructure development reflects institutional intentions to cultivate the ICV industry and attract AV applications through public investment. Accordingly, many pilot projects feature prominently in local government economic development strategies for digital transformation.

Table 2 | Comparison of key contextual features of the three clusters

		Innovation leaders (*n* = 4)	Specialized developers (*n* = 9)	Emerging participants (*n* = 17)
Cities		Beijing, Shanghai, Shenzhen, Guangzhou	Wuhan, Chongqing, Suzhou, Hangzhou, Wuxi, Nanjing, Hefei, Tianjin, Chengdu	Changsha, Zhengzhou, Xi'an, Fuzhou, Changchun, Jinan, Shenyang, Xiamen, Haikou, Shiyan, Ordos, Cangzhou, Wuhu, Zibo, Liuzhou, Jiangxing
Political and fiscal features	Strategic status	Tier-1 megacities functioning as national political/economic/ innovation centers	New Tier-1 cities functioning as regional economic hubs	Provincial capitals and small to medium industrial cities
	Fiscal capacity and self-sufficiency	High, enabling strategic investments	Relatively high, supporting specialized investments	Low, requiring targeted resource allocation
Industrial and innovative features	Industrial structure	Diversified and leading in both automotive and digital ecosystems	Strong manufacturing bases in automotive supply chains with capacity in AI and ICT sectors	Heavily focused on traditional industries like automotive manufacturing
	Innovation resources	Rich and comprehensive across all domains	Relatively rich with expertise in specialized emerging technologies and industries	Limited to particular sectors
	EV sales and penetration	High EV sales and penetration	Relatively high EV sales and penetration	Average to low sales, but some cities with very high penetration, such as Liuzhou
	Private car ownership (total and per capita)	High total ownership but relatively low per capita	High total and per capita ownership, especially in Suzhou and Chengdu	Low total ownership, but some cities have high total and per capita ownership: Zhengzhou, Xi'an, Changsha
Socio-demographic features	Population	Large and high-density	Medium-to-large with moderate density	Small to medium with lower density
	Urbanization and agglomeration	High	Relatively high	Relatively low, but some cities have high urbanization levels: Xiamen, Shenyang
	Public transport and ride-hailing use	High	Relatively high	Low
	Traffic intensity and road conditions	High with complicated road conditions	Relatively high with diversified landforms	Low and relatively simple road conditions

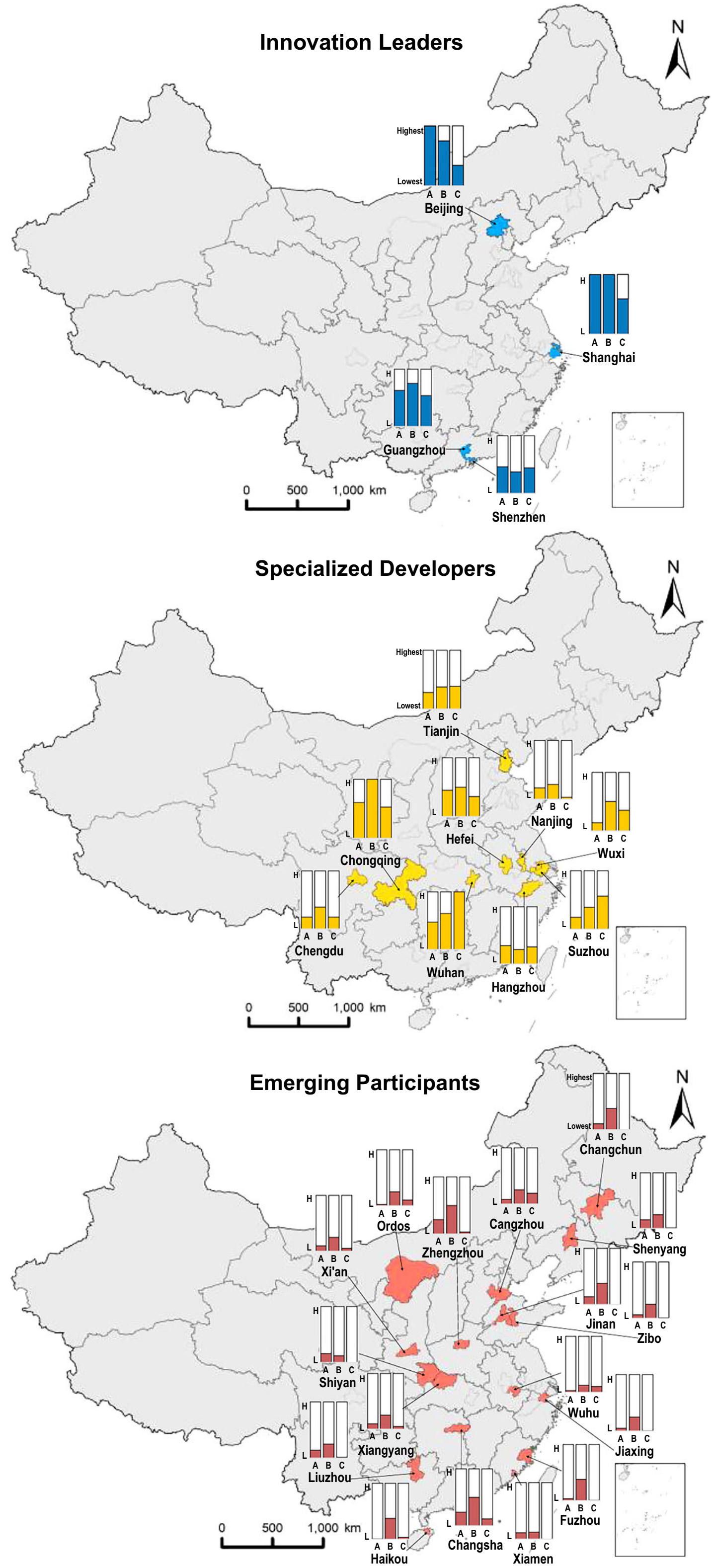

Fig. 1 | Location of pilot cities and summary of AV implementation activity by cluster. Bar charts show the relative intensity of AV implementation activity (data in Supplementary Table 4). Bar heights represent normalized values (0–100), where "L" denotes the lowest value in the dataset for that variable and "H" denotes the highest value. *X*-axis labels A–C represent: A=the number of AV-related policy documents issued (range: 3–114); B= the number of pilot projects implemented (range: 1–8); C=the total length (km) of roads licensed for vehicle trials (range: 6–3379). For example, Shanghai's value of 100 for indicator A indicates it has published the highest number of policy documents (114) in the sample, while Ordos and Wuhu issued the fewest (3).

Varying policy mixes and targeted market segments reflect contrasting aspirations and conditions

China's pilot cities have assembled comprehensive mixes of policy instruments to spur AV innovation. We examined each city's mix across four targeted market segments—demand-side, infrastructure, supply-side, and institutions (Fig. 3a)—as well as specific instruments employed (Fig. 3b), also noting their temporal emergence (Fig. 3c and Supplementary Fig. 1). Together, these market segments span the full AV value chain. Supply-side policies target upstream enabling technologies and components, vehicle manufacturing, and system integration, while demand-side policies focus on deployment and diffusion of AVs in downstream mobility and logistics services. Meanwhile, the domain of infrastructure captures roadside facilities, such as sensor installation, as well as cloud-based communication and data management systems. These digital infrastructures are particularly emphasized in the Chinese approach to AV development, reflecting the ICV agenda's focus on connectivity and vehicle-road-cloud integration. On the

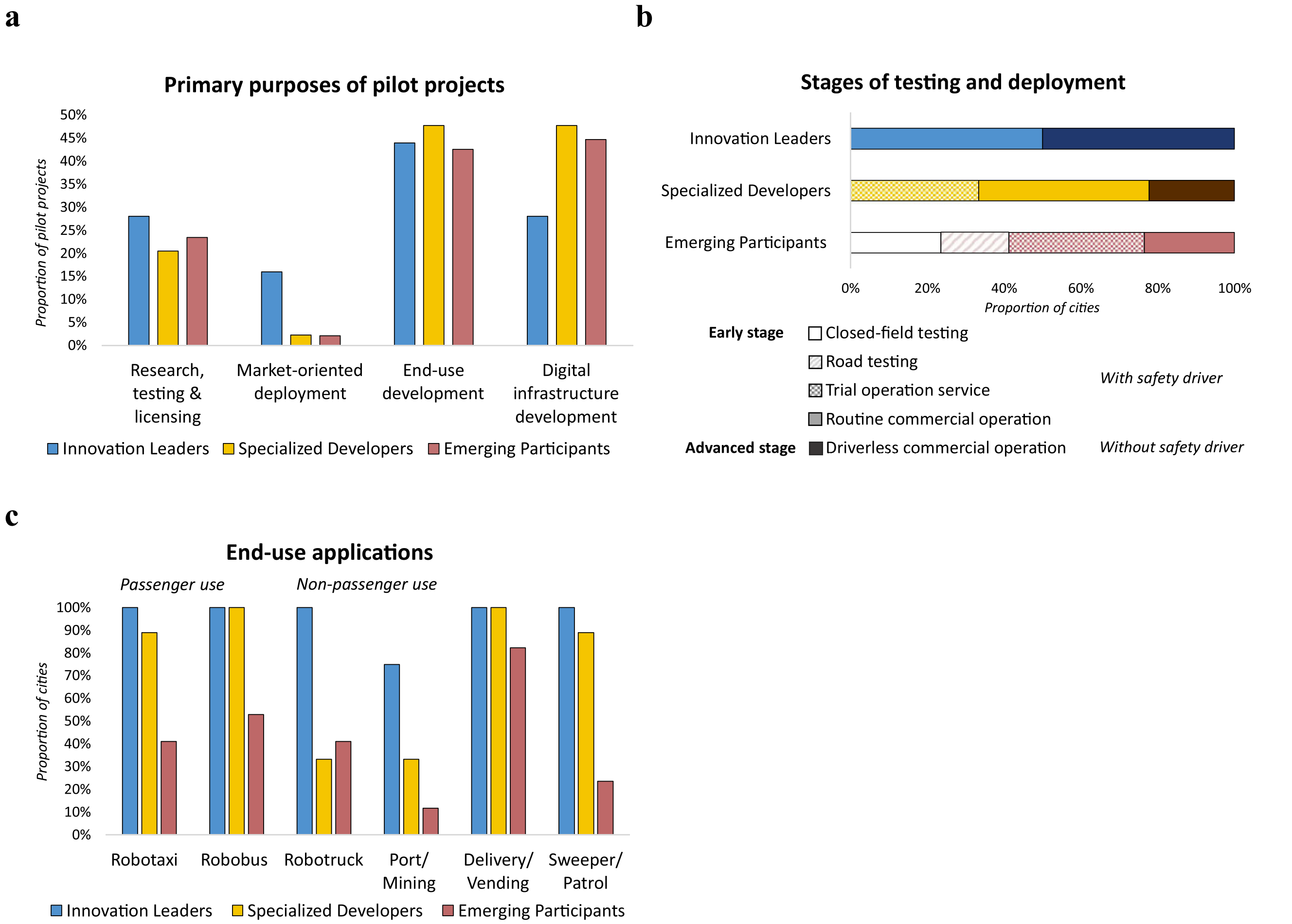

Fig. 2 | AV experimentation characteristics across city clusters. **a** Percentage of pilot projects by primary purpose within each cluster. Some projects serve multiple purposes and thus are represented in multiple coding categories (see Supplementary Table 5 for detailed categorizations). **b** Proportion of cities that have experimented with AVs by testing and deployment stages. The classification of deployment stages, spanning from early to advanced, specifically refers to passenger AV applications (Supplementary Table 6). **c** Proportion of cities with experimental AV deployment by end-use applications.

institutional side, enabling arrangements for AV experiments and governance frameworks are also critical for disruptive technologies such as AVs to enter and scale within the market.

Across most cities, we find a pronounced and temporally persistent emphasis on the supply side (Fig. 3c). This trend is strongly pronounced among *Emerging Participants*, which lack institutional and demand-side interventions. Despite differences in targeted market segments, the overall composition of policy instruments is strikingly similar, with planning tools dominating in all cities. While this reliance on top-down strategic planning indicates a high degree of uniformity and mimicking[49]—closer inspection of the specific instruments leveraged in each policy category reveals substantial variation, with many cities choosing approaches fitted to local contexts and innovation priorities.

The policymaking trajectories of *Innovation Leaders*, reflecting an evolution of innovation activities from technological development to real-world applications, have rapidly shifted from an initial supply-side focus toward infrastructural and demand-side interventions (Fig. 3c). City governments in this cluster actively foster market application of diversified cases, facilitating integration of AVs into urban transportation systems, and targeting end-users through information instruments. They organize promotional and experiential activities to raise public awareness, framing AV adoption as a solution to urban congestion and environmental challenges. Reflecting their stronger fiscal capacity, the instrument mixes of *Innovation Leaders* also feature higher utilization of market-oriented subsidies and economic incentives, typically targeting AV companies' testing, commercial applications, and technological development investments.

Innovation Leaders, in parallel, have actively deployed policies to address institutional challenges, seeking to accelerate AV testing and deployment toward driverless commercial operation ahead of national guidance. This approach has especially involved experimenting with regulatory instruments, including licensing for testing activities and the establishment of technical standards for AV operational processes. These institutional trials have generated valuable learning that has informed both peer cities and national-level policy formulation. For instance, the establishment of Beijing's "AV Policy Pilot Zone" introduced a series of standards for technical safety, product quality, and infrastructure management. By formulating the first regulatory policy that defines testing stages towards fully driverless operation and governs the commercialization of each specific end-use application, Beijing has provided a pioneering template for other cities to follow. Shanghai and Shenzhen, meanwhile, have trailblazed in addressing fundamental legislative issues that hampered AV innovation in other countries[7,9,50], particularly with regard to defining AV companies' liability in accident scenarios.

Specialized Developers closely follow *Innovation Leaders* in policymaking while maintaining a stronger emphasis on supply-side and infrastructural segments. Local government supply-side priorities are evident in their focus on upstream technology development, including vehicle-side sensors, processors, algorithms, and cloud systems[26,51]. Policy ambitions to develop core competencies around these supply chain sub-segments seek to

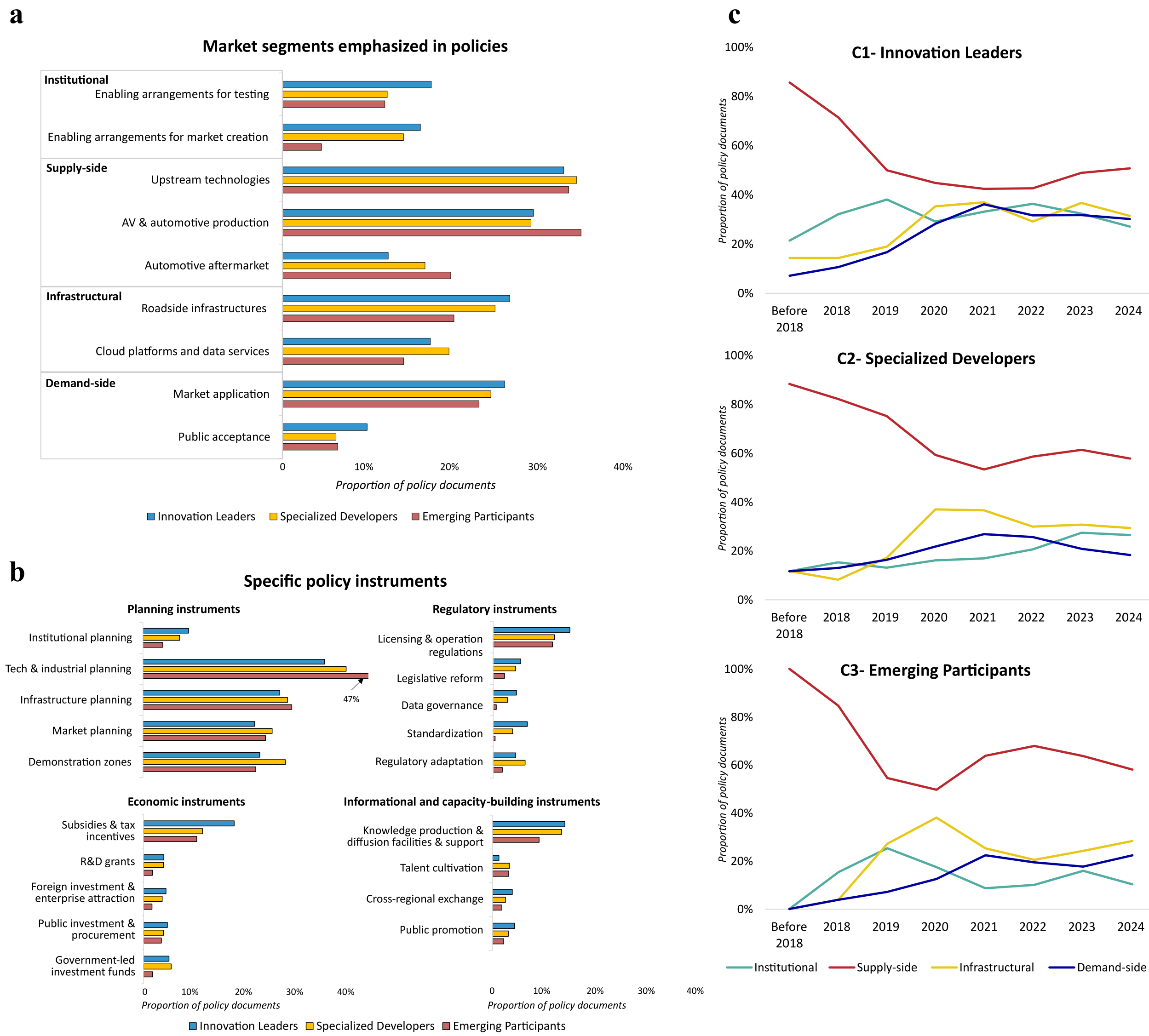

Fig. 3 | AV market segments targeted by policy mixes. a Static comparison of market segment priorities. Each bar length represents the percentage of policy documents addressing each market segment within each cluster. Individual policies may address multiple segments and thus are represented in multiple coding categories (see Supplementary Table 7 for detailed categorization). **b** Static comparison of the adoption of specific policy instruments. Each bar length represents the percentage of policy documents including each policy instrument within each cluster. Policy instruments are classified into 4 categories drawing on established policy frameworks (Supplementary Table 8). **c** Temporal evolution of policy attention toward different market segments across the three clusters from 2016 to 2024. Lines show the proportion of policies targeting each segment each year.

capitalize on existing industrial advantages in electronics, integrated circuits, sensors, and ICT equipment manufacturing while aligning industry structures with areas emphasized in national ICV and digital economy strategies.

Specialized Developers also show a marked increase in policies targeting infrastructure development, including intelligent roadside upgrades, 5G network deployment, and the establishment of computing centers and cloud-control platforms. By improving the infrastructural readiness of demonstration areas, these cities aim to create favorable environments and end-use cases for AV deployment. Policymakers also establish industrial parks and high-tech zones with upgraded facilities and services to attract and strengthen the capacity of small and medium-sized enterprises. Like *Innovation Leader* counterparts, *Specialized Developers* commonly employ government-led investment mechanisms, such as Hangzhou's ICV industry development fund, to mobilize capital for direct investment in infrastructure and industrial chain firms.

Like *Specialized Developers, Emerging Participants* share a stronger and persistent focus on developing AV supply chains, relying heavily on technology and industrial planning. The supply-side concentration in *Emerging Participants* reflects their traditional role as automotive manufacturing cities. Xi'an, a typical example, prioritizes planning instruments aimed at spurring technological innovation and the production of vehicle components like instrument panels, seats, and engines. While Xi'an's policies are underpinned by ambitions for industrial upgrading through AI and electrification, they also emphasize automotive aftermarkets and infrastructural facilities for technical verification and licensing.

Compared to the other two clusters, *Emerging Participants* give less weight to demand-side development. Although demand-side policies have grown slowly in prominence, these efforts mostly involve imitating and transferring upper-level strategies into local contexts to support the implementation of nationally designed pilot projects for end-use development. Demand-side governance strongly relies on planning instruments, with limited measures to stimulate downstream AV service provision through market creation or economic incentives. This largely reflects limited policy-making and fiscal capacities in *Emerging*

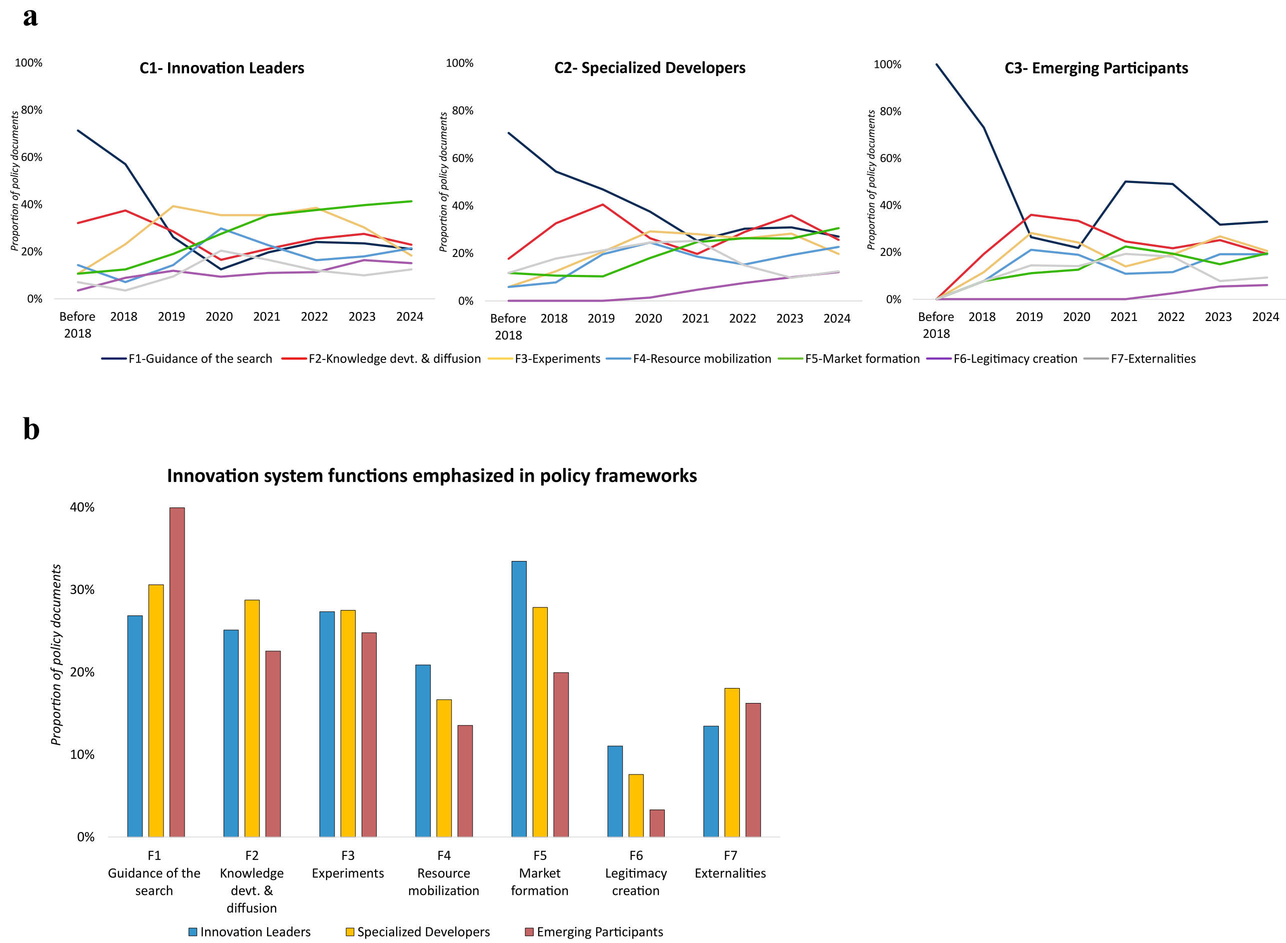

Fig. 4 | Functions of AV innovation systems emphasized in city-level policy frameworks. a Temporal evolution of TIS functions emphasized in policies across the three city clusters from 2016 to 2024. Lines show the proportion of policy documents targeting each innovation system function over time. These seven functions present the key innovation-inducing processes in a technology-specific innovation system that policies can potentially address. Guidance of search (F1) sets targets and strategies for technologies and industries at the early stage. Knowledge development and diffusion (F2) involves measures that facilitate learning, such as R&D projects, collaborative innovation platforms, and knowledge sharing events. Experiments (F3) capture policies that enable and promote testing and application of AV technologies in real-world settings. Resource mobilization (F4) covers financial incentives and organizational support to accelerate innovation progress. Market formation (F5) encompasses policies that create favorable ecosystems for niche technologies to deploy and diffuse, including demand cultivation, institutional alignment, and infrastructural readiness. Legitimacy creation (F6) aims to build legislative justification for new technologies and enhance societal acceptance to enable socio-technical transitions. Externalities (F7) refer to policies targeting technological applications, knowledge spillovers, and resource sharing in sectors beyond the automotive sector. Details of each TIS function are explained in Supplementary Table 9. **b** Static comparison of the distribution of TIS functions emphasized in policy documents in all years. Bar heights represent the relative share of policies addressing each innovation system function as the percentage of the total policies within each cluster.

Participants, which constrain their ability to independently foster broad end-use applications.

Evolving emphasis of innovation system functions reflects differing capacities and priorities

To further clarify how policy frameworks contribute to creating urban technological ecosystems, we examined the temporal emergence of innovation system functions emphasized in each city's policies. Functions were classified according to the Technological Innovation System (TIS) framework[43], which identifies seven system functions (Supplementary Table 9) enabling emerging technologies to progress from niche innovations to wider diffusion. The analysis reveals that city governments do more than reactively govern new technologies[9]. Rather, they proactively shape their surrounding innovation environment (Fig. 4). Furthermore, the temporal sequencing and evolving emphasis on innovation system functions reflect each city's underlying capacities and strategic priorities.

Revealed in Fig. 4a, all three city clusters share a strong initial emphasis on guidance of the search (F1). This is pursued through top-down planning policies that set specific targets and milestones, designating missions to relevant government departments. By signaling strategic directions for AV technologies—notably integrated vehicle-road-cloud development—planning policies seek to incentivize actors to enter and invest in this technological field. Among particularly proactive *Innovation Leaders* such as Beijing, Shanghai, and Guangzhou, guidance policies typically precede the design of on-the-ground pilot projects, responding to technological breakthroughs or national strategies for AV industrial chain development. After approximately 2018, however, the relative importance of guidance of the search (F1) declines markedly across all clusters, with other functions rising in prominence.

For *Innovation Leaders*, entrepreneurial experiments (F3) began attracting policy attention as early as 2018, reflecting the rapid progression of AV technologies in these cities from laboratory research to real-world deployment in urban transport. Pilot project planning and regulatory arrangements enabled these pioneering efforts, driving innovation by stimulating learning across mobility service providers, logistics firms, transportation authorities, and users. Another hallmark feature of *Innovation*

Leaders is the early and sustained focus on market formation (F5) for specific use cases following learning from AV trials. Robotaxi pilots exemplify this pattern. City policies promote their uptake in the routine operations of traditional taxi and car-hailing services, establishing institutional conditions to test business models and gauge market response. Market formation efforts are accompanied by intensive resource mobilization (F4), mainly public investment and subsidies to enhance infrastructural readiness, as well as pioneering market regulations to reduce institutional hurdles to widespread deployment of AV mobility services. An additional feature of *Innovation Leaders* is the earlier emphasis on legitimacy creation (F6). These cities have actively sought to cultivate user acceptance by organizing promotional and public test-ride events while championing societal and environmental benefits. Megacities like Beijing and Shanghai, for example, stress in their policy discourse the potential of AV technologies to mitigate traffic congestion while advancing decarbonization goals through shared public transport.

In *Specialized Developers*, the evolution of TIS function emphasis broadly mirrors that of *Innovation Leaders* but exhibits a later and weaker focus on entrepreneurial experiments (F3) and market formation (F5). These cities strongly emphasize knowledge development and diffusion (F2), reflecting strategic ambitions to strengthen technological research and upstream AV supply-chain capacity. To build technical and manufacturing competencies around core AV technologies, city governments have leveraged diverse learning mechanisms, including collaborative innovation and testing platforms, while establishing high-tech zones and industrial parks. However, because innovation activities supporting upstream development have mostly occurred in industrial zones distant from downtown areas, trials of AV applications have remained small, without scaling into market operations serving end-users in urban centers. Consistent with their strong orientation toward achieving externalities (F7), *Specialized Developers* cities seek to drive AV innovation through cross-sectoral knowledge spillover and resource sharing, especially across network infrastructure, data, and computing power. But rather than prioritizing autonomation directly, these cities pursue AV innovation as a derivative application of broader AI and 5G policies. This approach allows AV governance to serve the broader ambitions of these cities as well as established local industrial advantages in AI and 5G technologies.

Emerging Participants exhibit a persisting emphasis on guidance of search (F1), reflecting the nascent nature of their policy frameworks and innovation system formation. Most cities in this cluster have emulated strategies and practices by frontrunner cities, particularly *Innovation Leaders*, or adapted visions and roadmaps from national authorities. Constrained by lower innovation capacity and resources, top-down guidance has seldom been matched with concrete implementation activities from government departments or private firms. Although attention to knowledge development (F2) and experiments (F3) increased around 2019-20, this primarily reflects the initiation of field-testing and small-scale applications of AV trucks into logistics and traditional automotive manufacturing zones in cities such as Changsha and Liuzhou. Implemented in peripheral industrial areas distant from public view and urban transport systems, these limited-scale experimentation activities were not followed by market-oriented AV deployment (F5). Instead, recent policies place renewed emphasis on guidance of the search (F1) through strategic planning aimed at stimulating AV-related industrial development. This pattern indicates that local governments in *Emerging Participants* chiefly regard AV pilots as opportunities to attract high-tech companies and investments, leveraging these resources to advance the intelligent upgrading of incumbent automotive industries.

Discussion

This study investigated the mechanisms driving AV innovation in 30 Chinese cities. We find that the translation of national-level AV aspirations has produced a diverse landscape of city-level innovation pathways. Our cluster analysis identified three city archetypes—*Innovation Leaders, Specialized Developers*, and *Emerging Participants*—each reflecting distinct intensities of engagement with AV experimentation, development priorities, socio-economic conditions, and temporal development. These variations underscore the importance of contextualization when developing urban innovation mechanisms to support emerging technologies[42], revealing both risks and opportunities for advancing AV technology development and the wider transition toward sustainable urban mobility.

As summarized in Table 3, each cluster of cities embodies a distinct, integrated, and evolving configuration of mechanisms that spur AV innovation through pilot projects and policies targeting different market segments and system functions. *Innovation Leaders* more strongly support downstream service deployment through forward-looking institutional arrangements, including standards, licensing regimes, and data and liability governance. These iterative regulatory experiments and comprehensive, market-oriented policy developments in the early stages have enabled AV technologies to progress rapidly from laboratory research on the supply side to real-world application and market formation. *Specialized Developers* and *Emerging Participants*, by contrast, predominantly pursue manufacturing-oriented strategies, relying heavily on top-down planning instruments to build upstream supply chains, with limited attention to market formation and demand creation. *Specialized Developers* focus on fostering specialist competencies in upstream technology manufacturing, establishing demonstration areas, capacity-building facilities, and targeted investment funds while prioritizing digital infrastructure development, such as cloud platforms and computing facilities, to create favorable end-use environments. Over time, they exhibit some incremental progression toward market-oriented measures. By comparison, *Emerging Participants* place a stronger and more temporally persistent emphasis on supply-side development, supporting AV innovation to enhance automobile manufacturing and industrial upgrading, depending heavily on top-down strategies planned with incumbent local industries. Their AV testing centers on small-scale pilots replicating practices in pioneering cities, targeting lower complexity, passenger-free applications.

The adoption of differing mechanisms across pilot cities reflects the heterogeneous capacities and priorities of city governments in pursuing AV innovation, shaped by local institutional and socio-economic contexts. *Innovation Leaders* megacities command the greatest concentration of innovation resources, particularly core AV companies that drive rapid technological advancement and end-use application. These first-tier cities leverage their geopolitical and administrative status to pioneer trial regulatory frameworks ahead of national policy schemes, promptly responding to companies' real-world testing needs. Meanwhile, pressing urban traffic challenges build a compelling rationale for using these megacities as experimental arenas for integrating AVs into public transport services. By contrast, the industry-oriented patterns shared by *Specialized Developers* and *Emerging Participants* primarily seek to harness AV innovation activities to economic growth objectives. These cities are endowed with established industrial assets across critical AV value chain segments, pursuing opportunities in the reconfiguration process of automobility sectors with AV technologies. On the other hand, their ability to expand AV innovation efforts into market-oriented and downstream passenger application realms is hampered by structural barriers such as fewer core AV firms, limited policymaking autonomy, and lower public transport usage.

Variation in urban innovation mechanisms and contextual conditions creates multiple, interconnected opportunities for advancing AV development in China. For individual cities, important opportunities arise from specialization across automotive manufacturing, ICT, and mobility services, enabling them to leverage existing industrial bases and institutional capacities to build comparative advantages amidst China's transition to an intelligent, data-driven economy. The growing integration of ICV technologies further accelerates urban digital transformation while offering solutions to context-specific societal challenges, such as traffic congestion and safety risks in logistics and mining sectors. At the same time, the existence of diverse urban testing environments, driven by the pioneering experiences of frontrunner cities, facilitates inter-city learning and policy diffusion. Leading cities that establish enabling institutional arrangements

Table 3 | Summary of urban innovation mechanisms and objectives characterizing three pathways to autonomous mobility

Cluster	Core objectives	Experimentation activities	Market segments	Policy instruments	Innovation system functions
Early stage					
Innovation Leaders	Core technology advancement, downstream service deployment, and market creation	Testing pathways enabling firms to progress rapidly from closed-field testing to trial applications	Focus on supply-side technological R&D and enabling institutional arrangements for experimentation	Comprehensive strategic planning and pioneering regulatory frameworks	Emphasis on guidance of the search, knowledge development, and entrepreneurial experiments
Specialized Developers	Specialist upstream technology manufacturing and digital infrastructure development	Upstream technologies testing and digital infrastructure development	Predominant focus on upstream technology research and manufacturing across value chains	Technology and industrial planning, focused on establishing demonstration zones	Emphasis on guidance and upstream knowledge development while leveraging cross-sectoral externalities
Emerging Participants	Automobile manufacturing and industrial upgrading	Closed-field testing in traditional automobile manufacturing cities	Dominant supply-side emphasis on automobile and parts production, and the aftermarket	Top-down planning integrated with incumbent local industries	Emphasis on guidance
Later stage					
Innovation Leaders	No major change	Market-oriented deployment	Shift to demand-side cultivation with iterative institutional arrangements	Concrete economic incentives and regulatory trials to support market creation	Rapid transition to a focus on market formation
Specialized Developers	No major change	Increased application efforts supported by infrastructural coordination	Rising emphasis on digital infrastructure and institutional environment development	Increased capacity-building measures and incentives through shared facilities and investment funds	Incremental progression to market-oriented measures, along with continuous knowledge development
Emerging Participants	No major change	Small-scale pilots replicating practices of other cities, targeting lower complexity applications	Consistent supply-side focus with increasing attention on infrastructural preparation	Experiments with regulatory policies replicating the frontrunners to enable trial applications	Persistent reliance on guidance, with temporary testing and weak market formation

and demonstrate scalable downstream transport services generate transferable governance templates and practical knowledge that can be adapted by peers, reflecting the "nested structure" of disruptive innovation governance identified in earlier research[21,31]. For the national AV landscape, China's pool of pilot cities—driven by government-led urban planning and experimentation across diverse geographic and socio-economic contexts—collectively facilitates technological progress, infrastructure investment, and value-chain development. These combined dynamics reinforce the formation and expansion of China's national AV market and innovation ecosystem.

Nonetheless, our findings reveal several risks associated with fragmented investments and lock-in from China's urban innovation patterns. First, self-interested planning has channeled attention toward supply-side industrial development in many cities under traditional evaluation mechanisms that prioritize local economic growth[49,52]. Without upper-level coordination and cross-regional cooperation, such dynamics risk over-competition for resources and excessive production. Second, fragmented implementation serving local industrial priorities can limit the added value and transformative potential of AV pilots[28,29]. Particularly in cities with limited innovation capacity, redundant infrastructure projects and small-scale AV applications often imitate practices in peer cities, serving ambitions to capitalize on economic opportunities presented by development trends in AI and ICT sectors rather than addressing local mobility needs[25]. Yet prioritizing digital infrastructure readiness under the central government's ICV roadmap risks technological lock-in and misalignment with the evolving technological trajectories of local firms and international developments.

Several important implications for the governance of AV development emerge from our analysis. *Innovation Leaders* should prioritize consolidating niche markets, cultivating demand by offering stable downstream services while integrating AV systems with public transport. In parallel, these leading cities should evolve to address emerging safety incidents or social concerns to reduce uncertainty and strengthen public acceptance. Their experimentation with governance mechanisms can generate templates for other cities and national-level standardization. *Specialized Developers and Emerging Participants* should ensure their industrial investment and infrastructure projects translate to effective R&D outcomes and scalable services in high-demand areas. Rather than emulating megacities, they should prioritize lower-complexity applications, such as logistics and low-speed urban vehicles. More importantly, upper-level governance is needed to better integrate local priorities with national innovation objectives, while harnessing city-level creativity and differentiated competencies across upstream and downstream segments of the AV value chain. Establishing cross-city exchange and coordination mechanisms for standardization, data governance, and evaluation of pilot outcomes is essential to ensure that diverse urban pathways produce complementary learning rather than fragmented or redundant investments. Future research should therefore examine cross-cluster interconnections and coordination mechanisms at regional and national scales—for example, how AV and ICV value-chain roles are distributed and linked across China's major urban agglomerations.

Two key insights for scholarship and future studies can be distilled from our findings. First, our study demonstrates that cities should be conceptualized as complex and dynamic sites where actors and interests actively shape technology development trajectories in accord with local priorities and innovation capacities[12,17,18]. The extant literature frequently conceptualizes innovation environments as a single system at the national or sectoral level, paying limited attention to the existence of multiple, co-existing innovation systems and variations within a country[45,47,48]. In contrast, our study reveals a strong plurality at the city scale in terms of governance mechanism arrangements and innovation system configurations, shaped by diverse local conditions and motivations. This highlights a critical opportunity for scholars to pursue more comparative approaches at the sub-national level to examine how different configurations of contextual conditions give rise to divergent pathways of AV innovation[19,42]. Particularly given that diversity in governance and innovation trajectories also emerges over time, it is important that scholars account for temporal dynamics, as underscored by recent longitudinal analyses of firm reorientation in the context of low-carbon transitions[53,54].

Second, the evolving and context-specific pathways of urban innovation governance synthesized in Table 3 reveal that city actors use multifaceted approaches to govern AV development, leveraging varying combinations of AV experimentation, positioning in value chains, policy instruments, and emphasis on TIS functions. Moreover, this multi-perspective and temporally dynamic picture of urban technology governance—based on integration of three strands of scholarship—reveals a co-evolution of government mechanisms from early to later stages of innovation system development. The findings demonstrate how policy priorities evolve in response to learning from pilots, how policy instruments and pilot activities operationalize innovation system functions, and how cities leverage divergent portfolios and temporal sequences of governance mechanisms in accordance with local capacities and priorities. At the same time, the analysis reveals that the governance actions of city actors do not merely reflect reactivity to new technologies. Rather, city policymakers seek to proactively shape their surrounding innovation environment by simultaneously integrating socio-technical experimentation, policy mix development, market positioning, and innovation system function development, adapting these governance mechanisms to local opportunities and learning. These trends point to important opportunities for scholars to develop comprehensive methodological approaches to analyze how multiple governance mechanisms interact, co-evolve, and generate synergistic effects on the emergence of novel socio-technical systems. Such work could be advanced by integrating theories and methodological approaches from several relevant fields, such as urban experimentation, strategic niche management, policy mixes, and technological innovation systems.

We acknowledge several limitations of this research. First, our reliance on the coding of policy documents as the primary data source reveals only limited insight into policy-making motivations and the processes or barriers shaping the implementation of different governance mechanisms. Furthermore, the analysis may be affected by biases inherent in policy documents, as government actors often emphasize developmental perspectives that may not fully reflect on-the-ground realities. Second, by quantifying policies and pilot projects to assess the presence and prevalence of specific features across city clusters, our descriptive analytical procedure offers limited explanatory power for identifying causality. Our study, therefore, did not seek to assess the effectiveness of particular governance mechanisms or their combinations in spurring desirable outcomes for AV development. Third, the use of K-means clustering may obscure boundary cases and within-cluster heterogeneity. Data availability also limits our ability to examine all factors influencing cities' innovation capacity and contextual characteristics that may explain inter-city variations. Additionally, our qualitative analysis indicates a marked evolution in governance strategies for some cities, particularly *Innovation Leaders*. This raises the theoretical possibility that a city's cluster positioning could shift in the long run as its innovation capacities evolve—dynamics that our static clustering could not capture. Future research could examine the evolution of cities' attributes and innovation capacities using time-varying indicators and longitudinal clustering approaches. Fourth, our analytical framework centers on governance mechanisms led by public authorities and therefore does not fully capture the roles, practices, and perspectives of non-governmental actors—particularly private firms and end users—within the AV innovation ecosystem.

Methods

Study design and workflow

To identify and compare the core characteristics defining the temporal development and behavior of urban innovation mechanisms across cities, we assembled and analyzed a quantitative and qualitative dataset, drawing methodological inspiration from evidence mapping[55]. Our study followed the five-step design shown in Fig. 5.

Step one: sample construction

Our sample consists of all cities with administrative rank at prefecture-level or above that had implemented national-level pilot projects for AV technology development by the end of 2024. We identified cities from policy documents related to these pilot projects, published by relevant national ministries. We recognize that additional pilot projects exist at provincial and lower administrative levels. However, we limited our analysis to nationally authorized pilot cities to ensure that the selected cases shared the common feature of having on-the-ground implementation activities as well as reliable, documented data available for analysis.

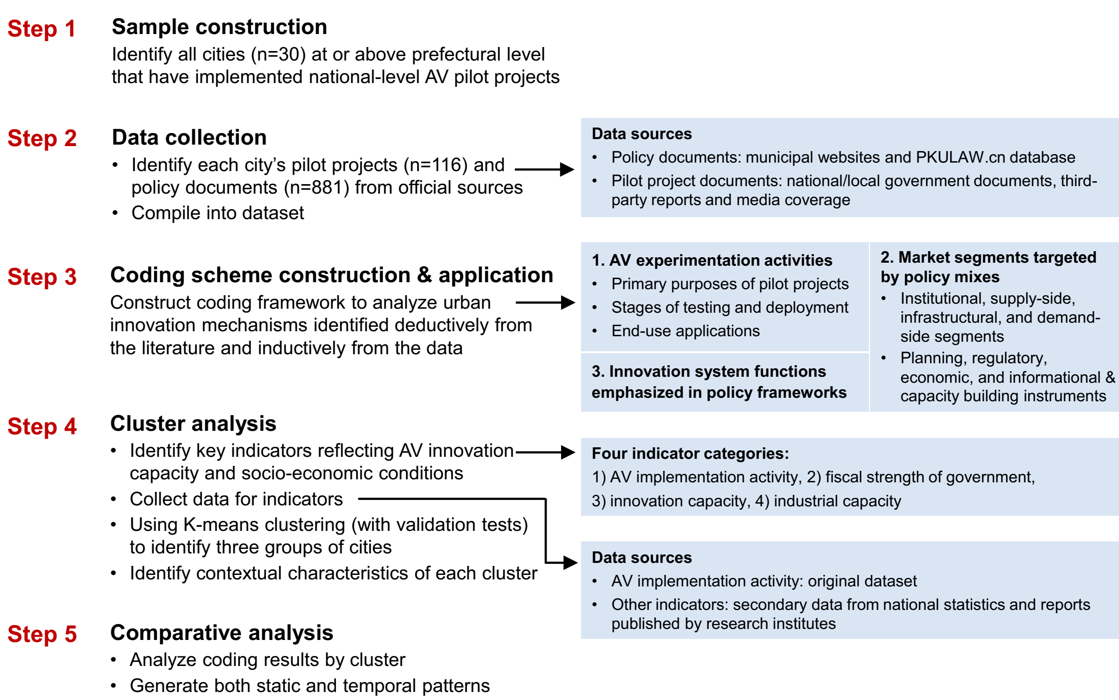

Fig. 5 | Research design.

Our sample comprises 30 cities (Supplementary Table 1) that implemented pilot projects across five categories (Supplementary Table 2). These cities represented a wide range of socio-economic conditions, ranging from Tier-one megacities such as Beijing to smaller Tier-four cities such as Shiyan and Ordos. This heterogeneity enabled comparative analysis across diverse innovation capacities and socio-economic conditions.

Step two: data collection

To examine AV innovation strategies and practices across the 30 cities, we constructed an original dataset comprising 881 policy documents issued by local governments and 116 pilot projects implemented in these cities (Supplementary data 1 and 2). Pilot projects provide evidence of on-the-ground experimentation and deployment, whereas policy documents reveal intended governance strategies and the policy instrument mixes used to enable, steer, and legitimize experimentation. Together, we examine these two sets of data as an interconnected suite of governance mechanisms that pursue the development of AV innovation systems and societal deployment.

Policy documents were collected from municipal websites, supplemented by PKULAW.cn, a comprehensive database of Chinese laws and regulations. Our policy database includes formal legislation, regulatory documents, and strategic policy schemes. It excludes working files and proposed policies that lack a coherent thematic focus or specific policy strategies and instruments. We identified relevant policies for each city by searching document titles and content using the following keywords in Chinese: "Autonomous Vehicles", "Self-driving Vehicles", and "Intelligent Connected Vehicles", the latter being a commonly used terminology in China, reflecting the integration of AV development within the broader ICV policy framework. The dataset spans from 2016, when the earliest policy document was drafted, through to the end of 2024. Data collection was conducted in multiple, iterative rounds between January 2024 and March 2025.

For AV experimentation activities, we compiled a comprehensive list of pilot projects implemented in each city, sourcing these through keyword searches on municipal websites, cross-referenced with third-party reports. Our dataset includes local-level projects developed by municipal and district governments, as well as nationally designed projects implemented at the city level. Our analysis focused specifically on projects involving road vehicles with Level 3 or higher automated driving capabilities, as defined by Chinese national standard GB/T 40429-2021. This ensures technological consistency across pilot projects while adhering to internationally recognized SAE terminology (explained in Supplementary Text 1). Project details were extracted from multiple sources. We identified the primary purposes of pilot projects from public documents released by national and local governments. For implementation details, including testing and deployment stages and end-use applications, we relied primarily on reports published by local governments and industrial associations. For cities lacking such official reports, we supplemented data with media coverage.

Step three: coding scheme construction and application

To systematically analyze the mechanisms driving AV innovation in pilot cities, we developed several coding frameworks that combined inductive and deductive approaches[46,56,57]. We first established preliminary frameworks deductively, drawing on existing theories and literature on urban experimentation and strategic niche management[29,39], policy analysis[12,20,40,41,58], and innovation systems[43,59]. We then inductively and iteratively applied these to our dataset with 10 randomly selected cities, subsequently refining our initial coding categories in accordance with empirical observations. This combined strategy ensured theoretical grounding while remaining responsive to empirical realities in China's technological and institutional context.

Coding decisions were carried out through a structured, iterative calibration and consensus process. The first author conducted the primary coding and maintained a running memo of uncertain cases and decision rationales. The second author reviewed a purposive subset of coded materials and provided an audit of category use, boundary conditions, and potential inconsistencies. Discrepancies and ambiguous cases were then adjudicated through team discussions involving all authors, resulting in refined definitions, inclusion/exclusion criteria, and clarifying examples. To ensure transparency and consistency across iterations, we maintained a versioned codebook and an audit trail for documenting. When decision rules were updated, we retrospectively revisited affected items in the dataset and revised codes as needed to preserve internal consistency. The final, detailed codebook is provided in the Supplementary Tables 5–9 to enable scrutiny and facilitate replication.

Our analytical approach comprises three complementary perspectives and frameworks, together capturing the multifaceted nature of urban innovation mechanisms (Table 4).

To understand how pilot cities directly engage with AV technology, we interpreted the pilot projects from three aspects derived from strategic niche management and urban experimentation literature. First, we classified the primary purposes of AV pilot projects into four categories (Supplementary Table 5) according to statements issued by national authorities. To further capture implementation progression and diversity across cities, we coded vehicle pilot projects by testing and deployment stages as well as end-use applications. The classification of the stages was defined based on national and local regulatory policies[60] and explained in detail in Supplementary Table 6.

We then conducted policy content analysis to investigate trends in market segmentation and policy instrument use, drawing on policy analysis studies. We identified nine distinct market segments of AV development and adoption (e.g., enabling arrangements for testing and upstream technologies) targeted by policy documents, organizing these into four broad market dimensions: institutional, supply-side, infrastructural, and demand-side[44]. To examine how policy mixes support and govern these market segments, we identified the specific instruments adopted by local governments (e.g., demonstration zones and subsidies), categorizing these into four major types: planning, regulatory, economic, and informational and

Table 4 | Analytical perspectives used to examine urban innovation mechanisms

Perspective	1. AV experimentation activities	2. Market segments targeted by policy mixes	3. Innovation system functions emphasized in policy frameworks
Sub-perspectives	- Primary purpose of pilot projects - Stages of testing and deployment - End-use applications	- Four key market segments: institutional, supply-side, infrastructural, demand-side - Major categories of policy instruments: planning, regulatory, economic, informational and capacity building	Seven functions of the Technological Innovation System (TIS) framework
Objective	To investigate how cities experiment with and utilize AVs in urban contexts	To identify the focus of city-level policy strategies on AV market segments, and the corresponding policy instruments	To understand how city-level policy frameworks seek to foster key innovation system functions
Basis in literature	Dowling and McGuirk[29], Ministry of Industry and Information Technology et al.[60]	Trencher[44], Rogge and Reichardt[40], OECD[58], etc.	Bergek et al.[59], Hekkert et al.[43], etc.

Table 5 | Validation test results of clustering analysis

K	Elbow method	Silhouette coefficient	Calinski-Harabasz index	Davies-Bouldin index
2	46.77%	0.47	24.60	1.03
3	26.38%	0.35	20.95	1.18
4	23.88%	0.37	20.39	0.97
5	17.19%	0.33	19.05	1.03
6	12.52%	0.21	17.41	1.02

capacity-building[40,58]. Detailed codebooks are provided in Supplementary Tables 7 and 8.

To further understand how city policies facilitate the evolving innovation processes of AV technology, we applied the Technological Innovation System (TIS) framework, which captures the systemic nature of technological development and the multiple functions required for successful socio-technical transitions. We coded policies according to seven key TIS functions described in TIS literature[41,43,59]: guidance of the search (F1), knowledge development and diffusion (F2), experiments (F3), resource mobilization (F4), market formation (F5), legitimacy creation (F6), and externalities (F7). Supplementary Table 9 provides detailed explanations of each function. Notably, we interpreted legitimacy creation (F6) as strategies for raising societal awareness of AV technology, for example, with regard to the societal and environmental benefits of AV development, and reformation of legislative frameworks. Additionally, in applying externalities (F7) to the context of China, we considered policies targeting technological applications, knowledge spillovers, and resource sharing in sectors beyond automobility or AVs, such as AI, 5G, ports, and tourism[61].

Step four: clustering approach and comparative analysis

To systematically identify commonalities and disparities among the 30 pilot cities in AV innovation, we conducted K-means clustering analysis. We developed 10 indicators across four categories: (1) AV implementation activity, (2) fiscal strength of government, (3) innovation capacity, and (4) industrial capacity (Supplementary Table 3). Data for the first category were extracted from our original dataset, while data for the remaining categories were sourced from national statistics and reports published by government research institutes. Indicator selection drew on established criteria for assessing geographical, technological, and institutional readiness for AVs[16,62]. While we acknowledge that this indicator set is not exhaustive due to practical constraints in data availability and reliability, it effectively identified distinct clusters of pilot cities with clear disparities in terms of AV innovation capacities, socio-economic characteristics, and innovation governance behavior.

A critical step in clustering analysis involved determining the optimal number of clusters. We tested models with two to six clusters and conducted multi-criteria statistical validation using four metrics, including the Elbow method, Silhouette coefficients, Calinski-Harabasz index, and Davies-Bouldin (DB) index (Table 5). While $K = 2$ demonstrates the highest statistical performance across most metrics, it oversimplifies categorizations and fails to capture heterogeneity in cities' innovation practices. We selected $K = 3$ as the best balance between statistical robustness and empirical interpretability. The inertia curve shows a clear point of diminishing returns at $K = 3$, evident by the Elbow method, and a strong Calinski-Harabasz ratio, indicating that the three-cluster solution provides a high between-cluster separation while maintaining internal cohesion. Empirically, it also aligns most with the tier-based urban classification in the Chinese context and supports interpretable archetypes for comparative analysis. We acknowledge the limitation of the K-means method that requires hard cluster membership because its distance-based logic forces each city into a single, mutually exclusive cluster. The silhouette scores indicate that not all cities are equally well-separated, reflecting unavoidable within-cluster heterogeneity and boundary cases. We therefore interpret clusters as "archetypal configurations" capturing dominant tendencies rather than fully homogeneous groups.

K-means clustering was performed using GEODA software for data normalization and processing. We labeled the three distinct city clusters as *Innovation Leaders, Specialized Developers*, and *Emerging Participants* based on indicators measuring AV implementation activity, innovation capacity, and economic conditions. The first cluster exhibits significant leadership across all innovation indicators, while the second cluster demonstrates specialized strengths in particular indicators, especially industrial capacity and implementation activity. The third cluster lags behind the first two clusters in overall innovation capacity but exhibits emerging AV experiments authorized as national-level pilots. We acknowledge that alternative clustering approaches exist, notably the diffusion of innovations theory originated by Rogers[63], which defines five categories of adopters, sequenced from innovators to laggards. However, our analysis focuses not solely on AV adoption but rather encompasses multiple dimensions, including production, institutions, policymaking, innovation system emergence, and socio-economic conditions.

Step five: comparative analysis of coding results

We generated visualizations of the coding results (Supplementary data 1 and 2), organized by the three clusters identified through *K*-means cluster analysis. These visualizations were then used to identify the common trends and cluster-specific variations from the three perspectives of our analytical framework.

Data availability

The data supporting this study are available as supplementary information. Policy documents, project information, and city-level socio-economic indicators were obtained from publicly accessible sources, including municipal and national ministry websites, national statistics, and reports published by government-affiliated industrial associations.

Code availability

The coding scheme is detailed in the method section. Supplementary Tables 5-9 provide further details on data collection and coding frameworks. Supplementary data 1 and 2 include names of selected cities ($n = 30$), policies in each city ($n = 881$), pilot projects implemented in each city ($n = 116$), and the binary coding results.

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Author contributions

Q.W., G.T., and A.T. conceived the study and collaboratively developed the coding scheme and theoretical framework. Q.W. performed the coding and data analysis and wrote the manuscript under the guidance and supervision of G.T. Both G.T. and A.T carried out revisions to the manuscript and helped Q.W. perform additional analyses, observations, and discussion of implications. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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