

M A N I F E S T O

FROM FLATLAND TO FULL SPECTRUM

*Liberating Transport Research Across
Dimensions, Geographies, and Time Horizons*

A Vision for the Next 50 Years of Transport Research
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PREAMBLE: THE DECLARATION

For fifty years, transport science has operated in flatland; a two-dimensional world of lanes, links, and planar networks. Our flow models assume vehicles travel along one-dimensional manifolds. Our equity models project citizens onto flat surfaces. Our environmental assessments treat the atmosphere above and the watershed below as someone else's problem. Our theories were calibrated on Western motorways and exported to the rest of the world as universal laws. We have built an extraordinary science of surfaces. It is no longer sufficient.

The next fifty years demand a full-spectrum liberation: the reconstruction of transport science across three frontiers simultaneously, from two dimensions to three dimensions, from the Global North to the whole world, and from engineering assumptions about human behaviour to the reality of how people actually move, adapt, and resist. These three liberations are not separate agendas. They are one agenda, because the same flatland thinking that confined our models to two dimensions also confined our theories to one geography and our behavioural assumptions to one kind of human.

We, the next generation of transport researchers, refuse to inherit a science that is dimensionally impoverished, geographically parochial, and behaviourally naïve. This manifesto is our commitment to build something better.

PART I: THE DIAGNOSIS — WHY FLATLAND SCIENCE MUST END

Transport science rests on unstated assumptions that were productive simplifications in the twentieth century but have become conceptual prisons in the twenty-first. We name seven, because naming them is the first step toward escaping them.

1. The Lane Assumption

From Greenshields (1935) through Lighthill–Whitham–Richards (LWR) (1955–56) to the Intelligent Driver Model (IDM) (2000) and every microsimulation tool in use today, traffic flow theory assumes vehicles occupy discrete lanes on one-dimensional segments embedded in two-dimensional networks. This is not a harmless simplification. It is a topological commitment that renders three categories of movement invisible: heterogeneous non-lane-based traffic, which is the dominant mode of surface movement across South Asia, Southeast Asia, and much of Africa; volumetric movement in three-dimensional airspace, where the concept of a “lane” has no physical meaning; and mixed-mode vertical interactions, where aerial and surface vehicles share the same urban space across different altitudes.

2. The Interaction Models Assumption

The microsimulation paradigm rests on a leader–follower dyad sharing a longitudinal axis. Every major car-following model, e.g., Pipes, Gipps, Wiedemann, encodes this structure. In three-dimensional space, there is no leader. Influence is spherical, not longitudinal. The

relevant framework is not car-following but sphere-of-influence dynamics, with closer kinship to Reynolds flocking and molecular dynamics than to anything in the traffic flow canon.

3. The Fundamental Diagram Assumption

Flow–density–speed relationships, defined per lane-kilometre, underpin the entire capacity analysis apparatus, Highway Capacity Manual (HCM) (HCM, 2010) Level of Service (LOS), volume-to-capacity ratios, and bottleneck theory. In volumetric space, density becomes a scalar field in \mathbb{R}^3 , flow becomes a vector field, and capacity becomes a property of a volume rather than a cross-section. The fundamental diagram does not generalise to three dimensions. It must be replaced.

4. The Equilibrium Assumption

Wardrop’s principles (1952) assume travellers converge on stable route choices within a fixed network topology. Dynamic traffic assignment relaxes temporal stationarity but preserves the planar network structure. In a world where aerial routes are created and dissolved in real time, where autonomous swarms self-organise, and where mobility platforms reshape supply and demand simultaneously, there is no fixed network on which to equilibrate. The equilibrium paradigm is not wrong; it is a special case masquerading as a general theory.

5. The Homogeneous-Agent Assumption

Even heterogeneous traffic models, multi-class LWR, mixed-traffic microsimulation, assume that heterogeneity can be captured by a finite set of vehicle classes with fixed parameters. The systems now emerging, human drivers, Level 3 AVs (Autonomous Vehicles), Level 5 AVs, delivery drones, air taxis, pedestrians, cyclists, rickshaws, all sharing space across surface and air, exhibit heterogeneity that is dimensional, not parametric. A drone does not possess a “desired speed” in the IDM sense. A rickshaw driver navigating Lahore traffic does not behave as a degraded version of a German motorway driver.

6. The Geographic Assumption

The field’s foundational theories were built on data from Western, motorised, lane-disciplined, homogeneous traffic environments. They are then exported to radically different contexts, e.g., Karachi, Lagos, Dhaka, Jakarta, and treated as universal laws with local *calibration*. This is not science; it is intellectual colonialism. The most complex, heterogeneous, and climate-vulnerable transport environments on Earth are treated as deviations from a Northern norm rather than as the frontier where new theory must be born.

7. The Fixed-Network Assumption

Infrastructure is treated as fixed and failure as external, with links and capacities assumed to persist while flow evolves. Under climate change, this breaks down. Floods, landslides, heat extremes, and coastal processes do not merely disrupt networks; they reshape them. Roads become channels, bridges fail, and terrain evolves through coupled environmental dynamics. The network is not a graph but a state-dependent physical system. Capacity is intermittently

destroyed and reformed, accessibility becomes stochastic, and topology is no longer an input but an outcome. A theory built on static infrastructure cannot describe a climate-driven world.

PART II: THE LIBERATION — THREE INTERLOCKING TRANSFORMATIONS

Against these seven constraints, we propose three interlocking liberations. They are not independent reforms; they are facets of a single paradigm shift. Dimensional liberation without geographic liberation merely gives the Global North new tools. Geographic liberation without behavioural grounding merely relocates the same reductive assumptions. Behavioural liberation without dimensional and geographic scope merely refines models that remain trapped in flatland and confined to a narrow slice of humanity.

Liberation 1: Dimensional — From Flatland to Full Volume

The Vertical Frontier

Urban Air Mobility, autonomous drone logistics, underground freight, and vertical urbanism are active engineering programmes. Yet the field possesses no established theory of volumetric traffic flow. We cannot rigorously define congestion in airspace, compute the capacity of a three-dimensional corridor, or model behavioural interactions between a human driver and a descending drone. The methodological foundations must be built from first principles:

- Three-dimensional flow field models using partial differential equations on manifolds, replacing planar network graphs with continuous volumetric representations.
- N-body interaction potential models replacing the car-following dyad, where influence decays with three-dimensional distance and is formalised through potential functions in \mathbb{R}^3 .
- Volumetric phase-space characterisation to replace the fundamental diagram, defining what congestion, free flow, and capacity mean when the medium is a volume, not a surface.
- Physics-informed neural network architectures that encode conservation laws while learning behavioural dynamics from volumetric observational data.

Claim 1 — Dimensional: Transport science is trapped in a 2D paradigm (the flatland diagnosis). The next 50 years require liberation into volumetric (3D), temporal, ecological, and social dimensions.

The Ecological and Disaster–Transport Coupling Frontier

The global road network represents the planet’s largest continuous impervious surface. In three dimensions, it aggressively reshapes watersheds, channels flood risks, fragments ecosystems, and generates terminal heat islands. Yet, classical transport science continues to treat these profound environmental interactions as mere externalities—variables assessed only after foundational design decisions have been finalised. As illustrated in Figure 1, this traditional paradigm of separation is not merely incomplete; it is fundamentally incorrect.

Natural hazards consistently expose the fatal limits of this isolated approach. Floods, landslides, and debris flows are not external disruptions striking a static transport system; they are dynamic physical processes governed by conservation laws, evolving continuously in space and time. When these forces interact with transport infrastructure, the system does not simply degrade—it fundamentally transforms.

The Pakistan's 2022 floods, which killed over 1,700 people and damaged or destroyed thousands of kilometres of road infrastructure, demonstrated the catastrophic consequences of this artificial separation. Roads concentrated floodwater; floodwater destroyed roads. The system was always coupled; only our models pretended otherwise. This pattern is not isolated. During the 2023 Derna flood in Libya, flood waves triggered by dam failures erased entire road corridors within minutes, severing urban connectivity and collapsing evacuation routes. In Brazil, recurrent flood–landslide events in 2024 transformed mountainous transport networks into cascading failure systems, where slope instability and runoff jointly dictated accessibility. Across Southeast Asia, extreme monsoon floods between 2024 and 2025 submerged dense urban transport grids, forcing mobility systems to operate under rapidly evolving hydrodynamic constraints.

Under these extreme conditions, transport can no longer be represented as abstract flow on a static topological network. As detailed in the feedback loop of Figure 1, the coupling process is continuous: hazard evolution triggers an infrastructure response, which immediately forces a mobility impact, necessitating an adaptive response that feeds back into the environment. During flood events, water depth, velocity, and terrain interact with vehicles, infrastructure, and human behaviour in real time. As roads submerge, flow resistance dynamically changes, accessibility collapses, and routing becomes entirely dependent on evolving physical constraints. Transport networks cease to function as passive substrates and instead become active components within a coupled hydro-physical system.

Mobility is no longer a network problem; it is a coupled, multi-physics system. This paradigm shift demands a radically new class of technological frameworks. To navigate this frontier, transport science must adopt the following advanced models:

- **Coupled Hydro-Transport Simulators:** Frameworks that integrate advanced hydrological models directly with traffic flow algorithms. These must compute flood inundation and network disruption simultaneously as a single dynamic system, rather than as sequential, disconnected processes.
- **Physics-Informed Machine Learning:** Advanced AI models that capture the complex, non-linear interactions between fluid dynamics and transport processes. These are essential for the real-time prediction of network cascading failures, accessibility loss, and recovery dynamics under extreme weather conditions.
- **Co-Evolutionary Digital Twins:** Bidirectional mirror worlds where hazard evolution and transport responses co-evolve. By fusing ubiquitous sensor data, remote sensing, and predictive modelling, these systems will support real-time scenario analysis, zero-latency early warnings, and dynamic, adaptive routing.
- **Unified Multi-Hazard Frameworks:** Comprehensive models that move beyond single-threat analysis to integrate flooding, landslides, infrastructure fragility, and compound climate stressors into a singular, probabilistic representation of systemic transport risk.

- **Symbiotic Nature-Based Design:** The engineering of transport corridors as ecological assets. Utilising permeable pavements, bioswales, green bridges, and floodplain-integrated road designs, infrastructure must be built with strictly quantified co-benefits for both human mobility and watershed health.
- **3D Environmental Impact Engines:** Spatial models that expand into the vertical axis, accounting for altitude-dependent emission dispersion, acoustic propagation from aerial vehicle swarms, and the vertical stratification of air quality in dense urban canyons.
- **Climate-Adaptive Topological Design:** Treating resilience to flooding, extreme heat, and atmospheric volatility not as an afterthought, but as a first-order mathematical design parameter. Robustness and physical adaptability must be embedded directly into the very topology and operation of the network.

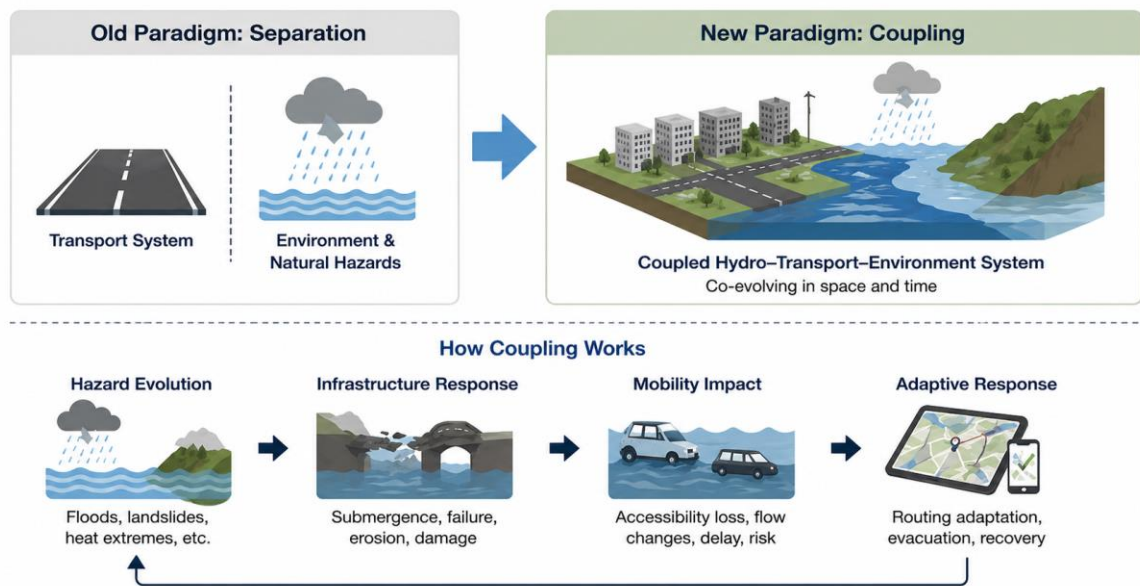


Figure 1. The Paradigm Shift in Infrastructure Planning: Transitioning from the isolated assessment of transport networks to a continuously co-evolving, coupled hydro-transport-environment system.

The Temporal Frontier

Transport planning still relies on equilibrium assignment as its analytical workhorse. The systems we are building — on-demand aerial taxis, autonomous swarms, real-time dynamic platforms — are fundamentally non-equilibrium. Time is not a parameter to be averaged away; it is a dimension in which the system lives:

- Neural stochastic differential equation frameworks modelling traffic as continuous-time stochastic processes rather than sequences of equilibrium states.
- Evolutionary game theory and reinforcement learning on dynamic, topology-varying networks where routes are created and dissolved in real time.
- Adaptive network formation models where the transport topology itself evolves endogenously with demand, technology, and environmental conditions.

Liberation 2: Geographic — From Periphery to Centre

The Problem with “Calibration”

When a model built on German motorway data is applied to traffic in Islamabad, the standard practice is to “calibrate” it to adjust parameters until it approximately fits local data. This practice embeds a profound assumption: that the structure of the model is universal and only the parameters are local. But a rickshaw weaving through mixed traffic in Lahore is not executing a degraded version of the Intelligent Driver Model. A matatu driver in Nairobi is not a poorly calibrated Wiedemann agent. These drivers operate within entirely different behavioural, institutional, and physical regimes that require different model structures, not different parameter values.

Claim 2 — Geographic: The transport field's theories were built in and for the Global North. The most complex, heterogeneous, climate-exposed, and rapidly urbanising transport environments are in the Global South, and these environments must become the places where new theory is generated, not merely tested.

The Reversal

We propose a fundamental reversal in transport science. The most complex traffic environments on Earth—characterised by mixed, non-lane-bound, multi-modal, and highly heterogeneous flows—operate under extreme climate stressors, from monsoon flooding to lethal urban heat. These systems are embedded in rapidly urbanising cities with dynamic, informal governance structures across the Global South.

Historically, these environments have been treated as chaotic edge cases to which Global North theories are awkwardly extended. We argue the exact opposite: These volatile environments are the general case from which universal transport theory must be built. The homogeneous, lane-disciplined, climate-stable motorway traffic of the Global North is merely a highly constrained, fragile special case.

Crucially, this reversal is not solely behavioural or institutional; it is profoundly environmental. The Global South represents the frontline of climate-exposed transport systems. Here, mobility is continuously sculpted by flash flooding, structural heat stress, and cascading, interacting hazards. Climate forcing is not an external disturbance or a rare “shock” to the system; it is the dominant driver of baseline dynamics. It fundamentally alters how transport networks evolve, fail, and regenerate.

This reversal has concrete methodological implications:

- Behavioural models must be built from Global South data as the primary training set, with Northern data as a validation subset, not the reverse.
- Heterogeneity-first model architectures, where the default is mixed, non-lane-bound, multi-modal traffic, and lane-disciplined flow is a constrained special case.
- Research funding and institutional structures that position Global South universities as theory generators, not as data collection sites for Northern research programmes.
- Publication norms that value new theoretical structures emerging from complex environments over incremental extensions of existing models to new geographies.

- Climate-aware modelling frameworks in which environmental forcing (e.g., rainfall intensity, flood propagation, and heat stress) is treated as an endogenous driver of transport dynamics rather than an external perturbation.

Climate Vulnerability as Theoretical Driver of System Dynamics

The transport networks of the Global South face existential climate risks that legacy Northern theory lacks the vocabulary to address. The 2022 Pakistan floods, which inundated one-third of the country and decimated infrastructure serving over 33 million people, represent the new baseline. Monsoon dynamics, glacial lake outburst floods (GLOFs), and compound atmospheric hazards are not marginal risks to be managed through retrospective "resilience analysis." They are the defining physical constraints that must dictate how transport networks are conceived, computed, and constructed from day one.

In these hyper-exposed environments, natural processes do not merely restrict transport systems; they rewrite their governing physics. Network topology becomes state-dependent. Infrastructure availability becomes violently intermittent. Accessibility shifts from a predictable metric to a highly stochastic probability.

Ultimately, system performance is dictated by seamlessly coupled hydro-climatic and mobility equations. The transport network can no longer be modelled as a fixed, dry mathematical graph; it is a dynamically mutating physical entity. A transport science that treats flooding, heat, and geological instability as "edge cases" is a science built for a climate that no longer exists.

Liberation 3: Behavioural — From Engineering Assumption to Human Reality

The Behavioural Blind Spot

Transport engineering has historically treated human behaviour as a nuisance variable, something to be averaged away at the macroscopic level, parametrised crudely at the microscopic level, or predicted as a black box by machine learning. None of these approaches is adequate for the systems now emerging. Mixed human–AV–drone environments require models that represent how people actually perceive, decide, adapt, learn, trust, fear, and resist, not how engineers assume they do.

What a Behaviourally Grounded Transport Science Requires

- Cognitive-load-aware interaction models for mixed-mode environments. A pedestrian crossing a street with drone deliveries overhead and autonomous vehicles at ground level faces a fundamentally different cognitive task than a pedestrian crossing a conventional street. Human factors research must be integrated into flow models, not bolted on afterwards.
- Trust dynamics in human–machine interaction. How quickly do humans calibrate trust in autonomous systems? How does trust vary across cultures, ages, and experience levels? How do trust failures cascade through a mixed traffic system? These are not engineering questions; they are behavioural science questions that determine whether technological transitions succeed or fail.

- Culturally situated behavioural models. Driving behaviour in Karachi reflects different social norms, risk perceptions, gender dynamics, and institutional contexts than driving in Stockholm. A universal behavioural model that ignores these differences is not universal; it is Northern.
- Resistance and adaptation dynamics. Technology adoption is not a diffusion curve. It involves active resistance, workarounds, informal adaptation, and social negotiation. Models of technological transition that assume smooth adoption are models that will be wrong about the next fifty years.

Behaviour as the Integrating Thread

Human behaviour is not one dimension among many. It is the thread that connects dimensional liberation to geographic liberation. The reason Northern models fail in the Global South is fundamentally behavioural: they encode Northern behavioural assumptions as structural features. The reason dimensional liberation matters is fundamentally behavioural: three-dimensional mixed-mode environments create novel behavioural challenges that flatland models cannot represent. Every technical innovation in this manifesto ultimately succeeds or fails based on how humans respond to it.

Claim 3 – Behavioural: Technology does not transform transport; human adaptation to technology does. Every dimensional and geographic liberation must be grounded in how people actually behave, adapt, resist, and learn, not in how engineers assume they will.

Human behaviour and technology

Humans and technology exist in a continuous loop whereby the actions of one category influence the other. This interaction co-exists in all fields of technology; however, our interest herein lies in how advances in transport technology will affect human behaviour and vice versa over the next 50 years. According to the United Nations World Population Prospects 2024, the world population is expected to grow from 8 billion to a projected 10.3 billion people. This increase is expected to drive demand as people's needs and problems need to be addressed, thereby motivating the development of new technologies such as fully autonomous flying robotaxis.

The adoption and success of these technologies will largely depend on human behaviour, such as the level of trust prevalent at that time. Similarly, the adoption of these advanced technologies, especially in transport, will in turn change habits as people opt for more efficient modes of travel. Algorithms and recommendations will also significantly influence choices and social behaviour. Overall, technology is expected to change the human mindset and expectations when artificial general intelligence is achieved, resulting in full market penetration of connected and autonomous vehicles both on land and in the air. For simplicity, this section has been divided into two subsections, including i) Change in human behaviour as we shift from 2-dimensional to 3-dimensional transport systems, and ii) A geographical comparison in human behaviour between developed countries and developing countries

Shift from 2D to 3D Transport Behaviour

Human behaviour is expected to shift from a two-dimensional to a three-dimensional transport system. By 2076, transport will likely operate across multiple dimensions, including autonomous vehicles on roads and aerial systems such as drones and flying robotaxis (see Figure 2 for illustration). This transformation will be driven partly by rapid technological advancements resulting from artificial intelligence, but also by increasing demand.

Consequently, humans will need to consider not only ground-based vehicles but also aerial systems, such as drone delivery services, which are expected to become commonplace. The interplay between these modes and the spatial dimensions of transport will require humans to be conscious of their full 360° environment, a task for which humans are inherently limited. As a result, policymakers will be required to implement regulations that ensure transport systems pose no threat to human mobility and safety. People will be able to move more easily, as autonomous systems will be designed to prioritise the safety of both passengers and pedestrians.

However, this technological development may also reduce human situational awareness, as individuals place increasing trust in automated transport systems. A critical caveat arises during system breakdowns or malfunctions, which may lead to operational failures in autonomous systems. Such incidents could have significant impacts on transport safety and traffic flow efficiency.

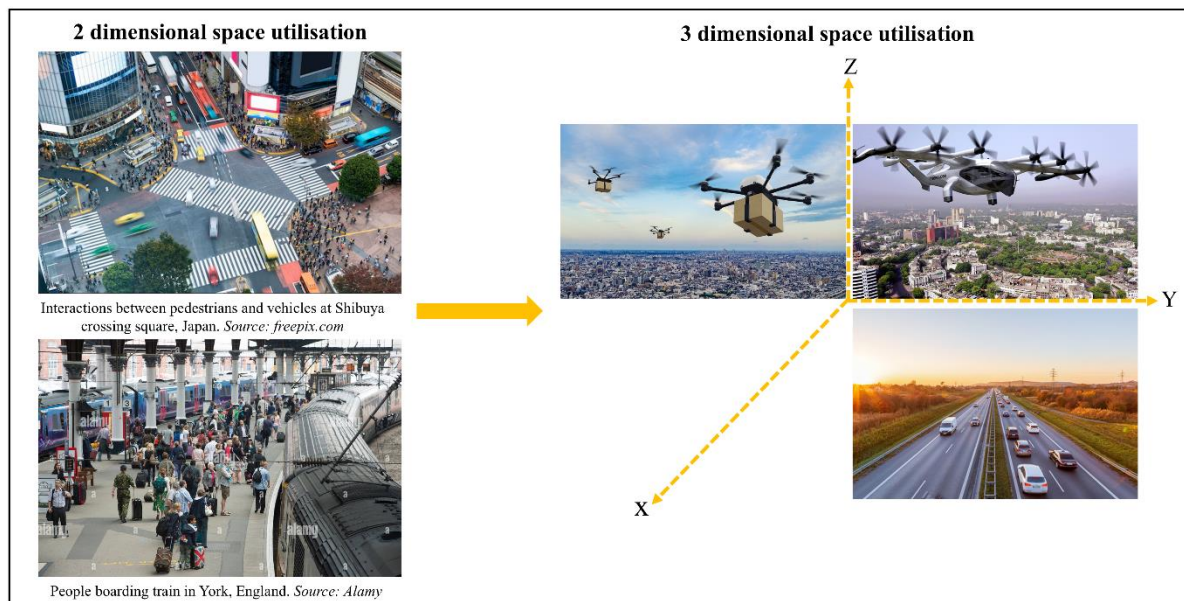


Figure 2. Two-dimensional space vs three-dimensional space

A geographical comparison of human behaviour between developed and developing countries.

Figure 3 compares homogeneous and heterogeneous traffic conditions. In homogeneous traffic conditions, commonly observed in developed countries such as the USA and the UK, vehicles are organised and generally comply with lane discipline. In contrast, heterogeneous traffic conditions, which are prevalent in developing and underdeveloped countries, consist of a mix of multiple vehicle types that often do not adhere to lane discipline.

Consequently, human behaviour differs significantly between these two environments due to a range of external factors. Specifically, crossing the road at high speed is considered relatively safer in homogeneous traffic environments but unsafe in heterogeneous traffic conditions (Ali et al., 2023). This difference arises because pedestrians must assess traffic conditions more carefully when crossing roads in mixed traffic.

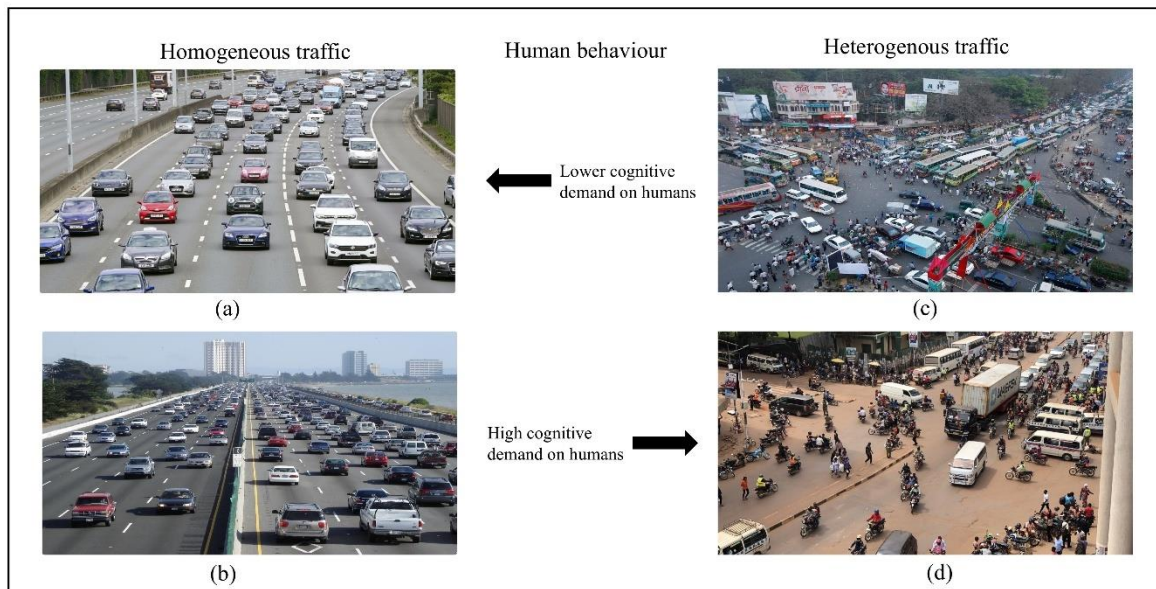


Figure 3 Homogeneous traffic in a) London b) USA, Versus Mixed and disorganised traffic in c) Dhaka, Bangladesh d) Kampala, Uganda.

PART III: THE PATHWAY – A PHASED TRANSFORMATION

A vision without a pathway remains aspiration. The transformation of transport must therefore be understood as a phased process, not a sudden technological rupture. Autonomous systems, volumetric mobility, behavioural intelligence, and climate-responsive infrastructure will mature at different speeds across regions and institutions.

Phase 1: Foundations (2026–2036) – Building the Tools and the Data

Traffic flow theory in 2026 essentially offers three tiers of modelling: macroscopic, mesoscopic models (kinetic/gas-kinetic analogies), and microscopic models. All three are analytically derived for idealised conditions and then calibrated against data. For the Global South and for 3D systems, none of these tiers works. Macroscopic models assume a well-defined fundamental diagram, which does not exist for mixed heterogeneous traffic where motorcycles, rickshaws, trucks, and pedestrians share space without lane discipline. Attempts to extend LWR to mixed traffic (multi-class models) still assume class-wise fundamental diagrams, the same parametric-class trap.

Microscopic models that do not hold when a motorcycle is simultaneously influenced by a truck ahead, a rickshaw to the left, a pedestrian to the right, and a bus behind, all at different relative positions in 2D (let alone 3D). Data infrastructure in the Global South is sparse. Loop detectors, which generated the data that calibrated Western models, barely exist in Karachi, Dhaka, or Lagos. But mobile phone penetration is near-universal, drone-based observation is becoming cheap, and GPS-equipped vehicles are increasingly common. The data exists; it is just different data, requiring different methods.

Research questions for Phase 1:

1. What is the mathematical form of vehicle interaction in non-lane-bound traffic?
Something entirely new?
2. Can we discover a "generalised fundamental relationship" for mixed traffic that relates density, flow, and composition without assuming lane-based definitions?
3. How do the discovered equations change across geographic contexts?
4. Are there universal structures with context-dependent parameters, or are the structures themselves different?

Trajectory Data Infrastructure for Complex Environments

Phase 1 must establish data collection programmes in 5–10 Global South cities using drone-based aerial observation (providing full-field trajectory data without infrastructure installation), mobile phone GPS traces (providing large-scale route choice and travel time data), and vehicle-mounted sensors on public transport fleets (providing continuous corridor-level data). From a methodological point of view, the data processing pipeline itself must be rebuilt. Current trajectory extraction algorithms are trained on lane-based traffic and fail on mixed traffic, vehicles are misidentified, trajectories are incorrectly linked, and the *ground truth* labelling assumes lane membership. Phase 1 needs computer vision architectures specifically designed for heterogeneous traffic, trained on Global South datasets.

Foundational Work on 3D Interaction Models

Even in Phase 1, when full-scale aerial traffic does not yet exist, we can begin building the mathematical and computational tools. Use existing drone swarm data (from logistics pilots), bird flock trajectory data (from ecology, a rich dataset for 3D collective motion), and simulated mixed aerial-ground scenarios to develop prototype 3D interaction models.

The key Artificial Intelligence (AI)/Machine Learning (ML) contribution: learn interaction potentials in \mathbb{R}^3 from trajectory data using graph neural networks where nodes are agents, edges represent interactions, and the edge function (the interaction potential) is learned rather than prescribed. This is an extension of Social Force models to 3D, but with learned rather than assumed force functions.

Global South integration in Phase 1

The critical institutional action: establish reverse research partnerships where Global South universities lead the research design, own the data, and set the theoretical agenda, with Global North institutions providing computational resources and methodological collaboration, not the other way around. Concretely, this means doctoral students in Lahore, Dhaka, or Nairobi should be first authors on the papers that discover new interaction laws from their cities' traffic, not second authors on papers led from European universities using their data. Publish research arguing that heterogeneity-first datasets should be the benchmark datasets for the field, the way ImageNet became the benchmark for computer vision. Create Mixed Traffic Net, an open, Global South-led trajectory dataset that becomes the standard training and evaluation set for traffic flow ML models.

A primary challenge for AVs' adoption in the Global South is that the technology must operate within transport environments shaped by informality, negotiation, and weak lane discipline, rather than within the orderly road conditions assumed by most current automation systems.

- Mixed-traffic responsiveness: AVs must move beyond lane-following logic and respond to mixed traffic involving cars, motorcycles, rickshaws, pedestrians, street vendors, animals, and informal stopping behaviour.

- Negotiated right-of-way: System design must account for negotiated movement, where right-of-way is often established through eye contact, speed adjustment, hand gestures, and social signalling rather than formal priority rules.
- Robust perception under environmental stress: Reliable deployment will require perception systems that remain robust under dust, flooding, heat, poor visibility, occlusion, weak road markings, and inconsistent signage.
- Governance and shared responsibility: Governance frameworks must address responsibility, insurance, public trust, and safety in mixed-autonomy environments where human drivers, vulnerable road users, and automated systems share the same uncertain space.

Human–Autonomy Interaction: Foundational Behavioural Science

Three interaction dynamics emerge in this phase and must be studied simultaneously. First, human adaptation to autonomous systems: early evidence already shows that drivers and pedestrians rapidly learn AV behavioural signatures, conservative yielding, predictable braking, and exploit them through aggressive gap-cutting, bold crossing, and deliberate provocation of AV braking to create space. Phase 1 must establish through naturalistic studies how quickly this strategic adaptation occurs, whether it stabilises or escalates, and how it varies across cultures and demographics.

Second, autonomous adaptation to human behaviour: current AV systems detect humans but do not model their intentions, risk appetite, or strategic learning. A vehicle that recognises a pedestrian but cannot anticipate that she will jaywalk because she has learned it always yields has perception without behavioural intelligence. Phase 1 must develop intent prediction models that represent cognitive and strategic dimensions of human behaviour and update in real time as the human population's behaviour evolves.

Third, cross-platform autonomous interaction: AVs from different manufacturers with different algorithms, safety margins, and sensor suites share roads without shared communication protocols. Unlike human drivers who negotiate through eye contact and gesture, independently designed AVs may produce deadlocks, oscillations, or unsafe emergent behaviours. Phase 1 must characterise these failure modes and identify minimum coordination standards.

In Global South environments, all three dynamics are amplified: strategic adaptation may be faster in populations already skilled at exploiting heterogeneous road users; intent prediction must handle rickshaws, animal-drawn carts, and pedestrian flows that follow social convention rather than traffic regulation; and cross-platform interaction must account for the long coexistence of autonomous and entirely non-automated vehicles.

PHASE 1: FOUNDATIONS (2026–2036)

Dimensional: Develop mathematical foundations for 3D flow theory. Publish the first volumetric interaction models. Build prototype coupled hydro-transport simulations. Establish 3D data collection using LiDAR and drone-based observation.

Geographic: Launch Global South traffic flow data consortia. Fund doctoral programmes building theory from heterogeneous traffic environments. Publish the first heterogeneity-first behavioural model architectures.

Behavioural: Integrate human factors into mixed-traffic microsimulation. Begin longitudinal studies of trust calibration in early AV deployments. Develop culturally situated behavioural measurement instruments.

Technology context: Level 4–5AVs in limited deployment. Early commercial drone delivery. Aerial vehicle prototypes in test corridors. Climate adaptation will become a policy priority.

Key deliverables: New mathematical formalisms. Foundational datasets. First-generation coupled models. Revised curricula in 20+ universities.

Phase 2: Integration (2036–2051) – From Prototypes to Practice

Operational Volumetric Flow Models

The prototype 3D interaction models from Phase 1 must become operational planning tools. This means volumetric microsimulation platforms that can represent mixed human-driver / AV/drone environments in continuous 3D space, not on layered 2D networks. Real-time prediction systems using trained neural operators that can forecast 3D traffic states (ground + aerial) 15–60 minutes ahead for air traffic management integration. Volumetric LOS metrics that replace the HCM's lane-based LOS with volumetric capacity utilisation measures, answering: *how congested is this cubic kilometre of urban airspace?* with the same rigour we currently answer: *what's the v/c ratio on this freeway segment?* In essence, these systems will be too complex for analytical solutions. Neural operator surrogates trained on high-fidelity simulations will be the only computationally tractable path to real-time volumetric traffic management.

Interpretable Behavioural AI for Mixed-Mode Governance

By Phase 2, autonomous systems will be making real-time decisions that affect human safety. Black-box neural networks are insufficient for this governance role. The field needs a physics-consistent neural network for human driver behaviour that is simultaneously predictive (accurate) and interpretable (we can explain why the model predicts a given action in terms of meaningful behavioural variables like risk perception, gap acceptance threshold, and trust in surrounding AVs). Causal behavioural models, not just correlational ones, distinguish "this driver slowed down because the drone descended" from "this driver slowed down while the drone descended." Causal inference methods (do-calculus, instrumental variables adapted for traffic, counterfactual simulation) integrated with deep learning. Formal safety verification of learned behavioural models, mathematical guarantees that a learned interaction model satisfies collision avoidance constraints under all conditions, not just empirically observed ones.

Adaptive Transfer Learning Across Geographies

A model trained on Dhaka traffic should be informative about Karachi traffic and about Lagos traffic, but not through simple parameter transfer (which assumes the same model structure). Phase 2 should develop: Meta-learning frameworks that learn *how to learn traffic dynamics across cities*, so that a model can be rapidly adapted to a new city with minimal local data. Domain adaptation methods that explicitly account for what varies across cities (vehicle mix, road geometry, cultural norms) and what is universal (physics of motion, collision avoidance geometry, cognitive limitations of human perception). Federated learning architectures that allow Global South cities to collaboratively train models without sharing raw trajectory data, preserving data sovereignty while enabling collective scientific progress

Coupled Multi-Hazard Transport Resilience Models

The Phase 1 coupled hydro-transport models evolve into multi-hazard systems: flooding + heat + air quality + seismic risk, all interacting with the transport network simultaneously. AI/ML's role: Multi-physics neural operators that can simulate compound hazard scenarios orders of magnitude faster than numerical solvers. Reinforcement learning for real-time adaptive routing during compound hazard events, rerouting traffic away from flood zones while avoiding heat-stress corridors and maintaining access to hospitals. Digital twin frameworks for climate-vulnerable cities, continuously updated with sensor data and capable of running scenario analyses for infrastructure investment decisions.

Global South integration

By Phase 2, the institutional reversal proposed in the manifesto should be visible: Global South-developed models are the defaults in major simulation platforms, not Northern models with Southern calibration. Concretely, the heterogeneity-first model architectures from Phase 1 are now the standard option in VISSIM, SUMO, and their successors, not as *developing country modules* but as the general-purpose engine, with lane-disciplined mode as a constrained special case. At least three major traffic flow theory textbooks have been written or significantly revised by Global South authors. The field's top-tier journals regularly publish papers where new theory emerges from Global South data, reviewed and validated by Global South researchers, without the framing of *we applied method X from a European university to data from a Southern city*. Research funding for traffic flow theory is structured so that at least 40% of PI-ships on internationally funded projects are held by Global South institutions.

Human–Autonomy Co-Evolution: Interaction at Scale

The Phase 1 dynamics now operate at the population scale and intertwine into co-evolutionary feedback loops. Behavioural gaming becomes systemic: entire driver communities have internalised AV profiles and adapted accordingly, while AV manufacturers update algorithms in response, which triggers further human adaptation. The critical research question is whether this co-evolutionary spiral converges to a stable equilibrium or requires active regulatory intervention. Simultaneously, trust dynamics bifurcate prolonged AV exposure produces over-trust and complacency in some populations (drivers disengaging from monitoring, pedestrians ceasing to check for vehicles) and persistent under-trust in others (older drivers, communities that have experienced AV failures). Phase 2 must develop dynamic, multidimensional trust calibration models that capture this heterogeneity. Trust is a process shaped by experience, social influence, and critical incidents, not a fixed parameter. Multi-platform interaction extends into three dimensions as autonomous aerial vehicles from multiple operators share low-altitude airspace alongside ground AVs. Different platforms with different flight envelopes and obstacle avoidance strategies produce unintended emergent collective behaviours, such as corridor formation, altitude stratification, and temporal clustering. These must be modelled through a multi-agent simulation that includes human ground-level responses: noise stress, visual distraction, fear, and the cognitive overload that pedestrians experience when navigating environments with simultaneous aerial and ground autonomous agents. Establishing the empirical boundaries of human cognitive capacity in multi-modal environments at what agent density does pedestrian decision-making degrade, and how vulnerable populations cope, is essential for airspace regulation and urban design.

In the Global South, co-evolution follows different trajectories: informal transport operators interact with AVs as professional competitors whose livelihoods depend on outmanoeuvring them; trust is shaped by different institutional credibility structures and collective experiences of technological failure; and three-way dynamics between human-driven, ground autonomous, and aerial autonomous vehicles persist at intensities that Northern cities may never experience.

PHASE 2: INTEGRATION (2036–2051)

Dimensional: Operationalise volumetric capacity analysis in planning practice. Deploy coupled hydro-transport models in climate-vulnerable regions. Integrate 3D accessibility indices into equity assessment frameworks.

Geographic: Global South research institutions leading international collaborative programmes. Heterogeneity-first models are adopted as defaults in major simulation platforms. Publication norms shifted.

Behavioural: Real-time behavioural adaptation models operating in mixed human–AV–drone environments. Trust dynamics incorporated into system design, not just evaluation. Cross-cultural behavioural databases established.

Technology context: Substantial level 4–5 AVs in urban deployment. Routine drone logistics. Early air taxi networks. Climate impacts are intensifying in the Global South.

Key deliverables: Integrated simulation platforms. Revised HCM/LOS for volumetric systems. Policy frameworks for 3D transport governance. Behavioural design standards.

Phase 3: Full Spectrum (2051–2076) – The New Normal

By 2051, the tools built in Phase 1 and operationalised in Phase 2 are no longer innovations; they are the field's standard apparatus. The research frontier shifts from building and deploying new methods to deepening, unifying, and stress-testing the full-spectrum paradigm under conditions of increasing complexity. Each research direction from the earlier phases reaches its mature form and reveals new open problems that the earlier phases could not have anticipated.

Flatland era (1935–2026)	Full-spectrum era (2051–2076)
Lanes and links	Continuous fields in \mathbb{R}^3
Microscopic models	Learned interaction potentials in volumetric space
Fundamental diagram	Volumetric phase-space characterisation
Parametric vehicle classes	Learned behavioural manifolds
Separated transport/environment models	Natively coupled multi-physics systems
Northern theory, Southern calibration	Universal theory from heterogeneous foundations

Volumetric Flow Theory as Default Science

The volumetric flow models prototyped in Phase 1 and operationalised in Phase 2 are now the default analytical framework. Two-dimensional, lane-based models survive only as reduced special cases taught historically, the way Newtonian mechanics is taught before relativity, not because they are wrong within their domain, but because students must understand they are domain-restricted. The fundamental relationship of the field is no longer flow-density on a lane but a learned, physics-constrained mapping in volumetric phase space relating agent density fields, velocity fields, and agent-type composition fields in \mathbb{R}^3 to emergent system-level properties such as throughput, safety, and environmental load.

The research frontier in this phase is unification and limit-testing. Can the volumetric phase-space characterisations discovered independently in different cities and contexts be unified into a single theoretical framework, or does the field require a family of related but structurally distinct theories analogous to the relationship between general relativity and quantum mechanics, where unification remains an open challenge? What happens to volumetric flow models at extreme densities during mass evacuation events, festival crowds in aerial-ground mixed space, or compound hazard scenarios where the normal operating assumptions break down? Are there phase transitions in volumetric traffic analogues of the laminar-to-turbulent transition in fluid dynamics, and if so, can they be predicted and governed? These questions are inaccessible until the volumetric paradigm is mature enough to be pushed to its limits, which is precisely the condition Phase 3 assumes.

Interpretable Behavioural AI as Governing Infrastructure

In Phase 2, interpretable behavioural AI was deployed in mixed-mode systems. In Phase 3, it becomes governing infrastructure, where the learned behavioural models are embedded in regulatory frameworks, insurance liability structures, and real-time airspace management systems. AI/ML is not a tool used by traffic flow theorists; it is the language in which traffic flow theory is expressed, just as calculus became the language of physics, not because it was fashionable but because the systems were too complex for analytical derivation and too safety-critical for black-box prediction.

The research frontier shifts to long-run co-evolution: how do human behavioural patterns change over decades of immersion in autonomous and semi-autonomous environments? Do trust calibration dynamics stabilise, or do they exhibit generational drift as populations grow up never having driven manually? How does behavioural deskilling, the atrophy of manual driving and navigation skills, affect system resilience during rare but catastrophic failures (cyber-attacks, solar storms disrupting GPS, compound climate events that overwhelm autonomous systems)? These are questions that require longitudinal behavioural datasets spanning decades, which Phase 1 initiated and Phase 2 maintained, and whose analytical payoff arrives only in Phase 3. The interpretable architectures developed earlier are essential here: understanding behavioural co-evolution requires models that can explain what changed and why, not merely that prediction accuracy shifted.

A further frontier is the governance of algorithmic equity. When a reinforcement learning agent manages aerial corridor allocation, dynamic pricing, or emergency rerouting in real time, how do we ensure it does not systematically disadvantage certain communities? How do we define fairness in volumetric access, where vertical position, temporal availability, and capability-based access all interact? And how do we audit these systems continuously, given that the behavioural models they rely on are themselves evolving? Formal algorithmic auditing frameworks combining interpretable model inspection, distributional impact analysis, and adversarial stress-testing must become standard regulatory practice, not optional academic exercises.

Coupled Multi-Physics Simulation as Standard Practice

The coupled hydro-transport models of Phase 1 and the multi-hazard resilience models of Phase 2 reach their mature form: a natively coupled multi-physics simulation where traffic flow, hydrology, atmospheric dispersion, heat dynamics, and ecological connectivity are modelled as a single integrated system. The transport network is no longer a graph overlaid on a passive landscape; it is a dynamic element within a living planetary system, and its simulation reflects that reality.

The research frontier is computational and epistemological. Can coupled transport–climate–ecology models run at sufficient resolution and speed to inform real-time infrastructure decisions during compound hazard events, or is there a fundamental computational barrier requiring permanent reliance on neural surrogate models? If surrogates are permanent

features of the analytical landscape rather than temporary approximations, what verification and accountability standards must they meet? How do we certify that a neural operator faithfully represents a coupled system it was trained to approximate, under conditions that differ from its training distribution? These questions connect traffic science to the broader computational science challenge of trustworthy scientific surrogates, and their resolution has implications far beyond transport.

The practical expression is the mature co-evolutionary digital twin: a continuously updated virtual replica of a city's full transport–hydrological–atmospheric–ecological system, capable of running decades-long climate scenario projections and minute-by-minute compound hazard management with equal fidelity. For climate-vulnerable cities in the Global South, which Phase 1's data infrastructure and Phase 2's institutional reversal have positioned at the centre of global transport science, these digital twins become the primary planning instruments, replacing the disconnected, discipline-siloed planning tools that characterised the flatland era.

Adaptive Transfer and Universal Theory

The meta-learning and federated learning frameworks built in Phase 2 have by now generated a definitive answer to the foundational question posed in Phase 1: what is universal and what is local in traffic dynamics? By 2051, the equation discovery programme will have been applied across dozens of cities on every continent. The accumulated evidence reveals whether human–vehicle interaction follows a single mathematical structure with context-dependent parameters or whether qualitatively different structures govern different cultural-technological regimes.

Either finding reshapes the field. If a universal structure exists, Phase 3 formalises it, producing the transport equivalent of the Navier-Stokes equations: a single governing framework from which all observed traffic phenomena can be derived as special cases. If multiple structures co-exist, Phase 3 develops the classification theory, a taxonomy of interaction regimes with rigorous criteria for determining which regime governs a given environment, analogous to the Reynolds number determining whether fluid flow is laminar or turbulent. In either case, the theory is built from the most complex cases (Global South heterogeneous traffic) and validated across all contexts, not the reverse.

The transfer learning challenge also matures. As autonomous systems proliferate globally, the traffic environments of different cities become simultaneously more technologically similar (shared autonomous platforms) and more behaviourally diverse (different cultural responses to the same technology). How transfer learning frameworks handle this paradox, increasing technological homogeneity coexisting with persistent behavioural heterogeneity, is a research question unique to Phase 3, because it requires the behavioural co-evolution data that only decades of longitudinal observation can provide.

Global South as Permanent Scientific Centre

The geographic reversal is complete and self-sustaining. The distinction between "Global North theory" and "Global South application" has dissolved not through diplomatic language or equity mandates, but through the logic of the science itself. The most general theory was built from the most complex cases. A student in 2070 learns traffic flow theory from examples in Dhaka, Nairobi, and Lima before encountering the simplified lane-based version as a historical special case, the way a physics student learns general mechanics before encountering the frictionless-plane simplification.

The research frontier in this phase is preventing regression. Institutional structures tend toward path dependence; the Northern research establishment's historical advantages in funding, publishing, and prestige do not disappear merely because the scientific centre has shifted. Phase 3 requires active maintenance of the structures built in Phases 1 and 2: Mixed

Traffic Net governance must remain under Global South control even as the dataset becomes the field's most valuable scientific asset. Editorial boards, grant review panels, and conference organising committees must reflect the geographic distribution of intellectual contribution, not the geographic distribution of historical institutional wealth. And the field must resist the temptation to re-centralise around whichever Global South institutions become most prominent, the point is not to create new centres of dominance but to sustain a genuinely distributed, multi-polar scientific community.

Human–Autonomy Maturity: Behaviour as Primary Design Domain

An entire generation has grown up never having driven manually. Phase 3 must investigate the long-run cognitive consequences: do autonomy-native populations develop different spatial awareness, lose manual vehicle control capacity entirely, or develop compensating new skills such as intuitive multi-modal volumetric navigation? The answer determines whether full-spectrum autonomy has traded everyday efficiency for catastrophic fragility because when autonomous systems fail during compound climate events, cyber-attacks, or cascading infrastructure collapse, a population without manual skills faces a resilience crisis that no technological redundancy can fully address.

Autonomous–autonomous co-evolution has by now operated for decades, and algorithms from different manufacturers and regulatory regimes have mutually adapted. This may have produced efficient emergent coordination or subtle pathologies: implicit collusion disadvantaging certain users, evolutionary arms races degrading safety margins, or lock-in effects where legacy algorithmic assumptions persist long after the conditions that produced them have changed. Detecting and correcting these pathologies requires combining multi-agent evolutionary game theory with interpretable AI architectures that make algorithmic behaviour auditable.

Aerial–human interaction has matured past novelty and fear into chronic exposure effects: populations beneath high-traffic corridors may exhibit long-run stress and health disparities; vertical inequality, quiet skies above wealthy districts, noise above poorer ones, may have produced measurable behavioural and health consequences traceable to corridor design choices made in Phases 1 and 2.

A foundational question emerges: what is the irreducible uncertainty floor of human behavioural prediction? After decades of increasingly sophisticated behavioural AI, if such a floor exists, the engineering implication is permanent; system design must accommodate irreducible human stochasticity through safety margins and graceful degradation rather than pursuing ever-higher prediction accuracy.

In the Global South, populations that leapfrogged from informal transport directly to autonomy may retain manual coping skills longer due to frequent infrastructure disruption from flooding and institutional instability, paradoxically making them more resilient to autonomous system failure than Northern populations. Whether this differential resilience persists or erodes as autonomy matures has implications for whether the field should deliberately preserve certain manual capabilities as civilisational insurance.

PHASE 3: FULL SPECTRUM (2051–2076)

Dimensional: Transport science operates natively in full volumetric space. 2D models retained as special cases. Coupled hydro-transport-atmosphere simulation is standard practice.

Geographic: The distinction between “Global North theory” and “Global South application” has been dissolved. Universal theory is built from the most complex cases, validated across all contexts.

Behavioural: Human behaviour is the primary object of transport science, not a nuisance variable. Interpretable, physics-consistent behavioural AI governs mixed-mode systems with demonstrated safety and equity.

Technology context: Mature 3D urban mobility ecosystems. Autonomous systems dominant. Climate adaptation is fully integrated into infrastructure design. Capability-based access metrics standard.

Key deliverables: A transport science that is volumetric by default, behaviourally grounded, geographically universal, and ecologically coupled, a full-spectrum science for a full-spectrum world.

PART IV: THE ETHICS — JUSTICE ACROSS EVERY DIMENSION

A dimensionally liberated transport science that reproduces existing injustices in new dimensions would be a failure, not an achievement. We ground our vision in four ethical commitments.

4.1 Vertical Justice

Aerial mobility must not create a new axis of inequality, e.g., quiet skies for the wealthy, noise and risk for those below. Every vertical mobility model must embed distributional analysis from inception. The communities beneath flight paths and vertiports must have voice in governance, not merely exposure to consequences.

4.2 Epistemic Justice

The knowledge systems of the Global South (indigenous mobility practices, informal transit networks, non-motorised transport cultures) must be recognised as legitimate knowledge, not as data to be extracted. Research partnerships must be structured around intellectual co-ownership, not data provision. The communities whose mobility patterns generate theory must share in the recognition.

4.3 Temporal Justice

The shift from fixed schedules to dynamic, on-demand systems risks creating a temporal underclass; those who wait while others are served instantly. Temporal equity must be a design constraint in every real-time mobility platform, not a measured outcome reported after deployment.

4.4 Climate Justice

The communities most exposed to transport-related flood risk, heat stress, and infrastructure failure are overwhelmingly the poorest and least responsible for climate change. For example, Pakistan lost over \$30 billion in the 2022 floods while contributing less than 1% of global emissions. A dimensionally liberated transport science must make these distributional injustices visible in its models, central in its design criteria, and non-negotiable in its priorities.

4.5 Access as a Right, not a By-Product

The passenger-kilometre as the field's primary success metric should be replaced. The purpose of transport is not to maximise movement but to enable people to reach the opportunities they value. This reframing is not decorative; it restructures what counts as a successful transport system, what models are built to optimise, and whose access matters.

PART V: THE COMMITMENT — WHAT WE REFUSE AND WHAT WE BUILD

What We Refuse

We refuse to build models that assume lanes where there are none, leaders where influence is spherical, equilibrium where systems are evolutionary, and homogeneity where the world is wildly diverse. We refuse to treat the Global South as a calibration exercise for Northern theory. We refuse to treat human behaviour as a nuisance to be averaged away. We refuse to separate transport from the watersheds it reshapes and the atmosphere it pollutes. We refuse to measure success by how far people move rather than whether they reached what they valued.

What We Build

We commit to a transport science that is volumetric by default, geographically grounded in the world's most complex mobility environments, behaviourally honest about how humans actually move and adapt. We also commit to a transport science that is ecologically coupled with the planetary systems that sustain us, temporally dynamic rather than equilibrium-bound, ethically accountable to the communities whose lives our models shape, and interpretable in its use of artificial intelligence.

The Test

We will ask of every transport model we build: In how many dimensions does it operate? Whose behaviour does it encode? Whose geography generated its theory? What watershed does it ignore? Whose access does it measure, and whose does it render invisible?

Research that cannot answer these questions is research the next fifty years cannot afford.

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