Quantifying Traffic Resistance and Supply Constraints: A Dual-Fluid RECM Approach based on Chengdu Taxi GPS Data

Ziming Cheng, Dake Wu, Ling Feng

Department of Physics, National University of Singapore, Singapore 117551

Email: e1546722@u.nus.edu, dake.wu@u.nus.edu, phyfeng@nus.edu.sg

Keywords: Human Mobility, Complex Network, Urban Traffic, GPS, Scaling Law

Extended Abstract

Motivation. The Human Flow Electrical Circuit Model (RECM) [1] successfully maps urban mobility onto resistive networks, revealing universal scaling laws [2][3]. However, existing models treat human flow as a single, time-averaged fluid. While suitable for rigid railways, this assumption fails in congestion-sensitive road networks, where supply-demand mismatches create an "apparent resistance" that masks the intrinsic topological efficiency. We ask: (1) How can we theoretically decouple a road network's intrinsic topology from the dynamic friction of vehicle supply shortages? (2) How does the city's effective topology evolve across temporal phases (e.g., ordered morning commutes versus chaotic evening peaks)? Answering these shifts mobility models from static descriptors to dynamic diagnostic probes for urban phase transitions.

Approach and Methodology. Based on the construction of the RECM and the verification of the relevant theories, we utilized the massive GPS trajectory dataset of taxis in Chengdu, China, and proposed the "dual-fluid" extension of the RECM framework. We expect to decouple traffic into two interacting fields: an active demand flow (occupied taxis) generating the baseline resistance network, and a supply field (ρ_{emp}, empty cruising taxis) acting as the connective medium. To measure macroscopic conductance, we execute Monte Carlo active probing. For each temporal phase, we randomly sample 10,000 Origin-Destination (OD) pairs, solving Kirchhoff's equations via Laplacian pseudo-inverse to compute the effective conductance (G_{eff}). We introduce a multivariate gravity model: $G_{\mathrm{eff}} \propto d^{-\gamma}\rho^{\alpha}_{\mathrm{occ}}\rho^{\delta}_{\mathrm{emp}}$, where the supply field acts as a coupled bottleneck. Model robustness is evaluated by cross-validations such as Akaike Information Criterion (AIC) and Nested F-tests.

Results. The Dual-Fluid RECM significantly outperforms standard models. Statistical validations generally support the dual-fluid assumption: the AIC drops drastically ($\Delta AIC \approx -1300$), and Nested F-tests reject the single-fluid hypothesis (p-value ~ 10^{-16}). By decoupling this supply-demand friction, our model recovers the network's intrinsic topology: the distance decay exponent (γ) drops from an inflated 1.15 (standard model) to a purified 0.80, close with scaling limits of efficient rail networks. Temporally, we quantify a macroscopic phase transition: during the highly ordered morning commute, the network maintains its intrinsic efficiency ($\gamma \approx 0.78$); conversely, during the saturated evening peak, the supply network structurally collapses, causing extreme topological degradation ($\gamma \approx 1.16$).

Conclusions and Outlook. Our model proves that the high apparent traffic resistance is significantly driven by supply-demand mismatch. Future work will incorporate other kinds of distance (like network distance) and smaller grid size to refine macroscopic scaling laws. Besides, it is also meaningful to compare the predictive accuracy (on congestion or best routines) of the Dual-Fluid RECM against the Standard RECM.

Ethics Statement. This study relies exclusively on anonymized, aggregated GPS trajectory data. No personally identifiable information was accessed, ensuring full compliance with privacy standards. *(Note: Generative AI was utilized solely for language refinement with full human oversight).*

References

[1] Zhong Z, Takayasu H, Takayasu M. Human mobility description by physical analogy of electric circuit network based on GPS data[J]. Scientific Reports, 2024, 14(1): 13380.

[2] Shida Y, Takayasu H, Havlin S, et al. Universal scaling laws of collective human flow patterns in urban regions[J]. Scientific reports, 2020, 10(1): 21405.

[3] Shida Y, Takayasu H, Takayasu M. Preserving universal mobility scaling laws with the human flow electrical circuit model[J]. Computational and Mathematical Organization Theory, 2026, 32(1): 3.

Table 1. **Distance decay exponent (γ) in different modes (Euclidean distance).** "Original" mode (i.e. standard model) means the mixed data (not distinguishing occupied/empty taxis). "Separation" mode excludes data for empty taxis. "Dual-fluid" mode means differential treatment for occupied and empty (as the supply field) taxis.

Mode	Data Input	Gamma (γ)
Original	Mixed Data	1.15 ± 0.018
Separation	Occupied Only	1.12 ± 0.014
Dual-fluid	With Supply Field	0.80 ± 0.014

Table 2. **Distance decay exponent (γ) in different modes (Euclidean distance).** Morning, noon, evening and night stand for 6:00-10:00, 10:00-15:00, 15:00-20:00 and 20:00-24:00 respectively. Here, γ in the morning is significantly lower than others.

Period	Gamma (γ)
Morning	0.78 ± 0.07
Noon	1.13 ± 0.09
Evening	1.16 ± 0.09
Night	1.00 ± 0.08