Efficiency–Equity Trade-Off Characterization in Hierarchical Traffic Congestion Pricing

Md Salik Parwez, Sai Teja Srivillibhutturu, Kushal Shah, and Habeeb Olufowobi
Department of Computer Science and Engineering, University of Texas at Arlington, Arlington, TX, USA
mdsalik.parwez@uta.edu, sxs5722@mavs.uta.edu, kxs7623@mavs.uta.edu, habeeb.olufowobi@uta.edu

***Abstract*— Congestion pricing is increasingly evaluated not only for its efficiency gains but also for its distributive consequences across travelers. While hierarchical pricing frameworks can adapt tolls dynamically, the policy implications of equity weighting remain insufficiently characterized. This paper presents a structured efficiency–equity trade-off analysis within a hierarchical Stackelberg congestion pricing framework. A scalar policy parameter governs the relative emphasis on inequality mitigation in the social objective, and a systematic sweep is conducted on a fixed urban grid network. The leader problem is solved via simulation-based policy search over candidate toll vectors, with traveler responses computed using Frank–Wolfe user-equilibrium assignment. Equity is quantified using the Gini coefficient of experienced generalized travel cost. The resulting efficiency–equity frontier reveals nonlinear regime transitions, including a distinct knee region where substantial reductions in inequality are achieved with limited efficiency loss. We further quantify the marginal efficiency cost of equity improvement and examine revenue interactions to inform policy feasibility. The findings demonstrate that modest incorporation of equity considerations can meaningfully reduce travel cost disparities without significant congestion degradation, providing quantitative guidance for equity-aware congestion pricing design.**

Traffic congestion pricing, efficiency–equity trade-off, hierarchical control, Gini coefficient, transportation policy, multi-objective optimization.

I. Introduction

Urban congestion pricing has long been studied as a primary instrument for managing traffic demand in dense metropolitan networks [1]–[3]. Beyond improving aggregate efficiency, modern pricing policies are increasingly evaluated through the lens of distributive equity, as tolling mechanisms may impose uneven burdens across travelers [4], [5]. This evolution has transformed congestion pricing from a purely operational optimization problem into a broader policy design challenge involving explicit trade-offs between efficiency and fairness.

Public acceptance of pricing programs is often shaped by perceived fairness [6]. Travelers may support tolling mechanisms that reduce congestion but remain sensitive to how costs are distributed across different user groups. Prior work has documented that the relationship between pricing acceptability and equity perceptions is nonlinear, suggesting that moderate fairness incorporation can improve social support without sacrificing operational effectiveness [5], [7]. Consequently, transportation agencies increasingly seek analytical tools that clarify how fairness considerations interact with traditional efficiency objectives. Understanding these interactions is essential for designing policies that are both operationally effective and socially acceptable.

Recent advances in hierarchical and Stackelberg game formulations have enabled structured congestion pricing frameworks that capture the leader–follower interaction between a central authority and adaptive travelers [8]–[10]. Within such formulations, a pricing authority sets tolls while drivers adapt route choices in response to observed generalized costs. Although these frameworks demonstrate promising performance improvements, most existing studies focus primarily on efficiency metrics such as total travel time or throughput. Fairness is often introduced as a weighted regularization term in learning-based traffic management frameworks [11], yet the system-level implications of this weighting remain insufficiently characterized in terms of how policy emphasis on equity reshapes global congestion patterns, inequality outcomes, and revenue generation.

This paper provides a structured efficiency–equity trade-off characterization within a Stackelberg congestion pricing framework. We introduce a scalar policy parameter λ that governs the weight assigned to inequality mitigation and conduct a controlled sweep over λ in a fixed 5×5 urban grid network. The leader problem is solved via simulation-based policy search over candidate toll vectors, evaluated against a Frank–Wolfe user-equilibrium follower.

The contributions are as follows:

- Formalization of an efficiency–equity objective parameterized by λ using the Gini coefficient of experienced travel cost.
- Empirical construction of the efficiency–equity frontier under systematic λ variation via simulation-based Stackelberg optimization.
- Policy-level interpretation of marginal trade-offs, including identification of regime transitions and connection to the price-of-fairness concept [12].
- Empirical identification of a knee operating region where substantial inequality reduction is achieved with limited congestion penalty, providing a practical guideline for equity-aware congestion pricing calibration.

The remainder of the paper is organized as follows. Section II reviews related work. Section III introduces the system model and problem formulation. Section IV describes the experimental setup. Section V presents results. Section VI discusses policy implications, and Section VII concludes.

II. Related Work

A. Congestion Pricing and Efficiency

Congestion pricing has long been studied as a mechanism for internalizing traffic externalities and improving network efficiency. Classical formulations focus on welfare maximization and system-optimal flow assignment, where tolls are designed to align individual route choices with socially optimal outcomes [1], [4]. These models primarily evaluate performance using aggregate efficiency indicators such as total travel time, total surplus, or throughput. While effective, early studies largely treat congestion pricing as an efficiency-driven optimization problem with limited attention to distributional consequences across travelers.

B. Equity in Transportation

Equity considerations have gained prominence in transportation policy discussions. The distributional impacts of tolling schemes have been examined using income-based welfare analysis, accessibility metrics, and measures of travel cost dispersion [5], [6], [13]. Various inequality indicators, including the Gini coefficient, Theil index, and Atkinson measure, have been adopted to quantify disparities in travel cost and accessibility [14]. These studies provide valuable insights into the social implications of pricing policies. However, equity is often evaluated ex post under fixed pricing strategies rather than being explicitly incorporated as a controllable design parameter within the optimization process.

C. Learning-Based and Hierarchical Pricing

Multi-agent reinforcement learning has been widely applied to traffic signal control, network coordination, and dynamic toll optimization [9], [10], [15]. Hierarchical and Stackelberg formulations provide a natural structure for modeling leader–follower interactions between system operators and network users [8]. Recent efforts have begun incorporating fairness-aware objectives into learning-based traffic management [11]. While such formulations acknowledge the importance of fairness, the geometric structure of the efficiency–equity trade-off and the marginal cost associated with equity improvement remain insufficiently characterized. In particular, how varying the strength of equity weighting systematically reshapes global network performance has not been fully explored.

D. Price of Fairness

The price of fairness – the efficiency cost incurred by imposing equitable outcomes – was formalized by Bertsimas et al. [12] in the context of resource allocation. Their work establishes that fairness constraints need not be arbitrarily costly in well-connected systems, and that a transition point exists beyond which fairness gains become disproportionately expensive. This paper adapts that concept to congestion pricing by constructing an empirical efficiency–equity frontier and quantifying the marginal efficiency cost as a function of λ, providing a transportation-specific instantiation of the price-of-fairness framework. This paper bridges policy-oriented equity analysis and hierarchical congestion pricing by constructing an empirical frontier under controlled policy weight variation, with emphasis on structured trade-off characterization and policy interpretability.

III. System Model and Problem Formulation

A. Hierarchical System Architecture

Figure 1 illustrates the hierarchical congestion pricing environment considered in this study. The interaction is modeled as a Stackelberg game between a traffic authority (leader) and travelers (followers). The central planner determines link tolls with the objective of balancing network efficiency and distributional equity, while travelers respond by selecting routes that minimize their individual generalized travel costs.

The leader's objective is parameterized by an equity weight $\lambda \in [0, 1]$, which governs the relative emphasis placed on inequality reduction in the composite social objective. This parameter serves as a policy control variable that allows continuous adjustment between efficiency-oriented and equity-oriented operating regimes. When λ is small, the pricing mechanism primarily seeks to reduce congestion and total travel time. As λ increases, greater importance is placed on reducing disparities in experienced travel costs among travelers.

Tolls are implemented through a toll controller that applies a vector of link tolls $\boldsymbol{\tau}$ to the transportation network. The resulting network state – consisting of link flows, travel times, and traveler costs – is used to compute system-level performance metrics including VHT, the Gini coefficient of generalized travel cost, and total toll revenue. These metrics are fed back to the policy search solver, which iteratively adjusts $\boldsymbol{\tau}$ to improve the pricing objective. Through this closed-loop interaction, the system converges to a policy-consistent equilibrium for each value of λ. Repeating this process across different values of λ produces a family of equilibria that collectively define the efficiency–equity frontier.

B. Network Model and Traveler Behavior

We consider a fixed 5×5 grid transportation network with directed links and 20 predefined origin–destination (OD) pairs. Each OD pair has a Manhattan distance of at least two links, ensuring non-trivial routing decisions. The grid structure provides multiple alternative paths between OD pairs, allowing congestion to emerge endogenously through route competition. Network topology and demand remain constant across all experiments to isolate the impact of policy parameter tuning.

Travelers are modeled as rational, homogeneous cost-minimizers. Each traveler selects a route that minimizes perceived generalized travel cost:

$$C_i = T_i + \tau_i, \tag{1}$$

where T_i denotes experienced travel time and τ_i represents the total toll paid along the chosen route. All travelers share the same cost function structure, reflecting a homogeneous

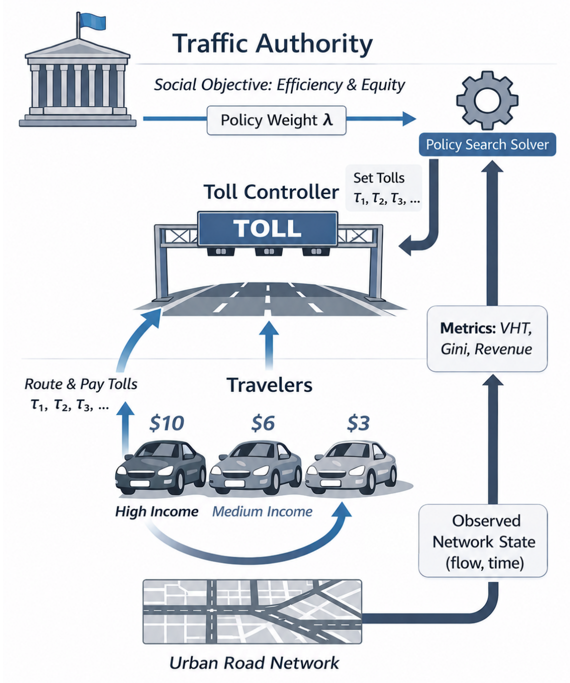

Fig. 1. Hierarchical congestion pricing framework. The traffic authority sets tolls via simulation-based policy search; travelers respond through cost-minimizing route choice; resulting efficiency and equity metrics are fed back to guide toll updates.

utility assumption consistent with classical traffic assignment theory [16]. The income heterogeneity illustrated in Fig. 1 is conceptual, motivating the equity objective; heterogeneous value-of-time modeling is a direction for future work. Link travel times follow the BPR function:

$$T_e(f_e) = t_e^0 \left(1 + 0.15 \left(\frac{f_e}{c_e}\right)^4\right), \tag{2}$$

where t_e^0 is free-flow time, f_e is link flow, and c_e is link capacity.

C. Efficiency Metric

Network efficiency is measured using total experienced travel time across all travelers in the network:

$$\mathcal{E}(f) = -\sum_{i=1}^{N} T_i, \tag{3}$$

where N is the total number of travelers. The negative sign ensures larger values of $\mathcal{E}(f)$ correspond to higher efficiency within the maximization formulation of the social objective.

D. Equity Metric: Gini Coefficient

In this study, equity is interpreted as *outcome equity* – the degree to which experienced generalized travel costs are uniformly distributed across all travelers, irrespective of income or origin–destination pair. This notion of fairness focuses on the dispersion of realized travel burdens rather than on income-based redistribution or spatial accessibility, and is consistent with horizontal equity principles in transportation policy [7], [14].

Outcome equity is operationalized using the Gini coefficient of experienced generalized travel cost [14], [17]:

$$\mathcal{I}(f) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} |C_i - C_j|}{2N\sum_{i=1}^{N} C_i}. \tag{4}$$

A lower value of $\mathcal{I}(f)$ indicates a more uniform distribution of experienced travel costs, while larger values reflect greater disparity in the travel burden imposed by congestion and tolling. The Gini coefficient has been widely used in transportation equity analysis because it provides a normalized and interpretable measure of cost dispersion [14].

E. Efficiency–Equity Objective

The congestion pricing authority seeks to balance efficiency and equity through a composite objective:

$$\max_{\boldsymbol{\tau}} \quad J(\boldsymbol{\tau}) = \mathcal{E}(f(\boldsymbol{\tau})) - \lambda \mathcal{I}(f(\boldsymbol{\tau})), \tag{5}$$

where $\lambda \in [0, 1]$ controls the relative importance assigned to inequality mitigation. When $\lambda = 0$, the objective reduces to pure efficiency maximization. As λ increases, greater weight is placed on reducing disparities in generalized travel cost.

IV. Experimental Setup

A. Network and Demand Configuration

All experiments are conducted on the fixed 5×5 grid described in Section III-B, with link free-flow time $t_e^0 = 1.0$ time unit, capacity $c_e = 10$ vehicles per time unit, and demand of 25 vehicles per OD pair. These parameters produce congestion consistent with a peak-period urban scenario in which demand at key links approaches or exceeds capacity, generating endogenous bottlenecks. Demand magnitude is held constant for all λ values, ensuring that variations in efficiency, equity, and revenue arise from congestion pricing policy changes rather than fluctuations in network load. This setting reflects a recognized limitation of synthetic grid networks, which do not fully capture the spatial heterogeneity of real urban demand patterns.

B. Simulation-Based Stackelberg Optimization

The leader problem is solved using a simulation-based policy search over candidate toll vectors. For each candidate $\boldsymbol{\tau}$, the lower-level traveler response is computed using Frank–Wolfe user-equilibrium (UE) assignment [16] with BPR link performance functions. The Frank–Wolfe procedure uses the Method of Successive Averages (MSA) step, iterating until convergence (tolerance 10^{-6}, maximum 100 iterations). The candidate toll vector that minimizes $-J(\boldsymbol{\tau})$ is selected for each value of λ.

The candidate search evaluates three toll structures: (i) Pigouvian-scaled tolls proportional to marginal congestion delay, swept from $0\times$ to $3\times$ the baseline Pigouvian vector (20 candidates) – this structure captures the efficiency-dominant regime where targeted tolls simultaneously reduce VHT and Gini; (ii) uniform tolls across all links (20 candidates) – this structure captures the equity-dominant regime where flat tolls equalize costs; and (iii) convex combinations of Pigouvian and uniform structures to capture the

Algorithm 1 Simulation-Based Stackelberg Toll Optimization

Initialize $\boldsymbol{\tau}^{(0)} = \mathbf{0}$; run Frank–Wolfe UE to get baseline VHT_0, Gini_0
Compute Pigouvian toll: $\tau_e^{\mathrm{pig}} \propto t_e^0 \alpha \beta (f_{e,0}/c_e)^{\beta-1}$
Set magnitude scale: $s = \mathrm{VHT}_0/\mathrm{Gini}_0$
for each $\lambda \in \{0.0, 0.2, 0.4, 0.6, 0.8, 1.0\}$ **do**
  Initialize best objective $J^* = -\infty$, $\boldsymbol{\tau}^* = \mathbf{0}$
  for each candidate toll vector $\boldsymbol{\tau}^{(k)}$ **do**
    Run Frank–Wolfe UE under $\boldsymbol{\tau}^{(k)}$; compute $\mathcal{E}^{(k)}$, $\mathcal{I}^{(k)}$
    $J^{(k)} = \mathcal{E}^{(k)} - \lambda \cdot \mathcal{I}^{(k)} \cdot s$
    if $J^{(k)} > J^*$ **then**
      $J^* \leftarrow J^{(k)}$; $\boldsymbol{\tau}^* \leftarrow \boldsymbol{\tau}^{(k)}$
    end if
  end for
  Record $\mathrm{VHT}(\lambda)$, $\mathrm{Gini}(\lambda)$, $\mathrm{Revenue}(\lambda)$ at $\boldsymbol{\tau}^*$
end for
return efficiency–equity frontier

transitional regime. A total of 40 candidates per (λ, seed) combination are evaluated with toll values constrained to $[0, 10]$. Algorithm 1 summarizes the complete procedure.

C. λ Sweep Evaluation Procedure

The policy parameter λ is varied uniformly over $[0, 1]$ with step size 0.2, yielding six operating points. For each λ, the solver runs under fixed network and demand conditions. Three system-level metrics are recorded: (i) total vehicle-hours traveled (VHT), (ii) Gini coefficient of generalized travel cost, and (iii) total toll revenue. All experiments are repeated across multiple random seeds to mitigate stochastic variability. Reported results correspond to mean values across seeds; observed variance remained small relative to the reported trends, supporting the robustness of the identified regimes and the statistical significance of the knee region. The marginal cost $\kappa(\lambda)$ in Fig. 4 is plotted at the midpoint between adjacent λ pairs, as it is a finite-difference quantity defined over an interval rather than at a single point.

D. Controlled Evaluation Design

To ensure internal consistency across experiments, network topology, OD demand distribution, BPR parameters ($\alpha = 0.15$, $\beta = 4.0$), and solver settings are kept identical for all λ values. No changes are introduced to the network or optimization settings during the sweep. This controlled design ensures that observed differences in efficiency, inequality, and revenue are attributable solely to policy weight tuning rather than artifacts of experimental variability.

V. Results: Efficiency–Equity Frontier Characterization

A. λ Sweep Behavior

Figure 2 reports system performance as the equity weight λ varies from 0 to 1.

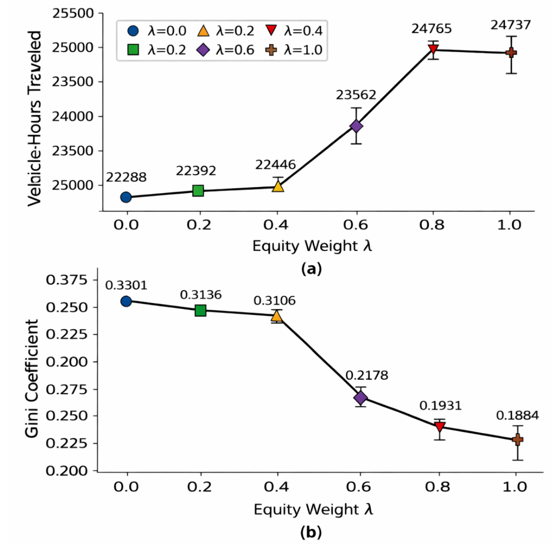

Fig. 2. System metrics as a function of the equity weight λ: (a) total vehicle-hours traveled (VHT) representing network efficiency, and (b) Gini coefficient of generalized travel cost representing inequality. Increasing λ shifts the system from efficiency-oriented to equity-oriented operation.

As λ increases, the Gini coefficient decreases monotonically, indicating progressively more uniform distribution of experienced generalized travel costs across travelers. Even modest increases in λ produce measurable reductions in inequality, suggesting that small policy adjustments can significantly influence the dispersion of travel burdens across the network.

In contrast, total vehicle-hours traveled (VHT) increases with λ. The increase is relatively gradual for small values of λ and becomes steeper in higher regimes, reflecting nonlinear sensitivity of congestion levels to equity emphasis. This behavior arises because enforcing greater cost uniformity redirects flows toward longer or more congested routes, increasing aggregate travel time even as cost dispersion decreases.

These trends collectively confirm that λ acts as an effective policy control parameter that continuously shifts system operation between efficiency-oriented and equity-oriented regimes.

B. Efficiency–Equity Frontier

To directly visualize the trade-off, we construct the empirical efficiency–equity frontier by plotting VHT against the Gini coefficient for all λ values, as shown in Fig. 3.

The frontier exhibits a nonlinear structure with three identifiable regimes:

- *Efficiency-dominant regime*: initial reductions in inequality are achieved with only small increases in VHT.
- *Transitional regime*: marginal efficiency cost begins to rise as further reductions in inequality require increasingly disruptive flow redistribution.
- *Equity-dominant regime*: additional inequality reductions incur disproportionately large congestion penalties.

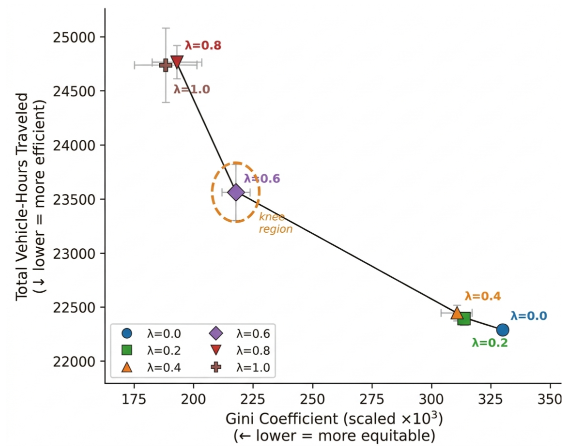

Fig. 3. Empirical efficiency–equity frontier from the λ sweep. Each point corresponds to a distinct policy weight λ, illustrating the trade-off between network efficiency (VHT) and inequality (Gini coefficient).

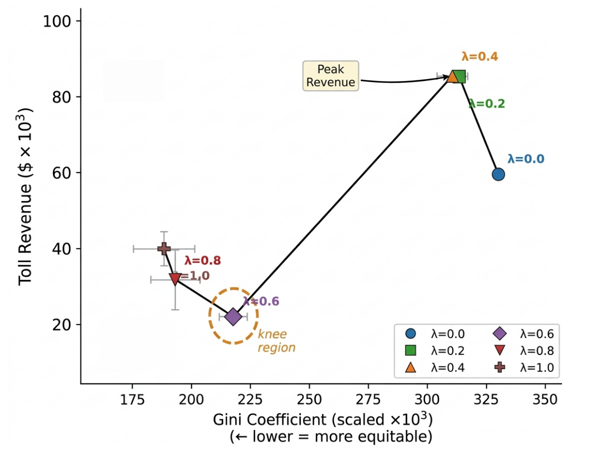

Fig. 5. Toll revenue versus inequality (Gini coefficient) across different equity weights λ, illustrating how equity emphasis influences the fiscal outcomes of congestion pricing.

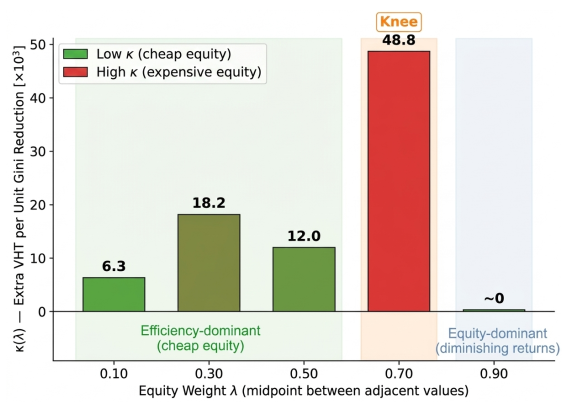

Fig. 4. Marginal efficiency cost $\kappa(\lambda)$ across the λ sweep, representing additional vehicle-hours traveled per unit reduction in inequality between adjacent λ values.

A visible knee region emerges between the efficiency-dominant and equity-dominant regimes, representing a Pareto-efficient operating point where meaningful reductions in inequality can be achieved with relatively limited efficiency loss. This structure is consistent with the price-of-fairness framework [12], which establishes that moderate fairness constraints need not be arbitrarily costly in well-connected networks.

C. Marginal Price of Equity

To quantify the cost of equity improvement, we compute the marginal efficiency cost per unit reduction in inequality between adjacent λ values:

$$\kappa(\lambda_k) = \frac{\mathrm{VHT}(\lambda_{k+1}) - \mathrm{VHT}(\lambda_k)}{\mathrm{Gini}(\lambda_k) - \mathrm{Gini}(\lambda_{k+1})}. \tag{6}$$

This discrete approximation captures the additional congestion incurred per unit decrease in inequality.

As shown in Fig. 4, $\kappa(\lambda_k)$ remains relatively small in the efficiency-dominant regime: at low λ, Pigouvian tolls proportional to marginal congestion cost simultaneously reduce VHT and Gini by redistributing flows away from bottlenecks, making early equity gains essentially free. Beyond the transitional region, $\kappa(\lambda)$ increases sharply as increasingly uniform tolls equalize costs but raise aggregate VHT. The peak near $\lambda = 0.7$ is consistent with the knee region at $\lambda \approx 0.6$; the slight shift arises from the finite-difference approximation used to compute marginal trade-offs between adjacent λ values.

TABLE I
SYSTEM PERFORMANCE ACROSS POLICY WEIGHT λ

λ	VHT	Gini	$\kappa(\lambda)$	Regime
0.0	22,288	0.330	—	Efficiency
0.2	22,392	0.314	6.3	Efficiency
0.4	22,446	0.311	18.2	Transition
0.6	23,562	0.218	12.0	Knee
0.8	24,765	0.193	48.8	Equity
1.0	24,737	0.188	≈ 0	Equity

D. Revenue–Equity Interaction

Figure 5 plots toll revenue against the Gini coefficient across λ values. Moderate equity emphasis preserves revenue levels while reducing disparity, suggesting compatibility between fairness objectives and fiscal sustainability. In this regime, toll adjustments redistribute flows without significantly compressing toll differentiation across links. However, strong equity weighting compresses toll variation and reduces revenue generation capacity. As tolls become increasingly uniform across the network, the pricing mechanism loses its ability to differentiate congestion levels across routes, reducing both revenue and operational effectiveness.

E. Summary of Results

Table I summarizes system-level outcomes across all λ values. The Gini coefficient decreases by 43% from $\lambda = 0$ to $\lambda = 1$, while VHT increases by approximately 11%. Revenue peaks at moderate λ, consistent with the compatibility of fairness and fiscal sustainability.

VI. Discussion

The efficiency–equity frontier confirms that hierarchical congestion pricing should be viewed as a tunable policy surface rather than a single optimal operating point [5]–[7], [18]. The equity weight λ simultaneously reshapes congestion performance, distributional fairness, and revenue outcomes. Such explicit parameterization is particularly valuable in policy settings, where transportation authorities must balance efficiency gains with equity considerations and public acceptance of tolling schemes.

A key structural insight is that early equity gains are essentially free: at low λ, Pigouvian tolls reduce both VHT and Gini simultaneously by redistributing flows away from bottlenecks. This aligns with the price-of-fairness literature [12], which shows that moderate fairness constraints impose limited efficiency penalties in well-connected networks. Beyond the knee, stronger equity weighting forces flows onto suboptimal routes, producing sharply increasing congestion costs and diminishing inequality returns. Similar nonlinear behavior has been documented in mobility intervention analyses [13], [14].

The $\kappa(\lambda)$ curve provides a transparent, quantitative indicator of policy sensitivity for communication between technical analysts and decision makers. Three practical tuning regimes emerge: low λ prioritizes efficiency with only indirect equity improvement; intermediate λ moderates cost dispersion while maintaining throughput; high λ emphasizes redistribution at significant efficiency and revenue cost. Consequently, selecting λ becomes a policy decision reflecting institutional priorities and social equity objectives rather than a purely technical optimization choice.

The revenue analysis highlights that moderate fairness integration coexists with stable revenue generation, whereas strong compression of toll differentiation reduces revenue capacity. This observation reinforces the need to jointly consider congestion mitigation, distributional fairness, and revenue viability in congestion pricing design [4], [5].

Limitations. The framework assumes homogeneous traveler utility without value-of-time heterogeneity, and the synthetic 5×5 grid does not capture the full structural complexity of real urban networks. The identified knee region may shift under different topologies or demand patterns. Confidence interval visualization across seeds, while showing small variance, is not included in the current figures and will be incorporated in future work. Extension to heterogeneous traveler classes, real-world network topologies, and multimodal transportation systems represents an important direction for future research.

VII. Conclusion

This paper presented a structured efficiency–equity tradeoff analysis within a hierarchical Stackelberg congestion pricing framework, solved via simulation-based policy search with Frank–Wolfe user-equilibrium follower responses. By systematically varying λ across a fixed 5×5 grid network, we constructed an empirical efficiency–equity frontier revealing nonlinear regime transitions and a distinct knee region where substantial inequality reductions are achievable with limited congestion impact. The marginal price-of-equity metric $\kappa(\lambda)$ quantifies how congestion costs escalate under stronger equity emphasis, with the key insight that early equity gains are essentially free due to the simultaneous congestion-reducing and inequality-reducing effects of Pigouvian tolls at low λ. Overall, the findings highlight that congestion pricing is best approached as a tunable multi-objective policy instrument, and the proposed framework offers a practical basis for transparent efficiency–equity trade-off analysis in real-world congestion pricing design.

References

[1] W. S. Vickrey, "Congestion theory and transport investment," *The American Economic Review*, vol. 59, no. 2, pp. 251–260, 1969.

[2] R. Arnott, A. de Palma, and R. Lindsey, "A structural model of peak-period congestion: A traffic bottleneck with elastic demand," *American Economic Review*, vol. 83, no. 1, pp. 161–179, 1993.

[3] H. Yang and H.-J. Huang, "The multi-class, multi-criteria traffic network equilibrium and systems optimum problem," *Transportation Research Part B: Methodological*, vol. 38, no. 1, pp. 1–15, 2004.

[4] K. A. Small, E. T. Verhoef, and R. Lindsey, *The Economics of Urban Transportation*. Routledge, 2024.

[5] J. Eliasson and L.-G. Mattsson, "Equity effects of congestion pricing: Quantitative methodology and a case study for stockholm," *Transportation Research Part A: Policy and Practice*, vol. 40, no. 7, pp. 602–620, 2006.

[6] M. Milenković, D. Glavić, and M. Maričić, "Determining factors affecting congestion pricing acceptability," *Transport Policy*, vol. 82, pp. 58–74, 2019.

[7] T. Litman, *Evaluating Transportation Equity*. Victoria Transport Policy Institute, Victoria, BC, Canada, 2017.

[8] T. Başar and G. J. Olsder, *Dynamic Noncooperative Game Theory*. SIAM, 1999.

[9] K. Zhang, Z. Yang, and T. Başar, "Multi-agent reinforcement learning: A selective overview of theories and algorithms," *Handbook of Reinforcement Learning and Control*, pp. 321–384, 2021.

[10] H. Wei, G. Zheng, H. Yao, and Z. Li, "CoLight: Learning network-level cooperation for traffic signal control," in *Proceedings of the 28th ACM International Conference on Information and Knowledge Management*, 2019, pp. 1913–1922.

[11] M. S. Parwez, S. T. Srivillibhutturu, and A. Al-Shammari, "Equity-aware dynamic congestion pricing in road transportation networks via hierarchical Stackelberg optimization," *IEEE Transactions on Intelligent Transportation Systems*, 2025, under review.

[12] D. Bertsimas, V. F. Farias, and N. Trichakis, "The price of fairness," *Operations Research*, vol. 59, no. 1, pp. 17–31, 2011.

[13] K. Martens, *Transport Justice: Designing Fair Transportation Systems*. Routledge, 2016.

[14] R. H. Pereira, T. Schwanen, and D. Banister, "Distributive justice and equity in transportation," *Transport Reviews*, vol. 37, no. 2, pp. 170–191, 2017.

[15] T. Chu, J. Wang, L. Codeca, and Z. Li, "Multi-agent deep reinforcement learning for large-scale traffic signal control," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 3, pp. 1086–1095, 2020.

[16] Y. Sheffi, *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Englewood Cliffs, NJ: Prentice-Hall, 1985.

[17] C. Gini, "Variability and mutability, contribution to the study of statistical distribution and relations," *Studi Economico-Giuridici della R. Università de Cagliari*, vol. 3, pp. 3–159, 1912.

[18] D. Levinson, "Equity effects of road pricing: A review," *Transport Reviews*, vol. 30, no. 1, pp. 33–57, 2010.