UCI

Institute of Transportation Studies

A Smart Mobility Platform with Equitable Peer-to-Peer Congestion Pricing and Its Policy and Equity Implications

Siwei Hu[a]
Ph.D. Candidate
siweih3@uci.edu

[a] Department of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Irvine, CA 92697-3600, USA

2024 Regional Conference & General Assembly

Southern California Association of Governments (SCAG)
59th Annual Regional Conference and General Assembly
May 2-3 | JW Marriott Desert Springs Resort & Spa in Palm Desert
Student Showcase| Poster Competition

Introduction

❑ Motivation

- ➢ Researchers and engineers have dedicated significant effort to developing advanced route guidance systems.
- ➢ The goal of such systems is to spread travelers more efficiently, steering the transportation networks to the System Optimal (SO) state.

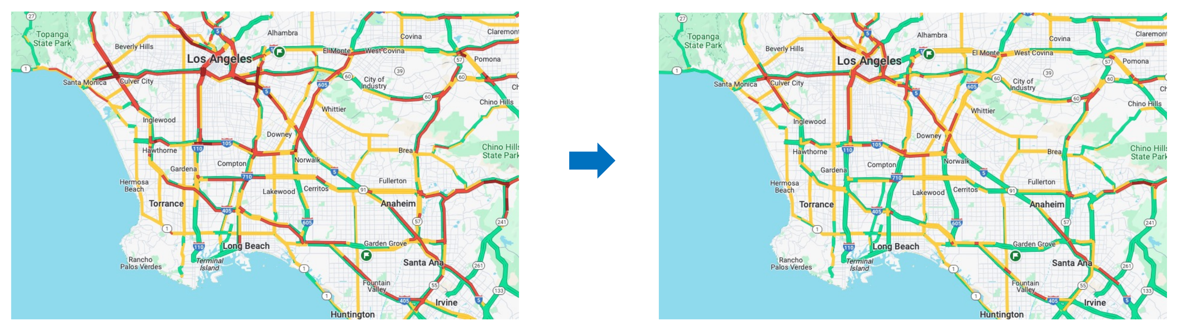

Figure 1 Illustration of Spreading Travelers and Reduce Congestion

- ➢ Guiding travelers to higher-cost routes without compensation can create unfairness issues, potentially deferring participation in such route guidance systems.

❑ Objectives and Contribution

- ➢ Introduce a novel smart mobility platform with equitable peer-to-peer congestion pricing that offers route and monetary exchange guidance for travelers.
- ➢ Show that the proposed platform can steer the transportation network to the Dynamic System Optimal (DSO) state, maintaining fairness among travelers.
- ➢ Examine the policy and equity implications of the proposed platform using the Los Angeles I-10 expressway corridor network dataset.

***Key words**: Route guidance system, Dynamic system optimal (DSO), Envy-free, Fairness, Peer-to-peer*

Assumptions

❑ Assumptions – An App-based Platform

- ➢ An app-based centralized route guidance platform that enables travelers to collaborate on their route choices with peer-to-peer monetary exchange.

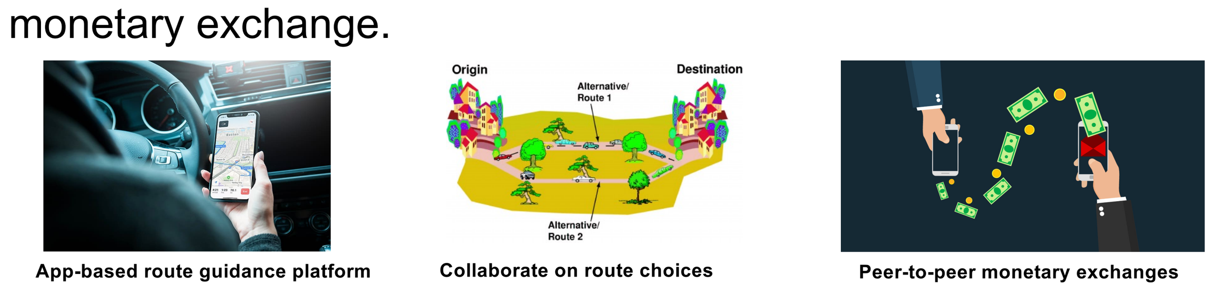

Figure 2 Illustration of A Centralized App-based Platform

❑ Envy – A Behavioral Mechanism for Fairness

- ➢ Agent i *envies* agent j if agent i prefers j's bundle to his/her own bundle (Varian, 1974).

$$x_j \succ_i x_i$$

- x: an allocation of some fixed amount of resources among n agents
- x_i, x_j: agent i and j's bundle

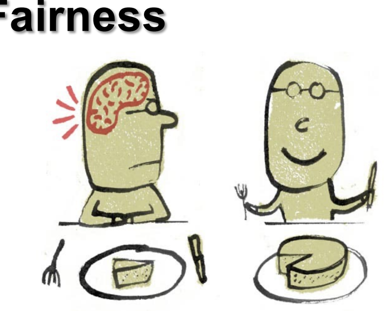

Figure 3 Illustration of Envy in the Cake-cutting Scenario

- ➢ An allocation is *equitable* if nobody prefers other agents' bundles to his/her own, resulting in an *envy-free* state.

$$x_i \succcurlyeq_i x_j \quad \forall i, j \in I$$

- I: the set of all agents

❑ Assumptions – Traveler's Behavior

- ➢ Travelers are utility maximizers while minimizing their envy.

Problem Description

➢ The proposed platform aims to address this problem:

✓ Given:

1. a set of travelers with ODs, departure times, and Values of Time (VOT);
2. a transportation network composed of links and nodes;

✓ Determine, for each Origin-Destination-departure Time (ODT) triad:

1. the Dynamic System Optimal (DSO) set of paths;
2. the number of travelers on each path;
3. the payments made to or received from the platform by each traveler;

✓ that (i) minimize total system travel time and (ii) ensure no traveler feels envy regarding their path's travel time and the payments transacted.

Methodology

❑ Definition of Envy

- ➢ Agent i's envy towards agent j, represented as e_{ij}, is defined by the equation below:

$$e_{ij} = \left(V_{ij}(\theta_i, t_j, p_j) - V_{ii}(\theta_i, t_i, p_i)\right)\delta_{ij}$$
$$\forall\, i, j \in I^{rst}; i \neq j$$

- $V_{ij}(\theta_i, t_j, p_j)$: agent i's valuation on agent j's selected route with its travel time t_j and the payment transacted p_j under i's VOT θ_i
- $\delta_{ij} = \begin{cases} 1 & if\ e_{ij} \geq 0 \\ 0. & otherwise \end{cases}$

❑ Problem Formulation

- ➢ A multi-objective mixed integer programming problem, calculating a solution $(\boldsymbol{x}, \boldsymbol{p})$ to minimize total system travel time and total maximum envy.

$$\min_{(\boldsymbol{x},\boldsymbol{p})} obj = \alpha \underbrace{\sum_{t\in T}\sum_{a\in A} x_{a,t} t_{a,t}(x_{a,t})}_{\text{Minimize total system travel time}} + \beta \underbrace{\sum_{i\in I} \max_{i\neq j}\{e_{ij}\}}_{\text{Minimize total maximum envy}}$$

ODT demand conservation constraint
$$q_\tau^{rs} = \sum_{i\in I}\sum_{k\in K_\tau^{rs}} h_{i.\tau}^{rsk} \quad \forall\, r,s \in R; \tau \in T^D$$

ODT agent-path usage indicator
$$h_{i,\tau}^{rsk} = \begin{cases} 0 & if\ path\ k\ is\ used \\ 1 & otherwise \end{cases} \quad \forall i \in I, k \in K_\tau^{rs}, r,s \in R, \tau \in T^D$$

Agent path-flow conservation constraint
$$\sum_{k\in K_\tau^{rs}} h_{i,\tau}^{rsk} = 1 \qquad \forall i \in I$$

Link flow-path flow conservation constraint
$$x_{a,t} = \sum_{i\in I}\sum_{r,s,k,\tau} h_\tau^{rsk}\delta_{i,t\tau a}^{rsk} \qquad \forall a \in A, t \in T$$

Path-link incidence matrix
$$\delta_{i,t\tau a}^{rsk} = \Psi\left[h_{i,\tau}^{rsk}, \forall i,r,s,k,\tau\right] \forall i \in I, k \in K_\tau^{rs}, r,s \in R, a \in A$$

Envy comparison
$$\sum_{a,t} -t_{a,t}\delta_{i,t\tau a}^{rsk}\theta_i + e_{ij} - p_{i\tau}^{rs} \geq \sum_{a,t} -t_{a,t}\delta_{j,t\tau a}^{rsk'}\theta_i - p_{j\tau}^{rs}\ \forall i,j \in I^{rst}, i \neq j$$

Budget balance constraint
$$\sum_{i\in I^{rst}} p_i^{rst} = B^{rst}\ \forall\, r,s \in R; \tau \in T^D$$

Non-negativity constraint
$$e_{ij} \geq 0 \qquad \forall i,j \in I^{rst}, i \neq j$$

❑ Solution Approach

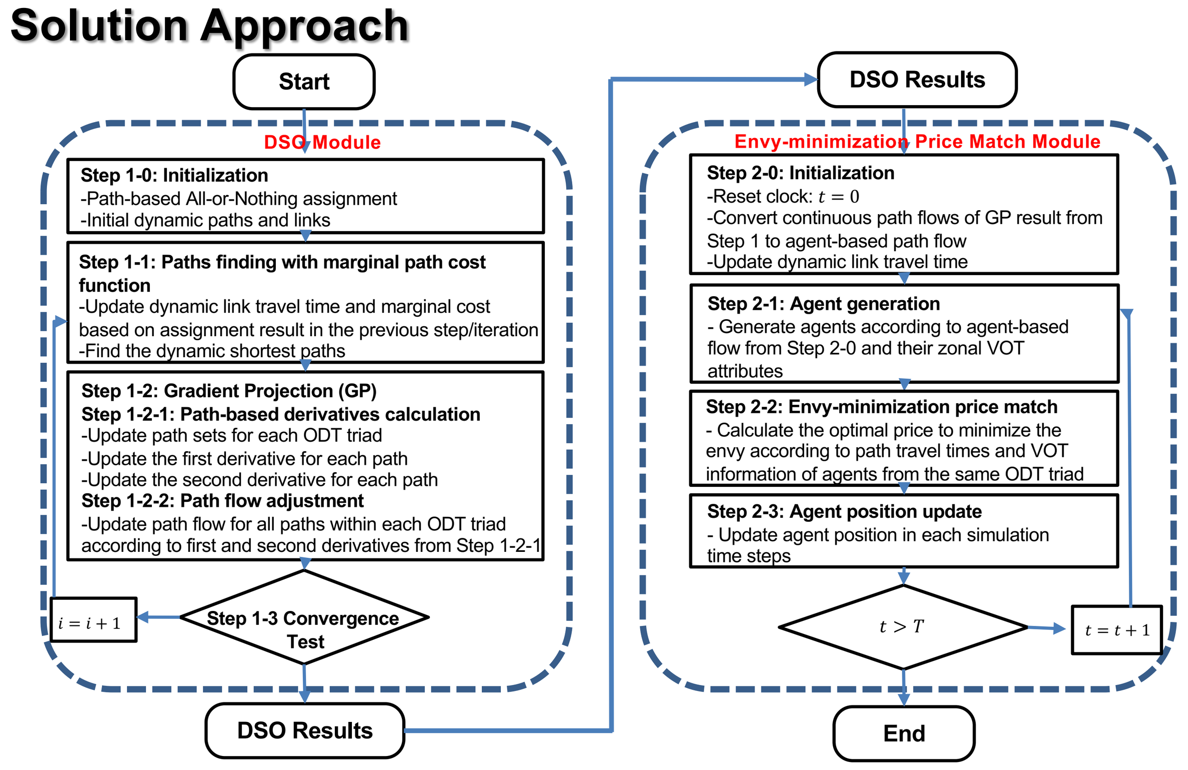

Figure 4: Flow Chart of the Solution Approach

Simulation Results

❑ Input Data

Figure 5: LA I-10 Expressway Corridor Network with 799 Nodes and 1,927 Links

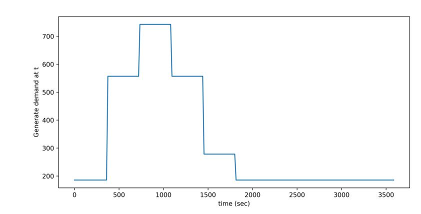

Figure 6: 1 Hour Morning Peak Demand with 78,196 Trips

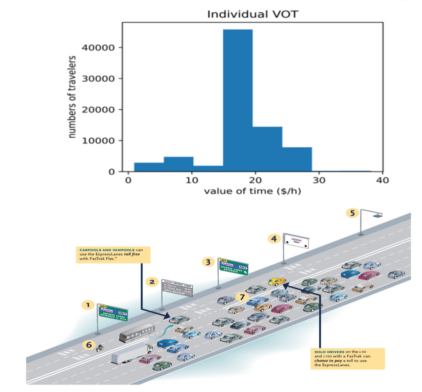

Figure 7: Travelers' VOT data from Bento, Roth and Waxman (2020)

❑ Network Results

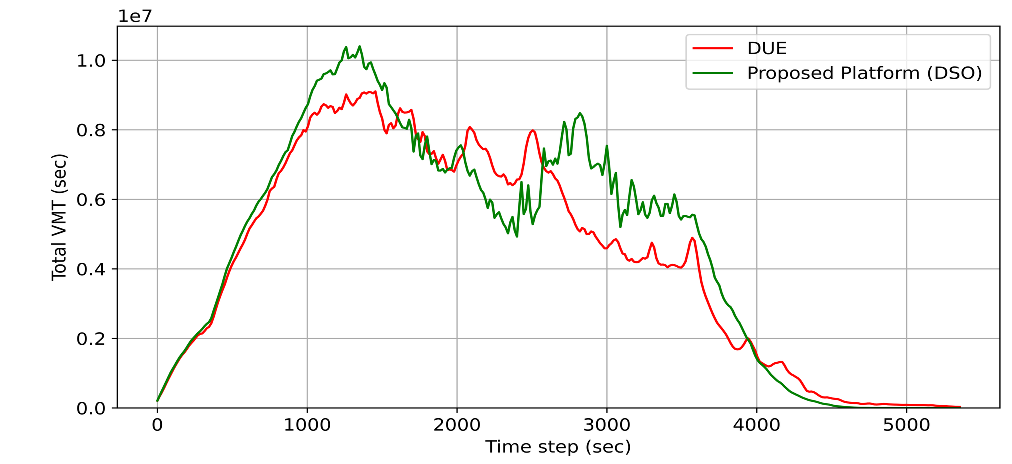

Figure 8: Time-dependent Network VMT

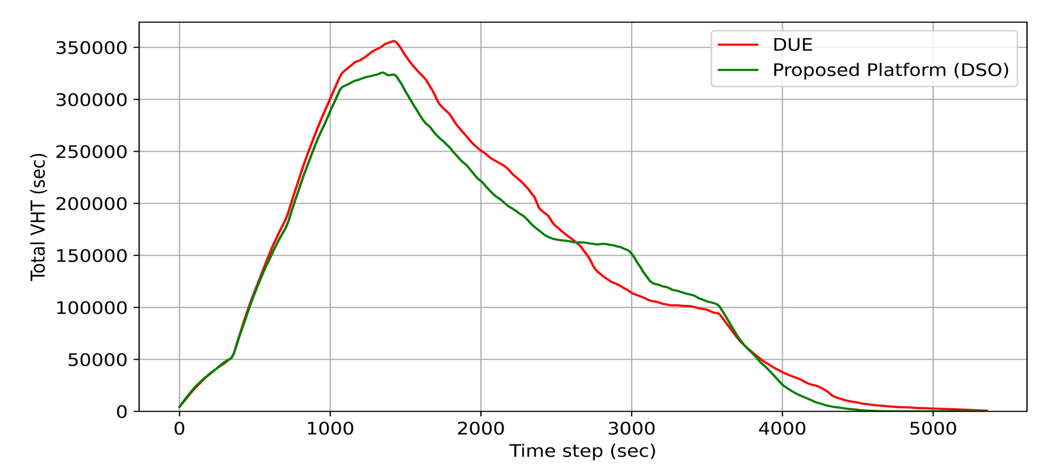

Figure 9: Time-dependent Network VHT

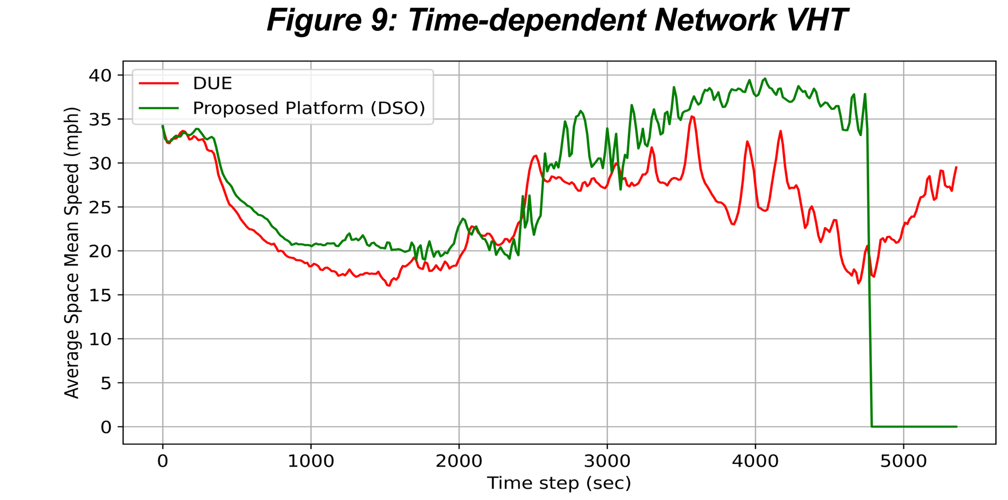

Figure 10: Time-dependent Network Space Mean Speed

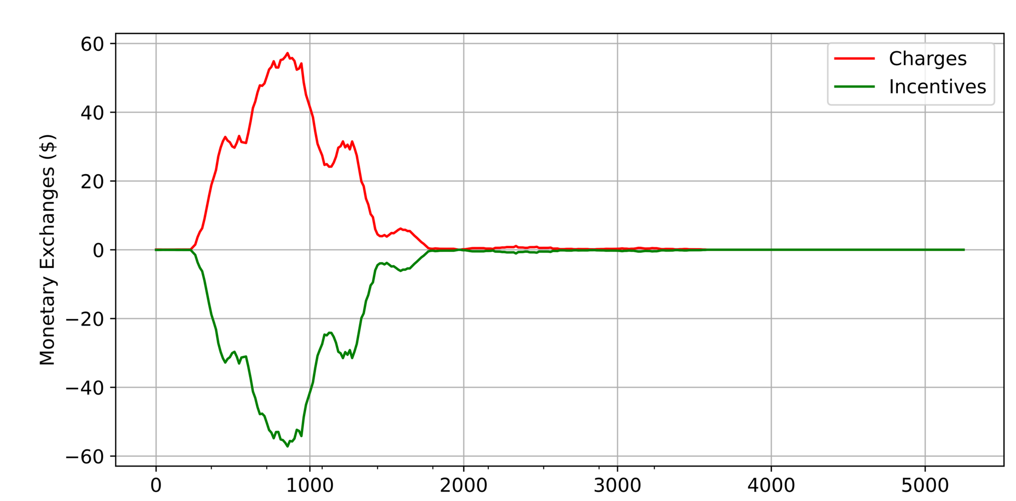

Figure 11: Time-dependent Network Charges and Incentives

Table 1: Network Level Equity Analysis between DUE and the Proposed Platform

Scenarios	VMT (mile)	VHT (hr)	Average SMS (mile/hr)	Sum of envy post-PM ($)	Sum of envy pre-PM ($)	Sum of EB post-PM ($)	Sum of EB pre-PM ($)	Total Transac. ($)	Agents Collab. on Routes	Average Transac. ($)
DUE	1.51E+09	4.82E+07	31.24	325.3	325.3	857.54	857.54	0	0	0
Proposed platform (DSO)	1.62E+09	4.58E+07	35.32	1.31E-07	3800.51	3227.13	7057.4	5482.25	6060 (7.75%)	0.904
Percentage change	+7.28%	-4.98%	+13.06%	-100%	+1068.31%	+276.32%	+722.98%	--	--	--

DUE: dynamic user equilibrium, DSO: dynamic system optimal, VMT: vehicle miles traveled, VHT: vehicle hours traveled, hr: hour, SMS: space mean speed, $: US dollar, PM: price match, pre-PM: before price match, post-PM: after price match, EB: extra benefit, Transac.: Transcaction, Collab.: collaboration

❑ Individual Results

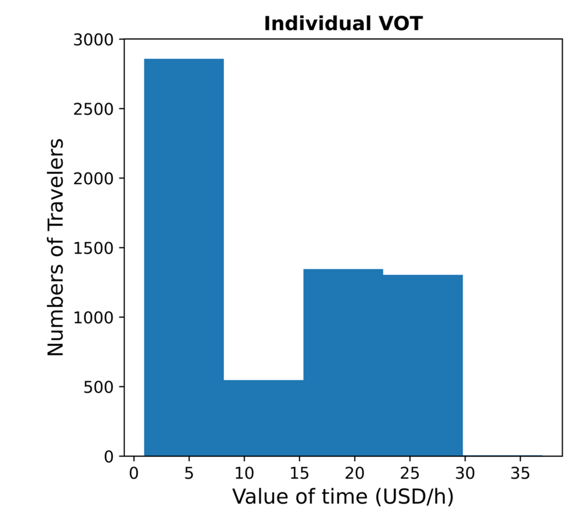

Figure 12: VOT Distribution of 6,060 Participants

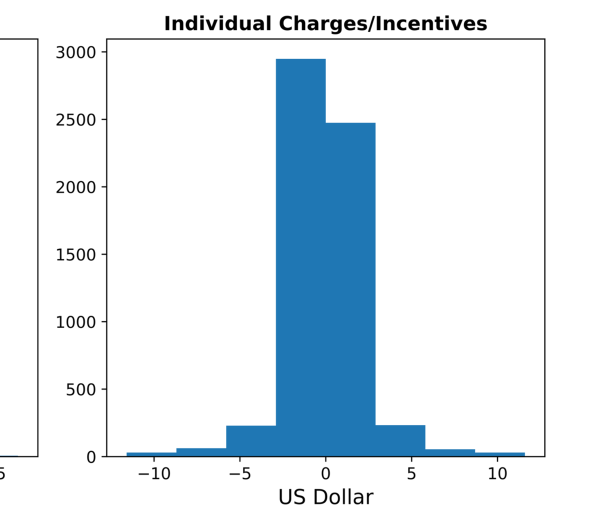

Figure 13: Individual Charges or Incentives of 6,060 Participants

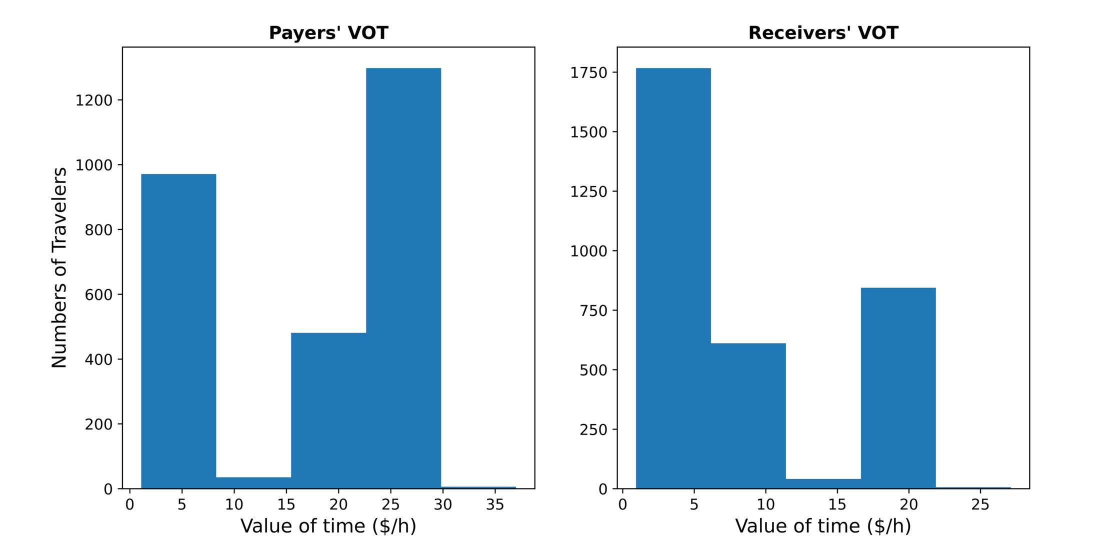

Figure 14: VOT Distribution of 2,791 Payers and 3,269 Receivers

Conclusion

- ➢ Envy is a simple metric and behavioral paradigm for transportation equity analysis when individual preference data (e.g., VOT, the value of urgency) are available.
- ➢ With 7.75% of travelers collaborating on their routes, the proposed platform can direct the transportation system to the Dynamic System Optimum (DSO) and envy-free state, leading to a 13.06% increase in space mean speed.
- ➢ The average payment on the proposed platform is $0.904, markedly lower than the LA I-10 expressway tolls, which range from $4.25 to $5.46 during peak periods.
- ➢ In cases where budget balancing isn't a concern, revenue from the platform can be allocated to support policy alternatives, like public transport, or to fund infrastructure development in disadvantaged communities.

Selected Reference

1. Varian, H. R. (1974). Equity, envy, and efficiency. *Journal of Economic Theory*, *9*(1), 63-91.
2. Nam, D. D. (2019). Modelling and Optimization of Smart Mobility Systems with Agent Envy as a Paradigm for Fairness and Behavior. University of California, Irvine.
3. Bento, A., Roth, K., & Waxman, A. R. (2020). Avoiding traffic congestion externalities? the value of urgency (No. w26956). National Bureau of Economic Research.

Acknowledgement

- This study was funded, in part, by PSR-20-31 TO 040 project by State of California, Department of Transportation (Caltrans). The authors would also like to thank Dr. Kevin Roth from Christensen Associates for his valuable comments on this research study.