Routing Guidance for Emerging Transportation Systems with Improved Dynamic Trip Equity

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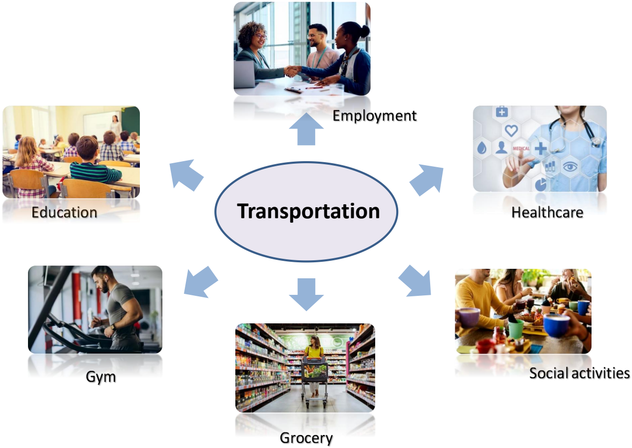
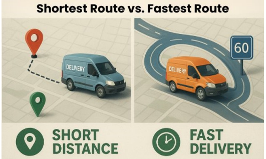
64th IEEE Conference on Decision and Control (CDC), Rio de Janeiro, Brazil
December 10-12, 2025

Motivation

Transportation Systems



Safety



Efficiency

Sustainability

Negative consequences without "Equity":

- Reinforces cycles of poverty and social exclusion
- Drive over-reliance on private vehicles
- Exacerbate traffic congestion
- Increase travel costs
- Cause environmental degradation, etc

Static Routing Guidance System (S-RGS)

- Flow-level macroscopic approaches
- Uniform guidance to all vehicles in the same flow
- May shift congestion from one point to another

Dynamic Routing Guidance System (D-RGS)

- Vehicle-level microscopic approaches
- Provide route to each specific vehicle based on real-time traffic data
- Address congestion effectively

Research Gap

Static Routing Guidance System (S-RGS)

- Flow-level macroscopic approaches
- Uniform guidance to all vehicles in the same flow
- May shift congestion from one point to another

Dynamic Routing Guidance System (D-RGS)

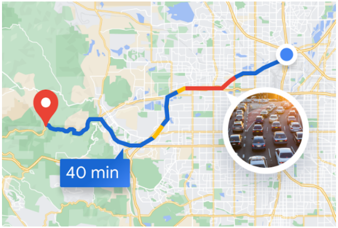
- Vehicle-level microscopic approaches
- Provide route to each specific vehicle based on real-time traffic data
- Address congestion effectively

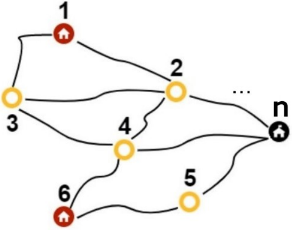
Our goal: Develop a D-GRS in emerging transportation systems with enhanced trip equity across vehicle types.

Outline

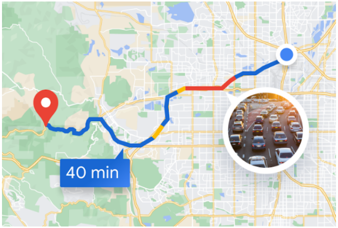
- **Routing Problem**
- **Dynamic Trip Index and Trip Equity (DTE)**
- **Routing Guidance with improved DTE**
- **Simulation Studies**
- **Conclusions and Future Work**

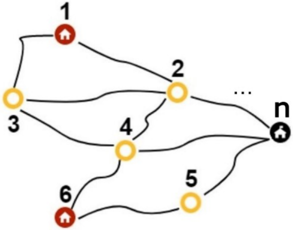
Routing Problem





- Feasible route: $r_{1,n} = \{(v_1, v_2), \ldots, (v_{n-1}, v_n)\}$
- Decision-making point (DMP): $\{v_k\},\ k = 1, \ldots, n-1$
- Set of feasible routes: $r_{1,n} \in \mathcal{R}_{1,n}$





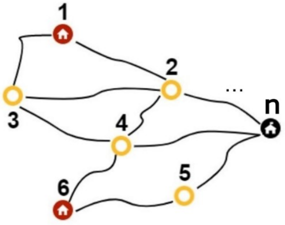
- Feasible route: $r_{1,n} = \{(v_1, v_2), \ldots, (v_{n-1}, v_n)\}$
- Decision-making point (DMP): $\{v_k\},\ k = 1, \ldots, n-1$
- Set of feasible routes: $r_{1,n} \in \mathcal{R}_{1,n}$

Problem: Develop a D-RGS that assists each vehicle in route planning at each DMP.

Key Challenges:

(i) Take into account real-time and potential traffic congestion.

(ii) Improve trip equity across travelers despite vehicle types.



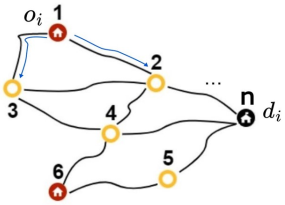
- **Addressing challenge 1**
  - Vehicle dynamics between DMPs:

$$a_{k+1}^{i} = a_{k}^{i} + \tau_{k,k+1}^{i}$$

  - Bureau of Public Road (**BPR**) function:

$$\tau_{k,k+1}^{i} = \tau_{k,k+1}^{0}\left(1 + \alpha\left(\frac{f_{k,k+1}^{i}}{c_{k,k+1}}\right)^{\beta}\right)$$

where $\tau_{k,k+1}^{0}$ is the free-flow travel time on (v_k, v_{k+1}).



Flow on adjacent edges

- **Addressing challenge 1**
  - Define monitoring window:

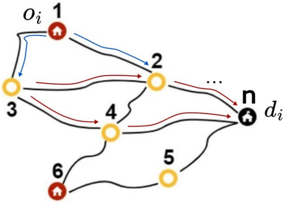
$$\mathcal{M}(a_k^i, \Delta t) := [\, a_k^i - \Delta t,\ a_k^i + \Delta t \,]$$

  - Define indicator function:

$$\mathbf{1}_{a_{k,k+1}^j} := \begin{cases} 1, & \text{if } a_{k,k+1}^j \in \mathcal{W}(a_k^i, \Delta t) \\ 0, & \text{otherwise} \end{cases}$$

  - Traffic flow monitored on each adjacent edge:

$$\tilde{f}_{k,k+1}^i = \frac{\sum\limits_{j \in \mathcal{N}(t) \setminus \{i\}} \mathbf{1}_{a_{k,k+1}^j} + 1}{2\Delta t}$$



Flow on future edges

▶ **Addressing challenge 1**

- Given route planning of other vehicles:

$$r^*_{k',d_j}(a^i_k)$$

- Estimate the arrival time of vehicle i:

$$\hat{a}^i_s = \begin{cases} a^i_k + \tilde{\tau}^i_{k,k+1}, & \text{if } s = k+1, \\ \hat{a}^i_{s-1} + \hat{\tau}^i_{s-1,s}, & \text{otherwise.} \end{cases}$$

- Traffic flow monitored on each future edge:

$$\hat{f}^i_{s,s+1} = \frac{\sum_{(v_s,v_{s+1})\in r^*_{k',d_j}(a^i_k),\, j\in\mathcal{N}(t)\setminus\{i\}} \mathbf{1}_{\hat{a}^j_{s,s+1}} + 1}{2\Delta t}$$

Dynamic Trip Index and Trip Equity

- **Addressing challenge 2**
  - Define Dynamic Trip indeX (DTX)

$$DTX_i(t) = \underbrace{\xi_1 \frac{\tau^i_{\min}}{\tau_i(t)}}_{\text{Efficiency}} + \overbrace{\xi_2 \frac{\phi^i_{\min}}{\phi_i(t)}}^{\text{Cost}} + \underbrace{\xi_3 \frac{q^i_{\min}}{q_i}}_{\text{Convenience}}$$

$$q^i_{\min} = \frac{T^i_{w,\min}}{T^i_{d,\max}}$$

Accessibility
Availability

  - Convex combination: $\xi_1 + \xi_2 + \xi_3 = 1$
  - $\tau^i_{\min}$: Minimum travel time between (o_i, d_i).
  - $\phi^i_{\min} = \epsilon^i_{\min}\tau^i_{\min}$: Minimum transportation cost.

Dynamic Trip Index and Trip Equity

- **Addressing challenge 2**

  - Define Dynamic Trip Equity (DTE) using **Gini Coefficient**

$$DTE_i(t) := 1 - \frac{\sum_{j \in \mathcal{S}_i(t)} \sum_{j' \in \mathcal{S}_i(t)} \left| DTX_j(t) - DTX_{j'}(t) \right|}{2 \left| \mathcal{S}_i(t) \right|^2 DTX_{i,\text{mean}}(t)}$$

where

$$DTX_{i,\text{mean}} = \frac{1}{|\mathcal{S}_i(t)|} \sum_{j \in \mathcal{S}_i(t)} DTX_j(t)$$

$$\mathcal{S}_i(t) = \left(\mathcal{C}_{i,p}(t) \cup \mathcal{C}_{i,a}(t)\right) \uplus \underbrace{\mathcal{C}_{i,h}(t) \uplus \cdots \uplus \mathcal{C}_{i,h}(t)}_{m}$$

$$\mathcal{C}_i(t) = \left\{ j \in \mathcal{N}(t) \middle| r^*_{k',d_j}(t) \cap r_{k,d_i} \neq \varnothing, r_{k,d_i} \in \mathcal{R}_{k,d_i} \right\}$$

Road resource competitors (RRCs)

- **Addressing challenge 2**
  - Perfect DTE in free-flow networks

Since $\tau_i(t) = \tau^i_{\min}$, the DTX is independent of time:

$$DTX_{i,0} = \xi_1 + \xi_2 \frac{\epsilon^i_{\min}}{\epsilon_i} + \xi_3 \frac{q^i_{\min}}{q_i}$$

Proposition 1

Perfect DTE can be achieved in a free-flow network if it satisfies:

$$DTX^p_{j,0} = DTX^a_{j,0} = DTX^h_{j,0}, \qquad \forall j \in \mathcal{C}_{i,0}(t),$$

where

$$DTX^p_{j,0} = \xi_1 + \xi_2 \frac{\epsilon^j_{\min}}{\epsilon_j} + \xi_3, \qquad j \in \mathcal{C}^p_{i,0}(t)$$

$$DTX^a_{j,0} = \xi_1 + \xi_2 + \xi_3 \frac{q^j_{\min}}{q_j}, \qquad j \in \mathcal{C}^a_{i,0}(t)$$

$$DTX^h_{j,0} = \xi_1 + \xi_2 \frac{\epsilon^j_{\min}}{\epsilon_j} + \xi_3 \frac{q^j_{\min}}{q_j}, \qquad j \in \mathcal{C}^h_{i,0}(t)$$

Routing optimization problem at each DMP

$$\max_{r_{k,d_i} \in \mathcal{R}_{k,d_i}} \quad DTE_i(a_k^i)$$

Subject to:

Dynamic of the vehicle

Dynamics of the vehicle's RRCs

Monitored traffic flow on adjacent edges

Estimated traffic flow on future edges

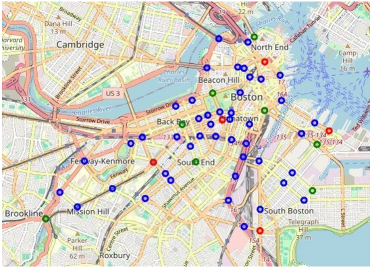
DTX of the vehicle

DTXs of the vehicle's RRCs

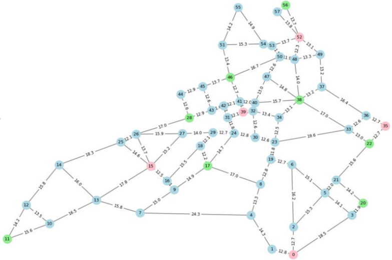
DTE related constraints

Simulation Studies

An urban road network in Boston



Road network topology



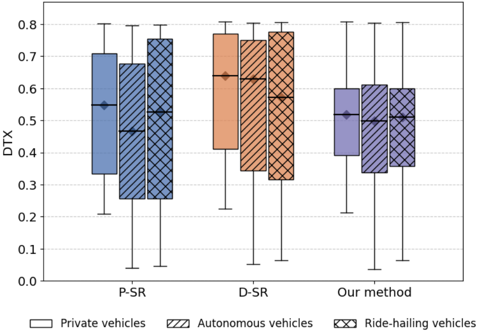
- 58 nodes, including 45 intersections, 8 origins, and 5 destinations.
- Free-flow speed: $27\,\mathrm{km/h}$, nominal travel time is obtained from *OpenStreetMap*.
- Road capacity is set as 5 vehicles per minute per lane.
- Yen's algorithm is used to select the 7 shortest routes from a DMP to each destination when forming the feasible route set.

Parameter settings of each vehicle type

Vehicle type	ξ_1	ξ_2	ξ_3	ϵ_i[\$/min]	$T_{w,i}$[min]	$T_{d,i}$[h]
$i \in \mathcal{N}_p(t)$	0.4	0.4	0.2	0.27	2	24
$i \in \mathcal{N}_a(t)$	0.4	0.4	0.2	0.1485	15	18
$i \in \mathcal{N}_h(t)$	0.4	0.4	0.2	0.1536	6	12

- 1,000 vehicles depart between 08:00–10:00 am.
- **Private vehicles** (500); **autonomous vehicles** (300); **ride-hailing vehicles** (200).
- Each ride-hailing vehicle serves 2 travelers.
- $\Delta t = 60$ seconds.

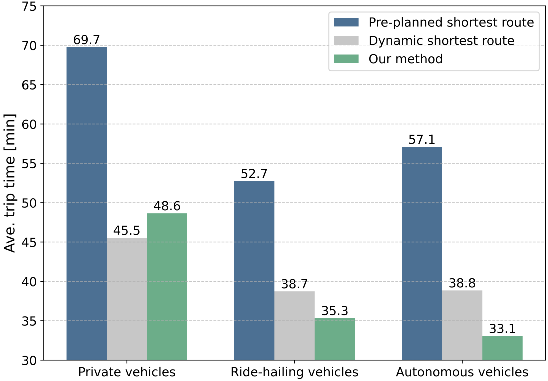
Comparison of the dynamic trip index (DTX)



- Pre-planned shortest-route (P-SR)
- Dynamic shortest-route (D-SR)

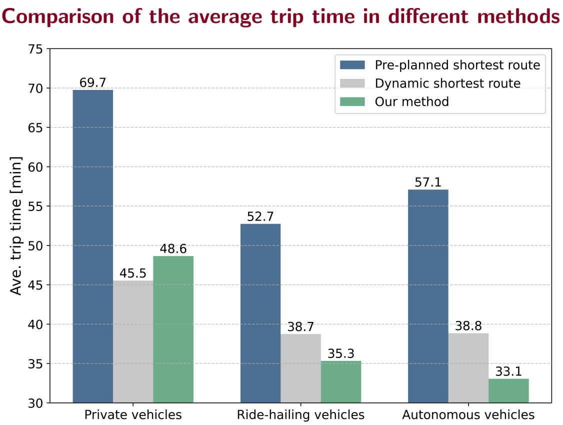
- The DTEs for the completed trips of all vehicles in P-SR, D-SR, and our methods are 0.734, 0.777, and 0.818, respectively.
- The proposed method achieves a more centralized distribution of DTX across all vehicle types, showing a more consistent and balanced trip equity.

Comparison of the average trip time in different methods



- The proposed method significantly reduces the average trip time for **private**, **ride-hailing**, and **autonomous vehicles** by approximately 30%, 33%, and 42%.

Simulation Studies



- The proposed method significantly reduces the average trip time for **private**, **ride-hailing**, and **autonomous vehicles** by approximately 30%, 33%, and 42%.
- Our method effectively redistributes travel costs across vehicle types via route optimization, contributing to a more equitable and efficient transport system.

Conclusions and Future Work

Conclusions:

- We present a novel framework to quantify trip equity in a dynamic emerging transport system, integrating trip time, cost, and convenience.
- We develop a D-RGS to optimize vehicle routes dynamically, which

  (i) incorporates **real-time** and **anticipated** traffic congestion;

  (ii) **enhances travelers' trip equity** despite vehicle types.
- We establish conditions ensuring the best trip equity in free-flow networks.

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Future work:

- Accurate traffic congestion estimation on future edges.
- Incentive design to enhance compliance with route recommendations.

Thank you for your attention!

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