Optimizing Information Values in Smart Mobility

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Outline

Background

- The Smart City concept is a combination of "ideas about how information and communication technologies might improve the functioning of cities" [1].
- A smart city includes a smart economy, smart mobility, a smart environment, smart people, smart living, and smart governance [2].

Figure: Smart City (Source: [3])

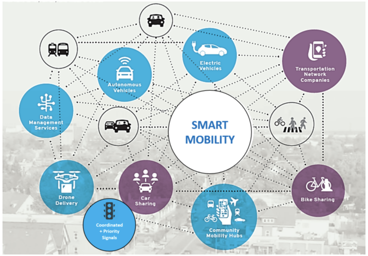
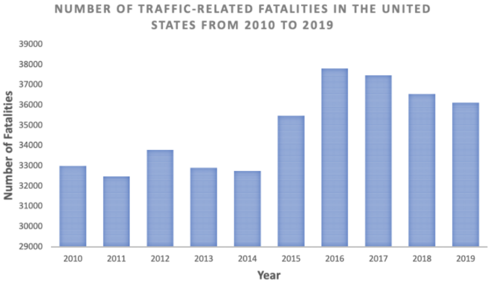


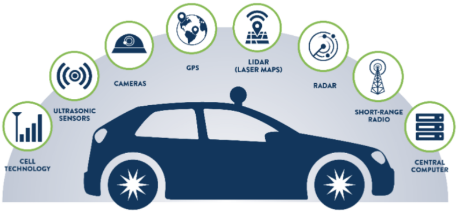
Figure: Smart Mobility (Source: [4])

Background

- Human error is one of the leading causes of accidents and fatalities on the road [5].
- To address this challenge, the United States government initiated programs such as the Automated Highway System (AHS) in 1994 [6].
- USDOT established a number of programs aimed at accelerating the deployment of CAVs [7].



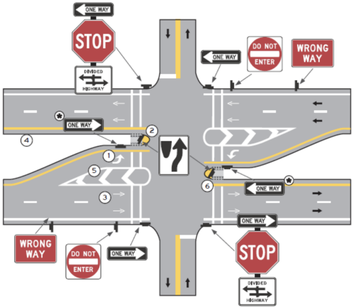
Source: NHTSA, USDOT



Source: MnDOT

Background

- There have been numerous studies conducted on the benefits of CAVs.
- However, CAVs cannot achieve their full potential on the road using age-old information sharing system.
- A shift in information sharing techniques by public entities (transport authorities) is required.
- This type of information is called *publicly-owned information*.



Conventional Information Sharing System

Future Information Sharing System

Source: USDOT

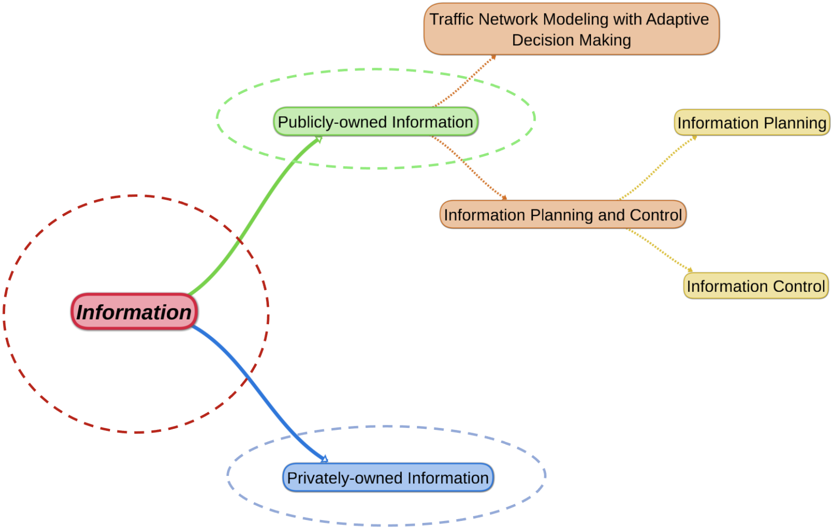
Background

- Transportation network companies (TNCs) such as Uber and Lyft for ride-sourcing services that provide private information to people.
- Ride-sourcing refers to a digital platform offered by private car owners to users requesting rides [8].
- TNCs publish information such as price, estimated time of arrival, vehicle location, etc. via an app.
- This type of information is called *privately-owned information*.

Motivation

- Publicly-owned Information
    - CAVs can make adaptive route changing decisions with the updated information from I2V devices.
    - Transportation system is an interconnected network. Any local route change or local traffic events has an impact on the network mobility and safety.
    - Plan and control information to improve network performance.
- Privately-owned Information
    - The information shared by TNC influences the travel behavior of drivers and riders, thereby affecting traffic congestion.

Dissertation Overview



Research Gap 1: Traffic Network Modeling with Adaptive Decision Making

- Safety and mobility implications of CAVs
  - Roundabout/signalized intersection/link/zone safety [9, 10, 11, 12, 13, 14].
- Adaptive Decision Making with Information Updates
  - Simulation-based Dynamic Traffic Assignment (DTA) [15, 16, 17]. However, calibration for large network is difficult.
  - Equilibrium routing decision [18] and user equilibrium with recourse [19]. These studies consider information implicitly in routing policies and the number of routing policies grows exponentially.

Main research gaps

- A network modeling framework is required to model adaptive routing behavior at a network level with information updates.

Research Gap 2: Information Planning

- Impact of different information-sharing provision
  - Pre-trip information [20, 21, 22]
  - Real-time information [23, 24, 25]

    Information is considered as an exogenous parameter for the models.
- Transportation network design for decision making process
  - Supply chain network design [26, 27], Signal timing [28], Transit route design [29, 30], Road improvement projects [31, 32], Service network design [33, 34], Evacuation planning [35, 36]

Main research gaps

- A modeling approach that incorporates information sharing locations into the model is still missing.

Research Gap 3: Information Control

- Congestion pricing and toll design
  - Design for fixed demand [37] and elastic demand [38], different pricing scheme [39], considering uncertainties [40]
- Variable Speed limit controls (VSLCs)
  - Physical-model based approach [41, 42, 43]. However, it requires accurate model of the system and faces computational difficulties.
  - Reinforcement-learning based approach
    - freeway bottleneck [44], ramp metering [45], work zone operation [46]. However, mostly used for small-scale problems.

Main research gaps

- Research on network performance improvement using VSLC is still limited.

Research Gap 4: Privately-owned Information

- Ride-sourcing services
  - Research on the potential value of dynamic pricing [47, 48, 49]. Most of these studies focus on temporal aspects and do not consider traffic equilibrium and transportation congestion.
  - Research on congestion effect
    - Vignon et al. [50]: The impact of both solo and pooling ride-sourcing services on traffic congestion. Nevertheless, it does not address the impact of spatial/dynamic pricing on congested network conditions.
    - Li et al. [51]: The optimal spatial pricing to maximize profits under different congestion pricing policies. However, the model is non-convex and the global optimal is not guaranteed.

Main research gaps

- A unified modeling framework that describes how heterogeneous stakeholders response to privately-owned information is still missing.

Research Goals

- Develop a novel and computationally tractable transportation network model to describe the traffic equilibrium patterns considering the adaptive routing of CAVs with en-route information updates.
- Develop a bi-level optimization framework for determining information sharing locations in the network.
- Develop a machine learning model, a deep deterministic policy gradient model, to optimize the control of real-time variable speed limit information sharing to improve network performance
- Develop a Stackelberg framework for spatial pricing of ride-sourcing services considering traffic congestion with convex reformulation.

System-level Impacts of En-route Information Sharing considering Adaptive Routing

Paper details: Afifah, F., Guo, Z., Abdel-Aty, M. Impacts of En-Route Information Sharing on System-Level Traffic Safety Considering Adaptive Routing. Available at SSRN 4062868. (2nd round review on Transportation Research Part C)

Methodological Overview

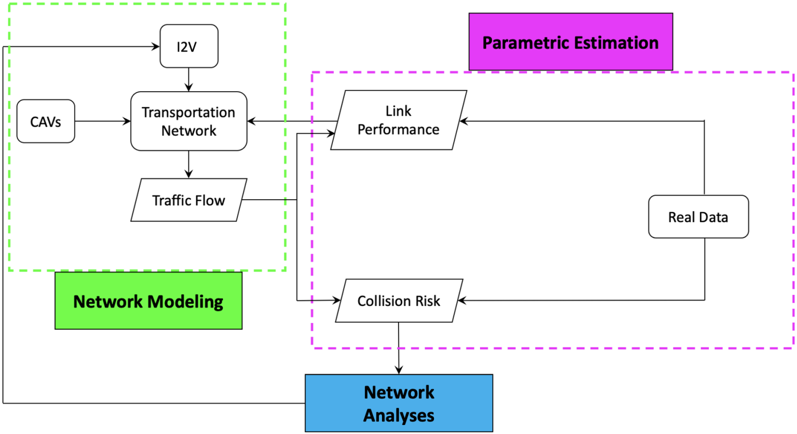


Figure: Methodology

Two-stage Stochastic User Equilibrium (two-stage SUE)

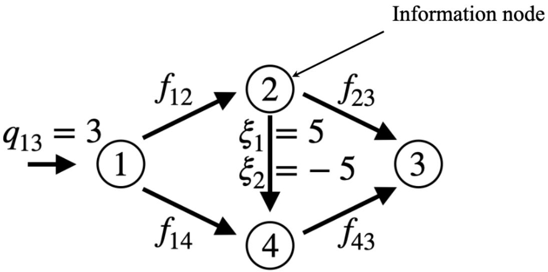


Figure: Four-node network

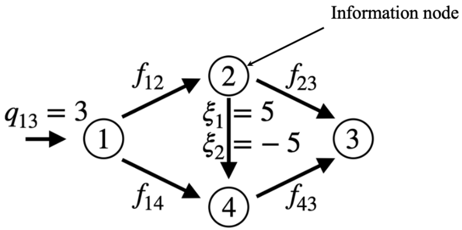
- Path: $p_1 = \{1, 2, 3\}$; $p_2 = \{1, 2, 4, 3\}$; $p_3 = \{1, 4, 3\}$
- Hyperpath: $\mathcal{P}_1^{rs} = \{p_1, p_2\}$ and $\mathcal{P}_2^{rs} = \{p_3\}$

Network Modeling

Definition: Two-stage Stochastic User Equilibrium (two-stage SUE)

- The expected travel time on all hyperpaths used in the first stage are equal and less than any unused path.
- The expected travel time on all paths used in the second stage are equal and less than any unused path.

- Path: $p_1 = \{1, 2, 3\}$; $p_2 = \{1, 2, 4, 3\}$; $p_3 = \{1, 4, 3\}$
- Hyperpath: $\mathcal{P}_1^{rs} = \{p_1, p_2\}$ and $\mathcal{P}_2^{rs} = \{p_3\}$



(a) Four-node network with stochastic link cost

Path	Flow		Travel Costs			
	ξ_1	ξ_2	ξ_1	ξ_2	Exp.	Var.
p_1	7/3	0	14/3	-	2.5	9.4
p_2	0	7/3	-	1/3		
p_3	2/3	2/3	4/3	11/3	2.5	2.7

(b) Equilibrium solution with risk-neutral adaptive behaviors

Two-stage Stochastic Network Model

- Objective:

$$\min_{x_p(\boldsymbol{\xi})\geq 0,\ \forall p,\boldsymbol{\xi}} \quad \mathbb{E} \sum_{a\in A} \int_0^{v_a(\boldsymbol{\xi})} t_a(u,\boldsymbol{\xi})\mathrm{d}u$$

- Constraints:
  - Flow conservation constraints

$$v_a(\xi) = \sum_{rs\in\mathcal{RS}} \sum_{p\in\mathcal{P}^{rs}} \delta_{ap} x_p(\xi), \forall a \in \mathcal{A}, \xi \in \Xi$$

$$(\gamma^{rs}(\xi)) \sum_{p\in\mathcal{P}^{rs}} x_p(\xi) = q^{rs}, \forall rs \in RS, \xi \in \Xi$$

  - Non-anticipativity constraint

$$(\lambda^{rs}_{a,k}(\xi)) \sum_{p\in\mathcal{P}^{rs}_k} \delta^{+}_{ap} x_p(\xi) = x^{rs}_{a,k} \ \forall rs \in RS, a \in \mathcal{A}, \boldsymbol{\xi} \in \Xi$$

Network Modeling

Theorem

The traffic flow pattern is following two-stage-SUE principles if and only if it is the optimal solution to the two-stage stochastic network model.

Proof.

Strategy: KKT conditions of the two-stage stochastic network model and the two-stage SUE principles are identical. $\square$

Parametric Estimation

- Link Performance

$$t_{\xi} = t_{0,\xi}[1 + \alpha_{\xi}(\frac{v_{\xi}}{c_{\xi}})^{\beta_{\xi}}]$$

$\xi = \{t_{0,\xi}, \alpha_{\xi}, \beta_{\xi}, c_{\xi}$ are random parameters that defines the shape of the function.

- Collision Risk

$$CR^{Link} = p = \frac{e^{\beta_0+\beta_1 q}}{1 + e^{\beta_0+\beta_1 q}}$$

p: likelihood of collision happening
β_0: the constant
β_1: the coefficient of link flow

Orlando Network

- Data Collection
  - Traffic Data: Regional Integrated Transportation Information System (RITIS)
  - Crash Data: Florida Highway Safety and Motor Vehicles (FLHSMV)
- Base Case
  - Incident links: 14-17, 17-14, 3-5, and 5-3
  - Information shared at node 10
- Scenarios
  - Normal Scenario
  - Incident Scenario

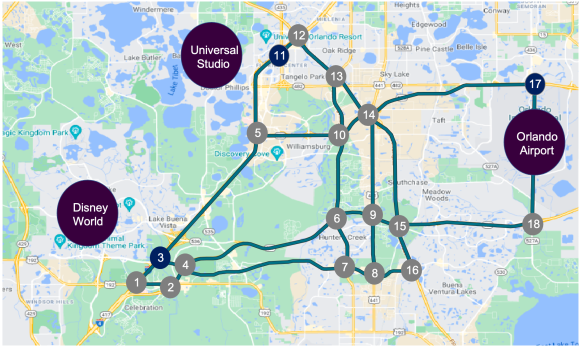


Figure: Orlando Transportation Network

Base Case Results

- Traffic from node 17 (Airport) to node 3 (Disney)
- Travelers' routing decision changes with en-route information
- Link flow after receiving information
  - Normal Scenario: Links 10-5-3
  - Incident Scenario: Links 10-6-4-3

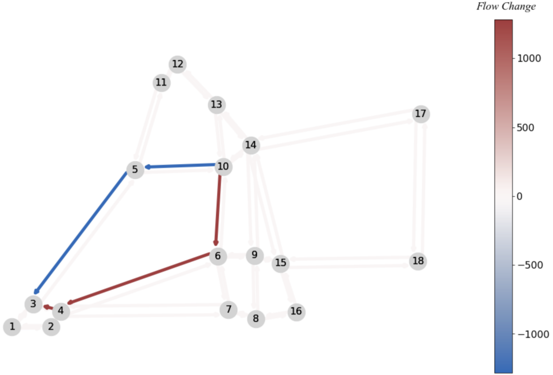
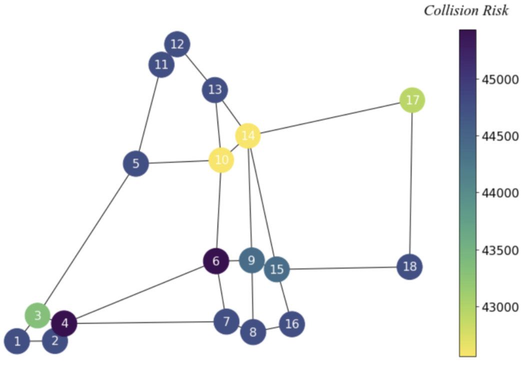
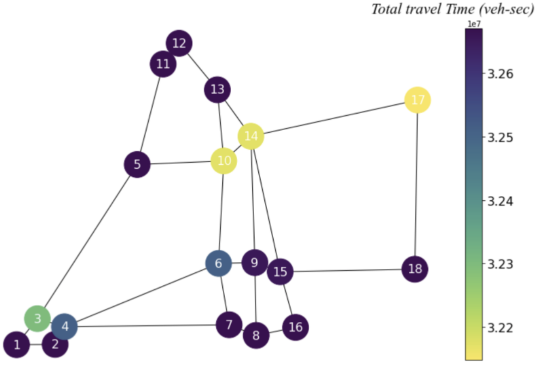


Figure: Re-routing due to en-route information

Sensitivity of Information Sharing Strategies



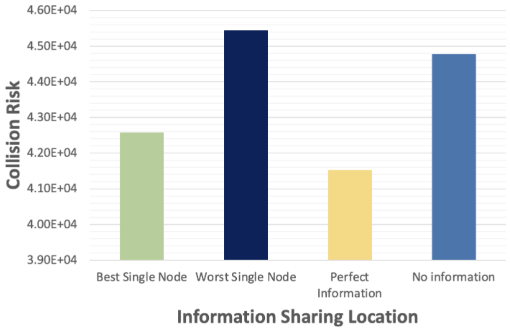
(a) Network Safety



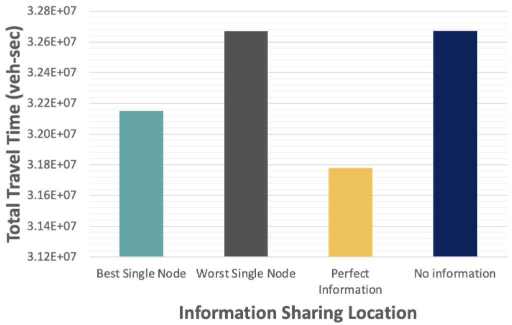
(b) Network Mobility

Figure: Network impacts of information sharing at individual nodes

Sensitivity of Information Sharing Strategies



(a) Network Safety



(b) Network Mobility

Figure: Comparison of different information sharing strategies

Sensitivity of Information Sharing Strategies

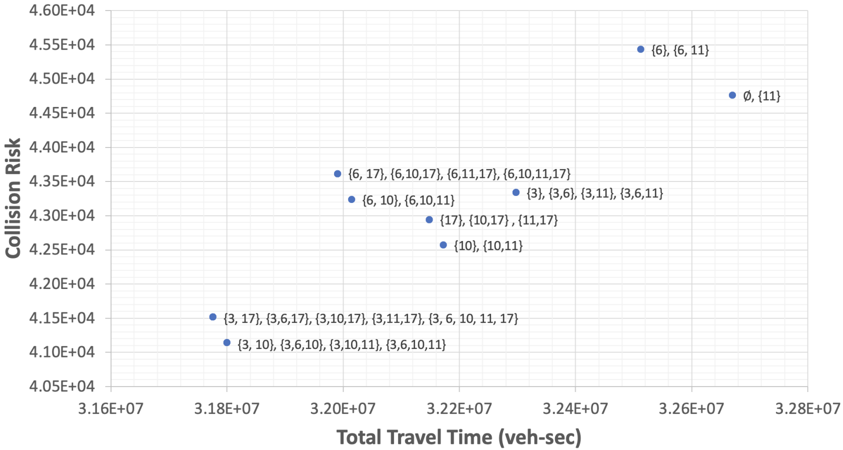


Figure: Pareto graph

Discussion

Contributions:

- We proposed a transportation network modeling framework to model the adaptive routing behavior of CAVs with information updates.
- We explored strategies to share information to improve network mobility and safety.

Findings:

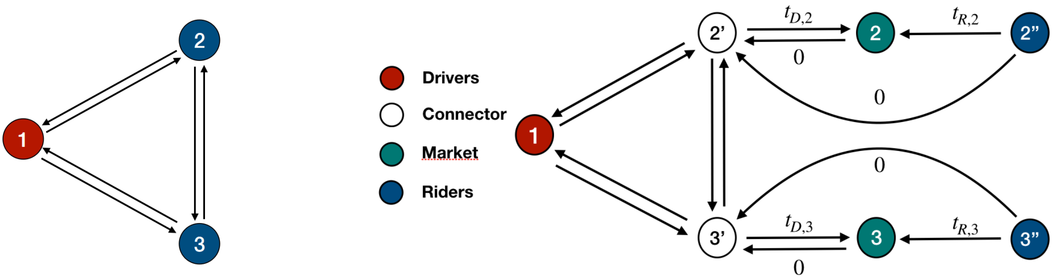
- The optimal information sharing strategies depend on specific network configurations.
- More/less information is not always better/worse for the network mobility and safety.
- Locational information sharing encourages the traffic to travel through information nodes to make informed rerouting decision.
- Potential extension: heterogeneous information? mixed traffic?

Spatial Pricing on Ride-sourcing Services in a Congested Transportation Network

Paper details: Afifah, F., Guo, Z. (2022). Spatial pricing of ride-sourcing services in a congested transportation network. Transportation Research Part C: Emerging Technologies, 142, 103777.

Problem Overview

- Decision makers: drivers, riders, TNCs
- Decisions
  - Drivers: relocation, routes
  - Riders: ride-sourcing/driving
  - TNCs: pricing
- Augmented transportation network, $\bar{\mathcal{G}} = (\bar{\mathcal{N}}, \bar{\mathcal{A}})$

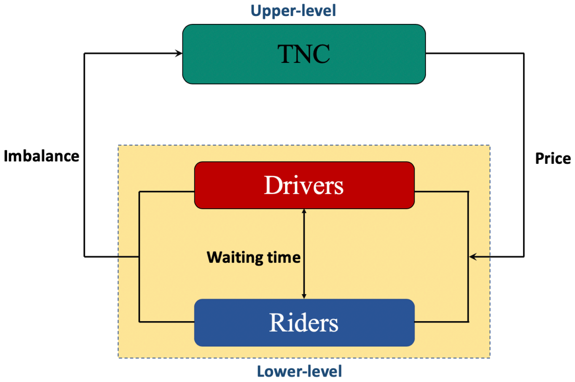


Key Assumptions

- Only one TNC serves in the study area
- The travel demand not requesting TNC services shifts to car driving
- Waiting time = Matching time + Pick-up time

Modeling Strategies

- Bi-level Optimization
  - Lower-level problem: capture the interactions between drivers' relocation, riders' mode choice, and all travelers' routing decisions.
  - Upper-level problem: a TNC determines spatial pricing strategies to fulfill its own objective in a two-sided markets.



Lower-level Problem

- Demand model

$$d_s = D_s - b_s \rho_s \quad (1)$$

- Drivers' utility function

$$U_{rs} = \beta_{0,s} - \beta_1 t_{rs} + \beta_2 \rho_s + \varepsilon_s \quad (2)$$

where:

U_{rs} : deterministic component of utility measure for a driver going from r to s;

β utility function parameters;

t_{rs} equilibrium travel time from r to s ;

ρ_s locational price at s;

d_s number of riders requested service at location s;

D_s, b_s : coefficients of demand function (model input);

ε_s impact of all unobserved factors that affect the person's choice. Assumed to have a extreme value distribution.

- Combined Distribution and Assignment (CDA)

$$\underset{\hat{\boldsymbol{v}},\check{\boldsymbol{v}},\boldsymbol{q}\geq\boldsymbol{0}}{\text{minimize}} \quad \underbrace{\sum_{a\in\mathcal{A}}\int_0^{v_a} t_a(u)\mathrm{d}u}_{\text{Wardrop User Equilibrium}} + \frac{1}{\beta_1}\sum_{r\in R}\sum_{s\in S}\ldots$$

$$\ldots \underbrace{q_{rs}(\ln q_{rs} - 1 - \beta_2\rho_s - \beta_{0,s})}_{\substack{\text{Logit Choice Model:}\\ U_{rs} = \beta_{0,s} - \beta_1 t_{rs} + \beta_2\rho_s}} \tag{3a}$$

subject to Traffic Flow Conservation Constraints (3b)

(considering both ride-sourcing and driving traffic)

Upper-Level Problem

- Modeling TNC desicion making behavior

$$\underset{\rho \in S}{\text{minimize}} \quad \sum_{s \in \mathcal{S}} m_s \longrightarrow \text{Total imbalance} \tag{4a}$$

subject to

$$m_s = \Big| \underbrace{\sum_{r \in \mathcal{R}} q_{rs}}_{\text{Driver Supply}} - \underbrace{(D_s - b_s \rho_s)}_{\text{Rider Demand}} \Big|, \ \forall s \tag{4b}$$

$$(3) \longrightarrow \text{CDA model: driver relocation and route choices} \tag{4c}$$

where:

m_s : demand-supply imbalance at s.

Solution Approach

Lemma (Balancing ride supply and demand)

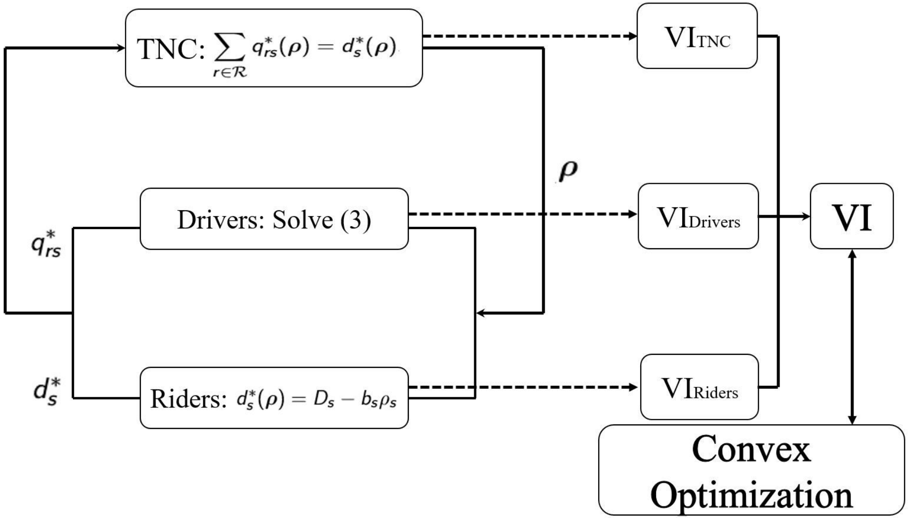
$\boldsymbol{\rho}^*$ optimizes problem (4) if and only if ride supply and demand are balanced at each location given $\boldsymbol{\rho}^*$.In addition, $\boldsymbol{\rho}^*$ is unique.

Decision making of TNC can be reformulated as

$$\sum_{r \in \mathcal{R}} q^*_{rs}(\boldsymbol{\rho}) = d^*_s(\boldsymbol{\rho}), \forall s \in \mathcal{S} \tag{5}$$

where $q^*_{rs}(\boldsymbol{\rho}) \in_{\boldsymbol{q}}$ (3), and $d^*_s(\boldsymbol{\rho}) = D_s - b_s \rho_s$

Reformulation Strategies



Single-level Convex Reformulation

Theorem (Single-level convex reformulation)

ρ solves bi-level problem (4) if and only if ρ solve single-level problem (6)

$$\underset{\hat{\boldsymbol{v}},\check{\boldsymbol{v}},\boldsymbol{q},\boldsymbol{d}\in_{+}}{\text{minimize}} \quad \frac{\beta_1}{\beta_2}\sum_{a\in\mathcal{A}}\int_0^{v_a} t_a(v_a)\mathrm{d}u + \frac{1}{\beta_2}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}} q_{rs}\left(\ln q_{rs} - 1 - \beta_{0,s}\right)\ldots \tag{6a}$$

$$\ldots + \sum_{s\in\mathcal{S}}\frac{1}{b_s}\left(\frac{d_s^2}{2} - D_s d_s\right) \tag{6b}$$

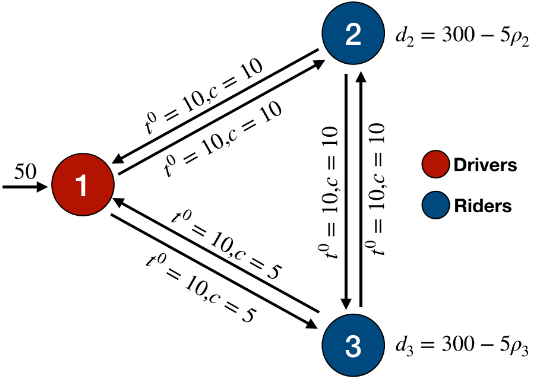
subject to

$$(3b)$$

$$(\rho_s) \quad \sum_{r\in\mathcal{R}} q_{rs} = d_s, \ \forall s \tag{6c}$$

Test Network - Three-nodes Example

- 3 nodes, 6 links
- lower capacity between node 1 and 3
- demand function $d_s = 300 - 5\rho_s$
- Link travel time $t_a = t_a^0[1 + 0.15 * (v_a/c_a)^2]$



Results - Equilibrium Prices and Total Travel Time

Figure: (a) Spatial Pricing

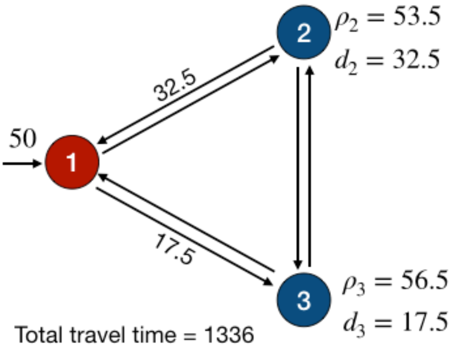
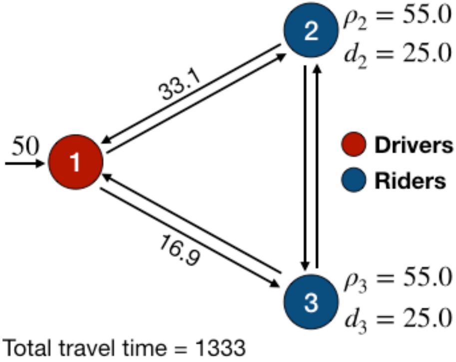
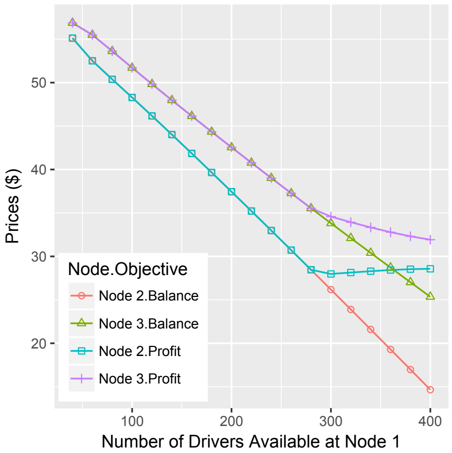


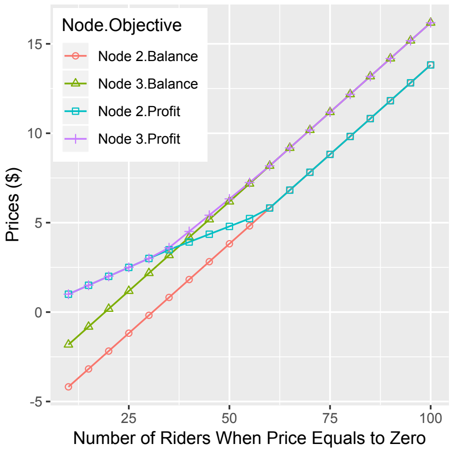
Figure: (b) Uniform Pricing



Different Objectives

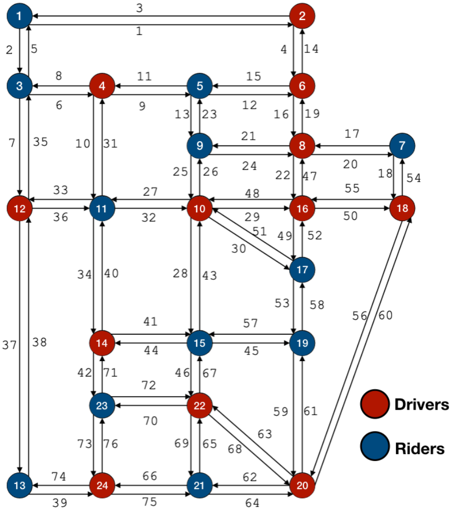
- Minimize imbalance v.s. Maximize profit





Test Network - Sioux Falls Network

- Data:
    - Driver and rider nodes (12 of each)
    - Drivers supply at each red node is 50
    - Demand function $d_s = 300 - 5\rho_s$
    - Link travel time $t_a = t_a^0[1 + 0.15 * (v_a/c_a)^2]$
- Computation time: 6.1s



Results - Sioux Falls Network

Figure: (a) Locational Prices

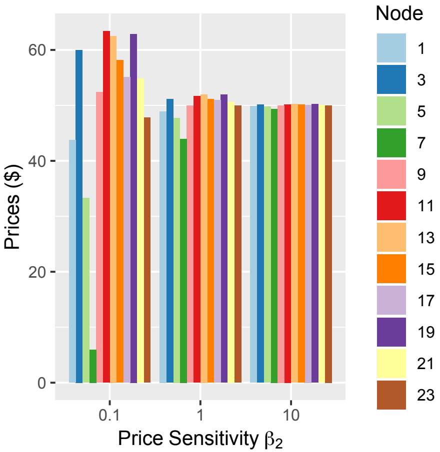
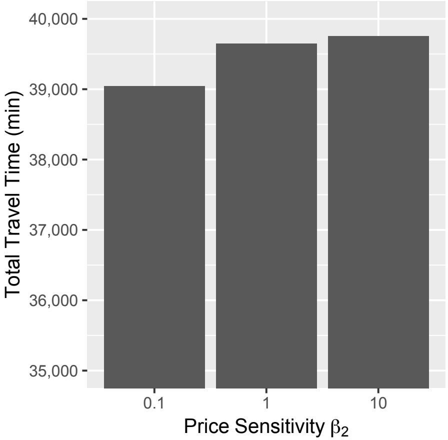


Figure: (b) Total Travel Time



Discussion

- Modeling: formulated a new modeling framework for ride-sourcing spatial pricing problems, considering leader-follower structure of TNCs, riders, and drivers, and transportation network
- Computation: under mild assumptions, the problem can be reformulated as a convex optimization problem, which can be efficiently solved by commercial nonlinear solver, such as IPOPT.
- Existence and uniqueness of optimal solutions are proved.
- Potential extension: temporal aspects? multiple TNCs?

Future Studies

Network Design Problem for Information Locations

- Methodology
  - Bi-level optimization modeling framework
    - Upper-level: determination of information sharing locations to minimize total travel time
    - Lower-level: user equilibrium with recourse
- Challenges
  - Nonlinear problem
  - Non-convexity issue
- Solution approach
  - Generalized benders decomposition
    - KKT formation of the lower level
    - Formation of the master problem and subproblem

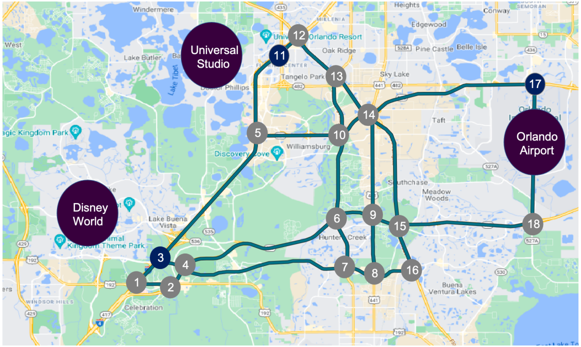


Figure: Orlando Transportation Network

Reinforcement Learning Model to Optimize Variable Speed Limit Controls

- Methodology: Deep deterministic policy gradient (DDPG)
- Challenges
  - Parameter tuning
  - Appropriate states and rewards of the model to improve safety and mobility
  - Positioning of VSLC that provides optimal system performance.
- Solution
  - Implementing the model in one-way link for parameter tuning, states and rewards determination
  - Implementing the model in smaller network
  - Using bi-level optimization method

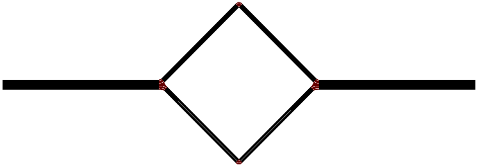


Figure: Four-node Network

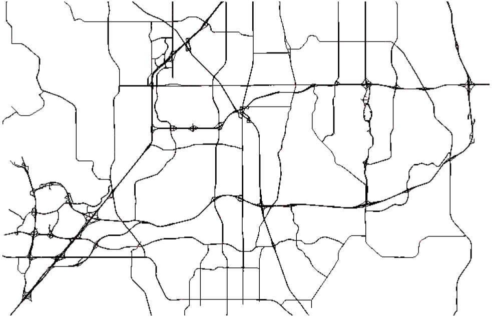
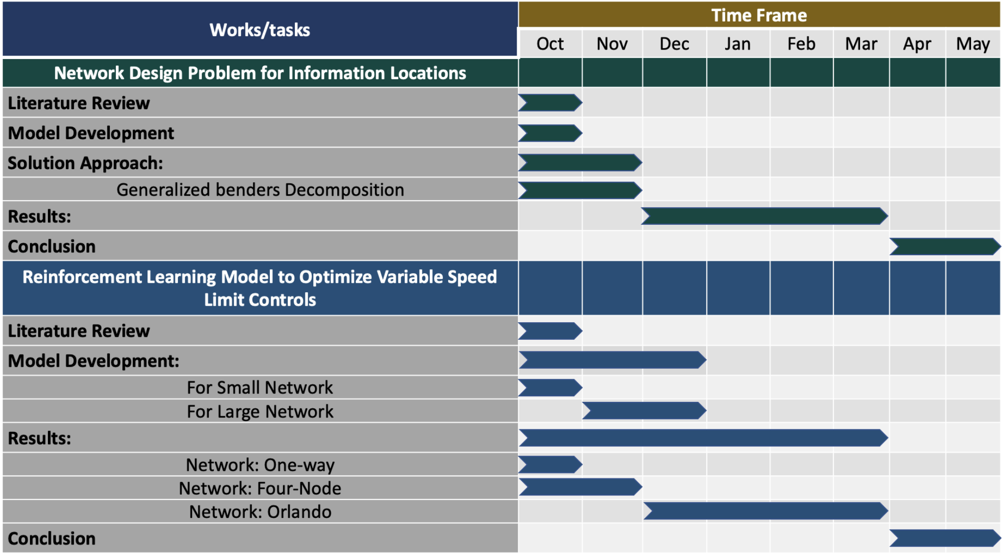


Figure: Orlando Network

Time Frame


Works/tasks
Time Frame
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Network Design Problem for Information Locations
Literature Review
Model Development
Solution Approach:
Generalized benders Decomposition
Results:
Conclusion
Reinforcement Learning Model to Optimize Variable Speed Limit Controls
Literature Review
Model Development:
For Small Network
For Large Network
Results:
Network: One-way
Network: Four-Node
Network: Orlando
Conclusion

Journals and Conference

- Journal Publications
  - **Afifah, F.**, Guo, Z. (2022). Spatial pricing of ride-sourcing services in a congested transportation network. *Transportation Research Part C: Emerging Technologies, 142, 103777.*
  - **Afifah, F.**, Guo, Z., Abdel-Aty, M. Impacts of En-Route Information Sharing on System-Level Traffic Safety Considering Adaptive Routing. *Available at SSRN 4062868.*
  - Guo, Z., **Afifah, F.**, Qi, J., Baghali, S. (2021). A Stochastic Multiagent Optimization Framework for Interdependent Transportation and Power System Analyses. *IEEE Transactions on Transportation Electrification, 7(3), 1088-1098.*
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Thank You

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