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

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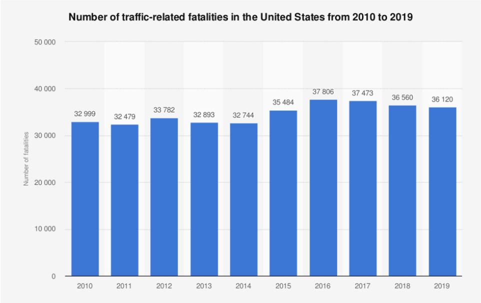
Outline

Background

- Number of road fatalities is high for each year.
- Around 30,000 fatal crashes in 2019 with a total of 36,120 deaths. (Source: National Safety Council)
- There has been a rapid advancement in the technologies for CAVs and I2V devices in the last few decades.



Source: NHTSA; US Department of Transportation

Source: United States Department of Transportation

Motivation

- 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.
- Leverage the CAV and I2V technologies to improve network safety.

Research Gaps

- Safety implications of CAVs
  - Roundabout/signalized intersection/link/zone safety [1, 2, 3, 4, 5, 6].
- Adaptive Decision Making with Information Updates
  - Simulation-based Dynamic Traffic Assignment (DTA) [7, 8, 9]. However, calibration for large network is difficult.
  - Equilibrium routing decision [10] and user equilibrium with recourse [11]. These studies consider information implicitly in routing policies and the number of routing policies grows exponentially.

Main research gaps

- Research on safety at network level considering en-route information is still limited.
- Information sharing strategies and locations are considered as exogenous or are not considered at all.
- Scalability issues

Contributions

- A computationally tractable transportation network model to describe the traffic equilibrium patterns considering the adaptive routing of CAVs with en-route information updates.
- Evaluate the impacts of information sharing locations on transportation safety at a network level with real-world traffic data considering adaptive routing of CAVs.

Methodological Overview

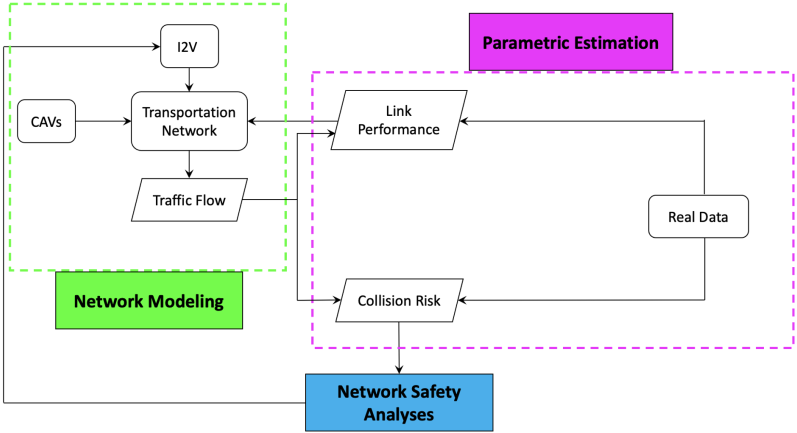


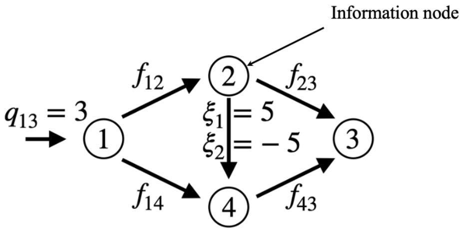
Figure: Methodology

Network Modeling

Definition: Two-stage Adaptive Stochastic User Equilibrium (ASUE)

- 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 Adaptive Stochastic Network Model

- Objective:

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

- 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

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

Network Modeling

Theorem

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

Proof.

Strategy: KKT conditions of the two-stage adaptive stochastic network model and the two-stage ASUE principles are identical. □

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

Network Safety Assessment

The network collision risk (CR) for a given scenario ξ is expressed as the total risk experienced by all the vehicles in the network.

$$CR_{\xi}^{Network} = \sum_{a \in A} CR_{a,\xi}^{Link} v_{a,\xi}$$

The network safety indicator is measured as the expected network safety risks.

$$CR^{Network} = \mathbb{E}_{\xi}\{CR_{\xi}^{\text{Network}}\}$$

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

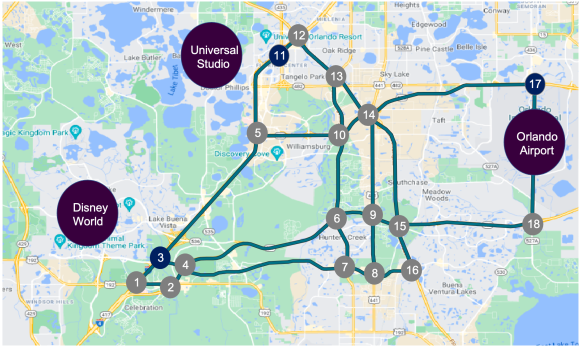


Figure: Orlando Transportation Network

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

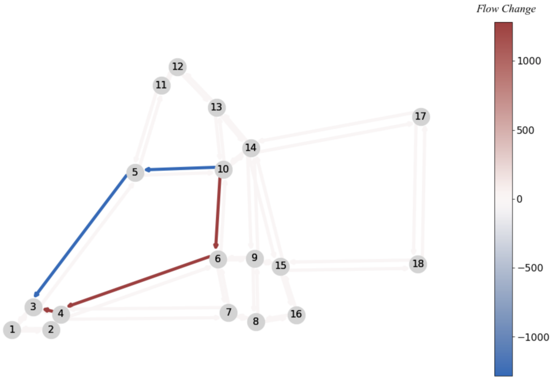
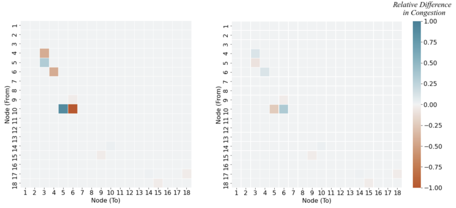


Figure: Re-routing due to en-route information

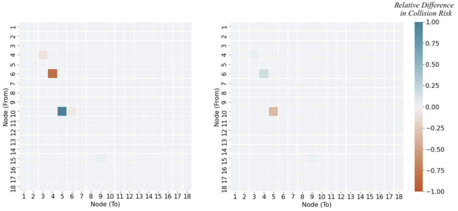
Base Case Results

- Network Mobility
  - Relative difference in congestion level between info. shared at node 10 and no information shared
  - Depending on the information shared at node 10, congestion level varies in the links.
- Collision Risk
  - Relative difference in collision risk in each link between info. shared at node 10 and no information shared
  - Traffic rerouting caused by information sharing may change link collision risk over the network.



(a) Normal Scenario (b) Incident Scenario

Figure: Congestion level

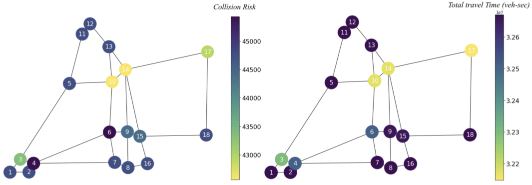


(a) Normal Scenario (b) Incident Scenario

Figure: Collision risk at each link

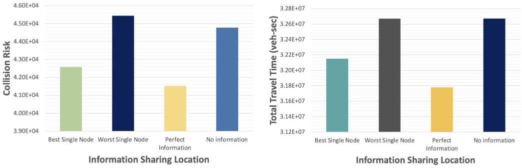
Sensitivity of Information Sharing Strategies

- The effect of information sharing on network mobility and safety may vary from node to node.
- Comparison of Information Sharing Strategies
  - Best single node
  - Worst single node
  - Perfect information
  - No information
- Perfect knowledge is the best strategy for both safety and mobility.
- No information sharing is not always the worst strategy.



(a) Network Safety (b) Network Mobility

Figure: Network impacts of information sharing at individual nodes



(a) Network Safety (b) Network Mobility

Figure: Comparison of different information sharing strategies

Sensitivity of Information Sharing Strategies

- Pareto optimal information sharing with candidate nodes (nodes 3,6,10,11, and 17)
- Information sharing at nodes 3,10 and nodes 3,17 are two Pareto optimal information sharing strategies with the least amount of information sharing nodes.
- More information sharing is not necessarily the best strategy (information paradox).

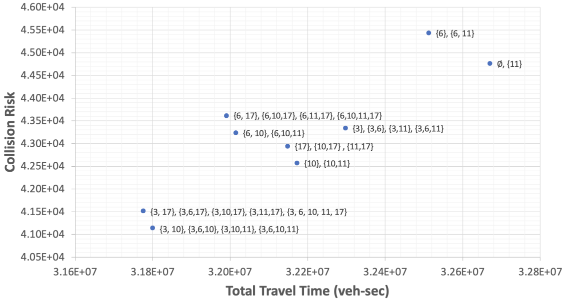
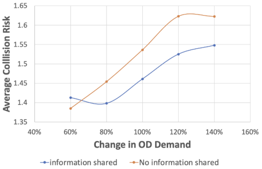
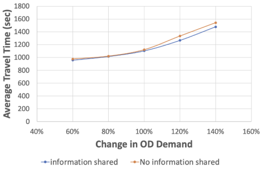


Figure: Pareto graph

- O-D Demand
  - Range of O-D demand from 40% decrease to 40% increase from the base case O-D demand
- Incident Severity
  - Low severity (20% capacity reduction) and high severity (80% capacity reduction) levels compared with the base case (50% capacity reduction)
- With the increase of O-D demand and incident severity, network mobility increases but the change in network safety is more complex.



(a) Network Safety



(b) Network Mobility

Figure: Information sharing at individual nodes

(a) Network Safety

(b) Network Mobility

Figure: Perfect information and no information sharing

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.

Discussion

Future work:

- Consider heterogeneous information sharing instead of universal information.
- Investigate other aspects of information sharing strategies such as what information to share, to which group of CAVs to share information.
- Extend the study for mixed traffic of CAVs and regular vehicles.

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Interested audience please refer to the following for more details:
F Afifah, Z Guo, M Abdel-Aty, "Impacts of En-route Information Sharing on System-level Traffic Safety considering Adaptive Routing," Available at SSRN 4062868.

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