Mitigating Cascading Failures for Safety in Transportation Networks in the Era of Autonomous Vehicles

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Publications

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16. Abstract
Bridge collapses, road closures, disruptions in the public transportation system, and major issues caused by autonomous vehicles (AVs) are everyday realities of our transportation infrastructure that not only cause inconvenience to the public but also constitute a major safety concern. When a particular component of the transportation system fails (e.g., due to an AV blocking a road), the failures and the associated congestion will likely be propagated to other parts of the transportation system, which may lead to further failures, and so on, potentially leading to a *cascade of failures* and a catastrophe in the whole city. Similarly, increasing deployment of AVs in the form of robo-taxis have not only led to several accidents but also events where seemingly *confused* AVs blocked certain roads for several hours. Given also the fact that increased congestion levels will likely lead to an increase in traffic incidents, there is a clear need for a better understanding of the impact of these cascading failures on the safety of the transportation system and the role that AVs play, both positive and negative, in them. This project aims to study the cascading effects of transportation network failures with an eye towards developing mitigation policies that maximize overall public safety. We are particularly interested in accounting for the increased presence of AVs, both to understand their impact on initiating or amplifying these failures, and to reveal how AVs can help mitigate cascading failures. Building on prior results where the goal was to minimize the overall delay/congestion, this project aims to reveal the impact of AVs on the safety of the overall transportation system by developing a comprehensive model that quantifies the safety impact of different failure events while taking into account the potential cascading effects.

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Mitigating Cascading Failures for Safety in Transportation Networks in the Era of Autonomous Vehicles

1 Project Summary

Bridge collapses, road closures, disruptions in the public transportation system, and major issues caused by autonomous vehicles (AVs) are everyday realities of our transportation infrastructure that not only cause inconvenience to the public but also constitute a major safety concern. When a particular component of the transportation system fails (e.g., due to an AV blocking a road), the failures and the associated congestion will likely be propagated to other parts of the transportation system, which may lead to further failures, and so on, potentially leading to a *cascade of failures* and a catastrophe in the whole city. A real-world example of this phenomenon took place on July 21, 2012, when a heavy rain shut down a metro line in Beijing and caused 100 bus routes to detour, skip stops, or cancel operation completely. Similarly, increasing deployment of AVs in the form of robo-taxis have not only led to several accidents but also events where seemingly *confused* AVs blocked certain roads for several hours. Cities such as Pittsburgh are particularly vulnerable to such cascade of failures and congestion propagation due to harsh weather conditions and existence of many bridges/tunnels creating bottlenecks. Given also the fact that increased congestion levels will likely lead to an increase in traffic incidents, there is a clear need for a better understanding of the impact of these cascading failures on the safety of the transportation system and the role that AVs play, both positive and negative, in them.

This project aims to study the cascading effects of transportation network failures with an eye towards developing mitigation policies that maximize overall public safety. We are particularly interested in accounting for the increased presence of AVs, both to understand their impact on initiating or amplifying these failures, and to reveal how AVs can help mitigate cascading failures. For example, a stalled robotaxi blocking an intersection in San Francisco would initially pose a safety threat to vehicles and pedestrians in its vicinity. In addition, depending on how long it blocks the road, this event may cause a congestion which can then cascade to neighboring roads, potentially leading to increased accident rates in the entire city. Our prior project laid out the initial work demonstrating how AVs can help reduce congestion more effectively by their ability to react in real time to vehicles around them, and their ability to be remotely and centrally controlled by fleet owners. Building on these results where the goal was to minimize the overall delay/congestion, this project aims reveal the impact of AVs on the safety of the overall

transportation system by developing a comprehensive model that quantifies the safety impact of different failure events while taking into account the potential *cascading* effects.

2 Project Results

2.1 Research Methodology

In the first year of the project, we have been focusing on building a comprehensive model of *cascading* failures and congestion propagation in the transportation network and developing metrics for quantifying the **safety implications** of different failure events, e.g., AV failures. A key novelty and contribution of the project is that these new metrics would encompass the potential cascading failure effects of the initial failure, ensuring a comprehensive evaluation of safety impacts of AV-related incidents. We have made good progress on the year-1 goals including i) a cascading failure and congestion propagation model for inter-connected transportation networks; ii) an initial set of metrics for quantifying safety implications of failures; and iii) preliminary methods, based on reinforcement learning, for optimal AV routing that *maximize* these safety metrics.

2.2 Results

In the interconnected transportation networks, the traffic flow redistribution can be described as the following figure.

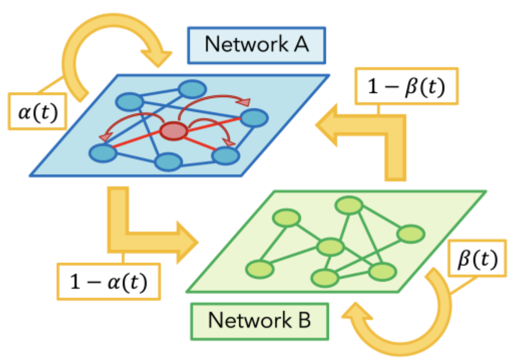

Fig.1 Illustration of interdependent network system.

The failure of a node in the transportation network can lead to additional traffic flow being diverted to adjacent nodes (or roads) or redistributed across other interconnected networks. Determining the optimal proportion of passengers to incentivize towards alternative networks in response to such a failure is a critical challenge. We propose a dynamic, step-wise optimization algorithm that minimizes the estimated extra flow caused by failures or congestion based on the current flow distribution strategy. This approach helps prevent cascading failures and alleviates potential congestion that could arise from such disruptions.

From the reference of Highway Safety Manuals, the general form of the Safety Performance Function (SPF) can be written as:

$$N = a \times \left(\frac{Q}{C}\right)^{b} \times e^{(\boldsymbol{c} \cdot \boldsymbol{X})}$$

Where:

- N = Expected number of crashes (over a specified period, e.g., per year).
- Q = Traffic flow (vehicles per hour, veh/h).
- C = Road capacity (vehicles per hour, veh/h).
- a, b is some constant, b is usually between 0.5 and 1.5
- $\boldsymbol{c} \cdot \boldsymbol{X}$ is the inner product of some explainable variable and their coefficients.

We consider a simplified case where the term $\boldsymbol{c} \cdot \boldsymbol{X}$ is constant across all roads, focusing solely on differences in road capacity. Suppose a natural disaster, such as an earthquake or storm, blocks half of the roads in a network. We simulate this scenario with a uniform distribution of extra road capacity ranging between 10 and 65, and an initial traffic flow uniformly distributed between 10 and 30. The figure below illustrates the expected number of crashes, N, under different strategies. By employing our proposed algorithms, we can mitigate the effects of cascading failures and reduce the risk of passengers being exposed to potential car crashes.

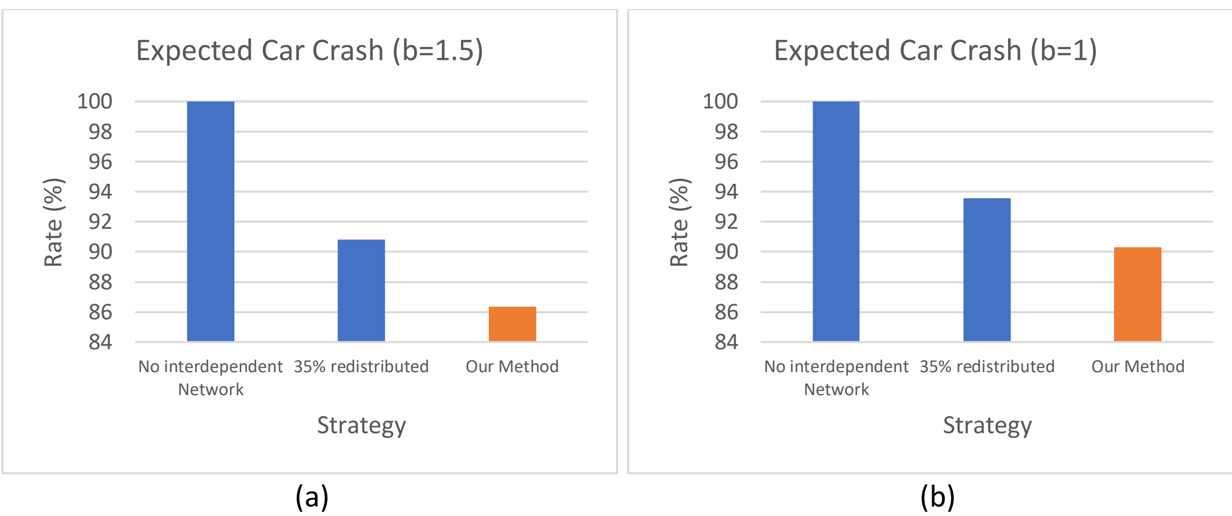

Fig. 2 The comparison results of expected car crash rate of our proposed dynamic step-wise optimization algorithms and other scenarios (No interdependent network and 35% fixed redistribution policy.) (a) exponent b=1.5, (b) exponent b=1

We can see from the simulation; our proposed method can reduce the expected car crash rate by at most 14%. This not only enhance the performance of the whole transportation network, but also guarantee the safety for all users on the road.

We then focus on a single network with autonomous vehicles. We evaluate the AVs' benefits with different AV-to-HV ratios. The AVs could collaborate to determine the areas to detour with the complete information of the system. The results in the figure below show that the collaboration of the AVs could prevent the system from failing. With a higher portion of AVs, eventually, there will be fewer congested areas on the map.

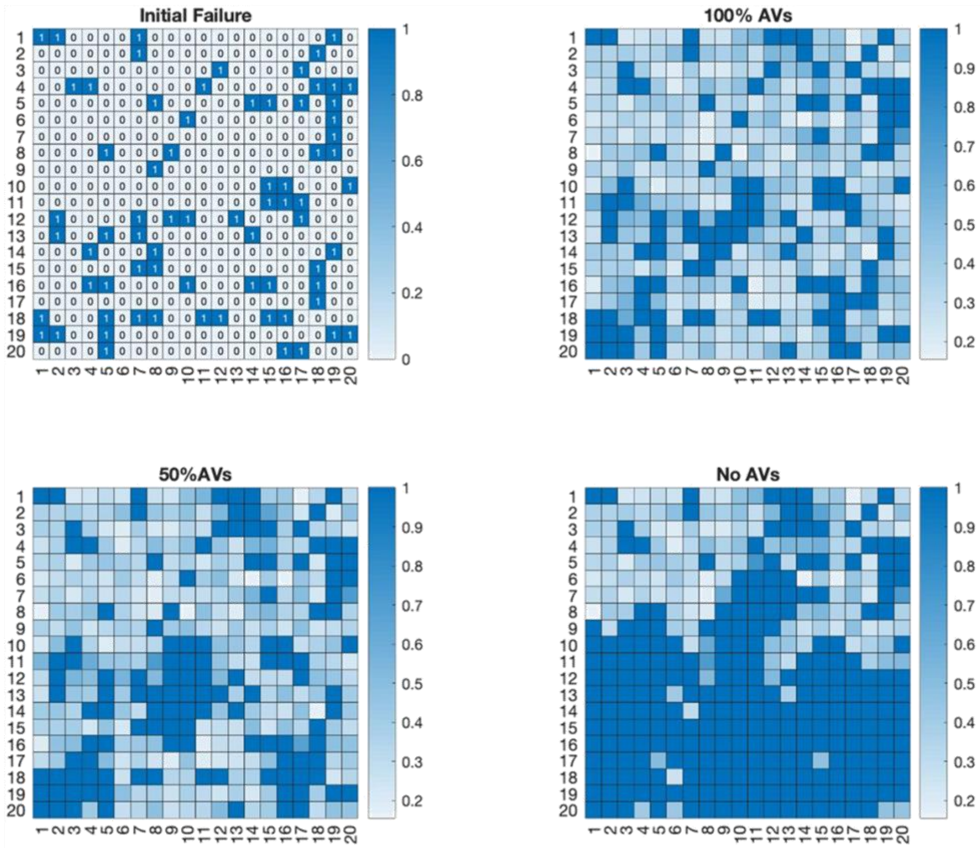

Fig. 3 Results for different portion of AVs. The darker the heavier the traffic is. Dark blue (value=1) indicate fully congested.

From Fig. 3, we can observe that without the deployment of autonomous vehicles (AVs), 256 blocks will eventually become fully congested. However, with 50% AV deployment, the number of fully congested blocks drastically decreases to 130, reducing congestion by nearly 50%, which equates to 32% of the total area on the map. In congested areas, safety risks increase significantly due to difficulties in maintaining safe distances and reduced reaction times. In other words, by deploying AVs, we can eliminate almost one-third of the high-risk areas in the city, where cascading failures lead to congestion.

Limitations. The results discussed above assume that autonomous vehicles (AVs) are fully functional. In reality, several incidents have occurred due to AV malfunctions. For instance, in July 2023, a group of Cruise autonomous vehicles stopped in the middle of a street in San Francisco, blocking traffic after losing connectivity. Similarly, in October 2022, a Waymo autonomous vehicle blocked a road in Phoenix after encountering an unexpected traffic situation. AVs not only face mechanical issues similar to those encountered by traditional human-driven vehicles, but they are also susceptible to communication failures, computational errors, or misjudgments by undisciplined machine learning models, which may introduce additional risks. The impact of such failures on traffic and safety can be modeled by incorporating the probability of vehicle malfunctions into the analysis. If AVs have a higher likelihood of failure, and this probability exceeds a certain threshold, the conclusion that AVs contribute to a safer driving environment might be challenged.

3 Conclusion and Recommendations for Future Work

In the second year of the project, we aim to build on year 1 results with the main goal of delivering the crucial pieces needed for developing guidelines and policies to enhance the safety of transportation networks amidst increasing AV deployment. In particular, the second year will focus on i) validation and testing the accuracy and effectiveness of the newly developed safety metrics using real-world data and simulations reflecting scenarios involving AV-related incidents and their cascading effects; ii) enhancing the developed model to simulate a wider range of failure scenarios, considering factors such as weather conditions, traffic volumes, and diverse city topographies; and iii) developing strategies to mitigate the risks associated with cascading failures induced by AV-related incidents through implementation of emergency protocols, adaptive traffic management systems, and AI-driven decision support tools.