Alternative Fuel Vehicles Evacuation Planning: Modeling and Numerical Experiments

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ABSTRACT

As the number of adopted electric and fuel cell vehicles increases, it is vital for communities to make evacuation and emergency preparedness plans, accounting for alternative fuel vehicles refueling and recharging needs. As an example, evacuation plans for conventional gasoline vehicles could be infeasible or dangerous for alternative fuel ones due to driving range constraints and recharging requirements that alternative fuel vehicles have in order to reach safety. In this paper, we propose an optimization framework to devise $|K|$ minimum spanning tree evacuation plans, routed to the safety node, for a set of different vehicle fuel types K. We impose constraints to capture recharging needs of alternate fuel vehicle types, as well as conflict constraints to ensure that all vehicles evacuate to safety seamlessly. We apply the proposed framework in a toy and Sioux Falls transportation networks with existing refueling and charging infrastructure deployment and uncover the necessity of alternative fuel vehicles to detour and reroute in order to reach the corresponding refueling infrastructure before reaching safety. Our research also demonstrates that denser siting of alternative fuel and charging infrastructure would support faster and more reliable evacuations.

Keywords: alternative fuel vehicles, evacuation planning, spanning trees, recharging, refueling

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1. INTRODUCTION

Economic, energy, and environmental benefits of alternative fuel vehicles [1] lead transitions to sustainable and decarbonized transportation, responsive to climate change concerns [2]. However, such emerging vehicle technologies come with limited access to infrastructure. This renders them most susceptible to being stranded during hazards that cause infrastructure disruptions. Hence, alternative fuel vehicles could pose challenges in evacuation and emergency planning [3, 4], due to their limited driving ranges and the existence of sparse refueling or charging infrastructure networks. These limitations make alternative fuel vehicle users particularly vulnerable during emergency states.

During a hurricane evacuation, alternative fuel vehicles need to reach safety promptly while ensuring that refueling opportunities are provided on their assigned path to safety to avoid battery depletion or an empty tank. Due to the increasing popularity of alternative fuel vehicles and the frequency of natural and human-made hazards, emergency management agencies must provide contingency plans to evacuees to enable safe evacuation routing alongside access to alternative refueling infrastructure. Densifying the sparse alternative refueling station network would address evacuation refueling needs, alleviate short driving range constraints, and facilitate more energy-efficient travel [5–7]; it also comes at a significant investment cost [8]. The other solution to address evacuation refueling needs is to carefully devise evacuation and disaster management plans that take into consideration the existence of alternative fuel vehicles.

In this paper, we propose expanding the emergency preparedness and transportation modeling literature by developing mathematical models for evacuation routing of alternative fuel vehicles, each with each own unique refueling or recharging infrastructure. This novel research endeavor sets out to address a timely objective: modeling alternative fuel vehicles evacuation routing to support fast evacuations. The evacuation planning proposed here aims to be safe and avoid conflicts, considering the case where multiple different evacuation routes need to be designed and followed simultaneously. In the United States, the practical need for such models is exacerbated by, for example, the frequent wildfire incidents in the west as well as the growing number and frequency of devastating hurricanes in the east and southeast.

2. METHODOLOGY

Alternative fuel vehicles operations are unique due to (a) frequent refueling and recharging stops, (b) a sparse refueling and recharging infrastructure network, and (c) long refueling and recharging time requirements. Range limitations and anxiety (i.e., the fear of exhausting the vehicle's range before reaching a destination or a fueling station) influence the behavior of drivers whose comfortable driving range or state of charge explains the variance in refueling and recharging decisions [9]. Traditional operations research models that, as an example, are used to route conventional gasoline vehicles, need to be adapted to address electric vehicle range and infrastructure limitations by modeling recharging processes at available stations [10]. Electric vehicle routes, under usual driving conditions, can be devised under the assumption that drivers select paths based on range anxiety and energy efficiency generalized cost [11]. Driving range constraints are introduced in our research, considering that alternative fuel vehicles that are several hops (or number of links τ) away from their safety node need to be routed to a refueling station first before reaching a shelter node.

Evacuation planning and disaster management are critical societal problems. When a disaster is imminent, having a plan that evacuates people from areas where they are endangered to safe zones empowers residents. Evacuation plans need to be safe, fast, robust, and seamless. Due to these objectives' nature, it comes as no surprise that the problem of evacuating people has attracted significant interest from the transportation engineering and operations research community. We refer the interested reader to recent surveys [12, 13], as well as an earlier overview of the state-of-the-art [14]. In that overview, two types of approaches are mainly reviewed: macroscopic and microscopic [14]. Macroscopic systems treat evacuees as general flows on a network; the approach we follow here is described as macroscopic.

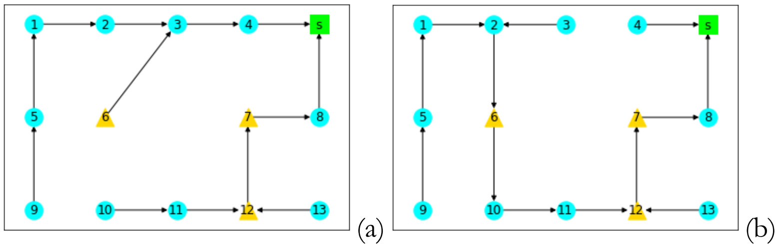
A crucial aspect of our model has to do with the seamlessness of evacuation operations. As an example, consider an evacuation plan that requires the residents in a specific location to follow multiple, different paths to safety. Even when this plan is optimal, it would confuse the evacuees and require significant coordination and enforcement efforts. On the other hand, if every evacuee has a single path to safety, this issue is alleviated. This is the main idea behind creating an evacuation tree where every evacuee has a single path to safety [15, 16]. Additionally, conflicts during an evacuation plan have to be minimized or completely avoided. Planning an evacuation while minimizing the number of conflicts arising at intersections is a common approach to eliminate such issues [17]. Conflicts can be more generally defined as evacuation plans that use the same roads, hence overloading specific areas and rendering them slow and dangerous [18]. A practice leveraged to optimally use the available road network is contraflow, which allows certain streets to reverse their direction, effectively increasing the road network's capacity leading to safety [19]. Contraflow has been studied in the literature (see, e.g., ([20–23]), among others) and is accounted for in our mathematical program.

An evacuation tree [15] is a routing plan that helps avoid conflicts and ensures that contraflow operations can occur. Our paper considers the case where multiple different evacuation trees need to be designed and followed simultaneously. This design could lead to conflicts between flows in different trees, requiring further efforts for coordination. We tackle this issue with the following novel mathematical program. Assume a given transportation network with known demands at major nodes that correspond to, for example, census tracts or traffic analysis zones. Among the nodes, one of them is considered to be a shelter area. Additionally, there is a set K of vehicles powered by different fuel types; in our transportation network, a subset of the nodes may serve as refueling and recharging stations for specific types of vehicles. With this information, the goal is to obtain $|K|$ minimum spanning trees routed to the shelter node. These are called evacuation trees [15]. Since there is interest in obtaining more than one tree, we need to ensure that a link selected to serve in one of the evacuation trees appears in the same direction in all other trees. That is, two links connecting two nodes in both directions may not both appear in the same or different evacuation trees to ensure seamlessness. Finally, the problem investigated is unique in the sense that vehicles that begin their trip far from the safety node need to be routed to refuel. Hence, every vehicle of type k located τ or more hops (i.e., links) away from the safety node in the k-th evacuation tree will have to pass through a refueling station, should it need to refuel during the evacuation operation.

The mathematical formulation is a non-linear program. The objective function aims to minimize the generalized evacuation cost by summing the time spent traversing each link on the network and the time spent charging. Constraints include keeping track of every link's total flow, enforcing flow preservation on each node, and allowing flow if and only if the corresponding link is part of an evacuation tree. Furthermore, conflict constraints prohibit the same link to appear in both directions in either the same evacuation tree or across different evacuation trees. Constraints also define the distance each node has to safety in an evacuation tree, enforcing that each node has exactly one distance to the safety node while setting that the safety node is the only one at a distance of zero from safety. Refueling considerations also enter the model. For example, when located at the safety node, any fuel vehicle type will no longer need to refuel. A vehicle located τ hops (i.e., links) or more away from safety needs to refuel. Finally, a set of constraints states that a node with vehicles that are considered to require refueling or recharging can either refuel the vehicles itself (if a refueling station is available at that node) or the subsequent node in the evacuation tree will need to keep track of that.

3. RESULTS

The application of our mathematical model through numerical experiments yields interesting results demonstrating (i) the importance of developing evacuation paths with refueling infrastructure considerations and (ii) that driving range anxiety and limitations influence the selection of optimal evacuation paths. As shown in Fig. 1a and b, the evacuation plan for a specific vehicle type is significantly different when accounting for refueling routing. Vehicles need to be rerouted to find the closest station to recharge, while still adhering to traffic assignment and conflict avoidance constraints. In Fig. 1b, evacuation demand from nodes $\{1, 2, 3, 5, 9\}$ is recharging at node 6 and vehicle demand from nodes $\{10, 11, 13\}$ is recharging at node 12.



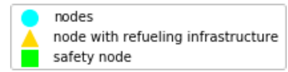


Fig. 1 Evacuation route (a) without and (b) with considering the refueling needs of a vehicle ($\tau = 2$).

We also conduct sensitivity analysis by varying the density of the alternative refueling infrastructure in the transportation network. We show that refueling detours can be minimized in the evacuation route plan of a specific vehicle type with a dense network of refueling infrastructure to support any refueling or recharging needs. In addition, the driving range limitations greatly impact the evacuation route plan. Greater driving range results in evacuation routes with fewer refueling detours for each vehicle type.

4. CONCLUSION

The numerical experiments show that the evacuation route plans for each vehicle fuel type change as we consider their recharging needs to reach safety. The changes represent the necessity of some vehicles to detour and reroute in order to reach the corresponding refueling infrastructure before heading to their safe destination. We also observe that the evacuation routes for each vehicle fuel type are different and infeasible to other vehicle fuel types due to different availability and placement of their refueling/recharging stations. Besides, the numerical experiments show that accounting for the driving range limit of a vehicle type is vital when planning the evacuation routes in emergency states. The total evacuation time of the vehicles in the network decreases as we increase the allowable distance limit for the refueling requirement. Lastly, the availability and placement of the refueling and recharging stations of alternative vehicle fuel types are important in providing faster evacuation. The experiments indicate that denser deployment of alternative fuel and charging infrastructure would support faster and more reliable evacuation planning.

ACKNOWLEDGEMENT
This research did not receive funding from agencies in the public, commercial, or not-for-profit sectors. The authors confirm full personal access to all aspects of the writing and research process and take responsibility for their paper.

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