Transportation Research Part D 86 (2020) 102458

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Can we evacuate from hurricanes with electric vehicles?

Kairui Feng[a], Ning Lin[a], Siyuan Xian[a], Mikhail V. Chester[b]

[a] *Department of Civil and Environmental Engineering, Princeton University, United States*
[b] *Civil, Environmental, and Sustainable Engineering, Arizona State University, United States*

ARTICLE INFO

Keywords:
Hurricane evacuation
Climate change
Power system
Electric vehicle
Transportation

ABSTRACT

The increasing usage of electrical vehicles (EVs) might not meet the safety requirement of massive hurricane evacuations, which may happen more frequently in the future climate. Here we investigate the challenge of widely using EVs for hurricane evacuation through analyzing the power demand during the vast historical evacuation before Hurricane Irma (2017). We find that, if the majority of the evacuating vehicles were EVs, Florida would face a serious challenge in power supply, with its six out of nine main power authorities, especially those in the mid-Florida, being short of power during the evacuation process. Also, the power outage in mid-Florida could induce cascading failure of the entire power network throughout Florida. We argue that policymakers need to consider the evacuation problem as EVs are increasingly adopted in disaster-prone regions. Potential solutions include developing centralized charging strategies, improving battery technology, and adopting hybrid vehicles in addition to EVs.

The improving economics and energy efficiency of electrical vehicles (EVs) is driving up the market share of the technology (Needell et al., 2016), and many countries are providing incentives to further increase their adoption (Green et al., 2014). The US EV Everywhere Initiative, for example, has a goal of producing EVs with sufficient range and fast-charging ability to "enable average Americans everywhere to meet their daily transportation needs more conveniently by 2022" (US DoE, 2012). EVs represent disruptive transportation technology and are emerging at a time when several other rapid changes are occurring. Of particular note are climate change and associated extreme events such as hurricanes (Knutson and Coauthors, 2020; Marsooli et al., 2019). Recent events such as Hurricanes Irma (2017) highlight the many challenges that transportation infrastructure and services are likely to face in the future with more extreme events. While much research is being done to understand the implications of EVs and extreme events, as separate phenomena, there remains little to no consideration of what the trends mean together. In particular, during a more frequently happening extreme event such as a severe hurricane, what are the mobility implications of an EV fleet? Hurricane Irma created the largest-scale evacuation in US history, involving about 6.5 million people in Florida on mandatory evacuation orders and, consequently, four million evacuating vehicles. Severe travel delays happened throughout the state due to traffic jams; some highways (with a 75-mph speed limit) were experiencing a 15-mph peak traffic speed under a tripled traffic volume, compared to the usual conditions (The Two-way Radio, 2017). If EVs were widely adopted, would evacuation on such a large scale be further challenged by the power shortage?

We investigate the challenge of widely using EVs for evacuation during disasters, when a large number of EVs within a specific region needs to be charged and recharged during a short period. In particular, we ask if the current power supply is sufficient and capable to support EV evacuation prior to the landfall of hurricanes. We use Hurricane Irma as an example and estimate the electricity demand for Florida before Irma's landfall under the hypothetical condition that all evacuating vehicles were EVs and compare the demand with estimated power constraints. Assuming the evacuation process (i.e., movement of the cars) would be the same as the

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E-mail address: kairuif@princeton.edu (K. Feng).

https://doi.org/10.1016/j.trd.2020.102458

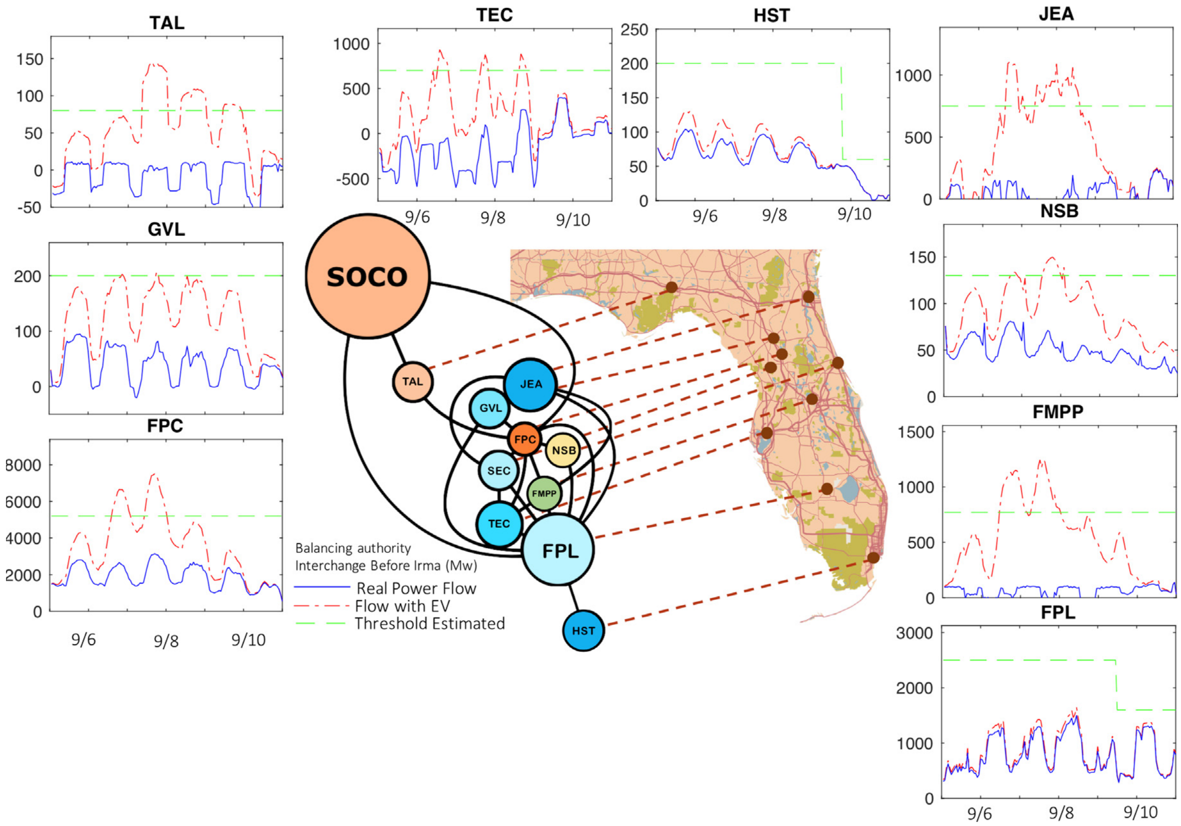

Fig. 1. Inter-balancing authority (BA) power demand inflow to Florida prior to Hurricane Irma's landfall (on Sep 11, 2017): Real electricity demand inflow (blue curve; data obtained from US Energy Information Administration EIA (2017), synthetic 100% EV scenario electricity demand inflow (dashed red curve; estimated), and the power bottleneck constraint (dashed green curve; estimated based on data from US Energy Information Administration EIA (2017) and Yang et al. (2017a). This research considers 10 authorities: TAL, GVL, FPC, TEC, JEA, NSB, FMPP, FPL, and HST in Florida and SOCO in Georgia (TAL, the City of Tallahassee; GVL, Gainesville Regional Utilities; FPC, Duke Energy Florida, Inc.; TEC, Tampa Electric Company; JEA, Jacksonville Electric Authority; NSB, New Smyrna Beach, Utilities Commission of; FMPP, Florida Municipal Power Pool; FPL, Florida Power & Light Co.; HST, Homestead, City of; SOCO, Southern Company Services, Inc). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

real case, we estimate the charging time history for each evacuating EV based on estimated traffic flow during Hurricane Irma (see Method). Summing up the estimated electricity demand from the evacuating EVs, we obtain the total electricity demand for each of the 10 power authority service areas in Florida (shown in Fig. 1). For each authority, the estimated EV electricity demand is added to the real inter-balance authority (BA) power demand inflow (blue curve in Fig. 1), to obtain the total power demand inflow (yellow curve in Fig. 1). The total power demand is compared with the power constraint estimated for each area (green line in Fig. 1). Based on the current generation and transformation ability of America's power network, the power constraint is claculated as estimated inter-BA power flow based on the power network capacity (Yang et al., 2017a) plus 20% of the maximum thermal power generation capability for each authority (considering the dispatch ability for different sources of energy; estimated based on the empirical operational data of Poland power network, Yang et al., 2017a). The generation ability of hydro- and other types of power sources is not flexible under an unexpected extreme power demand, so they are regarded as not reacting to the unexpected power demand. The shutdown of power generation stations including nuclear plants before hurricane landfall (to reduce potential flood impact; Washington Post, 2017) is also considered by a linear reduction of nuclear power production from the estimated power constraint.

As shown by the global electricity simulation result (Fig. 1), under the hypothetic evacuation condition and the current power supply capacity, the power demand would significantly exceed the capacity for northern and inland areas, although evacuation origins including Homestead (HST) and Miami (FPL) would experience no overflow. As the evacuation direction during Irma was from south to north, the EV evacuators in the origin, southern areas would pre-charge their cars before departure and drive long distances to escape from the hurricane risk. However, when the exodus reached inland Florida and batteries are depleted (resulting in recharge), the power service companies there would face enormous electricity pressure, and the EV power demand would rapidly exceed their safety margins. The most severely afflicted would be Florida Municipal Power Pool (FMPP; ~400 Mw shortage or supporting only 35% vehicles) and Duke Energy Florida (FPC; ~1000 Mw shortage or supporting only 45% vehicles), the local electricity retailers in the Orlando and Ocala areas, respectively. The City of Tallahassee (TAL) would suffer less power outage, because it mainly served upper Florida, which was not evacuated much during Hurricane Irma. Gainesville Regional Utilities (GVL) would be the only survivor in mid-Florida, thanks to the limited number of local householders (~20,000) they support compared to other companies (> 100,000 customers).

When the demand surpasses the supply ability, local power failure may lead to a larger-scale cascading failure in the power network (Yang et al., 2017b). As the bottleneck of the Florida power system, the mid-Florida power network connects the Miami power network and Southern Company Services – the largest electricity provider for Florida. During Hurricane Irma, the evacuation peak in mid-Florida occurred on September 8, leading to the power consumption's peaking and consequent outage (due to electric demand of EVs surpassing the supply) on September 7 and 8, which could induce cascading outage in Southern Florida. Then the evacuation peak occurred in northern Florida on September 9, leading to a power outage there for the next three days. This spatially-and-temporally-featured outage would severely affect the resilience of the power grid: even if the power grid in mid-Florida had been repaired at night on September 8, it could be disconnected again from the eastern US power grid, due to the failure of the power grid in northern Florida. Then the evacuation peak in mid-Florida would last longer due to the power grid failure and shortage of power supply. Due to the high connectivity of the power system, the extended evacuation peak, in turn, would trigger a further power outage. Our power flow simulation shows that one day of severe outage in mid-Florida could trigger three days of power failure over mid- and Southern Florida.

This simplified analysis considers only the border (inter-BA) capacity and assumes that the inflow can reach wherever the electricity is needed. In reality, the spatial specifics of electricity supply and demand are critically important. Local capacity varies and power failures happen locally. Also, the EV charging demand holds spatial variability. EVs traveling along specific evacuation corridors may demand more electricity from the local network, possibly exceeding the local capacity (Burillo et al., 2019; Hoehne and Chester, 2016). Also, possible catastrophic failure of the power network is not accounted for in the analysis. The failure of a local power network may trigger a large-scale collapse of power grids over the entire state of Florida and even threaten the power grids in Georgia and Louisiana (Yang et al., 2017b). Thus, the potential risk may be higher in reality.

One way to avoid such risk is to consider the levels of EV adoption commensurate to the capacity of the power system. If the EV occupancy rate in Florida were under 45%, the current power network would still function well under the Irma evacuation scenario. Actually, replacing a portion of traditional vehicles by EVs may help reduce the gasoline shortage in evacuations. Florida faced a massive gasoline shortage during Hurricane Irma – 58% gasoline stations in Gainesville, 40% in Miami, and 35% in Tampa ran out of gas, and many people lined up for hours to get the gasoline for evacuation (USA Today, 2017). The most convincing way to combine the benefits of EV and traditional vehicles under evacuation might be to use hybrid power. A typical hybrid power vehicle, such as the Chevrolet Volt 2018, can drive on electricity for ~ 50 miles (13% of total power) and on gasoline for ~ 350 miles (87% of total power). For the power grid in Florida, using as many hybrid vehicles as possible would not harm the power network during hurricane evacuations (power demand of 13% < demand threshold of 45%), and the electricity capacity can increase the vehicle's ability to search for gasoline in a larger area, overcoming the challenge of local gasoline shortages.

However, if EVs are more widely used, the power grid capacity may be enhanced to ensure that substations and power lines can provide enough electricity when large numbers of evacuees plugin, or large-volume or swappable batteries must be available. This consideration points to the prioritization of future research to identify where to strategically invest in grid capacity to meet the demand where and when people are most vulnerable (i.e., during evacuations). On the other hand, it may not be economical for the utilities to be set for exceptional evacuation needs, as the electricity demand from EVs during evacuations is much higher than the daily operation demand. Our analysis shows that, for example, the FMPP company would need to triple the power system capacity to meet the EV power demand under the evacuation during Irma. The development of more extensive and longer-lasting batteries could relief the problem since, if the battery range is longer, people will recharge less or may not need to recharge during evacuation – another motivation for developing new battery technology such as the solid-state battery (Motavalli, 2015). Similarly, swappable batteries and solar charging would work as it is independent of the main power system.

Furthermore, it may be possible to identify evacuation charging strategies that ensure the chargers, incentives, and management schemes are used during evacuations to ensure that those who need to evacuate can make the trip and those who are most vulnerable are prioritized. For example, not every EV needs to charge to full every time during the evacuation. Through a disaster optimized discharge schedule, it is possible to complete all evacuation trips with the current power network capacity constraint by avoiding unnecessary charging and recommending early recharge, although this remains unexplored. Strategies developed to solve classic evacuation problems (e.g., avoiding excess demand for roadway access by phased evacuation; Lindell et al., 2019) may be applied to develop the recharging strategy. It is reasonable to assume that with large-scale adoption of EVs the rules and behaviors that we have previously experienced with conventional vehicles no longer apply, and we must start to understand the new rules that would govern EV use.

This research is a specific case study, where the evacuation process of Hurricane Irma is adopted. Future studies should consider various possible events for different regions and possibly different evacuation behaviors between EV and non-EV scenarios. Nevertheless, based on this initial study, we argue that policymakers need to consider the evacuation problem in disaster risk zones as EVs are increasingly adopted. Specific charging strategies must be developed to avoid mounting demand peaks during evacuation. EVs might need to be equipped with batteries that would allow a higher travel range on a single charge. Also, proper use of EV and hybrid vehicles together would help to ease potential traffic crisis.

1. Method

The traffic on main highways in Florida was recorded during Irma evacuation. Feng and Lin (2020) estimated the traffic demand for all Florida highways (speed limit $\geq$ 35 mph) during Hurricane Irma, using the main-highway observations (Florida Department of

Transportation Traffic Count, 2017) and game-theory-based user equilibrium (UE) assignment model. Specifically, the UE algorithm was applied to a range of possible OD (origin–destination) distributions based on the pre-hurricane population distribution. The OD distribution that predicted the main highway observations most accurately was selected to represent the "real" traffic demands under Irma's evacuation. Although the UE model is an approximation method (Lindell and Prater, 2007), it was used for computational convenience to make the traffic analysis for the entire Florida region possible. Here, by also the UE model, we further estimate the trip planning between the OD pairs. Also, based on the estimated traffic demands, the evacuation traffic volume time series for each highway in Florida during Irma are estimated.

Then, we trace each evacuating vehicle through an agent-based approach to couple the evacuation process with the power recharge process. At each time step, a certain number of vehicles leave one place and head to another place, according to the traffic demand. Some of them have already evacuated from other places (with reduced battery power) and others are local (starting with full battery power). To differentiate them, we estimate the evacuating portion of incoming vehicles based on whether the incomers can find shelters or hotels. We assume that, when the local shelters and hotels (data obtained from Division of Emergency Management, 2019; STR, 2017) become full, new incomers have to keep going and occupy part of the outgoing evacuation flow (although in reality a large number of evacuees may choose to stay in peers' homes, according to Lindell et al., 2019). The remaining part of the evacuation flow is uniformly distributed into the local population.

Based on the reconstructed traffic time series, the battery power usage for each evacuating EV is estimated. All vehicles follow the Tesla Model 3 EV electricity consumption benchmark (Tesla Main Page, 2017). The electricity consumption changes with traffic speed – from 340 Wh/mile at 60 mile/h (maximum range 250 miles) to 600 Wh/mile at 5 mile/h (maximum range 150 miles) – mainly due to air-condition needs (Time, 2017). We assume that the vehicles recharge (to full capacity) immediately when they leave a highway and stay in a city. We also assume that all the vehicles must stop and recharge when their battery level is lower than 20% of the capacity. In reality, the charging schedule may impede an individual's original evacuation plan, but in this analysis, we simply assume the charging pattern is independent of the evacuation process. Also, we assume all the EVs will be charged to full at local chargers (e.g. friends' houses, restaurants, hotels, public park lots); according to the Tesla Model 3 EV electricity consumption benchmark (Tesla Main Page, 2017), we assume it takes 8 h for a vehicle to get fully charged from empty. (If we assume a significantly shorter charging time, e.g., 4 h, the evacuation process would become faster, as the average charging time for each trip would be shortened, from 3.2 h to 1.6 h. However, the power demands for all the BAs would not be significantly different.) Finally, the electricity consumption of EVs is directly added to the electricity load of a local authority to estimate the total power demand for each BA. This research considers 9 main authorities (BAs) in Florida included in the US Energy Information Administration (EIA) dataset (TAL, GVL, FPC, TEC, JEA, NSB, FMPP, FPL, and HST) and one authority (SOCO) in Georgia.

CRediT authorship contribution statement

Kairui Feng: Conceptualization, Methodology, Software, Writing - review & editing. **Ning Lin:** Conceptualization, Writing - review & editing. **Siyuan Xian:** Conceptualization, Writing - review & editing. **Mikhail V. Chester:** Conceptualization, Writing - review & editing.

Acknowledgments

Kairui Feng, Ning Lin and Siyuan Xian were supported by National Science Foundation (grants 1520683 and 1652448).

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