2024 Forum for Innovative Sustainable Transportation Systems (FISTS)
February 26-28, 2024, Riverside, California, USA

UNLOCKING THE POTENTIAL CONGESTION RELIEF FROM ELECTRIC VEHICLES (EVS) - FIELD EXPERIMENTS, OPEN DATABASE, AND SIMULATIONS OF EVS WITH ADAPTIVE CRUISE CONTROL (ACC)

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Abstract— **Today's mainstream vehicles are equipped with Advanced Driver Assistance Feature (ADAS) known as Adaptive Cruise Control (ACC) to allow for partial automation. ACC uses on-board sensors to automatically adjust speed and maintain safe following distance. Contrary to expectations that automation could relieve congestion, ACC on vehicles powered by internal combustion engines (ICE) could reduce capacity and worsen congestion because its limited initial acceleration during queue discharge could increase the average headway. Fortunately, when ACC is paired with fully electric vehicles (EVs), EV's unique powertrain characteristics such as instantaneous torque and regenerative braking could allow ACC to adopt shorter headways and accelerate more swiftly to maintain shorter headways during queue discharge, therefore reverse the negative impact on capacity. This has been verified in a series of field experiments, model calibration, and microscopic simulations; EVs with ACC could potentially increase capacity by 21.9% compared to their ICE counterpart.**

I. INTRODUCTION

Advancements in vehicle automation and driver assistance have presented new opportunities to reduce traffic congestion. While full automation may not yet be production ready, partial automation has become ubiquitous today. Using on-board sensors such as radar, most of the new vehicles sold today can automatically adjust the speed and maintain a safe following distance via an advanced driver assistance systems (ADAS) feature known as adaptive cruise control (ACC), and this will reinvent traffic flow and operations. Meanwhile, many researchers have paid significant attention to the traffic flow impact of ACC-equipped vehicles powered by internal combustion engines (ICE); recent field experiments demonstrate that ACC amplifies minor speed fluctuations into major disturbances further upstream and therefore is string unstable, [1-8]. In addition, ACC may reduce capacity [9-14]. Specifically, ACC could increase the average headway at queue discharge because the limited initial power and torque generated by ICE leads to delayed response during initial acceleration [11-14]. To capture these field observations, many have developed microscopic car following models [15-19] and macroscopic level models such as the fundamental diagram [20-21]. Others have investigated the interaction between ACC and human drivers [22]. Overall, most research findings on the traffic flow impact of ACC have been negative. However, the combination of EVs and ACC has been overlooked. With ever increasing EV adoption, the unique EV powertrain characteristics could present a new opportunity to improve capacity.

Internal combustion engine (ICE) gradually increases its torque output as the engine speed increases. Since power is the product of torque and engine speed, higher power on ICE would only be attainable after reaching higher engine speeds. But realistically, human drivers seldom operate at high engine speeds but rather at low to medium engine speeds (3500 revolutions per minute or lower) to maintain reasonable fuel economy and long-term powertrain reliability. Similarly, ADAS features such as ACC are designed to maintain moderate engine speeds and therefore could not generate significant acceleration under normal operation. Conversely, EVs produce very high maximum torque immediately upon moving from a complete stop, even at low engine speeds. Revisiting the concept that power is the product of torque and engine speed, EVs could produce relatively higher power at lower ranges of engine speeds as illustrated in Figure 1. As a result, EVs yield better acceleration under normal operating conditions. Furthermore, the electric motors apply regenerative braking immediately upon releasing the throttle and could yield an instantaneous deceleration of as much as 2.5 m/s^2 on mainstream EVs. If the mechanical brakes were applied in addition to the regenerative braking effect from simply releasing the throttle, EVs could easily apply a deceleration of 0.5 m/s^2 without much delay. Combining the instantaneous torque with the strong braking performance from electric motor's regenerative braking, EVs with ACC could potentially adopt shorter headways and accelerate more swiftly to maintain shorter headways when speeds fluctuate and during queue discharge, thereby improve capacity and reverse the previously mentioned negative impact of ACC.

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2024 Forum for Innovative Sustainable Transportation Systems (FISTS) | 979-8-3503-7066-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/FISTS60717.2024.10485597

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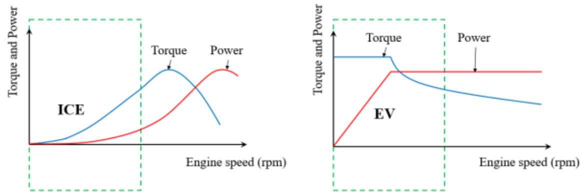

Figure 1. Torque and power vs. engine speed for ICE (left) vs. EVs (right).

This research intends to conduct field tests to quantify the potential impact of EVs with ACC on capacity and provide a novel and comprehensive set of trajectory level car following data. The data could then be used to develop and calibrate models to be integrated into simulation for scaled-up prospective analyses on the traffic flow impact of EVs with ADAS.

In the following section, the experiment setup will be discussed, followed by data analysis, preliminary model calibration and simulation analyses, and conclude with recommendations for future work.

II. Field Experiments

Field observation is the best research method because there are currently no established simulation tools that could accurately model ACC equipped EVs. Ideally, macroscopic level observations of traffic flow provide the most accurate measurement. This could be done by mounting cameras at an overpass overlooking multiple lanes of freeway. However, this method cannot yield any meaningful results in today's traffic stream that has very few ACC-equipped EVs. Instead, car-following experiments in controlled environments using two test vehicles, a leading vehicle as the point of reference, and a following vehicle that is an EV equipped with ACC, were conducted. The trajectory data could serve as benchmark for developing car following models, which can serve as inputs for microscopic simulation that could scale-up the two-vehicle car following experiment to larger traffic streams. Specifically, an ICE vehicle (Toyota Camry) with a 3,310 lb. curb weight and maximum power output of 203 horsepower at 6,600 rpm from a 2.5-liter naturally aspirated engine was used as the leading vehicle in the field experiments. For the following vehicle, we selected a mainstream EV (Hyundai IONIQ 5) from a legacy manufacturer with a 4,414 lb. curb weight and an electric motor that delivers 225 horsepower and 258 lb.-ft. of torque. These vehicles were selected to maintain consistent power to weight ratios with the ACC-equipped ICE vehicles (2020 Toyota Corollas) in the corresponding field tests [11, 14]. In addition, EVs two other manufacturers were tested – Tesla Model 3 and Polestar 2. The Tesla Model 3 has a curb weight of 3,686 lbs and its powertrain generates 221 horsepower and 302 lb-ft of torque. The Polestar 2, on the other hand, has a curb weight of 4,400 lbs and an output of 231 horsepower and 243 lb-ft of torque from its powertrain. The Polestar 2 provided an example with similar power to weight ratio from a legacy European manufacturer (Volvo) while the Tesla Model 3 represented an example of a high-volume EV from a non-traditional manufacturer. Although the power to weight ratio of the Tesla Model 3 is inconsistent and much more favorable compared with the other EVs tested, the Tesla Model 3 was selected to be inclusive of the popular options in today's EV market. EV models from other manufacturers were not attainable or available at the time of field tests. An ICE vehicle (2022 Toyota Corolla) with a 2,910 lb. curb weight and maximum power output of 139 horsepower at 6,000 rpm from a 1.8-liter naturally aspirated engine was used as the leading vehicle in the field experiments involving the Tesla Model 3 and Polestar 2 as the following vehicles. As discussed earlier, this is intended to maintain consistency with the vehicles tested in the corresponding experiments for ACC-equipped ICE vehicles [11, 14].

Trajectory data were collected using one of the most advanced GPS devices known as Racebox. Racebox offers a remarkably high 25 Hz frequency and excellent 10 cm accuracy. The GPS coordinates were used to determine speed, acceleration, and spacing between adjacent vehicles (via Haversine distance); headway can be determined using spacing and speed.

A. *Car-following Experiments*

Initially, both vehicles were aligned in a single lane with a distance Δ. Both vehicles then began to accelerate manually up to a pre-defined free-flow speed; there were four different free-flow speeds tested: 97 km/hr (60 mph), 89 km/hr (55 mph), 72 km/hr (45 mph), and 56 km/hr (35 mph). To avoid safety hazards and unnecessary interruption to nearby traffic at the test site, speeds above sustained free flow speeds above 97 km/hr (60 mph) and below 56 km/hr (35 mph) were not considered. After reaching the pre-defined free-flow speed, the driver of the following vehicle (EV) activated the ACC with the desired speed set the same as the free-flow speed, then manually accelerated slightly beyond the free-flow speed to approach the leading vehicle closer before re-activating ACC to allow ACC to automatically adjust the following distance by applying minor speed adjustments. This is a stabilization process intended to replicate the equilibrium condition at capacity where maximum sustained flow is observed. Beyond this steady state condition, the experiment replicated non-steady state condition in which vehicles approach the back of the queue and accelerate during queue discharge; the driver of the leading vehicle applied normal decelerations manually to a congested speed, remained at the congested speed at 10 second or more, then returned to the free-flow speed. The driver of the leading vehicle accelerated manually under normal acceleration while the following vehicle accelerated via ACC. Figure 2 displays an example of the speed profile tested with 89 km/hr (55 mph) free-flow speed and various congested speeds in the speed fluctuations: 72 km/hr (45 mph), 56 km/hr (35 mph), 40 km/hr (25 mph), 24 km/hr (15 mph), and complete stop, for a total of 5 fluctuations. The same procedures were applied to experiments using other free-flow speeds, with the same set of speed fluctuations for the case with 97 km/hr (60 mph) free-flow speed, 4 fluctuations for 72 km/hr (45 mph) free-flow speed, and 3 fluctuations for 56 km/hr (35 mph) free-flow speed. 8 repetitions were performed for each series of speed fluctuations, with 2 repetitions conducted for each gap setting (short, medium, long, and extra-long). In total, 136 repetitions were performed for all gap settings,

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encompassing various free-flow speeds and speed fluctuations with vehicles having the same desired speed.

In addition, the experiments tested cases with the maximum desired speed of the following vehicle set 8 km/hr (5 mph) and 16 km/hr (10 mph) higher. For each additional desired speed combination, 4 repetitions were tested, with one conducted for each gap setting (short, medium, long, and extra-long). Overall, an additional 136 repetitions were performed (68 trials for each desired speed combination).

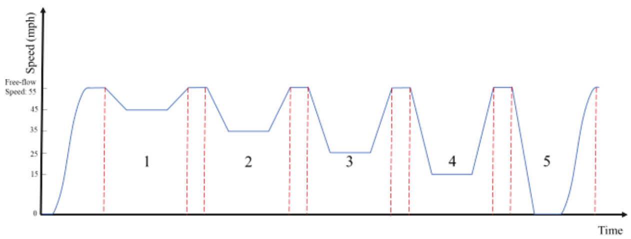

Figure 2. Example speed profile of field test.

B. *Test Site*

Field experiments were conducted on isolated portions of rural public roads in Dixon, California during off-peak hours. The remote location and lack of interference from other road users allowed us to reproduce various traffic conditions efficiently throughout the data collection process. Robben Rd. was primarily used while Pedrick Rd. and Sikes Rd. were alternate locations in case the conditions were less ideal on Robben Rd.

III. RESULTS AND DISCUSSIONS

Field experiments demonstrate that EVs with ACC can achieve considerably shorter headways as low as 1.23 second in idealized steady-state conditions. This is a result of EV's instantaneous regenerative braking that allows EVs to safely follow the preceding vehicles more closely at higher speeds.

Unlike ACC-equipped ICE vehicles, ACC-equipped EVs were able to maintain these shorter headways beyond the ideal steady-state conditions because EVs enabled responsive deceleration using regenerative braking when approaching the back of queue and instantaneous peak torque that results in nearly immediate acceleration once the leading vehicle began accelerating during queue discharge. This entails that the potentially higher capacities could be sustained even in non-steady state conditions. In comparison, previous research on ACC-equipped internal combustion engine (ICE) vehicles showed that headways increased by 1s to 1.6s in the same experiment [11, 14], due to the ICE's sluggish acceleration during queue discharge. Of course, this can be attributed to ICE's progressive power delivery with initially lower output that leads to unresponsive acceleration.

To effectively showcase these findings, Figure 3 presents a time-space diagram for both the leading and following vehicles. As depicted in the plots, the ACC-equipped EV follower Hyundai IONIQ 5 regained its initial minimum headway following a speed fluctuation intended to simulate approaching back of queue and accelerating during queue discharge, which contrasts with the car following behavior of conventional ACC-equipped ICE vehicles, as shown by Figure 9 obtained from earlier field experiments [11]. Figure 4 illustrates that ACC-equipped ICE vehicle exhibits a very gradual initial acceleration when returning to free-flow speeds during queue discharge. In the end, the headway increases. EVs produce strong initial acceleration from the instantaneous peak torque, and as illustrated in Figure 3, the slope of the time-space diagram is steeper for EV's acceleration.

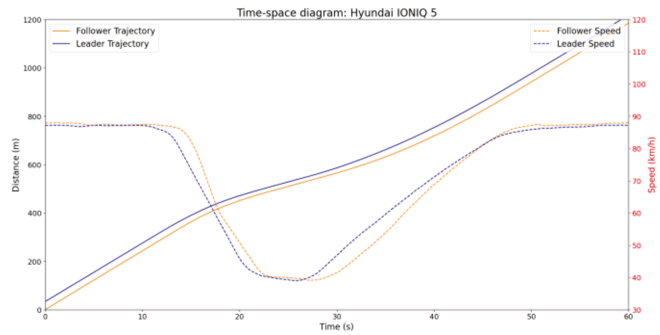

Figure 3. Time-space diagram: Hyundai IONIQ 5 (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap).

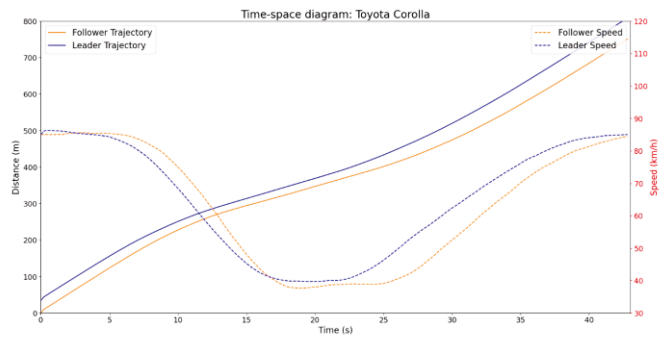

Figure 4. Time-space diagram: Toyota Corolla (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap).

Interestingly, Figure 3 also shows that the aggressive regenerative braking applied by the following vehicle (ACC-equipped EV) did not amplify the speed change from the 97 km/hr (55 mph) free-flow speed to the 40 km/hr (25 mph) congested speed. This is certainly different from the example shown in Figure 4, where the ACC-equipped ICE vehicle amplified the speed change relative to the speed fluctuations undertaken by the leading vehicles. Observations from both field tests and trajectories in Figures 3 and 4 revealed that ACC-equipped EVs immediately applied aggressive regenerative braking that enabled the follower to quickly reach and maintain its desired headway as leader began decelerating, whereas the limited braking capability resulted in the ACC-equipped ICE vehicle (follower) to decelerate for an extended period to speeds below that of the leading vehicle's final speed in the congested state to finally reach its desired headway, and ultimately amplifies speed change. This stark contrast could mean that ACC-equipped EVs may improve stability of traffic, a vastly different outcome than the string unstable car following behavior of ACC-equipped ICE vehicles demonstrated in Figure 4 and confirmed by various prior experiments [1-8].

Furthermore, these field experiments suggest another interesting finding: setting higher desired speed does not affect the car following behavior. As ACC-equipped EV accelerates swiftly to follow the lead vehicle and maintain the minimum headway, it would not be possible to accelerate beyond the leading vehicle speed even if the ACC desired speed was set

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higher, due to the minimum spacing and headway constraint. This is evident in the time space diagram shown in Figure 5. On the other hand, ACC-equipped ICE vehicles would accelerated beyond the speed of the leading vehicle to undergo a “catch-up” process before decelerating again to ensure that the minimum headway is maintained, as shown in Figure 6 [23].

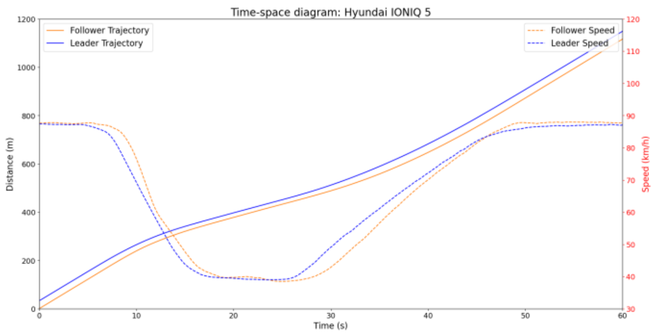

Figure 5. Time-space diagram: Hyundai IONIQ 5 (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap, 8 km/hr or 5 mph higher follower desired speed).

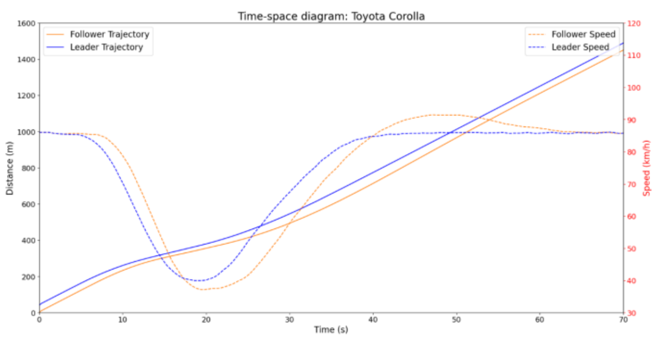

Figure 6. Time-space diagram: Toyota Corolla (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap, 8 km/hr or 5 mph higher follower desired speed).

For the other test vehicles, observations from the field tests of the Polestar 2 mirrored those from the experiments using the Hyundai IONIQ 5, exhibiting similar minimum headways that was also sustained in non-steady state conditions. As depicted in Figure 7, the time space diagram shows similar trajectories when decelerating while the Polestar 2 approaches the back of queue and when accelerating during queue discharge, though there appears to be a slight amplification of the speed change as opposed to the trajectories in Figure 3. However, the results for the Tesla field tests deviated from our expectations, as shown in Figure 8; Tesla was unable to regain its initial minimum headway after a speed fluctuation, exhibiting characteristics similar to those of ACC-equipped ICE vehicles [11, 14]. It appears that the ACC equipped by Telsa does not utilize the advantages of EV powertrain, especially the instant peak torque that provides immediate acceleration during queue discharge, instead, the ACC equipped by Tesla gradually accelerates at a leisurely pace as the leading vehicle accelerates during queue dissipation. Similarly, the same “catch-up” process associated with ACC-equipped ICE vehicles that is shown in Figure 6 can be found in Figure 9, when the desired speed of the follower (Tesla Model 3) is set higher than that of the leader. As an added note, the same string unstable behavior can be observed when examining Tesla Model 3’s trajectory in ACC mode, shown in both Figure 8 and Figure 9. Finally, the field experiments also revealed that the ACC system equipped by Tesla cannot maintain constant headway even at constant speeds, and this often led to inconsistent car following behavior that could render traffic flow modeling difficult and unreliable.

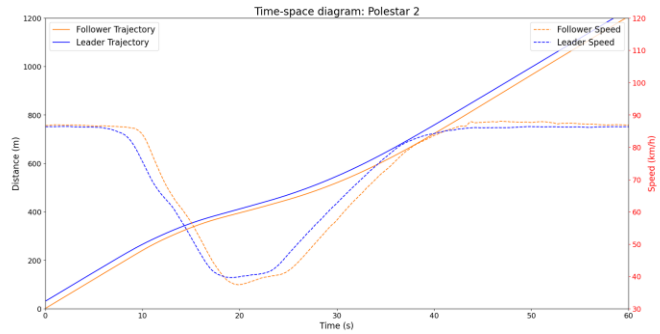

Figure 7. Time-space diagram: Polestar 2 (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap).

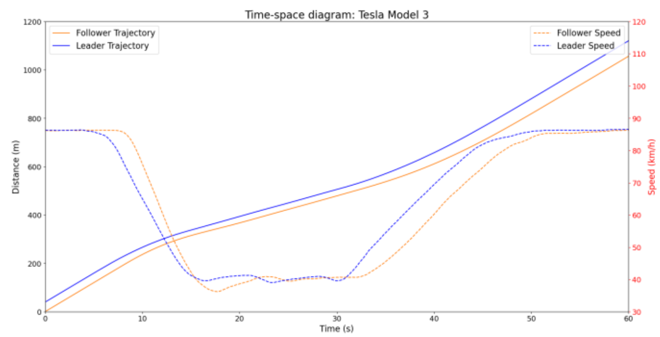

Figure 8. Time-space diagram: Tesla Model 3 (89 to 40 to 89 km/hr, 55 to 25 to 55 mph, short gap).

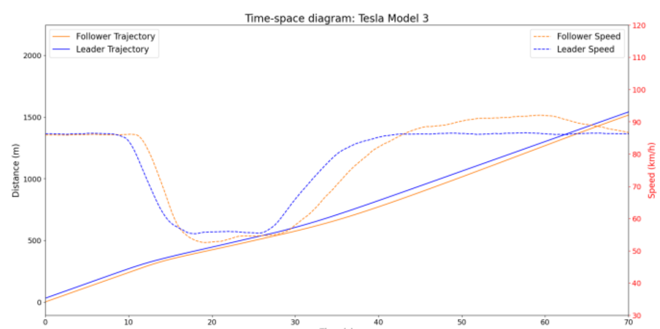

Figure 9. Time-space diagram: Tesla Model 3 (89 to 56 to 89 km/hr, 55 to 35 to 55 mph, short gap, 8 km/hr or 5 mph higher follower desired speed).

Nevertheless, this set of experiments provides very important initial insights on the potential benefits of electric powertrain to vehicle automation going forward. The data generated from these carefully planned experiments could be used to develop and validate microscopic level models for car following, which could be used as the underlying assumption in a scaled-up simulation of macroscopic traffic. Ultimately, the true capacity benefit that EVs with automation could offer would be validated and affirmed given the appropriate models and simulation tools developed based on empirical data.

To follow up, an asymmetric full speed range car following model [19, 23] was developed for the ICE field tests [11, 14], and the same model (shown in the following) was calibrated to reproduce the car following behavior of ACC-equipped EVs:

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For constant speed or deceleration: $a_{sv}(t-1) \leq 0$

$$a_{sv}(t) = K_1(d(t-\tau) - t_{hw}v_{sv}(t-\tau) - L) + K_2(v_l(t-\tau) - v_{sv}(t-\tau))$$

For acceleration: $a_{sv}(t-1) > 0$

$$a_{sv}(t) = K_3(v_l(t-\tau) - v_{sv}(t))$$

where:
$a_{sv}(t)$: the subject (following) vehicle's acceleration at time *t*,
K_1: control gain in position difference between the leading vehicle and the subject vehicle
K_2: control gain in speed difference between the leading vehicle and the subject vehicle during deceleration
K_3: control gain in speed difference between the leading vehicle and the subject vehicle during acceleration,
$d(t)$: distance gap between the subject vehicle's front bumper and the leading vehicle's front bumper at time *t*
t_{hw}: desired time gap of the ACC controller
L: length of the leading vehicle
$v_l(t)$: speed of the leading vehicle at time *t*
$v_{sv}(t)$: speed of the subject (following) vehicle at time *t*
τ: reaction delay

In comparison with the model parameters calibrated for ACC-ICE vehicle car following [19, 23], ACC-equipped EVs require large values of control gains to reflect EV's unique powertrain characteristics: strong regenerative braking and brisk acceleration from instant peak torque. Note that this model calibration did not include data from the Tesla Model 3 because Tesla's car following behavior did not exhibit a significant improvement over the ICE counterpart. Furthermore, the model did not require to be a piece-wise linear function; this simple linear model should suffice due to EV's ability to deliver constant peak power over a broader range of speeds.

After integrating the model calibrated for the collected EV field data into microscopic simulation software Aimsun via microSDK, simulation experiments of a 20 km freeway corridor (SR-99) in Sacramento, California demonstrate that ACC-equipped ICE powered vehicles yielded a capacity of 5335 veh/hr while the ACC-equipped EVs yielded a capacity of 6503 veh/hr, for three lanes in each direction at 100% market penetration. This equates to an increase of 21.9% in capacity. It is worth noting that this simulation represents a real-world corridor that includes various complex geometries such as cloverleaf interchanges and short weaving sections that diminish highway capacity to values much lower than the idealized capacities. Finally, we would like to refrain from making any direct comparisons with the capacities generated by human driven vehicles because the contribution of powertrain difference on human driver behavior and the subsequent highway capacity are largely unknown. This is because most human driven vehicles today are still powered by ICE and observations and empirical studies on the true impact of electric powertrain on human driver behavior (instead of ACC) cannot be conducted due to the low market penetration. With that in mind, the influence of powertrain, specifically fully electric vehicles that deliver peak performance over a broad range of speeds, is worth future investigations, beyond this study's focus on ACC-equipped ICE powered vehicles and EVs. With increasing popularity of fully electric vehicles, the overlooked benefit of potentially higher capacity and reduced congestion from EVs could have implications for future transportation planning and operations.

IV. Conclusion and Recommendations

Commercially available Adaptive Cruise Control (ACC) equipped vehicles have become increasingly prevalent on today's mainstream vehicles. ACC is an Advanced Driver Assistance Feature (ADAS) that allows for partial automation by automatically adjusting speeds and maintaining safe following distance using data collected from on-board sensors. The increasing adoption of fully electric vehicles (EVs) has brought new opportunities; EV's unique operating characteristics such as instantaneous torque and strong regenerative braking could improve capacity and mitigate congestion when EVs are paired with ACC.

Field experiments demonstrate that ACC equipped EVs can achieve a minimum headway as short as 1.23 second in steady state conditions. Moreover, deviations from the steady state conditions do not affect the minimum headway, as shown by an extensive set of field experiment with a wide range of speed fluctuations to simulate approaching back of the queue and queue discharge at and near disturbances and bottlenecks that may arise from ingress and egress at freeway on and off ramps, turning movements, or road geometric changes such as gradient and curvature, etc. Finally, EVs equipped with ACC could does not amplify speed changes further upstream, which could imply more stable traffic stream and less abrupt rapid propagation. Overall, ACC-equipped EVs could outperform ICE vehicles with ACC, as well as human drivers, in terms of capacity. Interestingly, our initial findings suggest this only applies to EVs from legacy manufacturers, whereas EVs from emerging manufacturers such as Tesla deliver car following dynamics akin to an ICE vehicle with ACC.

We recommend future experiments to capture the effect of lane change on ACC-quipped EV's car following behavior, as the receiving lane change car following behavior may be distinct from what had been observed in the car following experiments presented in this paper. In addition, future studies should conduct field tests in naturalistic environments where traffic conditions are more stochastic, especially in mixed environments with a combination of both ICE vehicles and EVs, especially ICE vehicles following EVs to determine the potential impact of a mixed traffic stream with vastly different powertrain characteristics. Finally, given the valuable data presented in this field study, future work should develop car following models unique to ACC-equipped EVs to capture the microscopic level car following behavior, and this would establish an important foundation for developing simulation platforms to perform prospective analyses at large scale; our preliminary model calibration and simulation experiment demonstrate that EVs could increase freeway capacity by 21.9% compared to its ICE counterpart, isolating the effect of human vs. automated driving behavior. This would address many unknowns related to ACC-equipped EVs, examples include macroscopic models such as the fundamental diagram and the effectiveness of implementing dedicated lane for fully electric vehicles operating in ACC mode, and all of which will

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prepare future researchers and practitioners for new opportunities in traffic operations and management in the era of increasingly automated and electrified vehicles. Especially in the near term, when the market penetration of ACC-equipped EVs is relatively small and traffic engineers will need rely heavily on effective traffic management strategies such as preferential lanes or dynamic tolls to fully take advantage of the capacity benefits offered by EVs equipped with ACC. Most of all, the effect of powertrain characteristics on traffic flow is often overlooked and this study will shed light on a new but very important perspective for traffic flow and operations in the coming years, as electrification of vehicle fleet becomes more common. We would finally suggest studying human driver behavior when operating EVs, in addition to EVs equipped with ACC.

V. APPENDIX

The field data known as MicroSIM ACC can be found in the following: https://github.com/microSIM-ACC/EV. The data organization is shown in Figure 10. For instance, a trial with long gap setting, +0 desired speed, free flow speed of 45mph and speed fluctuation down to 15 mph will be found in the path "Long\0_desired\45\15"

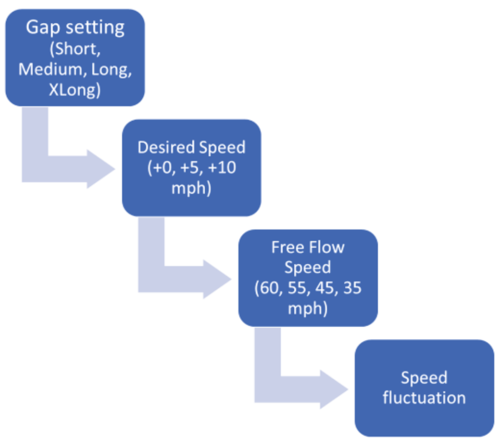

Figure 10. Field data folder organization.

A snapshot of few entries of a trial from field experiments is shown below.

Time (s)	Speed Follower (km/h)	Speed Leader (km/h)	Smooth Speed Follower (km/h)	Smooth Speed Leader (km/h)	Spacing (m)
2520	96.13	95.13	96.23	95.16	48.22
2520.02	96.18	95.15	96.22	95.17	48.21
2520.04	96.23	95.16	96.21	95.17	48.20
2520.06	96.18	95.16	96.20	95.17	48.21
2520.08	96.13	95.16	96.19	95.17	48.21
2520.1	96.14	95.10	96.18	95.17	48.20
2520.12	96.15	95.03	96.17	95.17	48.19

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