

Improving Dynamic Wireless Charging System Performance For Electric Vehicles Through Variable Speed Limit Control Integration

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Abstract—Electric Vehicle (EV) charging has been a significant barrier to the widespread use of EVs. Traditional EV charging methods depend on cables, and there are concerns about safety, accessibility, convenience, and weather. A recent development, dynamic (or in-motion) wireless charging, enables EVs to charge wirelessly by incorporating charging infrastructure into roadways, allowing EVs to charge while moving. However, the energy transferred relies heavily on vehicle speed and time spent in the charging lane. This paper proposes an innovative solution that combines dynamic wireless charging with Variable Speed Limit (VSL) control. This dynamic traffic control strategy adjusts speed limits based on real-time traffic, weather, and incidents. This integration of dynamic wireless charging and VSL has two potential benefits. First, it can motivate driver compliance with VSL through the incentive of charging. Second, it can promote smoother traffic flow and improve traffic safety by implementing lower speed limits at certain times. To verify these benefits, microscopic traffic simulations in SUMO were conducted under different EV penetration rates and VSL compliance rates. Simulation results reveal that the proposed approach can enhance dynamic wireless charging system performance while improving traffic flow and safety.

Index Terms—electric vehicle, dynamic wireless charging, variable speed limit, SUMO simulation

I. INTRODUCTION

The integration of Electric Vehicles (EVs) into people's daily life has remarkably reshaped urban transportation in recent years. As the focus on environmental sustainability and energy efficiency intensifies, EVs have emerged as an essential component in the global strategy to reduce dependency on fossil fuels and decrease greenhouse gas emissions. However, the widespread adoption of EVs is limited by practical issues

related to charging infrastructure, particularly the need for charging stations that are convenient and integrated into the existing traffic systems.

Traditional charging solutions for EVs are centered around home-based charging setups during nighttime or require drivers to visit station-based charging facility at specific locations. These methods are constrained by the physical limits of charging infrastructure and are typically restricted to residential areas, public parking lots, and designated charging points. Recent advancements in EV charging technology enable EVs to charge wirelessly while in motion [1], thereby enhancing the usability and convenience of electric vehicles by extending their operational range without necessitating frequent stops at charging stations. However, the energy charged through this technology relies heavily on the vehicle speed and time spent in the wireless charging lane.

In light of the above limitations, this study proposes an innovative solution that combines wireless charging with Variable Speed Limit (VSL) control. This integration has two potential benefits. First, it can motivate driver compliance with VSL through the incentive of wireless charging. Second, it can promote smoother traffic flow and improve traffic safety by implementing lower speed limits at certain times. To verify these benefits, microscopic traffic simulations are conducted in *Simulation of Urban Mobility* (SUMO) [2] to implement this integrated approach and observe the results. By investigating various scenarios with different levels of EV penetration and VSL compliance, this study aims to provide a comprehensive assessment of how dynamic wireless charging lanes, when controlled by VSL, can significantly improve both traffic flow and EV charging system performance.

This paper is organized as follows: Section 2 provides a literature review of EV charging technologies and Variable Speed Limit (VSL) methods. Section 3 outlines the integration of VSL and EV wireless charging. Section 4 discussed the detailed experiment settings in SUMO, which aims to explore the benefits of such integration at different EV penetration rates and VSL compliance rates. Section 5 discusses the results of these experiments, offering insights into the practical implications of integrating wireless charging infrastructure on highways and its potential effects on traffic flow and EV charging. Section 6 discussed some additional potential benefits of the proposed integration. Finally, conclu-

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sions are drawn in Section 7. This study seeks to contribute valuable knowledge toward the development of sustainable, efficient, and user-friendly wireless charging facilities that improve both traffic flow and traffic safety.

II. LITERATURE REVIEW

A. EV charging

EVs are a viable, eco-friendly alternative to gasoline-powered vehicles. To adopt EVs into the current transportation system, researchers have looked into the demand forecast of EV adoption and induced electricity [3], [4]; the impact of EVs on current traffic flow [5], [6]; deployment of Electric vehicle supply equipment (EVSE) to support the adoption of EVs [7]; vehicle routing problems with EVs [8], [9]; interaction between vehicle and grid [10], [11], and impact to infrastructure [12], etc. A significant barrier to large-scale adoption of EVs is consumer anxiety over vehicle range, which can be addressed with more accessible charging infrastructure [13] and emergency charging supply [14].

The EV charging methods can be categorized into three groups: battery swapping, wired charging, and wireless charging [15], and wireless charging can be further classified as stationary or dynamic (in-motion) wireless charging [16]. Dynamic wireless charging EVs can charge while in motion, addressing challenges related to short operating ranges caused by low energy density or small batteries [16], [17], and saving cost [16], [18]. These advantages of dynamic wireless charging could help promote the adoption of EVs [17]. According to the U.S. Department of Transportation (DOT), there are three power supply levels of EV charging: Level 1 (1 kW), Level 2 (7 kW - 19 kW), and Level 3 (50 - 350 kW) [19]. Power supply levels refer to the rate at which energy is transferred and indicate how fast an EV's battery can be charged. The charging rate is measured in amperes (current) and volts (voltage). Power is determined by multiplying current and voltage. Multiplying this power by the charging duration gives the total amount of energy transferred to the battery. Therefore, the energy charged per vehicle is proportional to the charging duration. This relationship may encourage drivers to follow the Variable Speed Limit (VSL), a traffic control strategy that lowers the speed limit based on downstream traffic conditions, allowing EV drivers to charge for more time on the dynamic wireless charging lane.

B. Variable Speed Limit

Variable Speed Limit (VSL) systems represent a sophisticated approach to managing urban motorway traffic flow to mitigate congestion and enhance road safety. As metropolitan areas continue to grow, the demand for road space has decreased the Level of Service (LoS) on motorways, characterized by reduced speeds, higher traffic density, and longer travel times. When traffic volume exceeds a motorway segment's designed capacity, bottlenecks destabilize the traffic flow. VSL operates by dynamically adjusting the speed limits displayed on Variable Message Signs (VMS) along the motorway, particularly ahead of bottleneck areas, to control

the rate at which vehicles enter these segments [20]. The primary goal of VSL is to maximize the existing infrastructure's operational capacity without expanding road capacity through additional lanes. This is achieved by smoothing traffic flow, reducing speed variances between vehicles and lanes, and decreasing the risk of accidents [21]. VSL system can achieve substantial benefits in key safety performance measures without significantly reducing mobility measures, even when driver VSL compliance rates are as low as 5% in sufficiently dense traffic [22].

Several VSL methods have been developed based on different logic and objectives. Rule-based reactive VSL, for instance, calculates speed limits based on thresholds for a given traffic flow state, including flow, density, and mean speed [23]. This approach may also incorporate weather-based logic to adjust speed limits in response to adverse conditions like fog, ice, or strong winds. In contrast, feedback VSL maintains traffic density at a critical set point by continuously monitoring current traffic conditions and adjusting speed limits accordingly. Open-loop-based VSL, on the other hand, utilizes an open-loop optimization process [24], [25] based on general macroscopic models of traffic flow but confronts the challenge of predicting stochastic traffic behavior [26]. Moreover, recent research has explored Reinforcement Learning (RL)-Based VSL, which represents a novel direction for developing adaptive and efficient traffic control systems [27]. Furthermore, recent research has also integrated Connected and Automated Vehicles (CAVs) with VSL, which automatically ensures vehicles comply with dynamically changing speed limits, further enhancing the effectiveness of VSL in managing urban motorway congestion, fuel efficiency, and safety [28]–[32].

III. METHODOLOGY

A. Integration of Wireless Charging and VSL Control

This paper proposes an innovative method that integrates with Variable Speed Limit (VSL) control into dynamic wireless charging. To do this, a highway is equipped with wireless charging equipment installed in specific lanes designated as wireless charging lanes. These lanes have inductive charging technology embedded in the road surface, allowing EVs equipped with compatible inductive receivers to charge while in motion. Due to the high cost of wireless charging infrastructure, it is not feasible to equip the entire highway with such lanes. Therefore, it is suggested that this charging lane should be strategically located upstream of a predictable congested area (e.g., downtown), not only to capitalize on the naturally slower traffic speeds, which increases the cruising time over the charging infrastructure but also to effectively implement VSL control for improving the overall traffic flow. On these wireless charging lanes, VSL controls are implemented. This control dynamically adjusts the speed limits based on real-time downstream traffic conditions (e.g., density), which are monitored through sensors (e.g., loop detector and traffic camera) installed downstream. It is designed to manipulate the vehicle speed in the charging lanes to promote smoother traffic flow both upstream and downstream

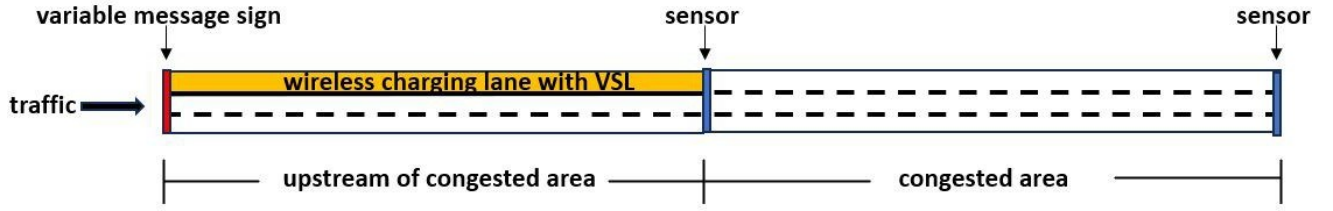


Fig. 1: Example of integration of wireless charging and VSL

while increasing the cruising time of EVs on charging lanes, which can enhance the amount of energy charged per vehicle. A variable message sign is installed at the entrance to the wireless charging section to indicate which lane is designated for wireless charging and to display the current speed limit. An example of such integration is provided in Fig. 1.

B. Rule-based VSL Control

In this paper, a rule-based VSL control strategy is selected to control the speed on the wireless charging lane. Rule-based VSL control determines its control outputs primarily based on real-time traffic data measured by traffic sensors, such as traffic speed, flow, and occupancy. Rule-based VSL control is more widely deployed in practice due to its ease of implementation, higher certainty, and interpretability [33].

The rule-based VSL control implemented in this paper follows these guidelines: The recommended speed limit of the VSL-controlled segment is closely aligned with the real-time speed of the most congested segment within the area of interest (downstream highway segment in this paper) measured by traffic detectors. To avoid significant fluctuations in speeds across the entire road, this measured speed is first rounded to the nearest 5 miles per hour and then incrementally increased by 5 or 10 miles per hour for upstream control points (if more than one). Ultimately, the recommended speeds for all control points range from 35 to 65 miles per hour. For instance, if there are three control points and the traffic sensors report an average speed of 37 miles per hour in the congested segment, the recommended speed limit for the control point closest to the congested area would be 40 miles per hour. The remaining two control points upstream would then have their recommended speed limits set at 50 and 60 miles per hour, respectively, increasing by a speed of 10 miles per hour.

C. Performance Metrics

In this paper, the impacts of the proposed approach on the

performance of the dynamic wireless charging system are evaluated from three aspects: energy, mobility, and safety.

- **Energy:** The energy impact of the proposed approach is assessed using the average energy charged per vehicle-kilometer. 1 kWh per vehicle-kilometer means a vehicle can charge an average of 1 kWh of energy for each kilometer traveled on this wireless charging lane controlled by VSL. The metric is proportional to the wireless charging duration on the wireless charging lane, i.e., the average time for each vehicle to traverse the

- **Mobility:** Mobility is assessed by average travel time T_{avg} given by (1) and average speed V_{avg} given by (2) in this paper. If T_{avg} is shorter or V_{avg} is higher, it indicates a network with higher overall mobility.
- **Traffic Safety:** Traffic safety is analyzed using two primary metrics: coefficient of variation (CV) in speed and average minimum time-to-collision (TTC) in each traffic conflict. The coefficient of variation is a statistical measure used to describe the relative variability of data points around the mean of the dataset and is defined as the ratio of the standard deviation to the mean, as calculated in (3). A lower CV in speed will increase traffic safety because lower speed differences decrease the risk of collisions, as drivers will have less need to constantly adjust their speed or change lanes to accommodate faster or slower vehicles. Additionally, traffic safety is assessed through average minimum time-to-collision. Time-to-collision (TTC), given by (4), is the time that is left until a collision occurs if both vehicles continue on the same course and at the same speed [34]. A TTC smaller than 3 seconds is often considered as a traffic conflict, a near-miss situation that, although it doesn't result in a crash, indicates a significant risk of collision. In this paper, we specifically record the minimum TTC observed during each of these conflict incidents when the TTC is below 3 seconds. The average of these minimum TTC values across all noted traffic conflicts is then calculated to assess the overall traffic safety of the network.

A description of the notations used in these metrics is listed in Table I.

TABLE I
TABLE OF NOTATIONS

wireless charging section.

Symbol	Description	Unit
N	total number of vehicles	veh
t_i	travel time of vehicle i traversing the road	hr
T_{avg}	average travel time of all vehicles	hr
v_i	average speed of vehicle i traversing the road	km/hr
V_{avg}	average speed of all vehicles	km/hr
σ	standard deviation	km/hr
CV	coefficient of variation	%
$v_{t,i}$	speed of vehicle i at time t	km/hr
$v_{t,i+1}$	speed of vehicle in front of vehicle i at time t	km/hr
$S_{t,i}$	spacing between vehicle i and its leader	m
$TC_{t,i}$	time-to-collision for vehicle i at time t	sec

$$T_{avg} = \frac{\sum_{i=1}^N t_i}{N} \quad (1)$$

$$V_{avg} = \frac{\sum_{i=1}^N v_i}{N} \quad (2)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (v_i - V_{avg})^2}{N-1}} \quad (3)$$

$$TTC_{t,i} = \frac{3.6 \times S_{t,i}}{v_{t,i+1} - v_{t,i}} \quad (4)$$

IV. SIMULATION

A microscopic simulation in SUMO [2] is used to investigate the impact of integrating VSL and EV wireless charging on energy, mobility, and safety. The simulated network is a 10km one-way 3-lane highway section with entrances and exits located every 2.5km, as shown in Fig. 2. At each entrance, the highway is temporarily extended to 4 lanes for merging purposes. These entrances and exits divide the highway into 4 sections in the longitudinal direction. It is assumed that the last two highway sections go through the downtown area, and thus, their entrances have much higher demand than the first two highway sections, especially during peak hours. This creates a predictable bottleneck between the second and third highway sections. To smooth the traffic flow while providing charging availability for EVs, a 2.5km VSL-controlled wireless charging lane is set at the leftmost lane of the second highway section. It is assumed that the wireless charging lane consistently provides a stable charging power of 100 kW, maintaining an average charging efficiency of 0.95 for vehicles traveling at varying speeds. This means, for example, if a vehicle remains in this lane for 1 hour, it can charge up to 95 kWh of energy. This assumption is realistic as up to 100 kW dynamic wireless charging power has been deployed in the real world [35] and up to 200 kW dynamic wireless charging power has been tested in a lab environment [36]. Finally, this wireless charging lane's real-time variable speed limit is updated every 5 min based on the downstream highway density using the aforementioned rule-based VSL control. For simplicity, it is assumed that all EVs will use this wireless charging lane while driving through this highway section.

Eight scenarios with 2 levels of EV penetration rates (15% and 30%) and 4 levels of VSL compliance rates (no VSL, 25%, 50%, and 100%) are simulated and compared. Each scenario was simulated for 10 times with different random seeds to ensure the statistical robustness of the results. Note that while a compliance rate 25% or 50% is typically considered as high in current real-world practice, it is likely to become realistic when wireless charging motivates EV drivers to adhere to the VSL to charge their vehicles more. A compliance rate of 100% represents an ideal scenario in which all vehicles on the wireless charging lane will follow the VSL,

V. RESULT AND EVALUATION

The simulation results across different scenarios are presented as boxplots in Fig. 3- 7. In each boxplot, the individual boxes represent the distribution of metrics derived from 10 iterations of each scenario. By examining these boxplots, the energy, mobility, and safety impacts of the integration of wireless charging and VSL control are discussed.

Energy is first evaluated using the average energy charged

per vehicle-kilometer. As is shown in Fig. 3, when the EV wireless charging lane is not regulated by VSL, the energy charged per vehicle-kilometer is notably low due to the high speeds typically maintained on highways. However, with the implementation of VSL on the wireless charging lane, there is a significant increase in the energy charged per vehicle-although this may not be practically achievable.

kilometer, which triples even at a modest VSL compliance rate of 25%. This boost in energy charge is substantial; for instance, at a 15% EV penetration and 25% VSL compliance, 2.55 kWh per vehicle-kilometer allows a medium-sized EV which consumes 15-20 kWh per 100 kilometers [37] to travel approximately 12.75 to 17 kilometers for every kilometer driven on the wireless charging lane. This distance is often sufficient to cover the one-way trip of a typical daily commute. Besides, the travel distance covered by the energy charged on the wireless charging will increase with the length of the wireless charging lane and the charging power.

Mobility is then evaluated using average travel time and average speed. Fig. 4 and Fig. 5 illustrate the change of travel time and change of average speed as VSL is implemented and its compliance rate increases. When the compliance rate is low (25%), we can observe a lower average travel time and higher average speed, indicating a positive impact of integrating VSL and EV wireless charging on mobility. By comparison, a higher compliance rate will have a negative impact on mobility, leading to longer travel time and lower speed. However, this drawback is minor compared to the substantial gains in energy charged.

Traffic safety is finally analyzed using two primary metrics: coefficient of variation in speed and average minimum time-to-collision in each traffic conflict. Fig. 6 compares the average CV in speed from different scenarios. It is obvious that CV in speed decreases as the VSL compliance rate increases, indicating that more people obeying VSL will reduce differences in speed and thus enhance safety. Fig. 7 compares the average minimum TTC in each traffic conflict from different scenarios. It can be observed that under all cases where VSL is implemented, the minimum TTC in each traffic conflict is higher than in cases where there is no VSL, showing an improvement in traffic safety via VSL. In summary, from both CV in speed and TTC, it is clear that as wireless charging lane attracts EVs to comply with the VSL, it leads to improved overall traffic safety.

VI. OTHER BENEFIT

In addition to the improvements in energy, traffic flow, and traffic safety identified through the simulation, the integration of wireless charging and VSL control have additional benefits on increasing VSL compliance rate.

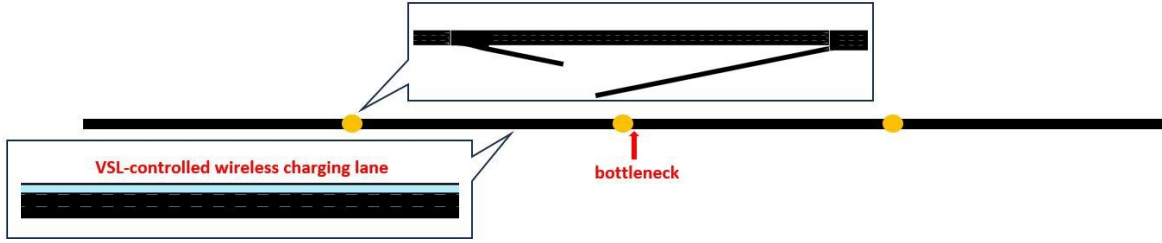
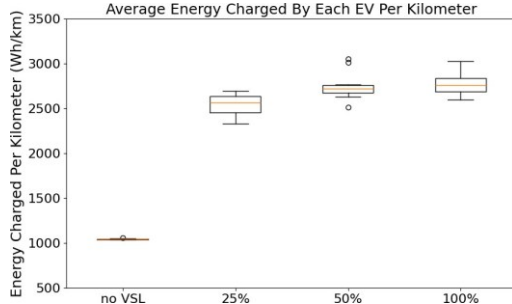
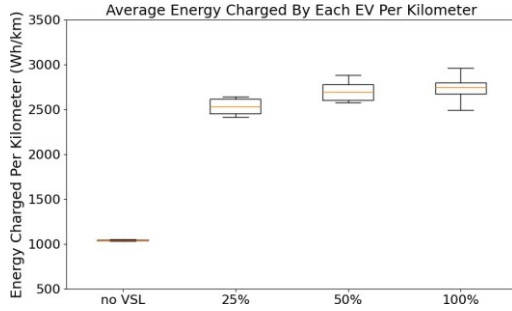


Fig. 2: Simulated network



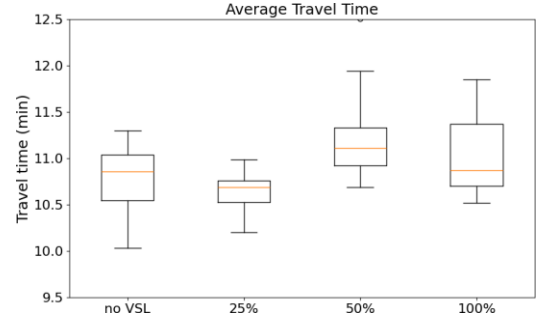
(a) 15% EV penetration rate



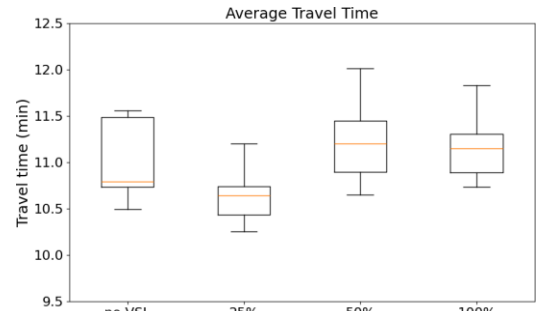
(b) 30% EV penetration rate

Fig. 3: Energy charged by each EV after traveling for one kilometer on the wireless charging lane.

VSL traffic congestion control has a long history of research and has garnered numerous favorable evidence through theory and simulations. However, individual human drivers in practice are not likely to follow VSL speed reduction recommendations, leading to a significant gap between theoretical and practical levels of VSL traffic control [38]. There are two main reasons for this discrepancy: First, drivers lack knowledge of downstream macroscopic traffic flow conditions. Thus, they cannot be confident that the VSL-recommended proactive speed reduction is reasonable to avoid congestion on the current road segment. Second, even with an understanding of VSL principles, drivers often face a conflict between collective benefit and individual gain. Drivers must decide whether to adhere to recommended speed limits, which contribute to overall traffic flow, or to exceed them for personal time savings. Without incorporating other benefits, many choose the latter in reality, resulting



(a) 15% EV penetration rate



(b) 30% EV penetration rate

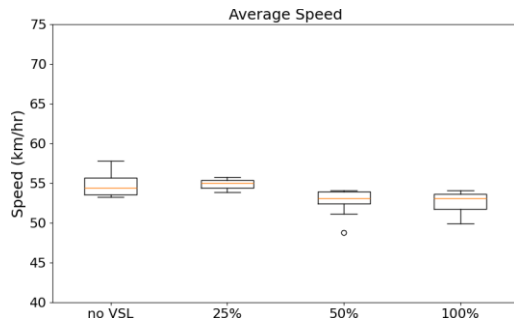
Fig. 4: Average travel time of all vehicles

in traffic behaviors that diverge from the optimal strategies proposed by VSL.

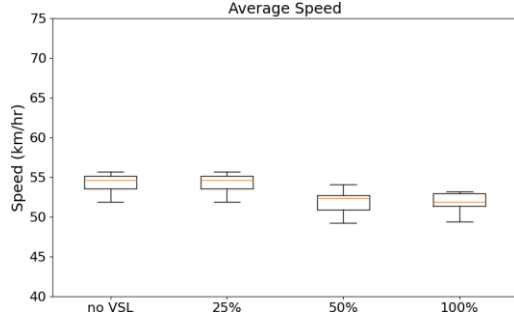
In the proposed approach, by providing tangible benefits through wireless charging, drivers are more likely to maintain speeds given by VSL control and thus align individual behavior with broader traffic management objectives. This increased compliance further contributes to the overall effectiveness of VSL, leading to a more efficient and safe driving environment.

VII. CONCLUSION

This paper studied the potential of integrating variable speed limit (VSL) control with dynamic wireless electric vehicle (EV) charging technologies on highways. Simulation results indicate that the application of VSL in conjunction with dynamic wireless charging lanes can effectively increase the energy charged per vehicle on the wireless charging lane and thus extend the operational range of EVs without necessitating detour to charging stations for charging.

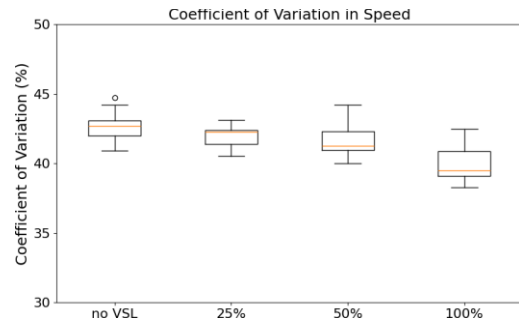


(a) 15% EV penetration rate

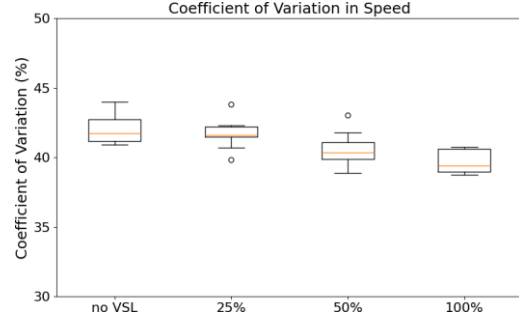


(b) 30% EV penetration rate

Fig. 5: Average speed of all vehicles



(a) 15% EV penetration rate



(b) 30% EV penetration rate

Fig. 6: Coefficient of variation for average speed

Moreover, simulation results also suggest that the increased compliance with VSL driven by the incentives of charging can smooth the traffic flow and increase safety. Overall, the findings of this paper are significant for traffic control and EV charging infrastructure development, suggesting that such integrative approaches can contribute to a more sustainable transportation network.

Future research should consider how the lane speed differentials caused by the VSL may dynamically affect vehicles' usage of each lane [39] and how the potentially increased lane change activities may affect the overall traffic flow [40]. In addition, future research should consider the distinctions in car-following behavior between electric vehicles and conventional vehicles and consider how this difference may affect the proposed approach. Finally, future research should also examine the potential rise in EV demand resulting from the deployment of dynamic wireless charging infrastructure and its implications for overall mobility.

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REFERENCES

- [1] A. A. Mohamed, A. A. Shaier, H. Metwally, and S. I. Selem, "An overview of dynamic inductive charging for electric vehicles," *Energies*, vol. 15, no. 15, p. 5613, 2022.
- [2] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Floettero, R. Hilbrich, L. Luken, J. Rummel, P. Wagner, and E. Wießner, "Microscopic traffic simulation using sumo," in *2018 21st international conference on intelligent transportation systems (ITSC)*. IEEE, 2018, pp. 2575–2582.
- [3] X. Cheng and E. Kontou, "Estimating the electric vehicle charging demand of multi-unit dwelling residents in the united states," *Environmental Research: Infrastructure and Sustainability*, vol. 3, no. 2, p. 025012, 2023.
- [4] T. A. Becker, I. Sidhu, and B. Tenderich, "Electric vehicles in the united states: a new model with forecasts to 2030," *Center for Entrepreneurship and Technology, University of California, Berkeley*, vol. 24, pp. 1–32, 2009.
- [5] Y. Kudoh, H. Ishitani, R. Matsuhashi, Y. Yoshida, K. Morita, S. Katsuki, and O. Kobayashi, "Environmental evaluation of introducing electric vehicles using a dynamic traffic-flow model," *Applied Energy*, vol. 69, no. 2, pp. 145–159, 2001.
- [6] Y. Li, X. Liu, F. Wen, X. Zhang, L. Wang, and Y. Xue, "Dynamic charging scheduling for electric vehicles considering real-time traffic flow," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 2018, pp. 1–5.
- [7] M. J. Kearney, "Electric vehicle charging infrastructure deployment: policy analysis using a dynamic behavioral spatial model," Ph.D. dissertation, Massachusetts Institute of Technology, 2011.
- [8] J. Lin, W. Zhou, and O. Wolfson, "Electric vehicle routing problem," *Transportation research procedia*, vol. 12, pp. 508–521, 2016.

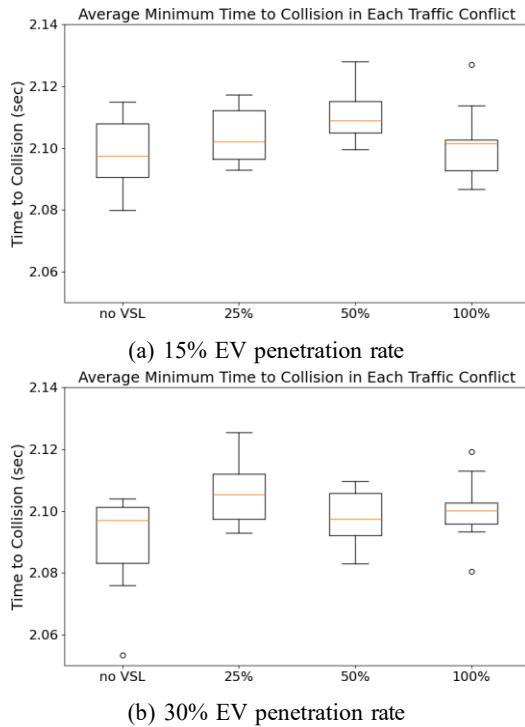


Fig. 7: Average minimum time-to-collision (TTC) in each traffic conflict

- [9] X. Cheng and J. Lin, "Is electric truck a viable alternative to diesel truck in long-haul operation?" *Transportation Research Part D: Transport and Environment*, vol. 129, p. 104119, 2024.
- [10] D. P. Tuttle and R. Baldick, "The evolution of plug-in electric vehicle-grid interactions," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 500–505, 2012.
- [11] X. Cheng, T. Mamalis, S. Bose, and L. R. Varshney, "On carsharing platforms with electric vehicles as energy service providers," *IEEE Transactions on Intelligent Transportation Systems*, 2024.
- [12] J. Sun, Z. Han, and Z. Zhang, "Quantifying the Benefits of Autonomous Vehicles to Roadway Infrastructure Efficiency," in *2024 Forum for Innovative Sustainable Transportation Systems (FISTS)*. Riverside, CA, USA: IEEE, Feb. 2024, pp. 1–6.
- [13] J. Neubauer and E. Wood, "The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility," *Journal of power sources*, vol. 257, pp. 12–20, 2014.
- [14] X. Cheng, H. Shen, Y. Huang, Y.-L. Cheng, and J. Lin, "Using mobile charging drones to mitigate battery disruptions of electric vehicles on highways," in *2024 Forum for Innovative Sustainable Transportation Systems (FISTS)*. IEEE, 2024, pp. 1–6.
- [15] M. Pei, H. Zhu, J. Ling, Y. Hu, H. Yao, and L. Zhong, "Empowering highway network: Optimal deployment and strategy for dynamic wireless charging lanes," *Communications in Transportation Research*, vol. 3, p. 100106, Dec. 2023.
- [16] S. Jeong, Y. J. Jang, and D. Kum, "Economic Analysis of the Dynamic Charging Electric Vehicle," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6368–6377, Nov. 2015.
- [17] S. Y. Choi, B. W. Gu, S. Y. Jeong, and C. T. Rim, "Advances in Wireless Power Transfer Systems for Roadway-Powered Electric Vehicles," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 18–36, Mar. 2015.
- [18] M. Fuller, "Wireless charging in California: Range, recharge, and vehicle electrification," *Transportation Research Part C: Emerging Technologies*, vol. 67, pp. 343–356, Jun. 2016.
- [19] U.S. Department of Transportation, "Charger types and speeds," <https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds>, 2023, accessed: insert access date here.
- [20] Y. Zhang, M. Quinones-Grueiro, Z. Zhang, Y. Wang, W. Barbour,

- G. Biswas, and D. Work, "Marvel: Multi-agent reinforcement-learning for large-scale variable speed limits," *arXiv preprint arXiv:2310.12359*, 2023.
- [21] F. Vrbanić, E. Ivanjko, K. Kus'ić, and D. Čakija, "Variable speed limit and ramp metering for mixed traffic flows: A review and open questions," *Applied Sciences*, vol. 11, no. 6, p. 2574, 2021.
- [22] Y. Zhang, M. Quinones-Grueiro, W. Barbour, C. Weston, G. Biswas, and D. Work, "Quantifying the impact of driver compliance on the effectiveness of variable speed limits and lane control systems," in *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2022, pp. 3638–3644.
- [23] S. Smulders and D. Helleman, "Variable speed control: State-of-the-art and synthesis," in *9th International Conference on Road Transport Information and Control, 1998.(Conf. Publ. No. 454)*. IET, 1998, pp. 155–159.
- [24] C. Zhou, Y. Zhao, J. Cao, Y. Shen, J. Gao, X. Cui, C. Cheng, and H. Liu, "Optimizing search advertising strategies: Integrating reinforcement learning with generalized second-price auctions for enhanced ad ranking and bidding," *arXiv preprint arXiv:2405.13381*, 2024.
- [25] C. Zhou, Y. Zhao, Y. Zou, J. Cao, W. Fan, Y. Zhao, and C. Cheng, "Predict click-through rates with deep interest network model in e-commerce advertising," 2024.
- [26] X. Yang, Y. Lu, and G. Chang, "Proactive optimal variable speed limit control for recurrently congested freeway bottlenecks," in *Transportation Research Board Meeting*, 2013.
- [27] Y. Zhang, M. Quinones-Grueiro, W. Barbour, Z. Zhang, J. Scherer, G. Biswas, and D. Work, "Cooperative multi-agent reinforcement learning for large scale variable speed limit control," in *2023 IEEE International Conference on Smart Computing (SMARTCOMP)*. IEEE, 2023, pp. 149–156.
- [28] J. W. Lee, H. Wang, K. Jang, A. Hayat, M. Bunting, A. Alanqary, W. Barbour, Z. Fu, X. Gong, G. Gunter *et al.*, "Traffic control via connected and automated vehicles: An open-road field experiment with 100 cavs," *arXiv preprint arXiv:2402.17043*, 2024.
- [29] X. Wang, S. Onwumelu, and J. Sprinkle, "Using automated vehicle data as a fitness tracker for sustainability," in *2024 Forum for Innovative Sustainable Transportation Systems (FISTS)*. IEEE, 2024, pp. 1–6.
- [30] Z. An, X. Wang, T. T. Johnson, J. Sprinkle, and M. Ma, "Runtime monitoring of accidents in driving recordings with multi-type logic in empirical models," in *International Conference on Runtime Verification*. Springer, 2023, pp. 376–388.
- [31] X. Wang, A. Liang, J. Sprinkle, and T. T. Johnson, "Robustness verification for knowledge-based logic of risky driving scenes," *arXiv preprint arXiv:2312.16364*, 2023.
- [32] A. Richardson, X. Wang, A. Dubey, and J. Sprinkle, "Reinforcement learning with communication latency with application to stop-and-go wave dissipation," in *2024 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2024, pp. 1187–1193.
- [33] B. Khondaker and L. Kattan, "Variable speed limit: an overview," *Transportation Letters*, vol. 7, no. 5, pp. 264–278, 2015.
- [34] K. Vogel, "A comparison of headway and time to collision as safety indicators," *Accident analysis & prevention*, vol. 35, no. 3, pp. 427–433, 2003.
- [35] "Wireless charging anywhere is here," Electreon, 2024, accessed: 2024-04-21. [Online]. Available: <https://electreon.com/technology/faqs>
- [36] V. Galigekere, "High power and dynamic wireless charging of electric vehicles (evs)," 2023. [Online]. Available: https://www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/elt197_Veda_2023_o%20-%20Veda%20Prakash%20G.%20N.pdf
- [37] H. Wang, X. Zhang, and M. Ouyang, "Energy consumption of electric vehicles based on real-world driving patterns: A case study of Beijing," *Applied energy*, vol. 157, pp. 710–719, 2015.
- [38] M. Matowicki and O. Pribyl, "Speed compliance in freeway variable speed limit system—case study of the prague city ring," *Transport Problems*, vol. 11, 2016.
- [39] G. Xu and V. V. Gayah, "Non-unimodal and non-concave relationships in the network macroscopic fundamental diagram caused by hierarchical streets," *Transportation Research Part B: Methodological*, vol. 173, pp. 203–227, 2023.
- [40] G. Xu, Z. Yu, and V. V. Gayah, "Analytical method to approximate the impact of turning on the macroscopic fundamental diagram," *Transportation research record*, vol. 2674, no. 9, pp. 933–947, 2020.