Quantifying the Impact of AV Penetration on Phantom Traffic Jam Formation: A Density-Preserving Multi-Lane Study

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***Abstract*—A unique advantage of emerging autonomous vehicle technology is the ability to link together in strings of communicating vehicles. This technology is called Cooperative Adaptive Cruise Control (CACC). Implementing a system like this can alleviate ”phantom traffic jams” and increase throughput at controlled intersections. Unlike most speculative advantages of Autonomous Vehicles, CACC-capable vehicles can be implemented with current technology, and their impact can be expected to increase as their market share grows. This paper investigates the effectiveness of CACC systems as the percentage of CACC-capable vehicles increases. Although the benefit of CACC is well established, it is unclear how many such vehicles are needed before measurable improvements appear, and whether these improvements disappear and penetration approaches 100%.**

Phantom traffic jams, stop-and-go waves that arise without any physical bottleneck, impose billions of dollars of annual economic cost on the U.S. transportation system. Cooperative Adaptive Cruise Control (CACC), a vehicle-to-vehicle (V2V) coordination technology deployable with current hardware, offers a near-term mitigation strategy. However, the penetration rate at which CACC begins to deliver measurable improvements in mixed human–AV traffic, and how this threshold shifts in realistic multi-lane road environments, remain open questions with direct policy implications. This paper presents a density-preserving microsimulation study sweeping CACC penetration from 0% to 100% across one, two, three, and four-lane ring-road configurations. Three independent seed runs per configuration mitigate AV-placement bias. Results show that meaningful phantom-jam suppression emerges at 40%–60% CACC penetration regardless of lane count. Lane switching provides 20%–24% congestion reduction at low penetration but becomes counterproductive to flow stability above 80%–90% CACC, a finding explained by the MOBIL lane-change incentive criterion persisting even when longitudinal coordination alone has stabilized the flow.

***Index Terms*—CACC, Cooperative Adaptive Cruise Control, Autonomous Vehicles, mixed traffic, connected vehicles**

I. Introduction

A. Motivation

Phantom traffic jams (slowdowns without a visible cause) are a well-documented phenomenon. They occur from small disturbances in driver behavior, such as slight changes in speed or following distance. These disturbances are amplified over time due to human drivers' overreaction. Sugiyama et al. (2008) demonstrated that, in the absence of external influences, natural fluctuations in driver behavior are sufficient to produce these traffic waves. As each driver reacts to the vehicle ahead's behavior, minor fluctuations can grow into significant slowdowns.

A roadway composed entirely of autonomous vehicles could eliminate such traffic jams. However, before AVs reach 100% adoption, roads will still feature a mix of AVs and human drivers. For the foreseeable future, traffic influencing systems must be designed with a mixed driver ratio in mind. This raises the question: what level of CACC-capable vehicle penetration is required to meaningfully mitigate traffic disruptions caused by human driving behavior?

B. Prior Art

Prior research has established that connected vehicle technologies can improve the performance of mixed traffic systems. A recent review by Pan et al. (2024) summarizes the effects of connected autonomous vehicles on mixed traffic. The review concludes that connected autonomous vehicles can improve traffic efficiency, stability, and safety in mixed traffic. This survey highlights the importance of studying mixed traffic rather than comparing purely human-driven vs purely autonomous roadways, as the latter will be more realistic in the near future.

Several other studies have examined specific CACC strategies within this mixed setting. Song et al. (2023) developed a data-driven CACC framework for mixed-heterogeneous vehicle platoons with unknown vehicle dynamics. Their framework enables CACC-capable vehicles to observe patterns in surrounding vehicles and predict their movements, helping maintain string stability. Wang et al. (2022) extended cooperative control to platoon lane-changing, demonstrating that CACC can improve mobility in complex traffic. More recently, a study by Molnar and Orosz (2024) showed that increasing the penetration of connected automated vehicles can reduce the bistable behavior that gives rise to phantom traffic jams. Building on prior work, the present study seeks to quantify the effects of increased CACC penetration on phantom traffic-jam formation in a mixed-traffic simulation.

II. Methodology

A. Simulation

To evaluate the effectiveness of CACC systems as a function of vehicle adoption rate, a traffic simulation was developed by modifying an existing JavaScript-based microscopic traffic simulator created by Martin Treiber. Although the original simulator supports multiple roadway scenarios and adjustable traffic parameters, this study focused on a single scenario to evaluate the effects of mixed traffic comprising both human-driven and CACC-equipped vehicles. Vehicles in the simulation were assigned as either ”conventional” or ”CACC-equipped” according to a specified proportion. The behavior of the CACC-equipped vehicles was then modified to incorporate cooperative car-following logic, enabling them to respond differently from conventional vehicles. Simulation runs were performed at multiple adoption levels, and traffic performance was evaluated using metrics for flow stability and phantom traffic-jam formation.

III. Results

The simulation results indicate that CACC systems, as a whole, are effective in avoiding phantom traffic jams and enhancing overall traffic flow. The following sections review the impact of varying CACC penetration rates on traffic flow and show the relative strengths of CACC using different lane configurations.

A. Baseline Phantom Jam Mitigation

The single-lane ring road is the best indicator of CACC effectiveness. As shown in the vehicle trajectory plots of Fig. 1, at 0% CACC penetration, the stop-and-go waves are clearly visible with the circulating diagonal bands of red and orange for the full simulation after the perturbation at $t = 30$s. As shown in Fig. 1, the stop-and-go pattern continues until about 60% CACC. At 60% and 80% CACC penetration, the wave pattern is muted but not entirely gone. At 100% CACC, the trajectories are nearly uniform and green, which shows that cars are in free flow after the initial perturbation.

The traffic flow metrics in Fig. 2 show three metrics being measured: average speed, speed standard deviation, and congestion (speed $< 18km/h$). The top graph shows the average vehicle speed after perturbation. We can see that most lower CACC penetrations (0% - 50%; solid lines) take longer to recover post-perturbation, whereas the dotted lines (60% - 100%) generally recover more quickly and also have higher average speeds. The speed standard deviation measures flow stability, and in all instances, after the perturbation, all CACC levels increase sharply. Still, none of the solid lines recover, whereas the dotted lines eventually recover to a $0km/h$ deviation. Most strikingly, the fraction of vehicles traveling at $18km/h$ or below is a direct proxy for congestion. Interestingly, we see that only 40% - 100% ever recover from congestion, whereas 0% - 30% remain around 0.25 under

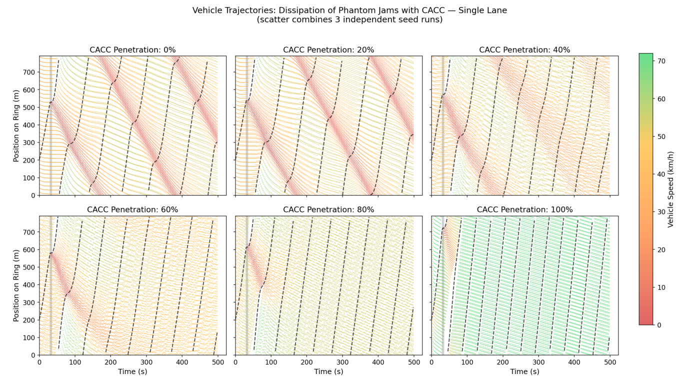

Fig. 1. Vehicle trajectories showing phantom jam dissipation with increasing CACC penetration on a single-lane ring road. Color encodes vehicle speed from stopped (red) to free-flow (green).

human-driven conditions. These results verify that CACC is a traffic shock absorber that significantly reduces phantom jams at penetration rates of 40% or higher.

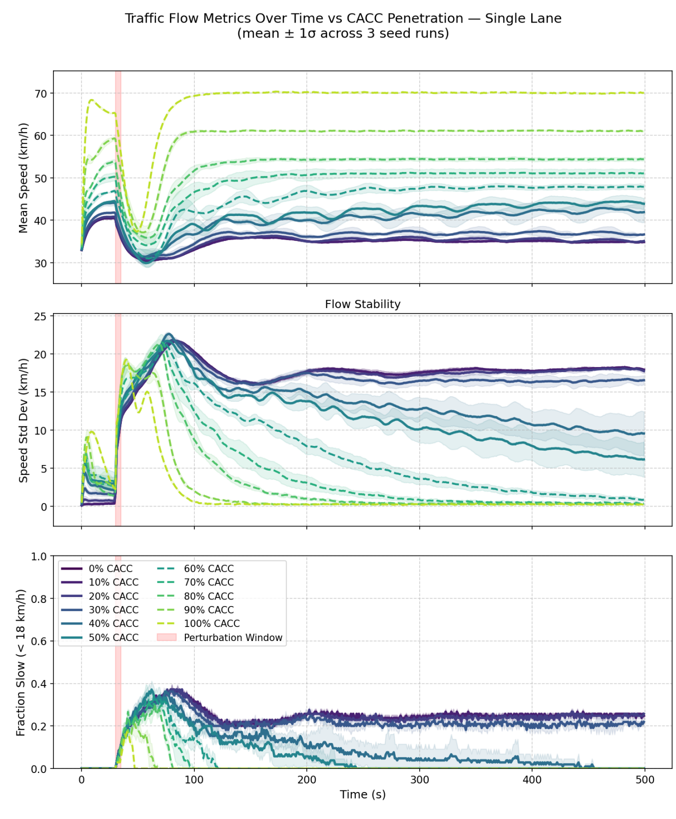

Fig. 2. Traffic flow metrics over time for the single-lane scenario at CACC penetration rates from 0% to 100%. Top: mean speed; Middle: speed standard deviation; Bottom: fraction of vehicles below 5 m/s.

B. Multi-Lane Traffic Metrics and Wave Dissipation

To test the effectiveness of CACC, we extended the simulation to include two, three, and four lanes while keeping the vehicle density at approximately 44.2 veh/km. The trajectory plots for the double-lane, triple-lane, and quad-lane are shown in Figs. 3, 4, and 5, respectively.

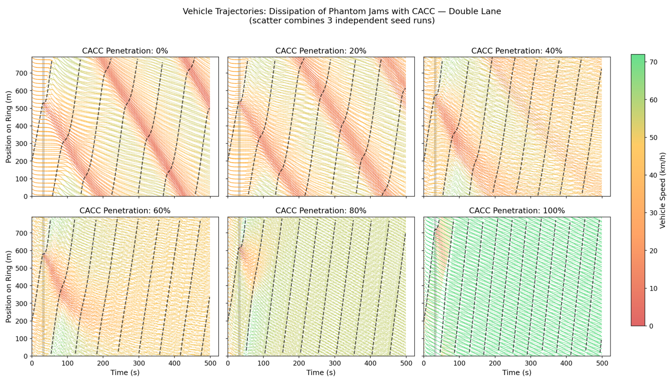

Fig. 3. Vehicle trajectories showing phantom jam dissipation across CACC penetration levels for the double-lane scenario.

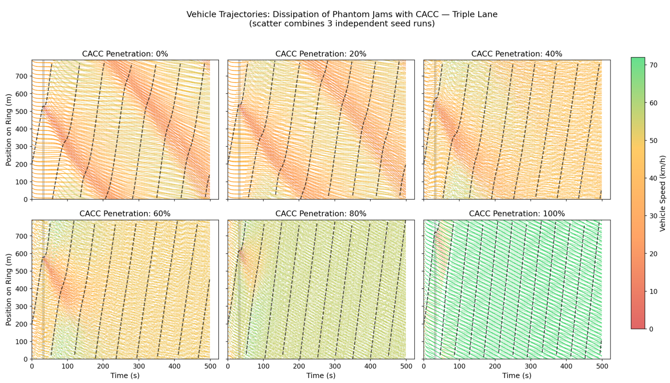

Fig. 4. Vehicle trajectories showing phantom jam dissipation across CACC penetration levels for the triple-lane scenario.

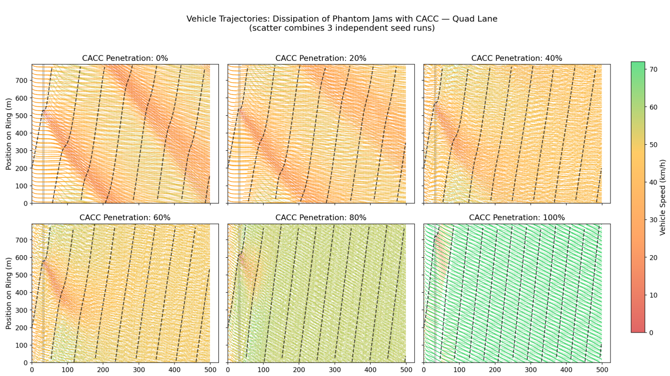

Fig. 5. Vehicle trajectories showing phantom jam dissipation across CACC penetration levels for the quad-lane scenario.

The metric plots for the double-lane show significant disturbance compared to the single-lane. There are fewer stop-and-go bands at 40% and 60%, though the wave width and density are higher, and the bands' gradient is more orange than red, like in the single lane. This shows that cars can navigate congestion using lane-changing maneuvers, even at 0% CACC. As shown in Fig. 6, double-lane results are more gradual but have more noise. These findings are quite similar to Fig. 2, with no significant differences, except that 100% CACC does not achieve the $0km/h$ speed standard deviation. This is likely due to the added lanes hindering the simulation and adding noise.

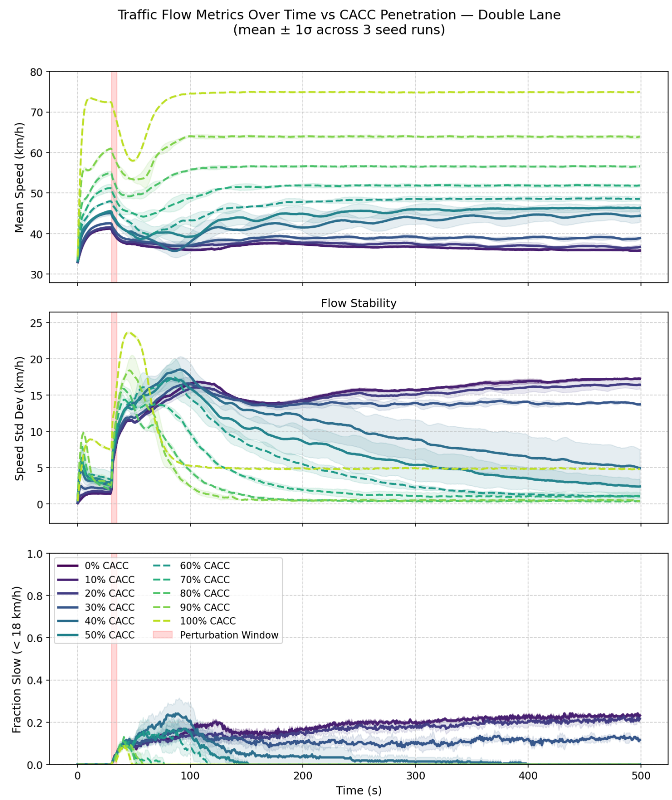

Fig. 6. Traffic flow metrics over time for the double-lane scenario at CACC penetration rates from 0% to 100%.

In the triple- and quad-lane cases (Figs. 7 and 8), we see that additional lanes improve early flow. We notice that the reduction in friction and speed variance for slow vehicles is only 20%-40%, about half of what is seen on a single-lane road. In the tri- and quad-lane, we see that after the perturbation window, the fraction of slow vehicles is nearly zero. This happens because other vehicles in other lanes can pass the slower traffic clusters without the clusters dissipating altogether.

Increasing the number of lanes isn't always beneficial. When considering flow stability as measured by standard deviation (SD), multi-lane flow is much noisier at moderate penetration rates (30% - 60%) than single-lane flow. In the multi-lane stability curves in Figs. 7 and 8, we see wider oscillations and do not plateau even beyond $t = 200$s. Especially at 90% and 100%, the speed standard deviation spikes sharply and then returns to $0km/h$, likely due to repeated lane changes. This confirms that, at higher CACC, additional lanes partially offset the benefits of the added communication.

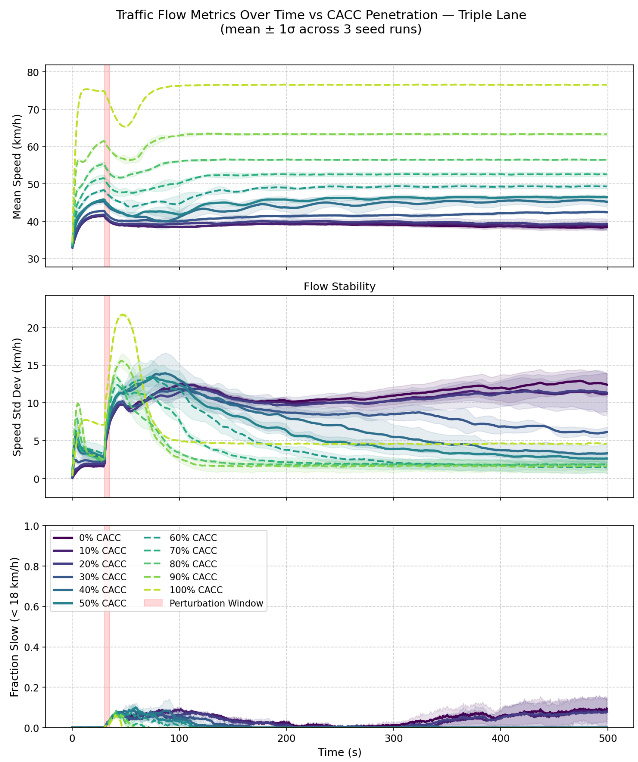

Fig. 7. Traffic flow metrics over time for the triple-lane scenario at CACC penetration rates from 0% to 100%.

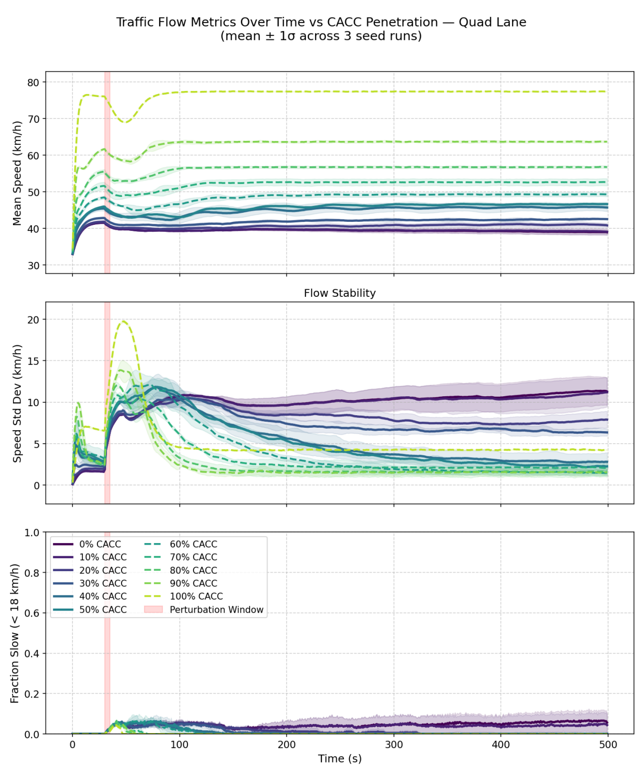

Fig. 8. Traffic flow metrics over time for the quad-lane scenario at CACC penetration rates from 0% to 100%.

C. Benefit of Lane Switching

To test the role of lane-switching in CACC control, per-lane speed, stability, and congestion were compared with the single-lane baseline in Fig. 9, which compares single-lane against double-, triple-, and quad-lane situations.

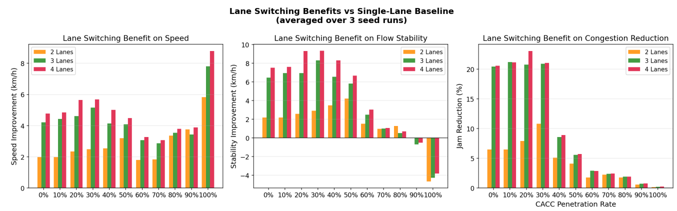

Fig. 9. Lane switching benefits relative to single-lane baseline across CACC penetration rates, measured by speed improvement (left), flow stability improvement (center), and congestion reduction (right).

As shown in the left graph in Fig. 9, lane switching is lane quantity and CACC ratio dependent. With 100% CACC, the four-lane configuration has an average speed improvement of 8.6 km/h over the single-lane configuration. While the two-lane configuration adds about 5.8 km/h to this, it demonstrates that higher CACC penetration with more lanes gives a higher speed improvement because cars can pass slower ones without the shock waves caused by human-driven cars.

The center graph illustrates flow stability, which is quite sensitive to lane switching. Stability improves at around 50%- 60% CACC penetration across all lane configurations. Generally, more lanes improve stability as CACC vehicles use open lanes to absorb shock waves. But at 90%- 100% CACC penetration, stability improvements are negative across all lane types, dropping to around $-4km/h$. This is because, at near-full CACC penetration, only cooperative coordination is needed to stabilize the perturbation, and lane changes introduce minor disturbances that hinder stability.

The graph on the right shows that at low CACC penetration (0% - 30%), congestion is reduced by $20\% - 24\%$ with 3-4 lanes relative to single lanes. Whereas in moderate CACC penetration (40% - 50%), the congestion-reduction benefits drop to around 5%. At extremely high CACC penetration levels, adding more lanes provides negligible benefit. Proving that CACC deployment should be prioritized over wider roads.

D. Concluding Results

In addition to the single comparative table, a unified comparison across all lane configurations is presented in Fig. 10.

Multi-lane roads consistently outperform single-lane roads in all three studies and all CACC penetration levels. The mean speed advantage after perturbation on multi-lane roads varies across $0\% - 100\%$ CACC, with four lanes and full penetration reaching over $72km/h$, vs single-lane full penetration reaching $64km/h$. The speed advantage increases exponentially with CACC penetration.

On the other hand, the flow stability comparisons show that, for high CACC penetration, the speed standard deviation for all configurations is lower at $5.4km/h$ when measured at $70\% -$

Fig. 10. Phantom jam mitigation comparison across lane configurations. Top row: absolute metrics. Lower rows: improvement of each multi-lane configuration relative to the single-lane baseline.

80%. In each flow stability graph comparing double, triple, and quad vs. single, we see that generally $90\% - 100\%$ CACC causes stability to drop by $5.4 km/h$.

Now, comparing congestion, we see it reduced by more than 20% over single-lane traffic, up to $50\% - 60\%$ at $CACC$ penetration. Three- and four-lane configurations reduce the jam fraction by more than 20 percentage points compared to single-lane configurations. As CACC penetration rises above 60% all, lane configurations decrease towards zero. These results indicate that when CACC penetration is low or moderate (below 60%), multi-lane roads provide a substantial benefit in reducing congestion by at least 20%. Partial CACC deployment is effective in eliminating phantom jams regardless of lane count and full CACC penetration.

IV. Authors and Affiliations

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Credit Authorship Contribution Statement

Aashish Harishchandre: Software - Logging Feature, Formal Analysis, Writing - Original Draft Preparation.
Lucas Wolstencroft: Conceptualization, Methodology, Validation, Writing - Review & Editing.
Prabhaav Ravikumar Pillai: Software - Scenario Feature, Data Visualization, Writing - Review & Editing.

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