ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

Coupling Effects of Heterogeneous Traffic Flow and Facility Design on Capacity of Tunnel Group Sections in CAV Environment

Tianxing Zhang [1, a, *], Dehua Wu [2], Jingsong Liu [2]

[1]College of Information and Intelligent Transportation, Fujian Chuanzheng Communications College, Fuzhou, China

[2]College of Civil Engineering, Fuzhou University, Fuzhou, China

[a]2009017@fjcpc.edu.cn

[*] Corresponding author

Abstract

With the advancement of connected and autonomous vehicle (CAV) technology, the traffic flow in highway tunnel group sections has transformed into a heterogeneous mix of CAVs and human-driven vehicles (HDVs). The operational capacity of these sections is influenced by multiple interdependent factors, including traffic composition, speed limit control, and tunnel configuration. Understanding the coupling mechanisms among these factors is essential for enhancing both efficiency and safety. In this study, we first analyze the characteristics of heterogeneous traffic flow under CAV conditions and the structural features of various tunnel group layouts. An integrated simulation model is then developed by combining an enhanced NaSch cellular automaton model with the Intelligent Driver Model (IDM), capturing the dynamic interactions among heterogeneous traffic, speed limits, and tunnel geometry. Through multi-scenario simulations, the individual and coupled influences of these factors on tunnel group capacity are systematically examined. The results indicate that: (1) Increasing the CAV penetration rate improves operational capacity significantly, with capacity growth tapering off after the rate exceeds 60%; (2) Each tunnel configuration corresponds to an optimal speed limit range, and a mismatch can cause considerable capacity reduction; (3) The coupling effect of traffic composition and speed control is particularly pronounced in long-span tunnel groups, where appropriately matching CAV penetration with speed limits can maximize capacity. This study elucidates the internal coupling mechanisms governing the operational capacity of tunnel groups and offers theoretical and technical support for the refined design and intelligent management of highway tunnel sections in a CAV environment.

Keywords

Connected and autonomous vehicle; Heterogeneous traffic flow; Tunnel group; Operational capacity; Coupling mechanism; Speed limit control.

1. INTRODUCTION

Highway tunnel groups, as key nodes of the transportation network, play an important role in improving the efficiency of cross-regional transportation and promoting regional economic development. However, due to the closed and narrow characteristics of tunnel sections, the operational capacity and traffic safety of tunnel groups are often restricted by multiple factors [1]. With the rapid development of intelligent transportation technology, connected and autonomous vehicles (CAVs) have gradually entered the practical stage, which has brought

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

profound changes to the composition and operation characteristics of traffic flow. The traffic flow in tunnel group sections has transformed from a single human-driven vehicle (HV) flow to a heterogeneous traffic flow composed of CAVs and HVs. Compared with traditional traffic flow, heterogeneous traffic flow has more complex dynamic characteristics, and its interaction with speed limit control measures and tunnel configuration parameters will have a significant impact on the operational capacity of tunnel groups [2-4].

At present, research on the operational capacity of tunnel groups primarily focuses on single factors, such as tunnel structural parameters, traffic flow characteristics, or speed limit control [5]. For example, some scholars have used field surveys and simulation methods to study the influence of parameters like tunnel length and lane width on capacity [6]; others have analyzed the impact of speed limit values on traffic flow efficiency [7-8]. However, under the CAV environment, the operational capacity of tunnel groups is in fact the result of the coupling effects of multiple factors, including heterogeneous traffic composition, speed limit control, and tunnel configuration. Existing studies lack a systematic analysis of the coupling relationships among these factors and fail to clarify the underlying mechanisms through which they jointly affect capacity.

Therefore, this study focuses on tunnel group sections in a CAV environment and investigates the coupling mechanisms through which heterogeneous traffic composition, speed limit control, and tunnel configurations jointly affect operational capacity. The specific research objectives are:

(1) to clarify the composition characteristics of heterogeneous traffic flow and the structural features of different tunnel configurations;

(2) to construct a coupled simulation model that accounts for interactions among multiple factors;

(3) to explore, through simulation experiments, the influence of individual factors and their combined effects on operational capacity; and

(4) to propose relevant recommendations for the optimal design and operational management of tunnel groups.

This research contributes to enriching the theoretical framework for traffic flow in tunnel groups under intelligent transportation environments and offers practical guidance for enhancing the operational efficiency and safety of such sections.

2. LITERATURE REVIEW

2.1. Research on Operational Capacity of Tunnel Groups

The operational capacity of tunnel groups is defined as the maximum number of vehicles that can pass through a tunnel group section per unit of time under given traffic conditions, roadway geometry, and control measures. Scholars worldwide have conducted extensive research on this topic. Early studies predominantly focused on the impact of tunnel geometric parameters on capacity. For instance, Liu et al. (2020) [9] collected field data and performed statistical analyses to examine the relationship between tunnel length, lane width, and operational capacity, proposing a capacity calculation model tailored for mountainous highway tunnel groups. Similarly, Wang and Zhang (2019) investigated how the design of tunnel entrances and exits influences traffic flow, finding that suboptimal designs can cause congestion and reduce capacity.

With advances in simulation technology, an increasing number of researchers have employed simulation tools to study tunnel group capacity. For example, Zhang et al. (2021) [10] developed a traffic flow simulation model for tunnel groups using VISSIM and analyzed the effect of varying traffic densities on operational capacity. Their results indicated that capacity declines

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

significantly once traffic density surpasses a certain threshold. Nonetheless, most of these studies were conducted under conventional human-driven vehicle (HV) conditions and did not account for the influence of Connected and Autonomous Vehicles (CAVs) on the operational capacity of tunnel groups.

2.2. Research on Heterogeneous Traffic Flow Under CAV Environment

In a CAV environment, traffic flow consists of a mix of Connected and Autonomous Vehicles (CAVs) and Human-driven Vehicles (HVs), forming a typical heterogeneous traffic stream. The differences in dynamic characteristics—such as acceleration/deceleration performance, response time, and car-following behavior—between CAVs and HVs introduce greater complexity into the operation of heterogeneous traffic flow. Scholars have conducted related research on the properties of such mixed traffic. For example, Chen et al. (2022) investigated the car-following behavior of heterogeneous traffic based on the Intelligent Driver Model (IDM) and found that increasing the CAV penetration rate can enhance traffic flow stability. Similarly, Li et al. (2023) developed a cellular automaton model for heterogeneous traffic and analyzed the effect of CAV penetration on traffic efficiency, demonstrating that traffic flow efficiency improves as CAV penetration rises.

However, most existing studies on heterogeneous traffic flow have focused on open highway segments, with limited attention given to tunnel group sections. Tunnel groups present distinct challenges—such as enclosed spaces, reduced visibility, and frequent speed changes—which further complicate the operational dynamics of heterogeneous traffic. Consequently, the influence of heterogeneous traffic composition on the operational capacity of tunnel groups remains an area requiring further investigation.

2.3. Research on the Influence of Speed Limit Control on Traffic Flow Operation

Speed limit control serves as a critical measure to ensure the operational safety of tunnel groups and also exerts a significant influence on their capacity. Numerous studies have examined the relationship between speed limits and traffic flow performance. For instance, Zhao et al. (2020) conducted field experiments to assess the impact of different speed limit values on the operational efficiency of tunnel sections, identifying an optimal speed threshold that balances safety and throughput. Similarly, Lee and Park (2018) analyzed how variable speed limit control affects traffic congestion and proposed an optimization method based on real-time traffic data.

However, existing research on speed limit control has predominantly focused on isolated tunnel sections, with limited attention paid to the alignment between speed regulations and the specific configurations of tunnel groups. In a CAV environment, the enhanced speed-adjustment capability of connected and autonomous vehicles may alter the effectiveness of speed limit strategies compared to conventional settings. Therefore, further investigation is needed to understand how speed limit control influences the operational capacity of tunnel groups under heterogeneous traffic flow conditions.

2.4. Summary of Existing Research

In summary, while existing research has contributed to understanding the operational capacity of tunnel groups, the characteristics of heterogeneous traffic flow, and speed limit control, several limitations remain:

(1) Most studies on tunnel group capacity have been conducted under traditional HV conditions, largely overlooking the impact of CAVs;

(2) Research on heterogeneous traffic flow has predominantly focused on open highway sections, with insufficient attention given to tunnel group segments;

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

(3) Little consideration has been given to the interactions among heterogeneous traffic composition, speed limit control, and tunnel configuration, leaving the coupling mechanisms through which these factors jointly affect operational capacity unclear.

In light of these gaps, this study will systematically investigate the coupling effects of heterogeneous traffic composition, speed limit control, and tunnel configurations on the operational capacity of tunnel groups in a CAV environment, using simulation-based experiments.

3. RESEARCH FRAMEWORK AND METHODOLOGY

3.1. Heterogeneous Traffic Flow Composition in a CAV Environment

Within a CAV environment, traffic flow is characterized by its heterogeneity, consisting of a mixture of Connected and Autonomous Vehicles (CAVs) and Human-driven Vehicles (HVs). The fundamental distinctions between CAVs and HVs are manifested in three key operational aspects:

(1) Response Speed: Leveraging Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, CAVs can access and process real-time traffic information. This enables them to respond to signals and the behavior of preceding vehicles with significantly lower latency compared to HVs.

(2) Car-Following Behavior: Through precise longitudinal control, CAVs are capable of maintaining a consistently shorter safe headway. In contrast, the following distance for HVs is typically larger and more variable, influenced by human factors such as perception-reaction time.

(3) Acceleration and Deceleration Performance: CAVs exhibit more stable and predictable acceleration and deceleration profiles, governed by predefined algorithms. The performance of HVs, however, shows greater variance due to differences in individual driving habits and vehicle mechanical characteristics.

To quantify the mixture of vehicle types, the composition of heterogeneous traffic flow is commonly defined by the CAV Penetration Rate—the ratio of CAVs to the total number of vehicles in the traffic stream. In this study, the CAV penetration rate is varied across six levels (0%, 20%, 40%, 60%, 80%, and 100%) to simulate a comprehensive range of heterogeneous traffic scenarios.

3.2. Structural Characteristics of Different Tunnel Configurations

Tunnel configuration refers to the geometric layout and structural arrangement of multiple consecutive tunnels within a group. The key parameters defining a configuration include the length of individual tunnels, the spacing between adjacent tunnels, the number of lanes, and the lane width.

This study focuses on three representative tunnel configurations to analyze their distinct impacts:

(1) Short-span Tunnel Group: Individual tunnel length < 500 m, with an inter-tunnel spacing of 100–300 m.

(2) Medium-span Tunnel Group: Individual tunnel length between 500–1000 m, with an inter-tunnel spacing of 300–500 m.

(3) Long-span Tunnel Group: Individual tunnel length > 1000 m, with an inter-tunnel spacing of 500–800 m.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

To maintain consistency and isolate the effects of tunnel length and spacing, the lane width is fixed at the standard 3.5 m. The study further examines two common lane configurations: two-lane and three-lane setups for each tunnel type.

3.3. Construction of Coupled Simulation Model for Operational Capacity

To assess the operational capacity of tunnel groups under CAV conditions, a coupled simulation model was developed by integrating an enhanced NaSch cellular automaton model with the Intelligent Driver Model (IDM). The NaSch model serves as a classic cellular automaton framework capable of simulating fundamental traffic flow dynamics, including acceleration, deceleration, car-following, and stochastic delay. However, as the conventional NaSch model does not adequately represent the dynamic characteristics of CAVs, it was enhanced in this study by incorporating CAV-specific communication features and precision control capabilities.

The improved NaSch model for CAVs incorporates the following key enhancements:

(1) Real-Time Information Sharing: Leveraging V2V communication, CAVs acquire real-time speed and position data from preceding vehicles, enabling proactive speed adjustment.

(2) Precision Car-Following Control: CAVs adopt an IDM-based optimal following strategy, which maintains a shorter yet safe headway while ensuring driving stability.

(3) Responsive Speed-Limit Compliance: CAVs accurately and smoothly respond to posted speed limits, demonstrating more stable and rapid speed transitions compared to HVs.

The simulation framework constructed in this study consists of five functional modules:

(1) Traffic Flow Generation Module: Generates heterogeneous traffic streams with specified CAV penetration rates.

(2) Tunnel Scene Construction Module: Configures tunnel-group geometries based on structural parameters such as tunnel length, spacing, and lane layout.

(3) Speed Limit Control Module: Implements and manages static or variable speed limit schemes.

(4) Traffic Flow Operation Module: Simulates the movement of heterogeneous traffic through tunnel groups using the improved NaSch model.

(5) Data Collection and Analysis Module: Records simulation outputs—including speed, density, and throughput—and analyzes the influence of various factors on operational capacity.

3.4. Design of Simulation Scenarios

To systematically investigate the coupling mechanisms through which heterogeneous traffic composition, speed limit control, and tunnel configurations jointly affect operational capacity, this study designed both single-factor and multi-factor coupled simulation scenarios. This approach allows for the isolation of individual factor effects as well as the analysis of their complex interactions.

3.4.1. Single-Factor Simulation Scenarios

To isolate the impact of each primary variable, three sets of single-factor scenarios were designed by holding two factors constant while varying the third:

(1) Traffic Composition Scenarios: With the tunnel configuration (medium-span tunnel group, two lanes) and the speed limit (80 km/h) fixed, the CAV penetration rate was varied across six levels (0%, 20%, 40%, 60%, 80%, 100%).

(2) Speed Limit Control Scenarios: With the tunnel configuration (medium-span tunnel group, two lanes) and the CAV penetration rate (50%) fixed, the posted speed limit was varied across five levels (60, 70, 80, 90, 100 km/h).

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

(3) Tunnel Configuration Scenarios: With the CAV penetration rate (50%) and the speed limit (80 km/h) fixed, the tunnel configuration was varied to include all three geometric types (short-span, medium-span, and long-span tunnel groups), each implemented with both two-lane and three-lane setups.

3.4.2. Multi-Factor Coupled Simulation Scenarios

To comprehensively examine the interaction effects among the three key factors, a full-factorial experimental design was employed. Key levels of each factor—CAV penetration rates (20%, 40%, 60%, 80%), speed limits (60, 70, 80, 90 km/h), and tunnel configurations (short-, medium-, and long-span groups)—were combined, resulting in 4 × 4 × 3 = 48 unique coupled scenarios. The two-lane configuration was used for this coupled analysis to maintain a manageable scope while capturing the core interaction dynamics.

For all scenarios, the total simulation duration was set to 3600 seconds. A 300-second warm-up period preceded data collection in each run to ensure the traffic flow reached a stable operational state, thereby guaranteeing the reliability of the collected performance metrics.

4. SIMULATION RESULTS AND ANALYSIS

4.1. Analysis of Single-Factor Influence

4.1.1. Influence of Heterogeneous Traffic Composition on Operational Capacity

The simulation results demonstrate a positive correlation between operational capacity and CAV penetration rate (see Figure 1). Under a pure HV scenario (0% CAV penetration), the capacity was 1850 pcu/h. A CAV penetration rate of 20% increased the capacity to 2100 pcu/h, representing a growth of 13.5%. When the penetration rate reached 60%, capacity rose significantly to 2650 pcu/h, marking a 43.2% increase compared to the baseline. However, beyond the 60% threshold, the rate of capacity growth began to taper off. At 100% CAV penetration, the capacity stabilized at 2850 pcu/h, showing only a marginal 7.5% increase relative to the capacity at 60% penetration.

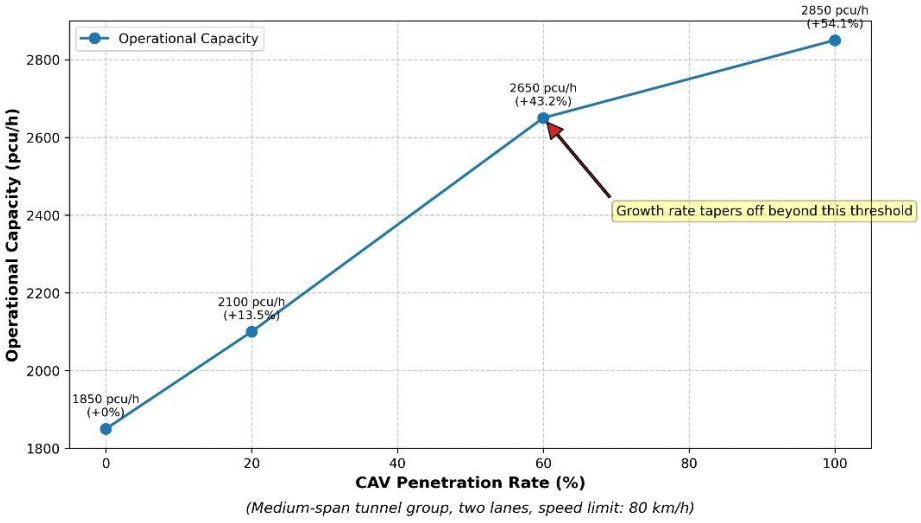


Figure 1. Operational capacity as a function of CAV penetration rate

This pattern can be attributed to the inherent advantages of CAVs, such as faster response times and precise car-following control, which enhance road resource utilization and mitigate congestion. As the CAV penetration rate increases, these characteristics elevate the overall efficiency of the mixed traffic flow. However, once the penetration rate exceeds 60%, the traffic stream essentially transitions into a CAV-dominant regime characterized by stable operations, leaving limited further room for capacity improvement.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

4.1.2. Impact of Speed Limit Control on Operational Capacity

The operational capacity exhibits a non-monotonic relationship with the posted speed limit, initially increasing before declining beyond a certain threshold (see Figure 2). The maximum capacity of 2450 pcu/h was achieved at a speed limit of 70 km/h. At limits below this optimum, traffic flow speed is constrained, leading to a steady rise in capacity as the limit increases. Conversely, when the speed limit exceeds 70 km/h, the higher travel speeds elevate safety risks within the tunnel-group environment. In response, drivers (or vehicle control systems) tend to maintain longer following distances to preserve safety margins, which reduces road-space utilization and ultimately diminishes capacity.

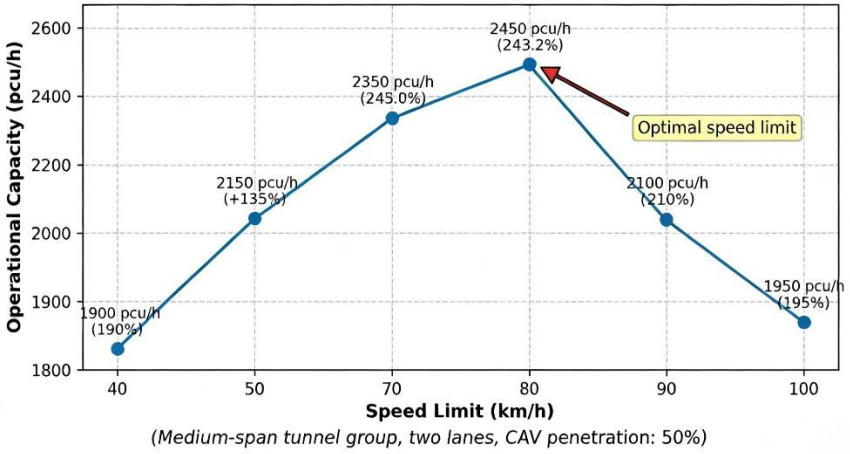


Figure 2. Operational capacity as a function of speed limit

These results indicate the existence of an optimal speed-limit range for tunnel-group sections. A properly set speed limit can effectively balance traffic flow efficiency with operational safety, thereby maximizing capacity. Conversely, an improperly set limit—whether too high or too low—compromises this balance and leads to a reduction in achievable throughput.

4.1.3. Influence of Tunnel Configuration on Operational Capacity

For a given number of lanes, operational capacity varies inversely with tunnel span. Conversely, for a given tunnel span, capacity increases with the number of lanes. Detailed numerical results are presented in Table 1.

Table 1. Operational capacity of different tunnel configurations (50% CAV penetration rate, 80km/h speed limit)

Tunnel Configuration	Single Tunnel Length Range (m)	Operational Capacity (pcu/h)
Two-lane short-span tunnel group	<500	2500
Two-lane medium-span tunnel group	500-1000	2350
Two-lane long-span tunnel group	>1000	2100
Three-lane short-span tunnel group	<500	3600
Three-lane medium-span tunnel group	500-1000	3450
Three-lane long-span tunnel group	>1000	3200

The reason is that the longer the tunnel length, the poorer the visibility and the higher the safety risk. Drivers need to reduce the speed and increase the following distance, resulting in a decrease in capacity. The increase in the number of lanes increases the road resources, which can accommodate more vehicles and improve the operational capacity.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

4.2. Analysis of Multi-Factor Coupling Effect

4.2.1. Coupling Effect of Heterogeneous Traffic Composition and Speed Limit Control

The analysis reveals a clear interdependence between the optimal speed limit and the CAV penetration rate. As the penetration rate increases, the speed limit that maximizes operational capacity also shifts upward. Specifically, the optimal speed limit rises from 60 km/h at a 20% penetration rate (yielding a maximum capacity of 2150 pcu/h) to 70 km/h at 40% (2350 pcu/h), and further to 80 km/h at penetration rates of 60% and 80%, achieving capacities of 2650 pcu/h and 2750 pcu/h, respectively (see Figure 3).

This demonstrates a significant coupling effect. The underlying mechanism is that CAVs possess superior speed-adjustment and safety-control capabilities, enabling the mixed traffic stream to operate safely and efficiently at higher speeds. Consequently, when designing speed limit strategies for tunnel groups, it is essential to account for the prevailing traffic composition. Ensuring a rational match between the posted speed limit and the characteristics of the heterogeneous traffic flow is critical for maximizing operational capacity.

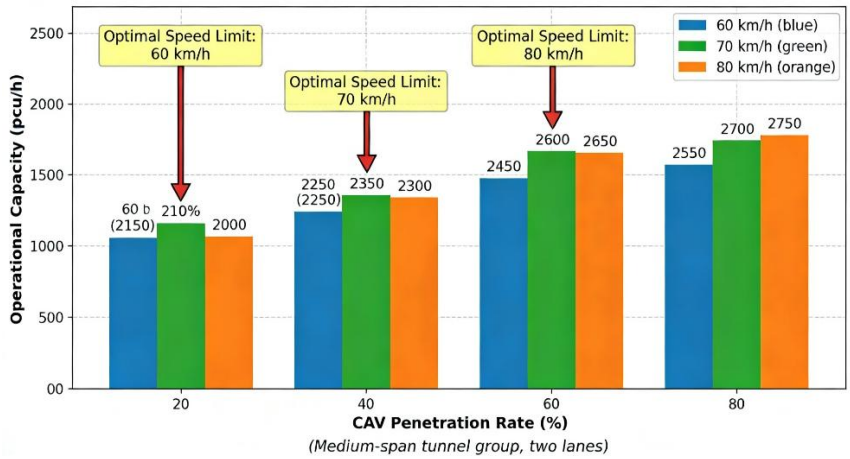


Figure 3. Coupling effect of CAV penetration rate and speed limit on operational capacity

4.2.2. Coupling Effect of Heterogeneous Traffic Composition and Tunnel Configuration

Across all tunnel configurations, operational capacity increased with higher CAV penetration rates, though the rate of improvement varied significantly. Long-span tunnel groups exhibited the greatest capacity enhancement, followed by medium-span and then short-span groups. Specifically, as the penetration rate rose from 0% to 100%, capacity increased by 50% for long-span tunnels, 43.2% for medium-span tunnels, and 35.1% for short-span tunnels. Furthermore, the capacity gap between different tunnel configurations narrowed as CAV penetration increased. For instance, the capacity difference between short-span and long-span tunnels was 450 pcu/h at 0% penetration, which decreased to 250 pcu/h at 100% penetration (see Figure 4).

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

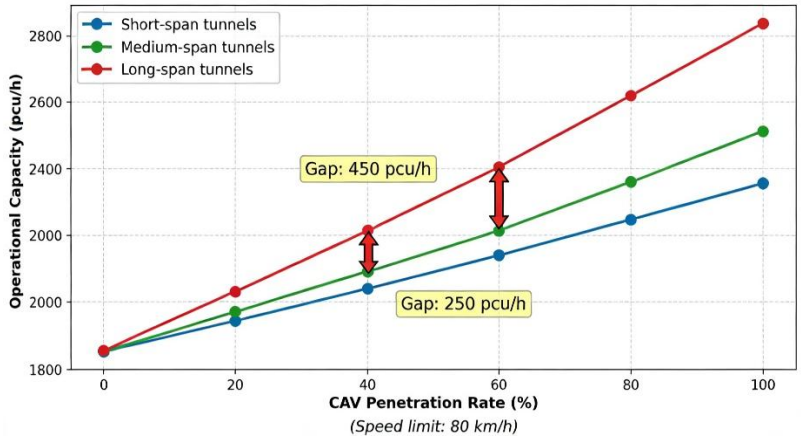


Figure 4. Coupling effect of CAV penetration rate and tunnel configuration on operational capacity

These results indicate that CAV technology can effectively mitigate the capacity limitations associated with suboptimal tunnel configurations. Higher CAV penetration rates reduce the sensitivity of capacity to tunnel geometry, implying that CAVs can compensate for design-related inefficiencies. This finding holds important practical implications for improving traffic performance in existing tunnel groups with less favorable geometries, suggesting that CAV deployment can be a viable strategy for enhancing operational efficiency without major structural modifications.

4.2.3. Coupling Effect of Speed Limit Control and Tunnel Configuration

The optimal speed limit varied significantly across tunnel configurations. Specifically, the short-span tunnel group achieved its maximum capacity of 2550 pcu/h at an 80 km/h speed limit, the medium-span group reached 2450 pcu/h at 70 km/h, and the long-span group attained 2250 pcu/h at 60 km/h. The corresponding data are summarized in Table 2.

Table 2. Coupling effect of speed limit and tunnel configuration on operational capacity

(CAV penetration rate: 50%)

Tunnel Configuration	60km/h	70km/h	80km/h	90km/h	100km/h
Short-span tunnel group	2400	2500	2550	2450	2300
Medium-span tunnel group	2350	2450	2350	2200	2050
Long-span tunnel group	2250	2200	2100	1950	1800

These results indicate that the optimal speed limit is inversely related to tunnel span. Longer tunnels are typically characterized by reduced visibility and heightened safety risks, which necessitates the adoption of lower speed limits to maintain safe operation.

4.2.4. Comprehensive Coupling Effect of Three Factors

To further examine the combined impact of heterogeneous traffic composition, speed limit control, and tunnel configuration on operational capacity, this study identified the maximum capacity achievable under each multi-factor scenario. The results confirm a significant integrated effect among the three factors. The highest capacity of 3650 pcu/h was achieved under the scenario combining an 80% CAV penetration rate, an 80 km/h speed limit, and a three-lane medium-span tunnel group. In contrast, the lowest capacity of 1650 pcu/h occurred under the scenario of 0% CAV penetration, a 100 km/h speed limit, and a two-lane long-span tunnel group.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

Analysis of variance (ANOVA) was conducted to assess the relative influence of each factor. The results indicate that, in terms of individual effect size, the factors can be ranked as follows: tunnel configuration > heterogeneous traffic composition > speed limit control. This suggests that tunnel geometry is the most influential factor determining tunnel-group capacity, followed by traffic composition, while speed limit control exerts a comparatively smaller independent effect. Importantly, however, the interactions among all three factors are statistically significant. This underscores that capacity is maximized not by any single factor alone, but through the appropriate matching of traffic composition, speed regulations, and tunnel design.

5. DISCUSSION

Simulation results demonstrate that the operational capacity of tunnel-group sections in a CAV environment is shaped by the coupled effects of heterogeneous traffic composition, speed limit control, and tunnel configuration. The main findings are as follows:

(1) Increasing the CAV penetration rate significantly enhances tunnel-group capacity, particularly below the 60% threshold. This aligns with findings by Li et al. (2023) on open highway sections, indicating that CAV technology improves traffic flow efficiency across different road types.

(2) Each tunnel configuration exhibits an optimal speed limit range, with the ideal value decreasing as tunnel span increases. This result diverges from studies focusing on isolated tunnels (e.g., Zhao et al., 2020), largely because the serial layout of tunnel groups introduces inter-tunnel interactions that complicate the effect of speed control.

(3) CAV technology can effectively compensate for capacity shortfalls caused by suboptimal tunnel geometries, offering a new perspective for upgrading existing tunnel-group infrastructure.

5.1. Theoretical and Practical Implications

The study contributes both theoretically and practically. Theoretically, it clarifies the coupling mechanisms governing tunnel-group capacity under CAV conditions and extends the traffic-flow theory for confined, serial infrastructures. Practically, it provides evidence-based guidance for the refined design and intelligent management of tunnel groups. For instance, in new tunnel projects, geometric parameters may be selected with reference to forecasted CAV penetration rates. In existing tunnels, speed limits could be dynamically adjusted in response to real-time CAV penetration to maximize throughput.

5.2. Limitations and Future Research

Several limitations should be acknowledged:

(1) The simulation model builds upon an enhanced NaSch cellular automaton, which simplifies certain traffic-flow dynamics. Future work could adopt more detailed microscopic models, such as multi-agent simulation frameworks, to improve behavioral accuracy.

(2) Only three factors—traffic composition, speed control, and tunnel geometry—were considered. Real-world capacity is also influenced by weather, driver behavior, and incident scenarios, which should be incorporated in subsequent studies.

(3) Scenario parameters were based on assumed values. Future research should validate the findings with field data from CAV-penetrated traffic streams to strengthen the practical reliability of the results.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

6. CONCLUSION

This study investigated the operational capacity of tunnel group sections in a connected and autonomous vehicle (CAV) environment, focusing on the coupling mechanisms among heterogeneous traffic composition, speed limit control, and tunnel configuration. By developing a coupled simulation model and conducting multi-scenario experiments, the main conclusions are as follows:

(1) The operational capacity of tunnel groups increases with the increase of CAV penetration rate, and the growth rate tends to be gentle when the penetration rate exceeds 60%. The CAV technology can improve the utilization rate of road resources and reduce traffic congestion, thus improving the operational capacity.

(2) There is an optimal speed limit range for different tunnel configurations. The optimal speed limit value decreases with the increase of tunnel span. The unreasonable speed limit (too high or too low) will lead to a significant reduction in the operational capacity of tunnel groups.

(3) The coupling effect of the three factors is significant. The influence degree of the three factors on operational capacity is: tunnel configuration > heterogeneous traffic composition > speed limit control. The reasonable matching of the three factors can maximize the operational capacity of tunnel groups.

(4) The CAV technology can effectively make up for the deficiency of capacity caused by unreasonable tunnel configuration. The higher the CAV penetration rate, the smaller the impact of tunnel configuration on capacity.

Based on these findings, the following recommendations are proposed:

(1) In designing new tunnel groups, geometric parameters should be selected in accordance with forecasted CAV penetration rates to optimize capacity.

(2) For existing tunnel groups, dynamic speed limit strategies should be implemented, adjusted in real time according to CAV penetration and traffic conditions, to balance safety and efficiency.

(3) Efforts should be accelerated to promote CAV adoption and develop intelligent transportation infrastructure, thereby raising penetration rates and enabling smarter tunnel group management.

Future work will refine the simulation model by incorporating additional influencing factors and validating results with field data. Research will also extend to examine the coupled effects of multiple factors on traffic safety in tunnel groups, providing more comprehensive theoretical and practical guidance for their operation in an intelligent transportation environment.

ACKNOWLEDGMENTS

This research was funded by Fujian Transport Science and Technology Project, grant number 202223, and was supported in part by School Science Innovation Foundation of Fujian Chuanzheng Communications College, China (No.20220209).

REFERENCES

[1] Yang, M., Wang, Y., Chen, J., & Zhang, Q. Evaluation of Design Method for Highway Adjacent Tunnel and Exit Connecting Sections Using VISSIM and Entropy-Based Multi-Attribute Decision Making. Entropy, 2022, 24(12), 1794.

[2] Chen, Y., Wang, X., Li, H. Following behavior of heterogeneous traffic flow under connected and autonomous vehicle environment. Journal of Transportation Systems Engineering and Information Technology, 2022, 22(4):189-196.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202601_12(1).0005

[3] Li, M., Zhang, Q., Chen, W. Simulation study on the influence of CAV penetration rate on traffic flow efficiency. China Journal of Highway and Transport, 2023, 36(3):201-209.

[4] Zhao, J., Liu, Y., Zhang, S. Experimental study on the influence of speed limit on operational efficiency of tunnel sections. Journal of Highway and Transportation Research and Development, 2020, 37(8):115-121.

[5] Lee, S., Park, B. Variable speed limit control for reducing traffic congestion in tunnel sections. Transportation Research Part C: Emerging Technologies, 2018, 96:345-360.

[6] Jiang, R., Wu, Z., Chen, Y. Heterogeneous traffic flow characteristics and capacity analysis under connected vehicle environment. Journal of Traffic and Transportation Engineering, 2021, 21(2):135-143.

[7] Zheng, Y., Li, S., Wang, J. Coupling effect of speed limit and traffic flow composition on highway capacity. Journal of Safety and Environment, 2022, 22(3):1123-1129.

[8] Van Arem, B., Van Driel, C. J. G., Visser, R. The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Transactions on Intelligent Transportation Systems, 2006, 7(4):429-436.

[9] Liu, J., Zhang, Y., Wang, L. Research on operational capacity of mountain highway tunnel groups based on field data. Journal of Highway and Transportation Research and Development, 2020, 37(5):101-107.

[10] Zhang, L., Li, J., Zhao, H. Simulation study on operational capacity of tunnel groups based on VISSIM. Journal of Safety and Environment, 2021, 21(2):654-660.