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Optimization of Dedicated Lane Configuration for Connected and Automated Heavy-Duty Trucks in Mixed Traffic Flow

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Abstract

With the rapid development of intelligent connected vehicle technology and sustained growth in freight demand, connected and automated trucks (CATs) have significantly increased their market share in airport freight corridors, forming a complex mixed traffic flow of human-driven and automated vehicles. To investigate the impact of dedicated CAT lane configurations under different market penetration rates (MPR) on traffic systems, this study establishes an evaluation framework for dynamic management of mixed traffic flows in intelligent freight corridors using the SUMO simulation platform. By integrating vehicle dynamics models and cooperative control algorithms, five lane management strategies were designed and evaluated through multi-dimensional metrics to systematically analyze traffic flow patterns under different penetration rates and strategy combinations. Results demonstrate that when CAT penetration exceeds 40%, dedicated lane strategies significantly enhance system performance: traffic efficiency improves by up to 19.31%, truck-related conflict risks are reduced by 100%, and average carbon emissions per vehicle decrease by 7%.

Keywords

Intelligent Transportation, Mixed Traffic Flow, SUMO, Connected Freight Trucks, Dedicated Lanes

1. Introduction

With the advancement of economic globalization and the establishment of China's "dual-circulation" development paradigm, the proportion of freight logistics in the national economy continues to increase, leading to growing pressure on freight corridor transportation. Among these, airport freight logistics serve as a critical strategic resource for national economic development. Simultaneously, alongside the continuous development of intelligent and connected technologies, the government anticipates that the market penetration rate of Connected and Automated Vehicles (CAVs) will exceed 30% by 2030, resulting in mixed traffic flows comprising both human-driven and automated vehicles. In response to these trends, freight corridors—which prioritize efficiency, safety, and environmental sustainability—are confronted with a dual contradiction: On one hand, the irreversible trend of human-machine mixed driving modes has disrupted the steady-state equilibrium of traditional transportation systems, as human-driven vehicles and CAVs exhibit significant differences in decision-making logic and reaction latency. On the other hand, coordination challenges arising from vehicle heterogeneity are becoming increasingly pronounced. Parameters such as dynamic performance, braking capability, and car-following distance of heavy-duty trucks (HDTs) differ considerably from those of passenger cars, making lane-level precise management of heterogeneous traffic flows a critical challenge.

To better leverage the advantages of connected vehicle technology and facilitate its widespread adoption, planners and designers must conduct relevant work before these vehicles become ubiquitous. Managed Lanes (MLs) have long been an effective strategy for managing complex transportation systems. Designed for vehicles meeting specific traffic flow criteria [1], MLs serve as an efficient and innovative solution for transportation agencies to manage severe congestion and increase capacity [2]. Compared to highway expansion, MLs present a more feasible alternative in terms of construction costs, environmental impact, and land use restrictions, enhancing traveler efficiency by improving travel capability, alleviating congestion, and increasing road safety [3]. Sala and Soriguera [4] noted that since CAVs share existing infrastructure with conventional vehicles, any mismanagement of CAV traffic could lead to reduced road capacity. To fully utilize the capacity improvements offered by CAVs, designing dedicated lanes with clear vehicle type permissions is a crucial approach. However, lane configuration management strategies for dedicated lanes should be carefully considered to maintain compatibility with traffic flow characteristics. Hall and Lotspeich [5] developed a linear programming model to optimize lane allocation on freeways. In a Markov chain-based lane management model for CAVs and conventional vehicles proposed by Ghiasi *et al.* [6], the focus was on the enhancement effect of CAV lane exclusivity on mixed traffic flows. Both Wang *et al.* [7] and Xiong *et al.* [8] proposed lane management strategies to evaluate the impact of CAV-dedicated lanes on energy conservation and traffic efficiency. Considering the benefits of CAV platooning, simulation analyses have demonstrated the positive impact of CAV-dedicated lanes on improving the capacity of mixed traffic flows on highways [9]. Furthermore, He [10] explored the effects of CAV lane policies on highway traffic efficiency. Experimental combinations of different lane strategies and traffic conditions indicated that at low CAV market penetration rates, CAV-dedicated lanes do not significantly impact traffic efficiency, suggesting the implementation of a "mandatory use" policy rather than setting up multiple dedicated lanes. Ye [11] conducted a modeling study to evaluate the pros and cons of establishing exclusive lanes for CAVs. The study found that at low CAV penetration rates, exclusive lanes for CAVs reduce the overall throughput of traffic flow. However, at moderate penetration rates, implementing dedicated lanes is more conducive to optimizing the advantages of CAVs in terms of traffic efficiency.

Although numerous studies have focused on mixed traffic flows composed of CAVs and HDVs, few have addressed the complexities of mixed traffic flows in freight corridors involving Human-Driven Vehicles (HDVs), Connected and Autonomous Trucks (CATs), and Human-Driven Trucks (HDTs). In such mixed traffic scenarios involving both CATs and HDTs, the implementation of dedicated lanes for CATs may become more complex and diverse. Therefore, this study aims to investigate the traffic impacts of establishing dedicated lanes for CATs under different Market Penetration Rates (MPR) and traffic volumes within this mixed traffic flow context, thereby enhancing the traffic efficiency of freight roads. This research fills a gap in the study of management strategies for novel mixed traffic flows involving heavy-duty trucks within intelligent and connected systems, and provides a scientific basis for the large-scale field testing of CATs.

2. Design of Lane Management Strategies

Lane management strategies that separate heavy-duty trucks from other vehicle types represent an effective approach to enhancing both the operational efficiency of truck transportation and corridor safety. Given the large inertia and inferior braking performance of heavy-duty trucks, the prevailing lane allocation pattern typically assigns trucks to the outermost lane while directing smaller vehicles to inner lanes. Extensive international field experiments have demonstrated that Truck-Only Lanes (TOL), which restrict large freight trucks to a single lane, effectively eliminate potential safety hazards caused by truck lane-changing behavior. This strategy significantly reduces the frequency of braking, acceleration, and overtaking maneuvers by heavy trucks.

Tailoring solutions to specific contexts, this study focuses on the freight corridor within the integrated airport collection and distribution system of "Yangshan Port-Donghai Bridge-Lianggang Avenue-Shanghai Pudong International Airport." The corridor is designed to support the efficient and safe movement of a high volume of heavy-duty trucks between the airport (Pudong Airport) and the port (Yangshan Port), minimizing potential conflicts between freight vehicles and other traffic. The section of Lianggang Avenue from Xin Siping Highway to the S2 Hulu Expressway spans approximately 13.1 km, with a design speed of 80 km/h. The elevated section is configured as a two-way, six-lane roadway, equipped with seven pairs of ramps along its entirety. Freight vehicles travel along the main elevated roadway, thereby avoiding the regulatory challenges and safety risks associated with complex at-grade intersection scenarios. Given that major accident locations and bottlenecks on expressways typically occur at ramp entrances and exits, this study selects the elevated section preceding the intersection of Lianggang Avenue and another major road, modeling the segment that includes these critical ramp areas.

Compared to scenarios where connected vehicles share lanes with human-driven vehicles (e.g., when MPR < 100%), establishing dedicated lanes for connected vehicles can enhance the safety [12], capacity, and efficiency [13] of highway facilities. Previous studies often assumed that traffic consists of only a small proportion of trucks, implying that traffic is predominantly composed of passenger cars. In reality, due to their greater length, weight, and maneuverability challenges, trucks not only alter speed distributions but also impact actual road capacity [14] [15]. In the past, since the proportion of trucks on most uncongested highways was minimal, these differences between trucks and passenger cars could be neglected in traffic simulation modeling. However, with China's development, road freight transportation (almost entirely accomplished by trucks) now accounts for nearly three-quarters of the country's total freight volume [16], generating substantial freight demand on highways. As the proportion of trucks increases and speed disparities widen, the safety implications cannot be overlooked, particularly when a dedicated lane has already been allocated for CATs.

To meet the smooth freight demand on Lianggang Avenue, this study proposes the following five lane allocation strategies based on the elevated road configuration of the already-constructed Lianggang Avenue:

Strategy 1: No Dedicated Lane (Baseline Scenario)

The current lane allocation scheme implemented on the elevated expressway of Lianggang Avenue is illustrated in Figure 1. Trucks are permitted to travel in the two rightmost lanes (Lane 2 and Lane 3), with Lane 3 designated as a low-speed lane. Passenger cars are allowed to use all lanes. In this configuration, car-following interactions between passenger and freight vehicles occur in the two outer lanes, while trucks are prohibited from entering the leftmost lane (Lane 1), which is reserved for passenger traffic. The retention of this existing allocation strategy is based on current traffic flow surveys, which indicate that by 2025, passenger and freight volumes on Lianggang Avenue are not expected to reach the design capacity threshold. Furthermore, the market penetration rate of connected and autonomous heavy-duty trucks remains insufficient in the near term. Thus, the conventional lane allocation approach is deemed adequate to meet daily operational demands in the coming years.

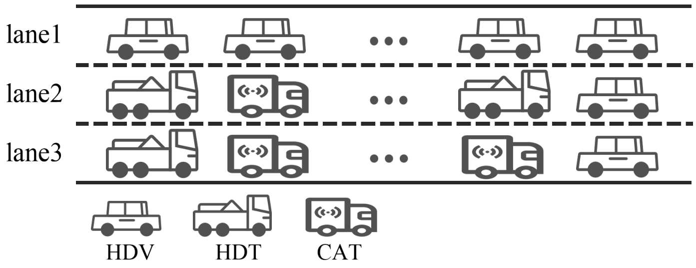

Figure 1. No dedicated lane configuration.

Strategy 2: Dedicated Lane for Connected and Automated Trucks (CAT)

As illustrated in **Figure 2**, compared to Strategy 1, this strategy designates the rightmost lane (Lane 3) as a dedicated lane exclusively for CATs. Only CATs are permitted to travel in this lane, while Human-Driven Trucks (HDTs) are restricted to Lane 2. This configuration effectively segregates human-driven and automated vehicles among heavy-duty vehicles. Human-Driven Vehicles (HDVs) are allowed to travel only in Lanes 1 and 2. This design is based on the future primary function of the freight corridor, which is to connect Yangshan Port and Pudong Airport, making it a "main route" for heavy freight trucks. Moreover, heavy-duty trucks account for approximately three-quarters of safety incidents in freight corridors, with most incidents caused by lane-changing behavior. The introduction of CATs is expected to significantly improve the transportation efficiency of the freight corridor [17]. Therefore, implementing a dedicated lane for CATs clearly restricts them to a single lane, ensuring communication within CAT platoons, reducing risks associated with automated driving technology failures, and separating conflicts among heavy-duty trucks, human-driven passenger cars, and CATs.

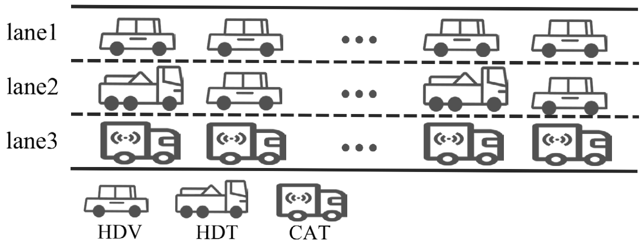

Figure 2. Dedicated lane for CAT.

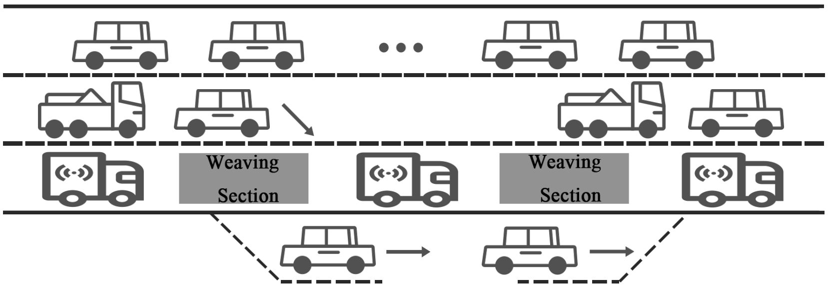

Figure 3. Design of on-ramp merging zone.

However, when vehicles need to enter or exit the elevated road via ramps, the dedicated lane configuration may restrict right-of-way for other vehicles. Thus, right-of-way must be allocated at ramps for vehicles entering or exiting. As shown in **Figure 3**, the simulated road section spans 3.2 km, divided into three 1-km straight segments. Exit and entrance ramps are set at 1.1 km and 2.1 km from the starting point, respectively, based on actual conditions. A fourth lane, 100 meters long, is provided at the ramps to facilitate lane changes and temporary occupancy. For scenarios with CAT-dedicated lanes, a 500-meter weaving section is implemented upstream of the exit ramp and downstream of the entrance ramp, providing 600-meter segments before and after for lane changes. All strategies in this study that involve right-side dedicated lanes will open permissions in ramp weaving sections to facilitate lane changes. Additionally, the length of the weaving section can be extended based on actual lane-changing demand to increase lane-changing opportunities.

Strategy 3: Dedicated Lane for Platooned Connected and Automated Trucks (CAT)

As illustrated in Figure 4, Strategy 3 designates the rightmost lane (Lane 3) as a dedicated lane exclusively for platooned CATs. Lane 2 serves as a mixed-use lane, permitting both Human-Driven Vehicles (HDVs) and Human-Driven Trucks (HDTs), while Lane 1 is reserved solely for HDVs. This platooning configuration demonstrates significant potential in enhancing freight road capacity, improving traffic stability and safety, as well as reducing fuel consumption and pollutant emissions. Truck platooning not only effectively lowers logistics costs but also promotes the intelligent development of port logistics and freight transportation systems.

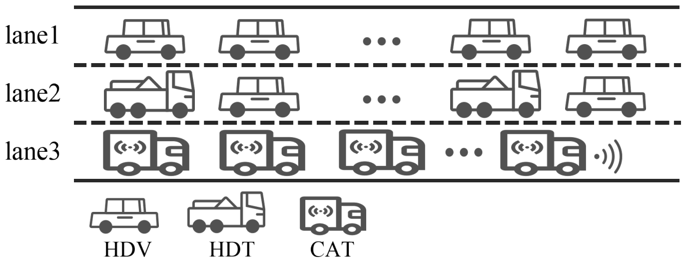

Figure 4. Dedicated lane for CAT platooning.

Strategies 4 & 5: Left-Side Dedicated Lanes for CATs (Standard and Platooned)

Strategies 4 and 5, illustrated in Figure 5 and Figure 6 respectively, are adaptations of Strategies 2 and 3. The dedicated lane is relocated to the leftmost lane (Lane 1). The central lane (Lane 2) becomes an express lane reserved exclusively for HDVs, while the original rightmost lane (Lane 3) is reconfigured as a mixed-use, low-speed lane primarily for HDTs but also permitting HDVs. The primary advantage of these strategies is the complete segregation of CATs to the innermost lane, significantly reducing weaving conflicts with merging and diverging vehicles in ramp areas. However, this configuration introduces a key limitation: for CATs to enter or exit via ramps, they must execute two consecutive lane-changing maneuvers—a requirement that becomes particularly challenging and potentially hazardous for a platooned truck fleet. Fortunately, relevant enterprises already plan to minimize lane-changing opportunities for CATs to circumvent the associated technical challenges and safety risks. Thus, this limitation can be mitigated through alternative means. These strategies trade CATs' lane-changing flexibility for substantially enhanced safety. Furthermore, as no dedicated lane is established on the right side, there is no need to designate weaving sections upstream of ramps.

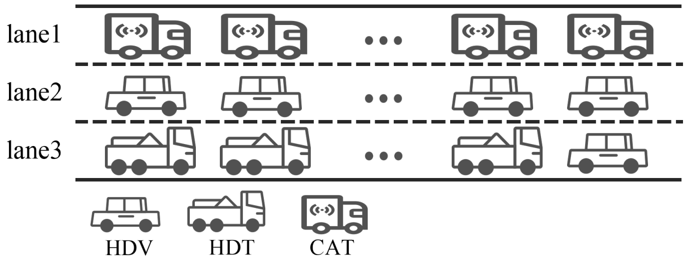

Figure 5. Left-side dedicated lane for CAT.

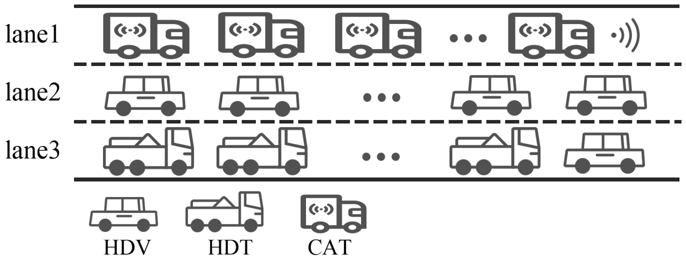

Figure 6. Left-side dedicated lane for CAT platooning.

3. Establishment of the Intelligent Connected Environment

This study utilizes SUMO (Simulation of Urban Mobility) software to construct the connected vehicle environment. SUMO is an open-source software widely employed in traffic flow simulation, particularly valued in transportation research for its open-source nature, making it highly suitable for testing and evaluating various vehicle control algorithms.

Table 1. Main vehicle parameters.

Parameter	HDV	CAT	HDT
length/m	5	16.5	16.5
accel/($m\cdot s^{-2}$)	2.6	1.7	1
decel/($m\cdot s^{-2}$)	4.5	2.5	1.5
minGap/m	2.5	0.5	2.5
speedDev	0.1	0	0.05
maxSpeed/($m\cdot s^{-1}$)	22.2	22.2	22.2
car FollowModel	IDM	CACC	IDM
Tau/s	1	1	2
lcStrategic	5	/	/
lcAssertive	2	/	/
emissionClass	HBEFA3	HBEFA3/HDV_G	HBEFA3/HDV_G

Autonomous driving technology can be simulated by employing advanced car-following models and adjusting vehicle reaction times, while the collaborative functionalities of intelligent connectivity are considerably more complex. To simulate traffic in an intelligent connected environment within SUMO, it is typically necessary to utilize TraCI (Traffic Control Interface) for external control, enabling information exchange between vehicles, dynamic route adjustments, and connected cooperative behaviors. Furthermore, to simulate the platooning strategies of intelligent connected vehicles, this study incorporates the Plexe-SUMO API, an extension module of SUMO specifically designed for simulating the platoon control of CATs. This module facilitates cooperative car-following, lane-changing, and acceleration/deceleration control among vehicles. The parameter settings for the three vehicle types are listed in **Table 1**, with all vehicles using SUMO's built-in "LC2013" lane-changing model.

In the parameter settings, "length" denotes the vehicle length, with passenger cars set at 5 m and heavy-duty trucks at 16.5 m. "accel" and "decel" represent the maximum acceleration and deceleration capabilities of the vehicles, which determine their braking performance in the simulation. In this study, the acceleration and deceleration values for CATs are set higher than those for HDTs. This is based on research findings indicating that drivers of human-driven heavy trucks exhibit high safety awareness and are particularly sensitive to acceleration and deceleration behaviors. In contrast, CATs, with their rapid response capabilities and precise state control, can perform more extreme acceleration and deceleration maneuvers, thereby fully leveraging the vehicle's performance. "minGap" refers to the minimum safe spacing between two adjacent vehicles when stationary. A value of 0 indicates that the front of the following vehicle would contact the rear of the leading vehicle. This study assumes that human-driven vehicles maintain a longer safe spacing. "speedDev" is the parameter for speed fluctuation. A value of 0 indicates that the vehicle maintains the most reasonable speed under the given traffic flow, while a value of 0.1 means the vehicle's speed fluctuates by 10% above and below the ideal speed, following a normal distribution to simulate the uncertainty of human driving. "Tau" denotes the desired time gap in car-following, *i.e.*, the ratio of the distance between the leading and following vehicles to the speed of the following vehicle. Previous studies generally agree that CACC vehicles maintain shorter following distances compared to human-driven vehicles, and passenger cars have shorter following distances than heavy trucks, owing to the faster response of intelligent connected vehicles and the lower inertia of passenger cars. "lcStrategic" and "lcAssertive" are key parameters in SUMO for controlling lane-changing behavior. "lcStrategic" (strategic lane-changing parameter) primarily influences the strategic considerations of vehicles when deciding to change lanes, *i.e.*, whether the lane change is part of a long-term plan. A higher value means the vehicle considers global traffic conditions more comprehensively during lane changes, rather than just local gaps and speeds. "lcAssertive" (lane-changing assertiveness parameter) mainly affects the aggressiveness of lane-changing behavior, *i.e.*, whether the vehicle dares to change lanes, especially in slightly congested traffic. For example, HDVs exhibit more aggressive and less rational lane-changing behavior [18]-[20]. A higher value indicates more decisive and proactive lane-changing behavior. Since the simulation scenario does not consider lane changes for heavy trucks, lane-changing parameters for heavy trucks need not be set. "emissionClass" is the parameter in SUMO for specifying vehicle emission characteristics. SUMO supports multiple emission models, with the most commonly used being HBEFA (Handbook Emission Factors for Road Transport). This model, based on the widely adopted European emission factor dataset HBEFA 3, provides emission characteristics for different vehicle types under various driving conditions. "HBEFA3" denotes the default emission model for passenger cars, while the parameter "HBEFA3/HDV_G" refers to the emission model for heavy-duty trucks (note: "HDV" here does not refer to human-driven passenger cars as mentioned earlier).

This study also incorporates the Plexe library to implement platooning strategies. When platooning for connected and automated heavy trucks is applied, the modifications and additions required for CAT vehicle attributes are summarized in **Table 2**.

Table 2. Grouped CAT parameters.

Parameter	CAT
carFollow Model	CC
ccAccel/($m \cdot s^{-2}$)	1.5
ploegKp	0.2
ploegKd	0.7
Tau/s	3

Among these parameters, "CC" represents the Cooperative Control model provided by Plexe, specifically designed for CACC platoon simulation. It indicates that vehicles within the platoon adopt a constant spacing strategy for cooperative car-following. "ccAccel" denotes the CACC control acceleration, defining the maximum acceleration of the CACC model during platoon operation, which influences the responsiveness of platoon members to the acceleration or deceleration of the preceding vehicle. "ploegKp" and "ploegKd" are control parameters of the CACC system, based on the classical PID controller principle in control theory. They enable speed adjustments based on information from the preceding vehicle to maintain a stable inter-vehicle spacing. It should be noted that the "Tau" parameter here differs from that in the previous table: in this context, its value represents the desired time gap between the leading truck of the platoon and the vehicle ahead, while the internal spacing within the platoon remains constant at the initially set value.

4. Evaluation Metrics

4.1. Capacity

The capacity is defined as the maximum number of standard vehicles that a road or specific transportation system can pass per unit of time, typically measured in passenger car units per hour (pcu/h). Since this mixed flow also includes heavy-duty trucks, it is necessary to separately count the number of passenger cars and heavy trucks passing within a unit of time. In addition to quantifying the numbers of different vehicle types, improvements in capacity are indirectly assessed by analyzing the Total Travel Time (TTT) and Loss Time of vehicles. This is because shorter dwell times of vehicles on a given road segment allow more vehicles to pass per unit of time, thereby indicating enhanced capacity. During the simulation, SUMO records the IDs of vehicles that pass the endpoint, and after the simulation concludes, TraCI is used to retrieve the total travel time and loss time of these vehicles. Finally, weighted averages are calculated separately for passenger cars and heavy trucks. The calculation methods are shown in Equations (1) and (2).

$$\text{LossTime}_n = \text{TTT} - L/v_f \tag{1}$$

$$\text{LossTime}_{\text{avg}} = \sum \text{LossTime}_n / N \tag{2}$$

where L is the length of the corridor, and v_f is the free-flow speed under that traffic volume.

4.2. Safety Level

During the simulation process, SUMO calculates the Time to Collision level (TTC) between leading and following vehicles in real-time at each simulation step. Supported by vehicle trajectory simulation data, it has been demonstrated that the quantitative metric TTC, as a surrogate safety measure (SSM), is beneficial for evaluating the safety performance of the proposed mixed traffic flow. The calculation formula is shown in Equation (3).

$$\text{TTC} = x_{n-1}(t) - x_n(t) - l/v_n(t) - v_{n-1}(t), \forall v_n(t) > v_{n-1}(t) \tag{3}$$

where $v_n(t)$ and $v_{n-1}(t)$ represent the speeds of the following vehicle $n - 1$ and the leading vehicle n at time t, respectively, while $x_{n-1}(t)$ and $x_n(t)$ denote the positions of the aforementioned two adjacent vehicles at time t. The parameter l corresponds to the length of the leading vehicle $n - 1$.

TTC indicates the estimated time until a collision would occur if both vehicles maintain their current speeds and trajectories without any braking or acceleration maneuvers. Based on prior research, a TTC threshold of 3 seconds is commonly adopted. Specifically, when the TTC falls below 3 seconds, the vehicle is considered to be at potential collision risk, and an accident is highly likely to occur unless emergency braking or evasive actions are taken. Therefore, in this study, TTC values for all vehicles are collected at each simulation time step, and the number of instances where TTC < 3 seconds is recorded. This count serves as an evaluation metric for safety performance. The statistical value can be used to quantify safety risks under different management strategies—a higher count indicates a greater potential for collision hazards in the given scenario, thereby enabling the assessment of safety levels in freight corridors under varying traffic conditions and control strategies.

4.3. Carbon Emission Level

Carbon emission levels are typically evaluated using carbon dioxide (CO_2) emissions as the metric. SUMO provides detailed emission models that calculate the CO_2 emissions of each vehicle during the simulation based on parameters such as vehicle type, travel speed, and acceleration. This study employs SUMO's HBEFA emission model to simulate and analyze the carbon emissions of different vehicle types. During the simulation, SUMO records the instantaneous CO_2 emissions of each vehicle at every time step and accumulates these values over the entire simulation period to obtain the total carbon emissions. The total emissions are then divided by the number of vehicles to derive the average CO_2 emissions per passenger car and per heavy-duty truck, respectively.

5. Case Analysis

To analyze the interaction between heavy-duty truck penetration rates and strategy selection, the simulation parameters are set as follows: the ramp entry/exit ratio is fixed at 0.1, the simulation duration is set to 3000 steps (5 minutes), the passenger car flow rate is set to 2000 vehicles/h, and the heavy-duty truck flow rate is set to 1200 vehicles/h. With the anticipated increase in freight demand, the peak hourly volume of heavy-duty trucks traveling between Yangshan Port and Pudong Airport is projected to reach 1200 vehicles/h, while the passenger car demand is expected not to exceed 2000 vehicles/h [21].

5.1. Analysis and Evaluation of Traffic Capacity

Figure 7 and **Figure 8** illustrate the trends of heavy-duty truck loss time and total travel time under different management strategies as the truck penetration rate varies. As the penetration rate increases, both the total travel time and loss time of heavy-duty trucks under all management strategies show a decreasing trend, indicating that the application of intelligent connected technology can effectively reduce travel delays and enhance truck traffic efficiency. In the low penetration rate phase (0% - 20%), the uncontrolled strategy (Strategy 1) outperforms the managed strategies. This is because, under low penetration conditions, allocating dedicated lanes for a small number of trucks leads to underutilization of road resources, thereby reducing overall traffic efficiency. When the penetration rate falls within the 20% - 40% range, the platooning strategies (Strategies 3 and 5) demonstrate significantly better performance than the uncontrolled approach, validating the technical advantages of cooperative vehicle platooning under moderate penetration rates. In the high penetration rate phase (>40%), the benefits of managed strategies become markedly evident. At this stage, the implementation of dedicated lanes not only avoids resource wastage but also fully leverages the synergistic effects of intelligent connected vehicles. When the penetration rate reaches 100%, the loss time of heavy-duty trucks under some managed strategies drops to zero, indicating unimpeded travel throughout the route. Quantitative analysis reveals that under 100% penetration conditions, the optimal Strategy 4 (left-side dedicated lane for heavy-duty trucks) improves the average travel time of trucks by 9% compared to the uncontrolled strategy, saving approximately 10 seconds per trip. A horizontal comparison shows that the scenario with a 100% penetration rate and the optimal management strategy achieves a 19.31% improvement in overall traffic efficiency compared to the scenario with 0% penetration rate and no management strategy.

In summary, the effectiveness of dedicated lane strategies for heavy-duty trucks is penetration rate-dependent: implementation under low penetration rates (<60%) reduces passenger car traffic efficiency, while net benefits are maximized only under high penetration rates (>60%). Moreover, the synergistic application of platooning strategies and dedicated lane strategies can further optimize corridor capacity.

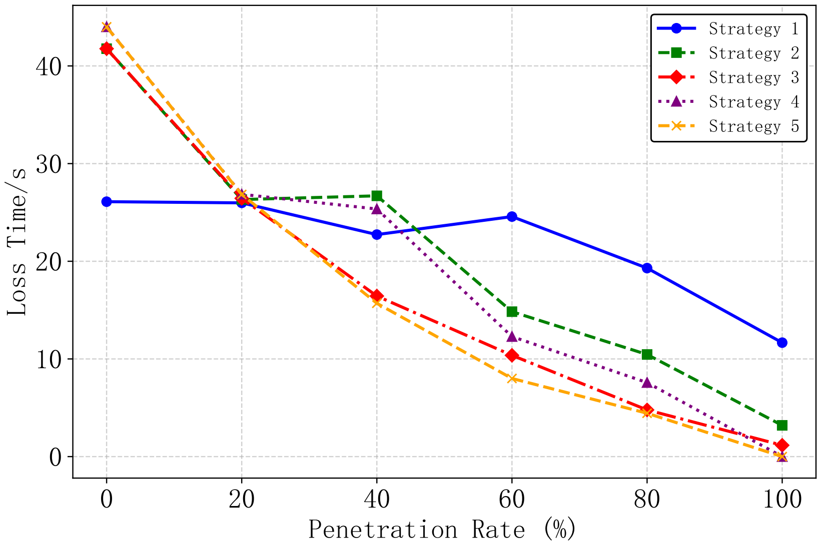

Figure 7. Variation of heavy-duty truck loss time with penetration rate.

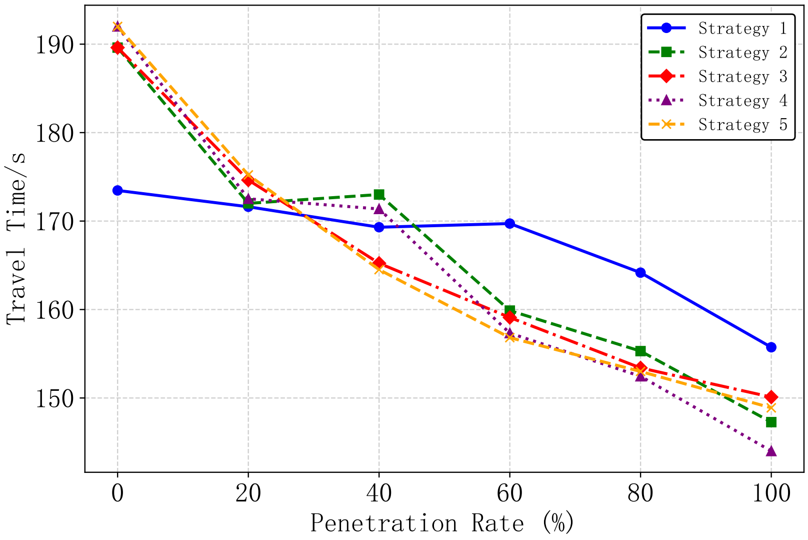

Figure 8. Variation of heavy-duty truck TTT with penetration rate.

5.2. Safety Level Analysis and Evaluation

Figure 9 displays the number of instances where the TTC threshold is exceeded under five different strategies across varying penetration rates. As the penetration rate of heavy-duty trucks increases, the number of dangerous occurrences under Strategy 1 (unmanaged) shows a monotonic rise. This is because CATs are dispersed across two mixed passenger-freight lanes. However, due to the car-following characteristics of CATs, which maintain a shorter following distance, continuous lane-changing behaviors of vehicles entering from ramps may interfere with CATs in the two right-side lanes, thereby elevating the risk level. Thus, as the penetration rate of heavy-duty trucks increases, it becomes necessary to implement dedicated lanes for them.

Under low penetration rate scenarios, the adoption of dedicated lane strategies may also yield negative effects. Although CATs in dedicated lanes do not pose risks, the excessive allocation of resources to CATs leads to higher traffic density in other lanes, consequently increasing the number of dangerous occurrences. Furthermore, the effectiveness of different strategies in improving safety levels varies across penetration rates, highlighting the need to select management strategies based on actual conditions. Among them, Strategy 5 generally delivers optimal safety performance in most scenarios. This is because platooning technology significantly enhances the traffic efficiency of truck platoons, thereby increasing the capacity of dedicated lanes. Additionally, situating the dedicated lane for CATs on the left side avoids lane-changing interactions between CATs and ramp vehicles on the right side.

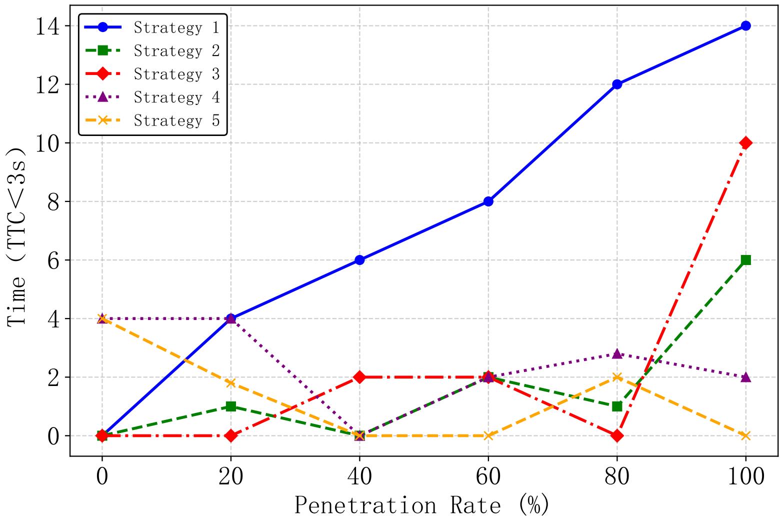

Figure 9. Variation of heavy-duty truck safety with penetration rate.

5.3. Carbon Emission Level Analysis and Evaluation

The carbon emission results are shown in **Figure 10**. As the penetration rate of heavy-duty trucks increases, the average carbon emissions per truck initially rise and then decline. However, when management strategies are implemented, the average carbon emissions per truck exhibit a negative correlation with the penetration rate: higher penetration rates correspond to lower carbon emissions, with a monotonically decreasing rate of change. The most significant change occurs within the penetration rate range of 0% to 60%. This indicates that intelligent connected technology significantly improves the car-following behavior of heavy-duty trucks, leading to more stable driving patterns, reducing abrupt acceleration and deceleration events, and thereby promoting more complete fuel combustion and lower carbon emissions.

Nevertheless, at low penetration rates (below 40%), the carbon emissions of heavy-duty trucks under dedicated lane management strategies are significantly higher than those under the no-management scenario. This is attributed to road resource underutilization, which leads to excessive traffic density in single lanes and results in congestion. When the CAT penetration rate reaches 40%, the "platooned dedicated lane for connected heavy-duty trucks" strategy reduces the average carbon emissions per truck by approximately 7% compared to the no-management strategy.

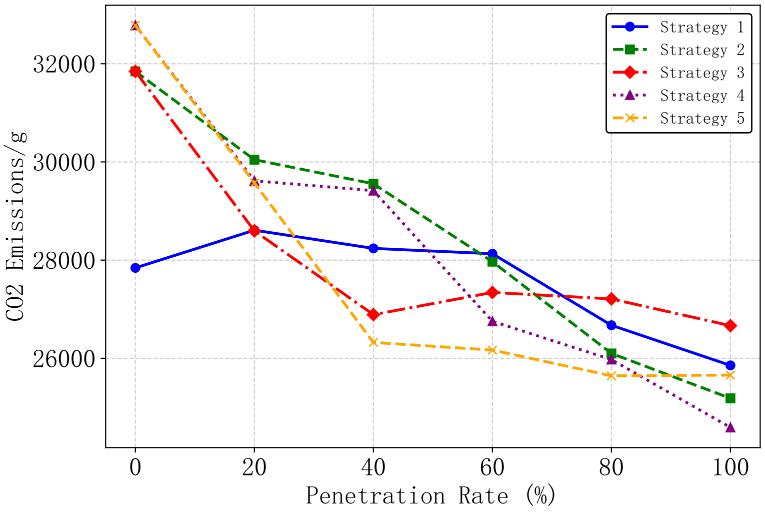

Figure 10. Variation of heavy-duty truck CO_2 emissions.

6. Conclusion

This study designs five lane management strategies and employs truck platooning technology for multi-scenario simulation. Through multi-dimensional evaluation of traffic capacity, safety, and emissions, it reveals traffic flow characteristics under different penetration rates and strategy combinations. These findings provide theoretical and practical support for the dynamic management of smart freight corridors. Future work should focus on field validation and promoting intelligent transformation through stakeholder collaboration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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