Journal of Innovative Technologies
Vol. 6 (2023)
https://academicpinnacle.com/index.php/JIT

Optimizing Truck Platooning within Road-Network Capacitated Vehicle Routing Problems

Nguyễn Văn Anh
Department of Transportation Engineering, Hanoi University of Science and Technology, Vietnam

Abstract

Optimizing truck platooning within road-network capacitated vehicle routing problems involves enhancing the efficiency and coordination of truck convoys traveling on complex road systems. This optimization focuses on leveraging the benefits of platooning, such as reduced fuel consumption and increased road safety, while addressing the constraints posed by vehicle capacities and road network limitations. By integrating advanced algorithms and real-time data, the aim is to develop routing strategies that maximize the utilization of road networks, minimize travel time, and ensure adherence to vehicle capacity restrictions. This approach improves the operational efficiency of freight transportation and contributes to sustainable logistics practices by reducing carbon emissions and optimizing resource allocation. The challenge lies in balancing the trade-offs between convoy coordination, route selection, and network capacities to achieve optimal performance in dynamic and often unpredictable traffic conditions.

Keywords: Truck Platooning, Vehicle Routing Problems (VRP), Road-Network Optimization, Capacitated Vehicle Routing

1. Introduction

Vehicle Routing Problems (VRPs) are combinatorial optimization problems that focus on determining the most efficient routes for a fleet of vehicles to service a set of customers with known demands. The primary objective of VRPs is to minimize the total distance traveled, travel time, or overall transportation cost while ensuring that each customer is visited exactly once by a single vehicle. VRPs have many applications in logistics, transportation, and supply chain management, where efficient routing can lead to significant cost savings and improved service levels. The complexity of VRPs arises from the need to consider numerous constraints such as vehicle capacities, customer time windows, and route length limits. Capacitated Vehicle Routing Problems

(CVRPs) are a specific type of VRP where each vehicle in the fleet has a limited carrying capacity, adding another layer of complexity to the routing problem. In CVRPs, the challenge is not only to determine the optimal routes but also to ensure that the load on each vehicle does not exceed its capacity. This constraint necessitates careful planning and allocation of customer demands to the appropriate vehicles, balancing the need to maximize vehicle utilization while minimizing travel costs. CVRPs are particularly relevant in industries such as retail, where vehicles must deliver goods to multiple locations, and the total weight or volume of the cargo must be considered. The significance of solving CVRPs efficiently is underscored by the potential benefits for businesses and the environment. Effective routing strategies can lead to reduced fuel consumption, lower operational costs, and decreased greenhouse gas emissions. Integrating ultra-wideband (UWB) radio with XGBoost decision trees allows for precise distance measurement, enhancing vehicle route optimization[1]. Furthermore, incorporating semi-supervised classification techniques to detect surface defects in striped patterns can improve fault detection and maintenance efficiency within vehicle route planning[2]. Additionally, improving the efficiency of vehicle routes can enhance customer satisfaction by ensuring timely deliveries. The integration of advanced optimization techniques and real-time data into CVRP solutions holds promise for further advancements in the field, enabling more dynamic and adaptive routing strategies that can respond to changing conditions and demands in real time. As such, CVRPs remain a critical area of research and application in the quest for more sustainable and efficient transportation systems.

Truck platooning refers to the practice of connecting multiple trucks in a convoy, using advanced driving support systems and wireless communication technologies to enable them to travel closely together with synchronized acceleration and braking [3]. The lead truck is typically controlled by a human driver, while the following trucks, equipped with automated driving systems, mirror the lead truck's movements. Semantic wireframe detection technology further optimizes convoy formations by precisely detecting and tracking the position and status of each truck[4]. This tight formation reduces aerodynamic drag, particularly for the trailing vehicles, resulting in improved fuel efficiency. Platooning leverages technologies such as vehicle-to-vehicle (V2V) communication, adaptive cruise control, and automated braking systems to maintain safe distances between the trucks, enhancing both safety and operational efficiency. The benefits of truck platooning are multifaceted. One of the primary advantages is the significant reduction in fuel consumption, which can range from 4% to 10% depending on the configuration and conditions. This reduction translates to lower operating costs and decreased greenhouse gas emissions, contributing to more sustainable logistics practices [5]. Additionally, platooning can improve traffic flow and reduce congestion by optimizing the use of road space and minimizing the variations in speed that often lead to traffic disruptions. The synchronized movement of platoons also enhances road safety by reducing the likelihood of human error-related accidents, thanks to the advanced driver assistance systems that ensure precise control and coordination among the trucks [6]. An improved reinforcement learning method based on anchor graph hashing can optimize the communication network in platoon driving[7]. The integration of these technological advancements lays the foundation for future autonomous and connected transportation. The technology serves as a stepping stone towards fully autonomous freight transport, where trucks can operate without human intervention for extended periods. Using graphene infrared photodetectors and bullseye plasmonic antennas, formation systems achieve higher detection accuracy and better environmental adaptability[8]. This progression could address driver shortages and improve the overall efficiency of logistics networks. Furthermore, the data collected from platooning operations can provide valuable insights for optimizing route planning, maintenance schedules, and fleet management. As truck platooning continues to evolve, it is poised to play a crucial role in shaping the next generation of intelligent transportation systems, offering a glimpse into a future where freight movement is safer, greener, and more efficient.

Optimizing truck platooning within capacitated Vehicle Routing Problems (VRPs) is crucial for maximizing the efficiency and sustainability of freight transportation networks. Combining the benefits of truck platooning with the constraints and objectives of capacitated VRPs allows for significant improvements in operational performance [9]. One of the primary importance lies in the substantial cost savings achieved through reduced fuel consumption. By maintaining close distances between trucks in a platoon, aerodynamic drag is minimized, leading to lower fuel usage across the fleet. When integrated into capacitated VRPs, these savings are further enhanced as the optimization algorithms ensure that the loads carried by each vehicle are maximized, thereby reducing the number of trips needed and improving overall fuel efficiency. Another critical aspect is the enhancement of road safety and traffic flow [10]. Truck platooning technology, which includes synchronized braking and acceleration, reduces the risk of accidents caused by human error. When these systems are optimized within the framework of capacitated VRPs, the benefits extend to better traffic management and less congestion on road networks. Efficiently routed platoons mean fewer disruptions and more predictable traffic patterns, which can lead to smoother and safer travel conditions for all road users. This not only improves the reliability of freight deliveries but also contributes to broader societal benefits by enhancing the overall safety and efficiency of transportation infrastructures[11].

Collaborative operational planning can enhance the efficiency of semi-autonomous truck platooning by coordinating the scheduling of drivers and trucks, thereby reducing labor and energy costs[12]. Furthermore, the environmental impact of freight transportation is significantly mitigated through optimized truck platooning within capacitated VRPs. The reduction in fuel consumption directly correlates with lower carbon emissions, helping companies meet sustainability goals and regulatory requirements. Additionally, optimizing vehicle loads ensures that resources are used more effectively, minimizing waste and the environmental footprint of logistics operations. This approach aligns with global efforts to combat climate change and promotes more responsible and sustainable business practices. In sum, the integration and optimization of truck platooning in capacitated VRPs offer a comprehensive solution that enhances economic efficiency, safety, and environmental sustainability in the transportation sector.

2. Literature Review

Optimizing truck platooning within road-network capacitated vehicle routing problems (CVRPs) presents a multifaceted challenge that requires careful consideration of various factors including fuel efficiency, traffic flow, and vehicle coordination [13]. Truck platooning involves multiple trucks traveling in a tight formation, reducing air resistance and fuel consumption. When integrating truck platooning into CVRPs, the primary goal is to optimize the routes such that the benefits of platooning are maximized without compromising the constraints of vehicle capacities and delivery schedules. This involves developing algorithms that can dynamically adjust routes based on real-time traffic conditions and the availability of platoon partners, ensuring that trucks can join and leave platoons efficiently. One of the critical components in optimizing truck platooning within CVRPs is the synchronization of vehicles. Trucks must be coordinated to meet at specific points within the network to form or maintain a platoon. This requires sophisticated scheduling algorithms that can predict the optimal rendezvous points and times, considering the varying speeds and routes of the individual trucks. Additionally, these algorithms must account for the legal and safety constraints associated with platooning, such as the maximum number of trucks in a platoon and the required distance between them. Effective synchronization reduces idle times and unnecessary detours, enhancing the delivery network's overall efficiency. The integration of platooning into CVRPs must also consider the heterogeneity of the fleet. Different trucks have varying capacities, performance characteristics, and destinations, which can complicate the formation of platoons [14]. Advanced optimization models need to factor in these differences to ensure that the benefits of platooning are not outweighed by the logistical complexities it introduces. For example, larger trucks with higher capacities might have different optimal routes than smaller ones, necessitating a flexible and adaptive approach to routing and platooning. By analyzing historical data and predicting the best strategies for platooning under different conditions, machine learning and artificial intelligence play a crucial role in addressing these challenges[15].

Figure 1, the routes for the vehicle routing problem (VRP), the solution involves creating efficient paths that trucks follow to deliver goods to various customer locations, indicated by person icons on the map. Each route begins at a central depot and strategically navigates through all designated customer points, ensuring that deliveries are completed while minimizing travel distance and adhering to vehicle capacity limits. In contrast, our cooperative routing problem introduces an additional layer of complexity by integrating mobile facilities, depicted by cash icons, which provide essential services to customers at specific locations. This requires a dual optimization strategy where routes are planned not only to meet delivery requirements but also to synchronize with the availability and positioning of mobile facilities. Consequently, the solution must ensure that these facilities are accessible to customers at convenient times and places, enhancing service efficiency and customer satisfaction.

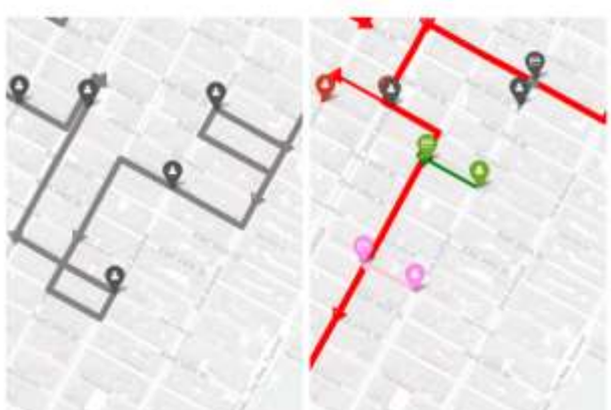

Figure 1: A route with VRP

Another crucial aspect is the impact of road network characteristics on platooning. Road conditions, traffic density, and the availability of suitable resting and rendezvous areas can significantly affect the feasibility and efficiency of truck platooning. Highways and major arterial roads might offer better opportunities for platooning due to higher traffic flow and more predictable conditions, whereas urban areas with frequent stops and variable traffic might pose greater challenges. Therefore, route optimization must account for these factors to identify the most suitable segments of the network for platooning, thereby maximizing fuel savings and reducing travel times [16]. Moreover, the incorporation of real-time data is essential for optimizing truck platooning within CVRPs. Traffic congestion, road closures, accidents, and weather conditions can all impact the optimal routing and timing for platoons. Utilizing real-time data allows for dynamic adjustments to be made, ensuring that the planned platoons remain viable and efficient despite changing conditions. This requires robust communication and data-sharing systems between trucks and centralized control centers, enabling real-time decision-making and coordination. The use of IoT (Internet of Things) technology and advanced telematics can facilitate this level of connectivity and data exchange, enhancing the overall effectiveness of the platooning strategy. The environmental and economic impacts of truck platooning must be carefully evaluated. While the primary goal of platooning is to reduce fuel consumption and emissions, it is important to ensure that these benefits are not offset by other negative impacts such as increased travel distances or times due to platoon formation [17]. A comprehensive analysis that considers both the direct and indirect effects of platooning is necessary to fully understand its benefits and drawbacks. Additionally, the economic implications for logistics companies, including potential cost savings from reduced fuel consumption and increased operational efficiency, must be considered to justify the investment in platooning technology and infrastructure. By taking a holistic approach that incorporates all these variables, it is possible to develop robust and effective solutions for optimizing truck platooning within CVRPs, leading to significant improvements in logistics efficiency and sustainability.

3. Case Studies and Future Directions

3.1. Case Study 1: North American Freight Network

In a large-scale pilot project across the North American freight network, a logistics company implemented truck platooning on major interstate highways. By utilizing advanced telematics and real-time traffic data, the company was able to coordinate platoons of three to five trucks traveling between major distribution centers. The results showed a significant reduction in fuel consumption, averaging 10% savings per truck, and a corresponding decrease in carbon emissions. The project highlighted the importance of selecting optimal routes that favor long, uninterrupted stretches of highway to maximize the benefits of platooning [18]. Challenges included maintaining platoon integrity in areas with high traffic congestion and ensuring compliance with varying state regulations regarding platooning.

3.2. Case Study 2: European Urban and Regional Logistics

In Europe, a regional logistics provider explored truck platooning in both urban and regional contexts. The focus was on integrating platooning with existing delivery schedules and capacity constraints in densely populated areas and inter-city routes. The company used machine learning algorithms to predict traffic patterns and optimize rendezvous points for platoons. The study found that while platooning was highly effective on regional highways, achieving a 12% reduction in fuel use, urban platooning faced significant obstacles due to frequent stops, variable traffic conditions, and narrower roads. This case study underscored the need for adaptive routing algorithms that can dynamically respond to urban traffic challenges.

3.3. Case Study 3: Asian Port-to-Inland Distribution

In an Asian logistics hub, truck platooning was tested for port-to-inland distribution routes. The project aimed to streamline the movement of goods from major ports to inland warehouses and distribution centers. The use of real-time data on port traffic, road conditions, and weather forecasts was crucial for optimizing the timing and formation of platoons. The results demonstrated that platooning could reduce delivery times by 15% and lower fuel consumption by 8%. However, the study also identified issues with coordinating platoons due to the high variability in port processing times and the need for more sophisticated scheduling algorithms to handle these complexities effectively [19].

Future advancements in truck platooning within CVRPs will likely focus on enhanced integration of real-time data. Leveraging IoT devices and advanced telematics will allow for more accurate and timely adjustments to platoon formations and routes. This includes not only traffic and weather data but also real-time information on road conditions and vehicle performance. Enhanced data analytics will enable more predictive and adaptive routing, ensuring that platoons can be maintained efficiently even in dynamic environments. The development of more sophisticated algorithms will be critical in addressing the complexities of truck platooning within CVRPs. These algorithms will need to incorporate machine learning techniques to predict traffic patterns, optimize rendezvous points, and dynamically adjust routes in response to real-time conditions. Future research should also explore the potential of decentralized decision-making systems, where trucks can independently negotiate and form platoons based on real-time data and pre-defined optimization criteria. As truck platooning becomes more prevalent, there will be a need for supportive regulatory frameworks and infrastructure investments. This includes standardized regulations across regions to facilitate seamless platooning operations and the development of dedicated platooning lanes or corridors on major highways. Infrastructure enhancements, such as smart traffic signals and dedicated rest areas for platoons, will also be important in supporting efficient platoon operations. Future research should continue to evaluate the environmental and economic impacts of truck platooning. Comprehensive studies that consider both the direct benefits (e.g., fuel savings, and emission reductions) and indirect effects (e.g., changes in traffic patterns, and infrastructure wear) will be essential. Additionally, exploring the economic implications for logistics companies, including cost-benefit analyses and potential ROI on platooning technologies, will help justify investments and encourage wider adoption.

4. Conclusion

In conclusion, optimizing truck platooning within road-network capacitated vehicle routing problems (CVRPs) presents a promising opportunity to enhance the efficiency and sustainability of logistics operations. By leveraging advanced algorithms, real-time data, and adaptive routing strategies, truck platooning can significantly reduce fuel consumption, emissions, and operational costs while maintaining delivery schedules and capacity constraints. Case studies from diverse regions underscore the tangible benefits and highlight the challenges, such as traffic congestion and regulatory variations that need to be addressed. Future advancements in data integration, algorithm development, regulatory support, and infrastructure investment will be pivotal in realizing the full potential of truck platooning, ultimately leading to a more efficient, cost-effective, and environmentally friendly transportation network.

Reference

[1] Y. Liu, L. Liu, L. Yang, L. Hao, and Y. Bao, "Measuring distance using ultra-wideband radio technology enhanced by extreme gradient boosting decision tree (XGBoost)," *Automation in Construction,* vol. 126, p. 103678, 2021.

[2] Y. Liu, H. Yang, and C. Wu, "Unveiling patterns: A study on semi-supervised classification of strip surface defects," *IEEE Access,* vol. 11, pp. 119933-119946, 2023.

[3] M. Lupi, A. Pratelli, and A. Farina, "Modelling and simulation of a new urban freight distribution system based on automatic van platooning and fixed split up locations," *IET Intelligent Transport Systems,* vol. 14, no. 9, pp. 1034-1047, 2020.

[4] Y. Zhou *et al.*, "Semantic Wireframe Detection," 2023.

[5] D. A. Lazar, S. Coogan, and R. Pedarsani, "Routing for traffic networks with mixed autonomy," *IEEE Transactions on Automatic Control,* vol. 66, no. 6, pp. 2664-2676, 2020.

[6] Z. Fu and J. Y. Chow, "Dial-a-ride problem with modular platooning and en-route transfers," *Transportation Research Part C: Emerging Technologies,* vol. 152, p. 104191, 2023.

[7] G. Sun, T. Zhan, B. G. Owusu, A.-M. Daniel, G. Liu, and W. Jiang, "Revised reinforcement learning based on anchor graph hashing for autonomous cell activation in cloud-RANs," *Future Generation Computer Systems,* vol. 104, pp. 60-73, 2020.

[8] X. Deng, S. Oda, and Y. Kawano, "Graphene-based midinfrared photodetector with bull's eye plasmonic antenna," *Optical Engineering,* vol. 62, no. 9, pp. 097102-097102, 2023.

[9] Y. Bouchery, B. Hezarkhani, and G. Stauffer, "Coalition formation and cost sharing for truck platooning," *Transportation Research Part B: Methodological,* vol. 165, pp. 15-34, 2022.

[10] J. Scholl, N. Boysen, and A. Scholl, "E-platooning: Optimizing platoon formation for long-haul transportation with electric commercial vehicles," *European Journal of Operational Research,* vol. 304, no. 2, pp. 525-542, 2023.

[11] A. Agárdi, "Analysis of the Multi-Objective Optimisation Techniques in Solving a Complex Vehicle Routing Problem," in *Vehicle and Automotive Engineering*: Springer, 2022, pp. 678-693.

[12] Y. Hao, Z. Chen, J. Jin, and X. Sun, "Joint operation planning of drivers and trucks for semi-autonomous truck platooning," *Transportmetrica A: Transport Science,* pp. 1-37, 2023.

[13] R. Rojas-Gualdron and F. Smarandache, *Neutrosophic Genetic Algorithm for solving the Vehicle Routing Problem with uncertain travel times*. Infinite Study, 2022.

[14] N. D. Yosodipuro, E. Javanmardi, J. Nakazato, Y. Tamura, X. Défago, and M. Tsukada, "Mixed-traffic Intersection Management using Traffic-load-responsive Reservation and V2X-enabled Speed Coordination," in *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, 2023: IEEE, pp. 1927-1934.

[15] W. Dai, "Evaluation and Improvement of Carrying Capacity of a Traffic System," *Innovations in Applied Engineering and Technology,* pp. 1-9, 2022.

[16] J. Jeong *et al.*, "A comprehensive survey on vehicular networks for smart roads: A focus on IP-based approaches," *Vehicular Communications,* vol. 29, p. 100334, 2021.
[17] R. She and Y. Ouyang, "Generalized link cost function and network design for dedicated truck platoon lanes to improve energy, pavement sustainability and traffic efficiency," *Transportation Research Part C: Emerging Technologies,* vol. 140, p. 103667, 2022.
[18] Y. O. Scherr, B. A. Neumann-Saavedra, M. Hewitt, and D. C. Mattfeld, "Service network design for same day delivery with mixed autonomous fleets," *Transportation research procedia,* vol. 30, pp. 23-32, 2018.
[19] R. Cheraitia, "Solving the consistent Vehicle Routing Problem with Profit using Simulated Annealing," Université jijel, 2021.