Academic Journal of Science and Technology
Vol. 7 (2024)
https://academicpinnacle.com/index.php/ajst

Capacitated Vehicle Routing Problem in Truck Platooning: Challenges and Solutions

Ahmed Hassan and Mohamed Salah
Department of Transportation Engineering, Alexandria University, Egypt

Abstract

Capacitated Vehicle Routing Problem (ACVRP) in truck platooning presents a multifaceted challenge in logistics and transportation optimization. Truck platooning, where multiple trucks travel closely together to reduce aerodynamic drag and fuel consumption, introduces complexities such as varying capacities, route constraints, and coordination among platooning vehicles. The ACVRP seeks to minimize costs while adhering to vehicle capacity limits and considering the interdependencies among platooned trucks. Challenges include the dynamic nature of platooning formations, the need for real-time decision-making, and the integration of vehicle-specific constraints. Solutions involve advanced mathematical models, heuristic algorithms, and machine learning techniques to optimize routing, scheduling, and platooning configurations. Addressing these challenges enhances efficiency, reduces operational costs, and promotes sustainable transportation practices in modern logistics scenarios.

Keywords: Capacitated Vehicle Routing Problem (CVRP), Truck Platooning, Routing, Vehicle Capacity Constraints

1. Introduction

The Capacitated Vehicle Routing Problem (CVRP) is a classic optimization challenge in logistics and transportation management, where the primary goal is to determine the most efficient routes for a fleet of vehicles delivering goods to various locations. Each vehicle has a limited carrying capacity, which adds a significant constraint to the problem. The objective is to minimize the total distance traveled or the overall cost while ensuring that all delivery demands are met without exceeding vehicle capacities [1]. This problem is fundamental in fields such as supply chain management, where efficient routing can lead to substantial cost savings and improved service levels. Due to the computational complexity of large-scale instances, CVRP is typically solved using exact algorithms, heuristic algorithms, and metaheuristic algorithms. In recent years, the application of reinforcement learning methods based on anchor graph hashing in cloud radio access networks has demonstrated the potential of AI technology in solving complex optimization problems[2]. Truck platooning involves a group of trucks traveling closely together, typically in a coordinated formation, using advanced driving technologies like adaptive cruise control and vehicle-to-vehicle communication. The lead truck dictates the speed and route, while the following trucks automatically adjust their movements based on the lead truck's actions. This technique offers several benefits, including significant reductions in aerodynamic drag, which leads to lower fuel consumption and greenhouse gas emissions. Additionally, platooning can enhance road safety by reducing human error and improving traffic flow through synchronized driving behaviors. It also offers potential improvements in logistics efficiency by allowing better utilization of road space and reducing traffic congestion.

Optimizing the CVRP in truck platooning scenarios is crucial for maximizing the potential benefits of both CVRP and truck platooning. In these scenarios, traditional routing methods need to be adapted to account for the dynamic nature of platooning, where the formation of trucks can change due to various factors such as traffic conditions, delivery schedules, and vehicle capacities. Effective optimization can lead to further reductions in operational costs by enhancing fuel efficiency, minimizing travel distances, and improving delivery times. Moreover, it ensures that the capacity constraints of each vehicle are respected while maintaining the integrity of the platoon, thereby optimizing the overall logistics network [3]. In this context, research on the application of deep learning models such as BERT can provide valuable insights for real-time decision-making, thus optimizing route planning[4]. For example, Hao et al. proposed a truck platooning planning method for the vehicle routing problem in road network capacity, utilizing dynamic programming and modified insertion heuristic methods to achieve this optimization goal. Addressing the CVRP in the context of truck platooning not only leverages the environmental and economic benefits of platooning but also paves the way for smarter, more resilient transportation systems capable of adapting to real-time challenges and opportunities. The Capacitated Vehicle Routing Problem (CVRP) in truck platooning is an extension of the traditional CVRP, incorporating the unique dynamics and constraints associated with platooning. In this context, the objective remains to determine the optimal routes for a fleet of vehicles, each with a specified capacity, to deliver goods to various locations. However, additional considerations are introduced by the need to maintain and manage platoons—groups of trucks traveling in close formation to improve fuel efficiency and reduce emissions. This involves not only minimizing travel distances and costs but also coordinating the routes and schedules of multiple trucks to ensure they can form and maintain platoons as much as possible[5]. Key elements include synchronizing departure times, managing inter-vehicle distances, and dynamically adjusting routes in response to real-time conditions [6]. Key Objectives and Constraints in CVRP for Truck Platooning. Minimizing Total Travel Distance and Cost: As with traditional CVRP, the primary objective is to minimize the overall distance traveled and associated costs. Maximizing Platoon Formation and Duration: Maximizing the time trucks spend in platoons to leverage the benefits of reduced aerodynamic drag and fuel consumption. Adhering to Vehicle Capacity Constraints: Ensuring that the load carried by each truck does not exceed its capacity. Balancing the load distribution among trucks while forming efficient platoons. Ensuring Timely Deliveries: Meeting delivery time windows and customer demands while coordinating platoon movements. By addressing these challenges and adhering to these objectives, the CVRP in truck platooning aims to achieve an efficient, cost-effective, and sustainable logistics operation that leverages the technological advancements in autonomous and connected vehicle systems [7].

2. Challenges in CVRP in Truck Platooning

Dynamic platooning formations have emerged as a promising solution to revolutionize the trucking industry. This innovative approach involves the coordinated movement of multiple trucks near each other, acting as a single unit. The concept behind dynamic platooning is to improve safety, reduce fuel consumption, and increase road traffic efficiency. In this article, we will explore the description of dynamic platooning formations, the challenges in coordinating multiple trucks, vehicle-specific constraints, the impact of these constraints on routing decisions, the importance of real-time decision-making, and the need for quick adjustments in routing due to dynamic platooning, as well as handling real-time data and feedback. Dynamic platooning formations refer to the synchronized movement of trucks in a convoy-like formation [8]. Unlike traditional platooning, dynamic platooning allows trucks to form and dissolve platoons as needed, even if they have different origins and destinations. This flexibility enables trucks to join or leave a platoon at any point along their route, optimizing the overall efficiency of the convoy. The coordination of dynamic platooning formations is facilitated through advanced technology, such as vehicle-to-vehicle (V2V) communication, which enables real-time exchange of information among the vehicles.

Figure 1, depicts an example network for vehicles in platooning, showcasing the concept of closely following vehicles in a convoy led by a professional driver in a lead vehicle. The figure illustrates the coordination system that maintains a secure gap and speed among the platoon leader and followers throughout the trip. It showcases the inter-vehicle dynamics in a platoon formation, with variables representing the position, velocity, and acceleration of each vehicle. The figure also highlights the environmental benefits of platooning, such as improved traffic flow and reduced fuel consumption [9]. Additionally, it demonstrates the use of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication for platooning. The figure emphasizes the importance of creating a stable network for reliable and quick transmission of information among platoon members. Overall, the example network figure provides a visual representation of the concepts and technologies involved in vehicle platooning.

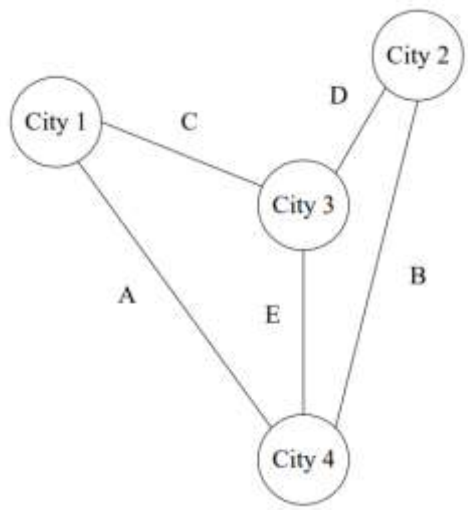

Figure 1: Example network for a vehicle in platooning.

Coordinating multiple trucks in a platoon presents its fair share of challenges. One of the primary challenges is the need for efficient dispatching strategies that facilitate the formation and coordination of platoons across different fleets. Each truck has its fixed route and objectives, and the challenge lies in ensuring that individual truck objectives align with the overall benefits of platooning. Coordinating the waiting times of trucks at hubs along their routes is also crucial for successful platoon coordination [10]. Research on frequency-selective high-transmission helical terahertz plasma antennas provides a reference for optimizing communication. Efficient dispatching and coordination strategies are essential to ensure that trucks join and leave platoons seamlessly, minimizing disruptions and maximizing the benefits of dynamic platooning Vehicle-specific constraints, such as variations in truck capacities and capabilities, add another layer of complexity to dynamic platooning [11]. Trucks within a platoon may have different fuel efficiencies, power capabilities, or cargo capacities. These constraints must be taken into account when making routing decisions to ensure that the platoon operates efficiently and effectively. For example, trucks with lower fuel efficiencies may need to be strategically positioned within the platoon to optimize fuel consumption. Similarly, trucks with higher power capabilities can help maintain the desired speed and stability of the platoon. Balancing these constraints is crucial to achieve the desired outcomes of dynamic platooning [12].

The impact of vehicle-specific constraints on routing decisions cannot be understated. Routing decisions need to consider factors such as fuel cost, vehicle capabilities, and the overall objectives of the platoon. Optimal routing can lead to improved fuel savings, reduced emissions, and enhanced operational efficiency. For example, Li et al. proposed a one-shot segmentation method based on a prototype contrastive convolutional network, providing new insights for vehicle routing planning in platooning[13]. Therefore, it is vital to incorporate vehicle-specific constraints into the routing algorithms to ensure that trucks within a platoon are assigned routes that align with their capabilities while maximizing the benefits of platooning. Real-time decision-making plays a pivotal role in the success of dynamic platooning formations [14]. The dynamic nature of platooning necessitates quick adjustments in routing due to changing road conditions, traffic patterns, and other external factors. Real-time data and feedback, obtained through sensors and V2V communication, enable trucks to adapt to these changing conditions effectively. Advanced technologies, such as artificial intelligence and machine learning, can analyze real-time data and provide valuable insights to support informed decision-making. These technologies enable trucks to adjust routes and speeds promptly, ensuring safe and efficient platoon operation. In this context, the application of semi-supervised learning in image classification, particularly the fusion of labeled and unlabeled data, further enhances these systems' capabilities [15].

Dynamic platooning, also known as truck platooning, refers to a technique where multiple trucks travel near each other, forming a convoy-like formation. These trucks are equipped with advanced communication and control systems that allow them to coordinate their movements and maintain a safe distance between each other. This technology has gained attention in the transportation industry due to its potential benefits in terms of fuel efficiency, safety, and traffic management. One of the key benefits of dynamic platooning is improved fuel efficiency. When trucks travel in a platoon, they can take advantage of reduced aerodynamic drag, resulting in lower fuel consumption. Studies have shown that platooning can lead to significant fuel savings, ranging from 5% to 18%. In addition to fuel efficiency, dynamic platooning also offers safety advantages. With connected driving technology, trucks in a platoon can communicate with each other and synchronize their movements[16]. This enables automatic braking and virtually zero reaction time, reducing the risk of accidents caused by human error. However, there are several challenges in coordinating multiple trucks in a dynamic platooning system. One of the main challenges is the coordination of vehicle-specific constraints. Trucks may have variations in capacities and capabilities, such as different maximum speeds or braking capabilities. These constraints need to be taken into account when forming platoons and making routing decisions. Real-time decision-making is another crucial aspect of dynamic platooning. As platoons are formed and disbanded dynamically, there is a need for quick adjustments in routing to accommodate changes in the platoon composition. This requires handling real-time data and feedback from the trucks in the platoon, as well as integrating information from external sources such as traffic conditions and weather updates

3. Solutions to Address CVRP Challenges in Truck Platooning

Optimization models tailored for dynamic platooning play a crucial role in maximizing the efficiency and effectiveness of this transportation technique [17]. These models aim to address the challenges associated with coordinating multiple trucks and integrating vehicle-specific constraints. By leveraging heuristic algorithms, machine learning techniques, and advanced technologies, these optimization models enable real-time decision-making and data-driven approaches to improve fuel consumption and overall efficiency.

A deep learning-based multifunctional end-to-end model for optical character classification and noise reduction provides technical support for vehicle-to-vehicle communication and data processing[18]. One of the key aspects of optimization models for dynamic platooning is the integration of vehicle-specific constraints in mathematical formulations [19]. Trucks in a platoon may have different capacities, capabilities, and constraints, such as maximum speeds, braking distances, and acceleration rates. To optimize the platoon formation and routing decisions, these constraints need to be considered. Mathematical models are developed to incorporate these constraints and optimize the platoon composition while ensuring safety and efficiency. Heuristic algorithms play a vital role in real-time decision-making for dynamic platooning. As platoons are formed and disbanded dynamically, the system needs to make quick adjustments in routing to accommodate changes in the platoon composition or external factors, such as traffic conditions. Heuristic methods, such as metaheuristics and adaptive algorithms, are applied to efficiently search for near-optimal solutions within a reasonable timeframe. These algorithms enable real-time decision-making, ensuring that the platoon maintains its effectiveness and adapts to changing conditions promptly. Machine learning techniques are also employed in optimizing dynamic platooning. Predictive routing and dynamic adjustments can be achieved using machine learning models. By utilizing advanced detection algorithms, semantic wireframe detection aids in the creation of high-resolution road maps, which include the identification of lanes, road edges, and other critical features. This level of detail is particularly crucial for the safe and efficient formation and maintenance of truck platoons[20]. These models analyze historical data, real-time feedback, and external factors to predict optimal routes for the platoon. By using machine learning, the system can continuously learn and adapt to changing conditions, improving efficiency and fuel consumption. Data-driven approaches enable the system to make informed decisions based on patterns and trends identified in the data, leading to better optimization outcomes.

The integration of advanced technologies is a crucial aspect of optimization models for dynamic platooning. Internet of Things (IoT) and vehicle-to-vehicle communication play a significant role in enabling real-time data exchange and coordination among trucks in a platoon. These technologies facilitate the sharing of information, such as speed, location, and road conditions, allowing for better decision-making and synchronization [21]. Additionally, automated decision-making systems can be implemented, leveraging the data and feedback from the trucks to make autonomous routing decisions in real time. These advanced technologies enhance the efficiency and safety of dynamic platooning. Vehicle-to-vehicle communication (V2V) refers to the exchange of information between vehicles using wireless communication technology. This communication allows vehicles to share important data about their movements, such as speed, position, and direction, with nearby vehicles. By enabling vehicles to communicate with each other, V2V technology aims to improve road safety, enhance traffic efficiency, and enable new applications and services. The primary purpose of V2V communication is to enhance situational awareness on the road. When a vehicle detects a potential hazard or danger, such as sudden braking or a disabled vehicle, it can transmit this information to nearby vehicles. The receiving vehicles can then use this information to alert their drivers or trigger automated safety systems, helping to prevent accidents and improve overall road safety. V2V communication relies on wireless communication protocols, such as Dedicated Short-Range Communications (DSRC) or Cellular Vehicle-to-Everything (C-V2X). These protocols allow vehicles to exchange data in real time, creating a network of connected vehicles. The range of V2V communication can extend up to several hundred meters, providing a wide coverage area for information sharing. Vehicle-to-vehicle communication is a technology that enables vehicles to exchange information with each other in real-time. By sharing data about their movements and potential hazards, V2V communication enhances road safety, improves traffic efficiency, and enables the development of advanced driver assistance systems. As technology continues to advance, V2V communication is expected to play a crucial role in the future of transportation.

4. Conclusion

In conclusion, the Capacitated Vehicle Routing Problem (CVRP) in truck platooning presents several challenges that need to be addressed for efficient and effective operations. The integration of vehicle-specific constraints, such as truck capacities and capabilities, into optimization models tailored for dynamic platooning is crucial. This allows for accurate routing decisions and the optimal utilization of resources. Heuristic algorithms provide real-time decision-making capabilities, enabling quick adjustments and flexibility in dynamic platooning operations. Machine learning techniques offer the potential to further optimize fuel consumption and efficiency by leveraging data-driven approaches. The integration of advanced technologies, such as vehicle-to-vehicle communication and automated decision-making systems, enhances coordination and safety in platooning formations. Overall, the solutions discussed in this paper provide valuable insights and strategies for addressing the challenges of the CVRP in truck platooning, paving the way for more sustainable and efficient transportation systems.

Reference

[1] 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.

[2] 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.

[3] R. Cheraitia, "Solving the consistent Vehicle Routing Problem with Profit using Simulated Annealing," Université jijel, 2021.

[4] Y. Wu, Z. Jin, C. Shi, P. Liang, and T. Zhan, "Research on the Application of Deep Learning-based BERT Model in Sentiment Analysis," *arXiv preprint arXiv:2403.08217,* 2024.

[5] 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.

[6] 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.

[7] Y. Hao, Z. Chen, X. Sun, and L. Tong, "Planning of Truck Platooning for Road-Network Capacitated Vehicle Routing Problem," *arXiv preprint arXiv:2404.13512,* 2024.

[8] S. M. Darwish and B. E. Abdel-Samee, "Game theory based solver for dynamic vehicle routing problem," in *The International Conference on Advanced Machine Learning Technologies and Applications (AMLTA2019) 4*, 2020: Springer, pp. 133-142.

[9] H. Bi, X. Zhu, F. Lu, and M. Huang, "The meal delivery routing problem in e-commerce platforms under the shared logistics mode," *Journal of Theoretical and Applied Electronic Commerce Research,* vol. 18, no. 4, pp. 1799-1819, 2023.

[10] O. Dukkanci, B. Y. Kara, and T. Bektaş, "The green location-routing problem," *Computers & Operations Research,* vol. 105, pp. 187-202, 2019.

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

[12] T. Huizingh, "Improving a Vehicle Routing Problem algorithm at Districon," University of Twente, 2021.

[13] L. Li, Z. Li, F. Guo, H. Yang, J. Wei, and Z. Yang, "Prototype Comparison Convolutional Networks for One-Shot Segmentation," *IEEE Access,* 2024.

[14] E. Taniguchi, R. G. Thompson, and A. G. Qureshi, "Recent developments and prospects for modeling city logistics," *City Logistics 1: New Opportunities and Challenges,* pp. 1-27, 2018.

[15] S. Li, P. Kou, M. Ma, H. Yang, S. Huang, and Z. Yang, "Application of semi-supervised learning in image classification: Research on fusion of labeled and unlabeled data," *IEEE Access,* 2024.

[16] 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.

[17] J. Choi and B. Do Chung, "Optimizing vehicle route, schedule, and platoon formation considering time-dependent traffic congestion," *Computers & Industrial Engineering,* vol. 192, p. 110205, 2024.

[18] S. Xiong, X. Chen, and H. Zhang, "Deep Learning-Based Multifunctional End-to-End Model for Optical Character Classification and Denoising," *Journal of Computational Methods in Engineering Applications,* pp. 1-13, 2023.

[19] V. Liatsos, M. Golias, J. Hourdos, and S. Mishra, "The capacitated hybrid truck platooning network design problem," *Transportation Research Part A: Policy and Practice,* vol. 181, p. 103999, 2024.
[20] Y. Zhou *et al.*, "Semantic Wireframe Detection," 2023.
[21] F. Luo and J. Larson, "A repeated route-then-schedule approach to coordinated vehicle platooning: Algorithms, valid inequalities and computation," *Operations Research,* vol. 70, no. 4, pp. 2477-2495, 2022.