Developing planning and collaboration models for the efficient integration of truck platoons in forestry transportation

by

Saba GAZRAN

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Mr. Mikael Rönnqvist, Thesis Co-Supervisor
Département de génie mécanique, Université Laval

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Mr. Matthieu Gruson, External Examiner
Département d'analytique, opérations et technologies de l'information, UQAM

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FOREWORD

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In memory of my beloved father.

Développement de modèles de planification et de collaboration pour l'intégration efficace des pelotons de camions dans le transport forestier

Saba GAZRAN

RÉSUMÉ

Un peloton de camions, ou "truck platooning", consiste à former un convoi de deux camions ou plus, se déplaçant de manière rapprochée et synchronisée grâce à la technologie de conduite automatisée et de communication véhicule-à-véhicule (V2V). Les camions suiveurs ajustent automatiquement leur direction, vitesse et freinage en fonction des actions du camion de tête, ce qui permet de réduire la consommation de carburant et, selon le niveau d'automatisation, de diminuer le nombre de conducteurs nécessaires. Cette thèse doctorale examine le potentiel de la technologie de peloton de camions pour améliorer l'efficacité et la durabilité du transport, notamment des produits forestiers. Elle est divisée en trois phases.

La première phase présente une revue systématique de la littérature sur la planification du transport utilisant les pelotons de camions. Cette revue explore les modèles développés dans la littérature pour différents niveaux de planification (notamment dans un contexte de collaboration), les avantages de la planification du transport utilisant les camions en peloton ainsi que les défis rencontrés. Selon la revue, plus de 80% des articles ont été publiés entre 2019 et 2023. L'étude souligne le manque de modèles de planification stratégique-tactique et de collaboration axés sur l'industrie forestière, ainsi que de modèles qui traitent de l'intégration des pelotons de camions aux niveaux de planification à long et moyen terme. La deuxième phase se concentre sur le développement d'un modèle de programmation linéaire en nombres entiers mixtes (MILP) pour évaluer l'efficacité des camions en peloton dans les chaînes d'approvisionnement forestières amont. Elle explore l'intégration progressive des camions en peloton dans le réseau de transport. De plus, cette phase analyse les avantages du peloton de camions (réductions de coûts, consommation de carburant et main-d'œuvre) ainsi que les facteurs qui influencent son efficacité. Cette phase démontre des économies potentielles de coûts allant de 3% à plus de 20%, des réductions de la consommation de carburant de 1 à 16% et des réductions du nombre de conducteurs de 3% à plus de 50% selon le scénario notamment le niveau d'intégration des pelotons de camions dans le réseau de transport. Les principaux facteurs influençant l'efficacité du peloton sont les distances moyennes de transport, les opportunités de retour en charge et les niveaux d'accès des pelotons de camions aux zones forestières. La dernière phase se concentre sur la collaboration entre des entreprises de transport utilisant les pelotons de camions. Les résultats indiquent que la collaboration utilisant les pelotons de camions peut générer des économies de coûts supplémentaires de 1 à 19%. Cette phase analyse différents scénarios de collaboration. De plus, elle examine le partage des coûts entre les entreprises participantes. Elle fournit un modèle de planification de transport basé sur le MILP et utilise des modèles basés sur la théorie des jeux pour le partage des coûts. Les phases 2 et 3 présentent des applications à des études de cas inspirées des chaînes d'approvisionnement forestières amont dans la province de Québec, au Canada.

Ce projet doctoral présente des modèles d'aide à la décision qui prennent en compte les caractéristiques (avantages et contraintes) du peloton de camions et qui peuvent être mis en œuvre dans le monde réel pour réduire les coûts de transport, la consommation de carburant et le nombre de conducteurs nécessaires (dans un contexte de pénurie de main-d'œuvre). Cela contribue à rendre le transport forestier plus durable.

Mots-clés: Peloton de camions, transport, planification, collaboration, partage des coûts, revue systématique de la littérature, Recherche Opérationnelle

Developing planning and collaboration models for the efficient integration of truck platoons in forestry transportation

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ABSTRACT

Truck platooning consists in forming a convoy of two or more trucks traveling close to one another, synchronized in their movements using automated driving technology and vehicle-to-vehicle (V2V) communication. The following trucks can automatically adjust steering, speed, and braking based on the actions of the lead truck. This leads to reduced fuel consumption and depending on the automation level to less truck drivers. This doctoral thesis investigates the potential of truck platooning technology in improving the efficiency and sustainability of product transportation in particular in forestry. It is divided into three phases.

The first phase presents a systematic literature review on truck platooning transportation planning. This review explores the models used in the literature for different planning levels (notably in collaboration contexts), the benefits of truck platooning transportation planning alongside the challenges it faces. According to the review, more than 80% of the papers were published between 2019 and 2023. The study highlights the lack of strategic-tactical planning and collaboration models focused on the forestry industry, as well as models that address the integration of truck platoons at long-term and mid-term planning levels. The second phase focuses on developing a Mixed-Integer Linear Programming (MILP) model for evaluating the efficiency of truck platooning in upstream forest supply chains. It explores the gradual integration of truck platooning into the transportation network. Moreover, this phase analyzes truck platooning benefits (cost savings, fuel consumption, and labor), as well as the factors that influence its efficiency. This phase demonstrates potential cost savings between 3% to more than 20% and fuel consumption reductions of 1-16%, and reductions in the number of drivers between 3% to more than 50% depending on the scenario notably level of platooning integration to the transportation network. The key factors influencing platooning efficiency are average transportation distances, backhauling opportunities, and access levels of truck platoons to forest areas. The last phase focuses on collaboration between carrier companies using truck platooning. The results indicate that collaboration using truck platooning can yield additional cost savings of 1-19%. This phase analyzes different collaboration scenarios. Moreover, it investigates cost-sharing between the companies in the collaboration. It provides an MILP transportation planning model and uses Game Theory based models for cost sharing. Phases 2 and 3 present applications to case studies inspired from upstream forest transportation networks in the province of Quebec, Canada.

This doctoral project presents decision-making models that consider the characteristics (benefits and constraints) of truck platooning that can be implemented in the real-world to reduce transportation costs, fuel consumption, and the number of drivers required (in a labour shortage context). This contributes to more sustainable forest transportation.

Keywords: Truck platooning, transportation, planning, collaboration, cost sharing, systematic literature review, Operations Research

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LIST OF ABBREVIATIONS

ACAM	Alternative Cost Avoided Method
ACC	Adaptive Cruise Control
CA	Continuous Approximation
CACC	Cooperative Adaptive Cruise Control
CORS	Canadian Operational Research Society
EPM	Equal Profit Method
ÉTS	École de Technologie Supérieure
GHG	Greenhouse gas
ILP	Integer Linear Programming
IP	Integer Programming
LP	Linear Programming
MIP	Mixed-Integer Programming
MILP	Mixed-Integer Linear Programming
NLP	Nonlinear Programming
OR	Operations Research
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

INTRODUCTION

0.1 Background

Transportation is an important component of supply chain operations, representing a significant portion of operational expenses. For example in countries such as Canada and Sweden, transportation cost is approximately one-third of the total raw material costs in the forest industry (Audy et al., 2023). Another issue in transportation is the high level of greenhouse gas (GHG) emissions caused by fuel consumption. Moreover, truck driver shortage is a serious problem in some industries. These issues can be addressed by developing optimization models and using new technologies such as truck platooning by decreasing transportation costs, fuel consumption, and the number of human drivers needed.

Truck platooning is a technology in the autonomous vehicles area that involves automated driving systems and vehicle-to-vehicle (V2V) communication enabling a convoy of trucks to travel closely together with synchronized steering, speeds, and braking (Alam et al., 2015). This closely coupled formation of trucks significantly reduces aerodynamic drag, leading to increased fuel efficiency (Maiti et al., 2017). The reduction in air drag between the vehicles in a platoon results in improved fuel efficiency of 4-20% (Alam et al., 2015). Beyond environmental benefits, truck platooning could reduce the need for truck drivers depending on the automation level, and leads therefore to cost reduction. This could contribute to more sustainable and efficient transportation.

From an automated driving perspective truck platooning can be categorized into three types (Bhoopalam et al., 2018):

- With-driver platooning, which incorporates driver-assistance systems in all trucks within the platoon (automation level 3). While maintaining platoon formation, drivers are needed in all trucks and remain in control, ready to take action if necessary. The benefit is lower fuel consumption.

- Hybrid platooning combines autonomous and assisted technologies. In this type, only the first truck is manually operated by a driver and the other trucks are driven autonomously (automation level 4). The benefits are fewer drivers as well as lower fuel consumption.
- Autonomous platooning involves fully autonomous trucks, with no driver in all trucks (automation level 5). This type of platooning requires higher truck automation levels and the benefits are low fuel consumption and no need for drivers.

While truck platooning has some benefits, it also poses some challenges, especially in the early stages of the adoption and integration of the technology with existing ordinary trucks and transportation networks. The infrastructure requires specialized lanes and dedicated communication systems add complexity and require substantial investment and coordination. In order for truck platooning systems to be deployed smoothly and efficiently, companies, operators, and technology providers must cooperate effectively (Roukouni et al., 2020). In order to adopt truck platooning in transportation, it is necessary to analyze how the use of this technology can be optimized and efficiently integrated with existing (ordinary) trucks and transportation networks to benefit from its advantages.

The exploration of truck platooning in transportation planning is a new field of study, presenting a problem that can be investigated at the strategic, tactical, and operational levels (Bhoopalam et al., 2018). Planning is essential for efficiently integrating truck platooning into the existing transportation system. At the strategic level, truck platooning transportation planning explores the long-term effects of this technology. This includes the design of the transportation network as well as investments required in infrastructure and vehicle fleets. At the tactical level, truck platooning transportation planning focuses on mid-term decisions. As an example, this involves planning the material flow movement between various nodes within the network, such as forest areas, terminals, and mills. This enhances the coordination of goods movement and optimizes the utilization of platooning technology to meet demands (Albiński et al., 2020). At the operational level, truck platooning transportation planning focuses on short-term decisions such as vehicle routing.

It is important to first focus on strategic and tactical transportation planning before exploring operational aspects to ensure a solid foundation (Noto and Noto, 2020). These planning levels create a structured process that informs and enhances operational planning effectiveness. This sequential approach guarantees that operational decisions are coherent with the strategic vision (Iliopoulou and Kepaptsoglou, 2019). This research aims to contribute to the successful adoption of truck platooning through a systematic literature review on truck platooning transportation planning and further by providing strategic-tactical approaches applied to the forestry sector. These approaches include optimizing network design for platoon trucks and creating models to gradually integrate truck platooning technology that combines ordinary and platoon trucks to maximize efficiency and cost savings.

The forest supply chain plays a significant role in countries such as Canada, where forests are a key component of the economy (Feng and Audy, 2020). From lumber and paper manufacturing to biofuel production, the forestry industry contributes significantly to economic growth, employment, and international trade (Kaulen et al., 2023). Forest transportation is characterized by long distances from forest areas to processing mills (Feng and Audy, 2020). This leads to high costs, making transportation a substantial portion of total operational expenses (Roos, 2023). Moreover, the environmental impact of forestry transportation, particularly in terms of GHG emissions is a significant concern (Zhao et al., 2023). Traditional transportation technologies contribute significantly to the sector's carbon footprint. In addition, the forestry sector like many others reliant on heavy-duty transportation faces driver shortage challenges (Wang et al., 2022).

The importance of addressing transportation challenges in forestry is highlighted by industry-driven initiatives and the industry engagement that is being conducted in the province of Québec in Canada on truck platooning and pioneering work in the area of hybrid truck platooning (Cools, 2019). The aim is to employ this technology for the enhancement of forest transportation logistics across Canada. This effort underscores the sector's shift towards innovative, technology-driven solutions to its longstanding logistical challenges. This initiative serves as a critical inspiration for this thesis, by placing the research within a practical framework that directly responds to the industry needs. In this research, we focus on the hybrid type of truck platooning. By focusing on hybrid truck platooning this research aligns with the efforts to operationalize truck platooning in forestry transportation.

This thesis investigates the problem of integration and optimization of truck platooning technology in transportation notably in the forestry sector. The main research questions of this thesis are: What planning models are proposed to address truck platooning transportation, and what collaboration approaches and models are proposed for transportation using truck platooning? How can truck platooning be integrated into forestry product transportation networks to enhance cost efficiency, reduce fuel consumption, and improve driver utilization? What collaborative and cost-sharing methods can facilitate truck platoon adoption in the forestry sector?

0.2 Research objectives

To address the research questions, the following phases were followed:

- Review and analyze existing models and methods in the literature in the field of transportation planning, specifically aiming to understand how these approaches have contributed to optimizing truck platooning transportation planning. Moreover, this review explores the benefits and challenges associated with truck platooning transportation planning, to identify areas where further research and development could lead to improvements.

- Develop a decision-making model for identifying the suitable solution at the strategic-tactical decision level to plan truck platoon transportation in different situations like different network structures and gradual technology integration scenarios in which technology adoption occurs incrementally rather than simultaneously across all networks. Truck platooning integration impacts can be assessed across different technology readiness levels using this approach.
- Develop models that can address collaboration practices between different carrier companies with and without platooning technology at the strategic-tactical planning level and address the cost-sharing problem between the companies while considering gradual technology adoption, different collaboration types, and node coverage levels in the network.

0.3 Research methodology

Figure 0.1 illustrates the research questions and the methodologies used.

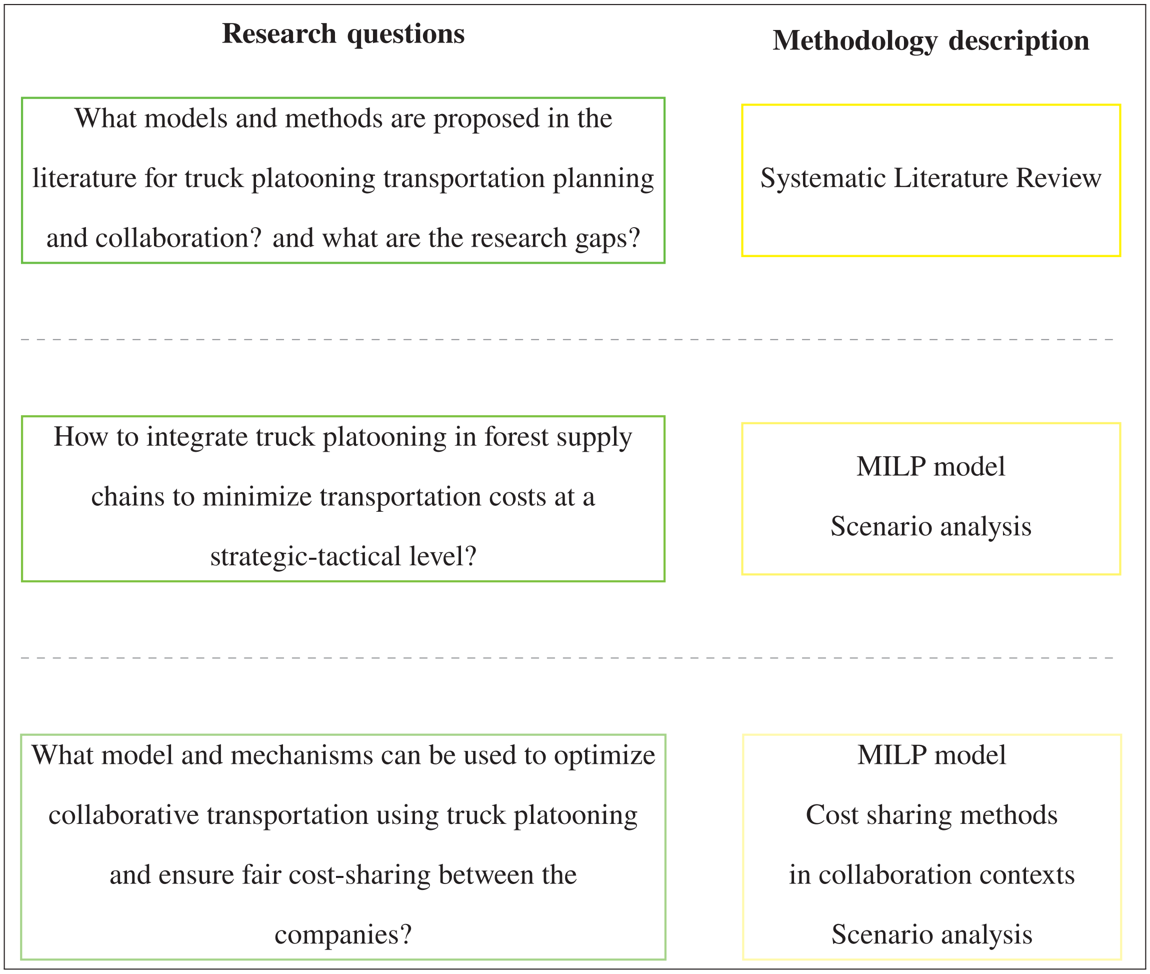

Figure 0.1 Research questions and methodologies

A systematic literature review was conducted to study what has been done in the literature and identify the research gaps. The review explored different models and methods used in the literature for truck platooning transportation planning. By using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, it investigated 114 research articles to identify what are the benefits and challenges related to truck platooning and what are the planning methods and collaboration models used in the truck platooning transportation literature. As research databases, Scopus, Web of Science, Compendex, and Inspec were used. The selected papers were analyzed to determine which models and methods were developed and how to improve truck platooning transportation efficiency at different planning levels. Furthermore, we looked for articles that related to Operations Research and simulation. Research trends, gaps, and future directions were discussed in this systematic review. The results of the review and research gaps guided the research in the next phases of the thesis. The paper presenting this study is submitted to the Transportation Research Part E: Logistics and Transportation Review journal in May 2024.

Figure 0.2 summarizes the research problem, methodology and contributions of the first paper.

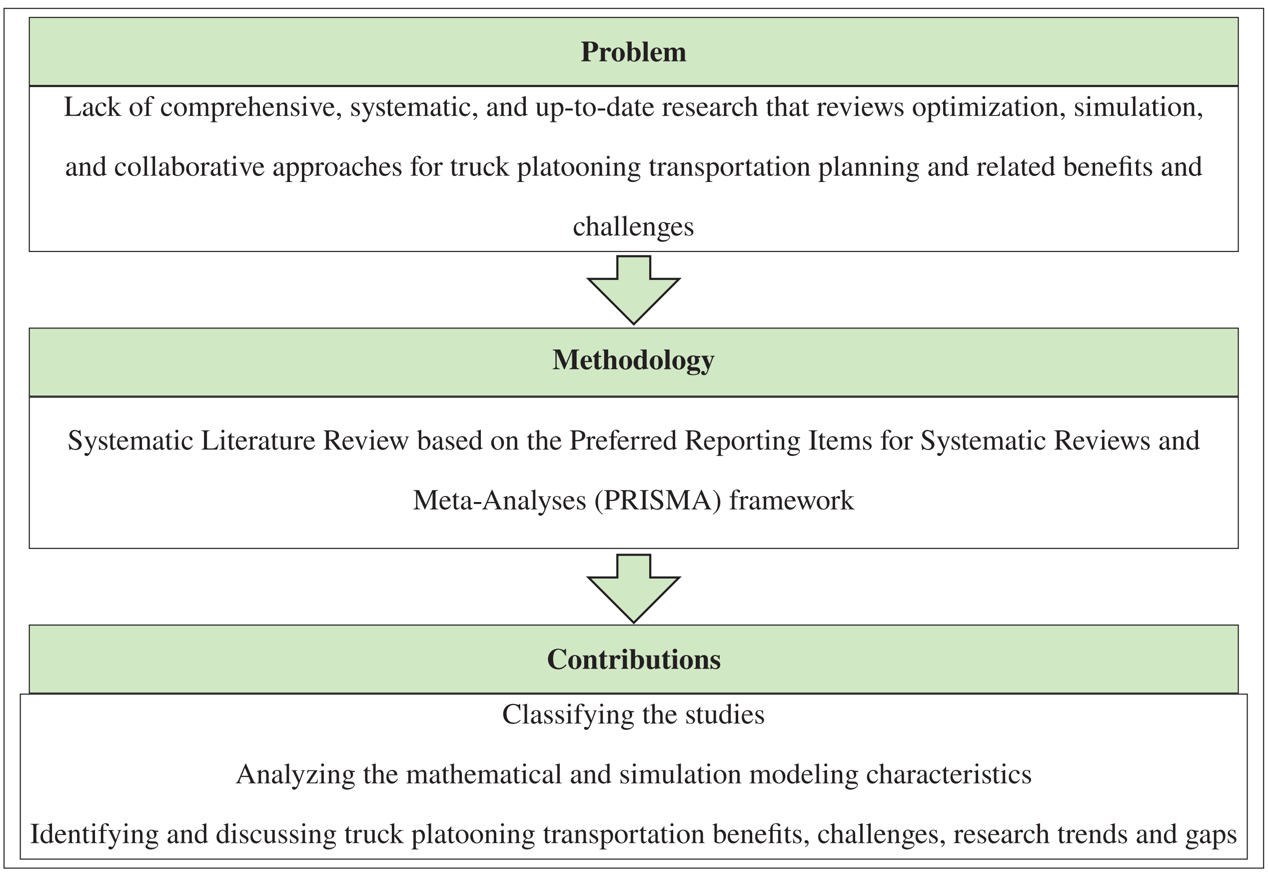

Figure 0.2 Research problem, methodology and contributions of article #1 (Gazran et al., 2024)

The second phase of research focused on developing a Mixed-Integer Linear Programming (MILP) model to optimize strategic-tactical truck platooning transportation planning in the forestry sector. The model optimizes terminal location, direct and backhaul route selection, and truck deployment. It focuses on reducing total transportation costs. Scenarios related to the gradual integration of truck platooning into the transportation network were considered to represent the first stages of introducing the technology in forest transportation. The model is applied to various realistic scenarios to assess truck platooning impacts under different conditions. This includes the analysis of different network structures and access levels for truck platooning to nodes in the network. The model is used to demonstrate cost efficiency, fuel savings, and driver-related advantages. The article presenting this work published in the Canadian Journal of Forest Research in 2023.

Figure 0.3 summarizes the research problem, methodology and contributions of the second paper.

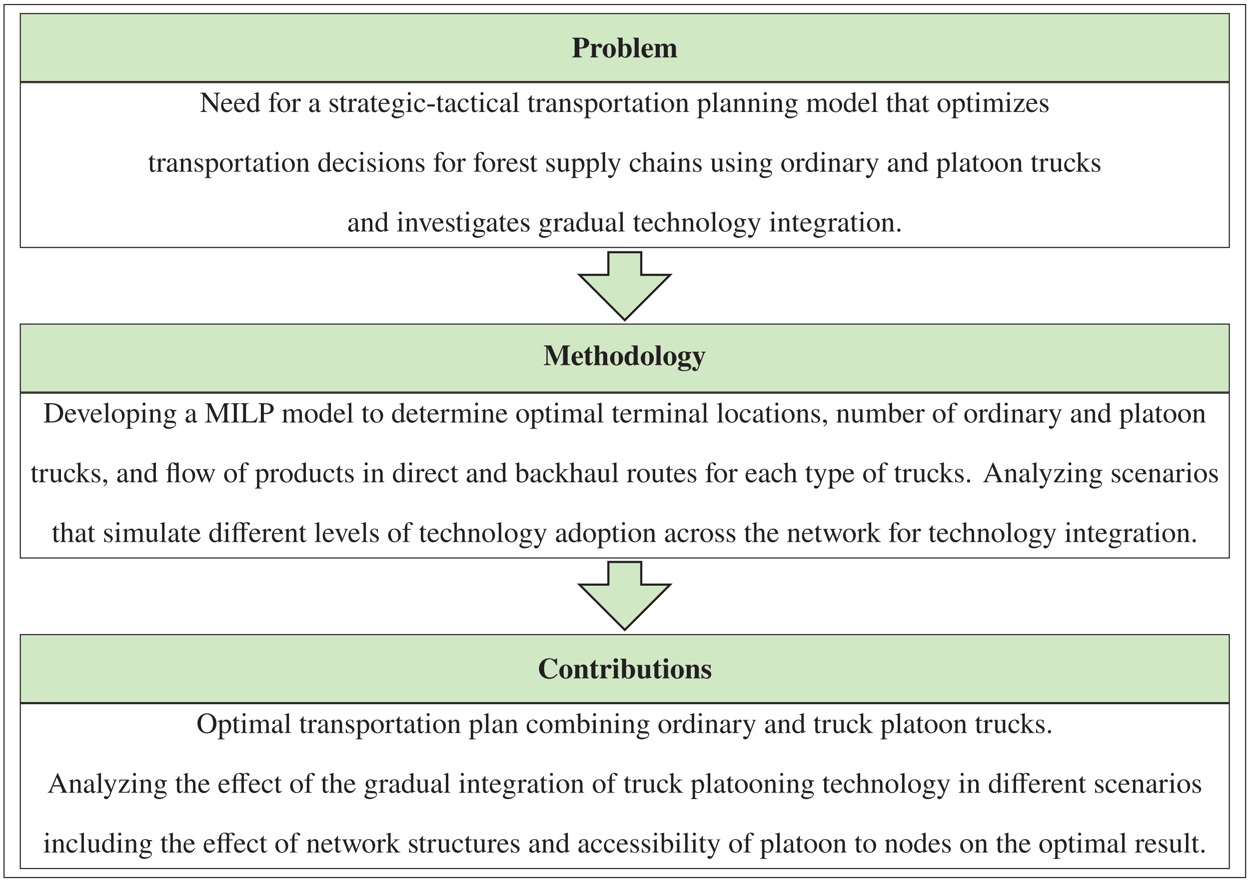

Figure 0.3 Research problem, methodology and contributions of article #2 (Gazran et al., 2023a)

The third phase of research focused on developing a MILP model to optimize the transportation costs in the context of semi- and full-collaboration. The model is an adaptation of the MILP model described above (second phase of research) to the collaboration context. Second, cost-sharing mechanisms were applied to allocate the cost savings between the different companies involved in the collaboration. Moreover, a two-stage cost-saving allocation method was proposed to ensure a fair distribution of cost savings resulting without and with platooning among the collaborating carrier companies. The article presenting this study is submitted to INFOR: Information Systems and Operational Research journal in July 2023.

Figure 0.4 summarizes the research problem, methodology and contributions of the third paper.

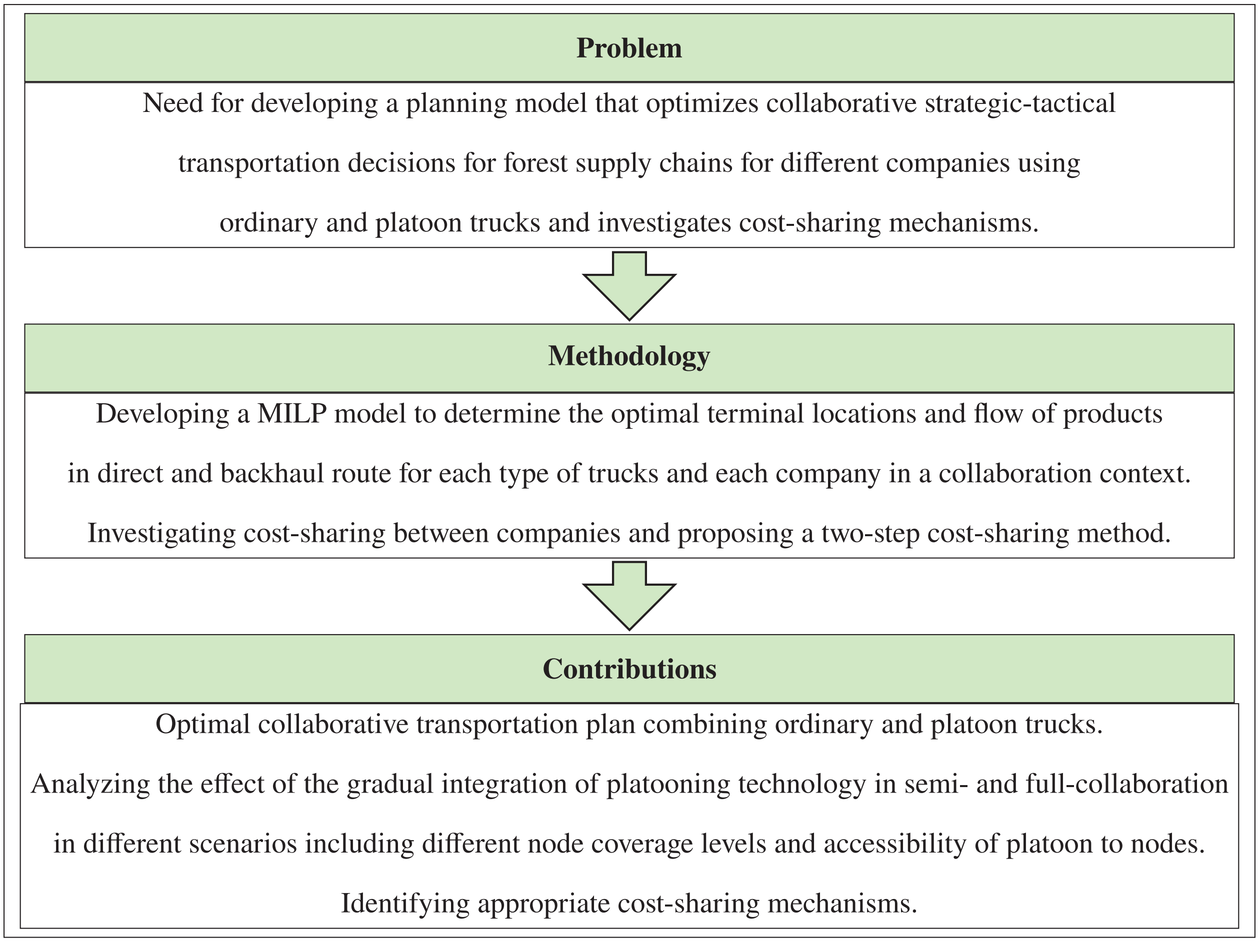

Figure 0.4 Research problem, methodology and contributions of article #3 (Gazran et al., 2023b)

0.4 Case studies

In this thesis, two case studies were used to evaluate the potential benefits of truck platooning in forestry transportation. They are inspired from the configuration of upstream forest products supply chains in the province of Québec (Canada). Case studies 1 and 2 are used in papers 2 and 3, respectively.

Case Study 1:

The first case study focuses on the integration of truck platooning into the forestry sector's transportation network. We built this case study based on 27 randomly generated realistic instances, considering six different scenarios to analyze potential benefits including cost savings, reduction in the number of drivers, and fuel consumption. The scenarios are constructed by combining the use of direct and backhaul routes for ordinary and platoon trucks and the level of accessibility to forest areas for truck platoons.

The six main scenarios are:

- Scenario S01: Ordinary trucks with direct transportation between all nodes (base-case scenario).
- Scenario S02: Ordinary trucks with direct and backhaul transportation between all nodes.
- Scenario S03: Ordinary trucks with direct transportation between all nodes and direct truck platooning transportation between terminals and mills (platoons not allowed to visit forest areas).
- Scenario S04: Ordinary trucks with direct and backhaul transportation between all nodes, and direct and backhaul transportation for platoon trucks between terminals and mills (platoons not allowed to visit forest areas).
- Scenario S05: Ordinary trucks with direct transportation between all nodes and direct transportation for platoon trucks between terminals, mills, and a limited number of forest areas (without backhauling).
- Scenario S06: Ordinary trucks with direct and backhaul transportation between all nodes and direct and backhaul transportation for platoon trucks between terminals, mills, and a limited number of forest areas.

The instances were generated to represent various transportation networks with different numbers of nodes, products, and node locations.

Case Study 2:

The second case study explores collaborative transportation involving different carrier companies. This study is based on 30 randomly generated instances. Three companies are considered, of which one uses platooning technology. The instances vary based on the level of coverage of supply, terminal, and demand nodes, as well as the accessibility level of truck platoons to forest areas.

Six scenarios were considered to analyze the potential benefits of using truck platooning in the context of collaboration. All scenarios include backhauling. Semi-collaboration involves partial cooperation between companies, including shared use of vehicles and terminals. Full collaboration involves complete integration of the companies' transportation networks, including shared vehicles, terminals, and orders:

- Scenario 1: No-collaboration with ordinary trucks only.
- Scenario 2: No-collaboration with ordinary and platoon trucks.
- Scenario 3: Semi-collaboration with ordinary trucks only.
- Scenario 4: Semi-collaboration with ordinary and platoon trucks.
- Scenario 5: Full-collaboration with ordinary trucks only.
- Scenario 6: Full-collaboration with ordinary and platoon trucks.

The remainder of this thesis is organized as follows:

Chapter 1 presents the literature review paper, Chapter 2 the paper on truck platooning transportation planning in the forestry sector (non collaboration context) and Chapter 3, truck platooning transportation planning and cost sharing in the forestry sector in collaboration contexts. Chapter 4 presents the conclusion, summarizing the key findings and suggesting potential areas for future research.

CHAPTER 1

A SYSTEMATIC LITERATURE REVIEW ON TRUCK PLATOONING TRANSPORTATION PLANNING

Saba Gazran[1,2,3] , Tasseda Boukherroub[1,2,3] , Mikael Rönnqvist[2,3,4]

[1] Department of Systems Engineering & Numerix Laboratory, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal, QC, Canada H3C 1K3
[2] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT),
Université de Montréal, Pavillon André-Aisenstadt, CIRRELT, CP 6128, Succursale Centre-ville Montréal, QC, H3C 3J7, Canada
[3] FORAC Consortium,
1065, av. de la Médecine, Université Laval, Québec, QC, G1V 0A6, Canada
[4] Département de Génie Mécanique,
1065, av. de la Médecine, local 1504, Université Laval, Québec, QC, G1V 0A6, Canada

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Abstract

Truck platooning is a technology where two or more trucks closely follow one another using automated driving technology. This technology has gained considerable attention for its potential to transform the transportation sector by addressing transportation challenges such as transportation costs, fuel consumption, and driver shortage issues depending on the automation level. This study presents a systematic literature review that explores the opportunities of using truck platooning in transportation. By using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, it analyses 114 research articles to identify what the benefits and challenges related to truck platooning are and what the planning methods and collaboration models used in the truck platooning transportation literature are. It also discusses research advancements and gaps in the literature on transportation planning and collaboration using truck platooning. More than 80% of articles have been published since 2019 indicating the trend and importance of an up-to-date literature review.

Keywords: Truck platooning; transportation; benefits; challenges; planning; collaboration; systematic literature review

1.1 Introduction

In recent years, truck platooning has gained increasing attention as a new autonomous and connected transportation technology. A truck platoon consists of a group of trucks that travel closely together in a convoy-like arrangement connected through advanced communication and control systems (Zhang et al., 2020). The first truck in a platoon works as the "platoon leader", it transmits data on speed, acceleration/deceleration, and steering among others to follower trucks enabling them to automatically synchronize their movements and keep safe distances (Alam et al., 2015). The close position of the vehicles provides aerodynamic efficiency, resulting in reduced air resistance and improved fuel usage (Scholl et al., 2023).

Depending on the automation level all the trucks could have drivers, or at higher automation levels a driver may be needed on the first tuck, while subsequent trucks can operate autonomously (Bhoopalam et al., 2023b). Key motivations for using truck platooning include addressing the shortage of qualified truck drivers, improving road safety through advanced sensor technologies and automated systems, optimizing traffic flow and decreasing congestion, and improving efficiency and reliability (Faber et al., 2020). Furthermore, the technology aligns with sustainability goals by reducing emissions through reduced fuel consumption (Paddeu and Denby, 2022). Through the advancement of truck platooning technology implementation is expected to bring significant changes to transportation (Bridgelall et al., 2020).

Truck platooning technology has existed for many years, with early attempts dating back to the 1990s (Neubauer et al., 2020). Truck platooning gained significant attention in the 2010s due to the rapid growth of vehicle automation (Atasayar et al., 2022). Truck platoons through Adaptive Cruise Control (ACC) systems, equipped with sensors like radar or lidar, detect the distance between a truck and the vehicle ahead (Tsugawa et al., 2016). ACC adjusts the speed of each truck based on the leader truck's actions which ensures a safe following distance while reducing driver intervention. Furthermore, Cooperative Adaptive Cruise Control (CACC) takes ACC a step further by integrating Vehicle-to-Vehicle (V2V) communication and exchange information technology (Chen et al., 2018). With CACC, trucks in a platoon react to the lead truck's movements but also communicate their actions to other platoon members. This enables more accurate and synchronized actions. To ensure safety, truck platooning systems incorporate collision avoidance technologies (Hyun et al., 2021). Sensors and cameras detect potential obstacles or risks around trucks.

There are three distinct types of truck platooning based on drivers' involvement levels (Bhoopalam et al., 2018):

- *With-driver platooning* where each truck within a platoon is driven by a human. The driving responsibilities are similar to those of individual truck drivers. Drivers control their vehicles' speed, direction, and maneuvers. Trucks travel closely to each other but operate as independent units. With-driver platooning reduces air resistance, enhancing fuel efficiency for all trucks involved in the convoy.
- *Hybrid platooning* is the type where the lead truck is driven by a human, while the other trucks are autonomous. Autonomous systems enable the following trucks to closely follow the lead truck's movements while maintaining a consistent and safe distance. The lead driver remains responsible for making decisions that affect the entire platoon, such as route changes or stops. Hybrid platooning benefits are lower number of drivers, reduced costs, and lower fuel consumption.
- *Fully autonomous platooning* is the type with no human drivers. Each truck is equipped with autonomous driving systems that enable them to operate independently and as part of a group. Trucks communicate with each other, ensuring synchronized formation, speed, and safe driving distances. Fully automated platooning results in lower costs and fuel consumption and does not require any human driver.

The choice of platooning type depends on factors such as technology development level, legal frameworks, safety considerations, and industry preferences (Fakhfakh et al., 2020). As an example, legal considerations for autonomous vehicles and commercial truck operations influence truck platoon implementation. Therefore, different decision-makers and stakeholders (i.e., governments, cities, companies, etc.) worldwide are working to create rules and standards for platooning technology.

Our study provides a current and comprehensive review of the literature on truck platooning transportation, with a focus on its potential benefits, challenges, and planning approaches. This is crucial due to the growing importance of truck platooning in recent years. There is a need for systematic exploration of this evolving field, aiming to discuss the benefits, challenges, planning models, and collaboration aspects of truck platooning transportation. Moreover, our paper emphasizes the critical role of planning aspects in truck platooning transportation. Efficient planning is crucial in transportation, however, truck platooning introduces unique characteristics that require adaptations to traditional planning models. For example, truck platooning involves the coordination of multiple vehicles traveling closely. This can affect the optimization of travel time, fuel consumption, and costs. This coordination introduces features and constraints that may not exist in traditional transportation scenarios. Decision-makers must consider factors such as platoon formation strategies, routing algorithms designed for truck platooning, and the integration of platooning into long-term transportation planning processes. Traditional optimization models may need to be modified to account for detours and truck platooning-specific objectives, such as maintaining optimal platoon formation over varying road conditions and enhancing coordination between trucks to improve overall operational efficiency. Moreover, routing algorithms should take into account the synchronized departures and arrivals of trucks, as well as platoon formations. Furthermore, collaboration models in truck platooning involve negotiating cost-sharing mechanisms, coordinating platoon formation among multiple carriers, and incentivizing participation in platooning. These collaboration models may require new game-theoretic approaches or coalition formation algorithms to ensure fair and efficient outcomes for all stakeholders involved. By reviewing the literature on truck platooning, we aim to identify the challenges and opportunities posed by this transportation approach. We also aim to understand how these factors influence planning and collaboration models at different levels, including operational, tactical, and strategic decision-making within transportation networks.

This will provide insights into the advancements and gaps in the field and inform future research directions to address the unique characteristics of truck platooning in transportation planning optimization.

Although there exist literature review studies on truck platooning transportation, there is a need to make a new contribution in this field. First, truck platooning is rapidly progressing with technology and application advancements, requiring updated and comprehensive reviews to cover the latest developments. Moreover, truck platooning involves interactions between technical, operational, and regulatory factors, requiring in-depth investigation of decision-making and planning. Furthermore, as truck platooning can enhance transportation efficiency, a thorough understanding of its benefits, challenges, and optimal planning approaches is crucial for maximizing these potential benefits across entire transportation networks and industries, including large-scale freight operations and supply chains. Bhoopalam et al. (2018) focused on truck platooning transportation planning with a framework for classifying transportation planning problems related to truck platooning. It focused on Operations Research (OR) models. Zhang et al. (2020) and Pi et al. (2023) provided an overview of research works on fuel and energy savings related to truck platooning. Roukouni et al. (2020) investigated the role of simulation games, to help actors find interactive solutions at the Port of Rotterdam. Gazran et al. (2021) reviewed truck platooning transportation planning literature with a specific focus on OR methods. Lesch et al. (2022) provided an overview of platoon coordination approaches, focusing on cooperative driving technology. Wu et al. (2023) provided a review on vehicle group intelligence in a connected environment. These reviews address specific areas (e.g., energy savings) of truck platooning, and those that focus on planning aspects review articles published in 2020 or before. As truck platooning research has grown in recent years, this research topic requires a new study that updates the knowledge and state of the art in the field. To the best of our knowledge, our study is the first one to discuss the aspects of benefits, challenges, planning, and collaboration models related to truck platooning transportation in one study. Furthermore, it is the first systematic literature review dedicated to truck platooning transportation planning.

This study provides a systematic literature review on transportation planning and collaboration models as well as on the benefits and challenges of truck platooning in transportation. Our objective is to provide a comprehensive understanding of truck platooning transportation planning and collaboration in this new context. To achieve this goal, we have formulated three research questions:

1. What are the planning models proposed to address truck platooning transportation? We aim to investigate transportation planning models focusing on how they address truck platooning challenges and opportunities. The focus here is on OR and simulation techniques designed for optimizing truck platooning transportation planning.

2. What are the collaboration approaches and models proposed for transportation using truck platooning? Our goal is to explore the collaborative mechanisms and models proposed in the literature. We are interested in understanding how the collaborating parties cooperate and share the related costs and benefits resulting from collaboration in this specific context.

3. What are the benefits and challenges of truck platooning? We aim to investigate the advantages and obstacles associated with truck platooning, emphasizing transportation planning and collaboration.

This systematic literature review contributes to the truck platooning transportation planning literature in three ways:

- It provides a comprehensive overview of the literature on truck platooning transportation planning. It presents the benefits and challenges and investigates which planning and collaboration models are used.
- It investigates the characteristics of the problems considered such as platooning technology types. Furthermore, it describes the goals, constraints, decisions considered in the transportation problems studied and how they are addressed in the models proposed as well as the results.
- It presents a discussion on the trends, gaps, and future research avenues.

This review provides a useful resource for researchers and practitioners to gain a better understanding and knowledge of truck platooning transportation planning and collaboration in this context, as well as the benefits and challenges related to this transportation technology. The application of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021) coupled with a rigorous selection of keywords and research databases, provides a basis for accuracy, comprehensiveness, and reproducibility. Our literature review covers a vast and diverse collection of relevant papers in the field of transportation planning.

The remainder of this paper is structured as follows: Sections 1.2 and 1.3 describe our research methodology and the assessment of the articles selected respectively. Sections 1.4 and 1.5 review the literature related to planning and collaboration approaches used for truck platooning transportation respectively. Section 1.6 presents the benefits and challenges of truck platooning. Section 1.7 provides a discussion. Finally, our conclusions and research perspectives are summarized in Section 1.8.

1.2 Methodology

To conduct our study, we used the systematic literature review method. This method was chosen for its precision, transparency, and reproducibility in data collection. According to Xiao and Watson (2019), eight common steps are necessary to conduct a systematic literature review as presented in Figure 1.1. We adapted these steps to fit our study better. The framework aligns with the essential principles of systematic reviews, yet emphasizes steps such as developing and validating the review protocol and assessing the quality of studies, which we found more applicable to our research objectives.

PRISMA (Page et al., 2021) provides a checklist and flow diagram to help improve systematic review and meta-analysis reporting. The PRISMA guidelines cover various aspects of the systematic review process, including the identification, screening, and inclusion of studies, data extraction, assessment of study quality, and presentation of results. In the following, we present

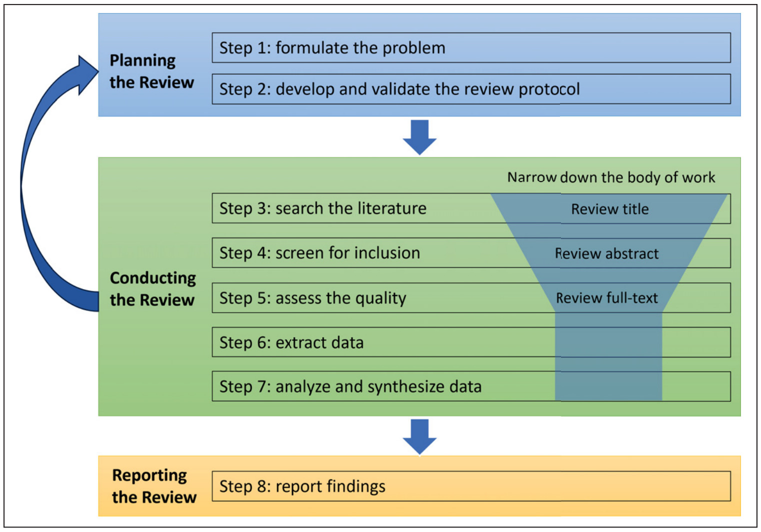

Figure 1.1 Process of the systematic literature review according to Xiao and Watson (2019)

how the steps of our research process were conducted following the the systematic literature review process outlined in Figure 1.1.

- **Step 1: formulate the problem**

  First, the scope and objectives of the systematic literature review need to be defined. In order to select relevant keywords, the main research questions were precisely formulated. Our research questions are summarized below:

  1. What are the transportation planning models proposed to address truck platooning transportation?

  2. What are the collaboration and coordination approaches proposed for transportation using truck platooning?

  3. What are the benefits and challenges related to using truck platooning?

- **Step 2: develop and validate the review protocol**

  The search process is a critical step as it requires specific keywords to identify and limit the scope of the study. To do this, we have identified and categorized seven key concepts. These concepts, outlined in Table 1.1, include:

  Transportation: This concept serves as one of the central themes, positioning our study within the transportation field.

Platooning: At the core of our investigation, "platooning" represents a central concept under study.

Truck: refers to the truck vehicles that engage in platooning, which is the focus of our research.

Benefits/Challenges: we seek to uncover both the advantages ("benefits") and the obstacles ("challenges") associated with platooning in the trucking industry, with a specific focus on transportation planning. We are not primarily concerned with technical aspects but rather planning and operational considerations.

Planning: emphasizes the decision-aid aspect of our research. We are interested in planning at the strategic, tactical and operational levels.

Collaboration: refers to the coordination and cooperation between different parties (truck drivers, freight companies, etc.) in the truck platooning transportation context.

Model/Method: underline the analytical tools and approaches proposed in the literature for decision support (planning and collaboration), focusing on techniques in the field of OR and simulation.

The use of synonymous keywords and related concepts as illustrated in Table 1.1, are pivotal for our search strategy. This is driven by the recognition that authors may employ varied terminology to depict similar or close concepts or aspects within the domain of transportation planning and collaboration. This ensures that our research covers relevant studies regardless of the authors' specific terms and prevents potential omissions. This will enhance the accuracy and comprehensiveness of the literature review.

The different concepts and key words are combined in research equations aiming at answering the three previous research questions.

To address the first research question, we explored the literature related to planning and models/methods used. By focusing on these aspects, we aimed to examine the transportation planning models and methods proposed in the literature.

Research equations 1 combines concept 1 AND concept 2 AND concept 3 AND concept 5 AND concept 7 (e.g., truck platooning transportation planning method).

Table 1.1 Keywords combination set used for the literature review

Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
Transport*	Platoon*	Truck	Benefit*	Plan*	Collaborat*	Model*
Logistics	"Virtually connected"	"Heavy-duty vehicle"	Impact*	Design	Coordinat*	Framework
Suppl*	"Autonomous and connected"		Effect*	Schedul*	Coalition	Approach
Deliver*	Convoy		Advantage*	Rout*	"Cost shar*"	Method*
			Challenge*		"Benefit shar*"	"Mathematic* model"
			Barrier*			"Mathematic* method"
			Drawback*			"Optim* model"
			Obstacle*			"Optim* method"
						"Operation* Research"
						OR
						Simulation
						"Game Theory"

To address the second research question, we focus on collaboration and the models/methods proposed in this context. This enables us to analyze studies that explore collaborative and coordination approaches proposed in the context of truck platooning transportation.

Research equations 2 combines concept 1 AND concept 2 AND concept 3 AND concept 6 AND concept 7 (e.g., truck platooning transportation collaboration model).

Research equation 3 combines concept 1 AND concept 2 AND concept 3 AND concept 4 AND (concept 5 OR concept 6) (e.g., truck platooning transportation planning challenges; truck platooning transportation collaboration benefits).

Besides keywords, we defined a list of inclusion and exclusion criteria to focus on relevant articles (see Table 1.2).

- **Step 3 and 4: search the literature and screen for inclusion**

  Based on the key-words combination (presented in step 2) we defined equations in *Scopus, Web of Science, Compendex, and Inspec* which offer comprehensive and reliable scientific works. These databases were selected not only due to their widespread use but also because

Table 1.2 Inclusion and exclusion criteria

	Criteria
Inclusion	Papers published up to the end of 2023 (without limitation on the starting date).
	Publications in English in peer-reviewed journals.
	Theoretical studies, review articles, as well as case studies related.
Exclusion	Papers that mention truck platooning as a technology but do not analyze transportation planning.
	Papers focusing on passenger transportation, waterways and railroads.
	Papers that only focus on limited aspects, such as control algorithms for vehicle motion; analysis of road systems; off-road vehicles; ”manual” platooning; etc.
	Papers that are not accessible in full text from the research libraries.
	Studies that were first prepared and then expanded.

of their significance to the research community in transportation planning. A first screening step was performed using the *Rayyan* software (Ouzzani et al., 2016) which is a web tool designed to help researchers work on systematic reviews by speeding up screening and selecting relevant studies. The titles, abstracts, and keywords were screened and we identified potential relevant studies. The last selection step was based on the full-text review of the articles.

- **Steps 5 and 6: assess the quality and extract data**

  The final selected articles were read carefully (step 5). Throughout the readings, notes were taken (Step 6) to systematically identify the problem addressed, the context and country, the type of truck platooning technology discussed, the benefits, challenges, and planning and collaboration methods.

- **Steps 7 and 8: analyze and synthesize data and report findings**

  In the last two steps, the data is analyzed and the main results are reported to address our research questions. This detailed analysis involves careful examination of each article. This process extends beyond basic browsing and involves a thorough and systematic reading of the chosen articles. In the following section, we describe the results of steps 7 and 8.

1.3 Assessment of the articles

A total of 114 papers were reviewed in our study (see Figure 1.2). The distribution of the selected studies over time can be seen in Figure 1.3. The review process following PRISMA (Steps 3 to 6) is presented in Figure 1.2. The flow diagram shows the number of articles identified, included, and excluded at each stage of the process.

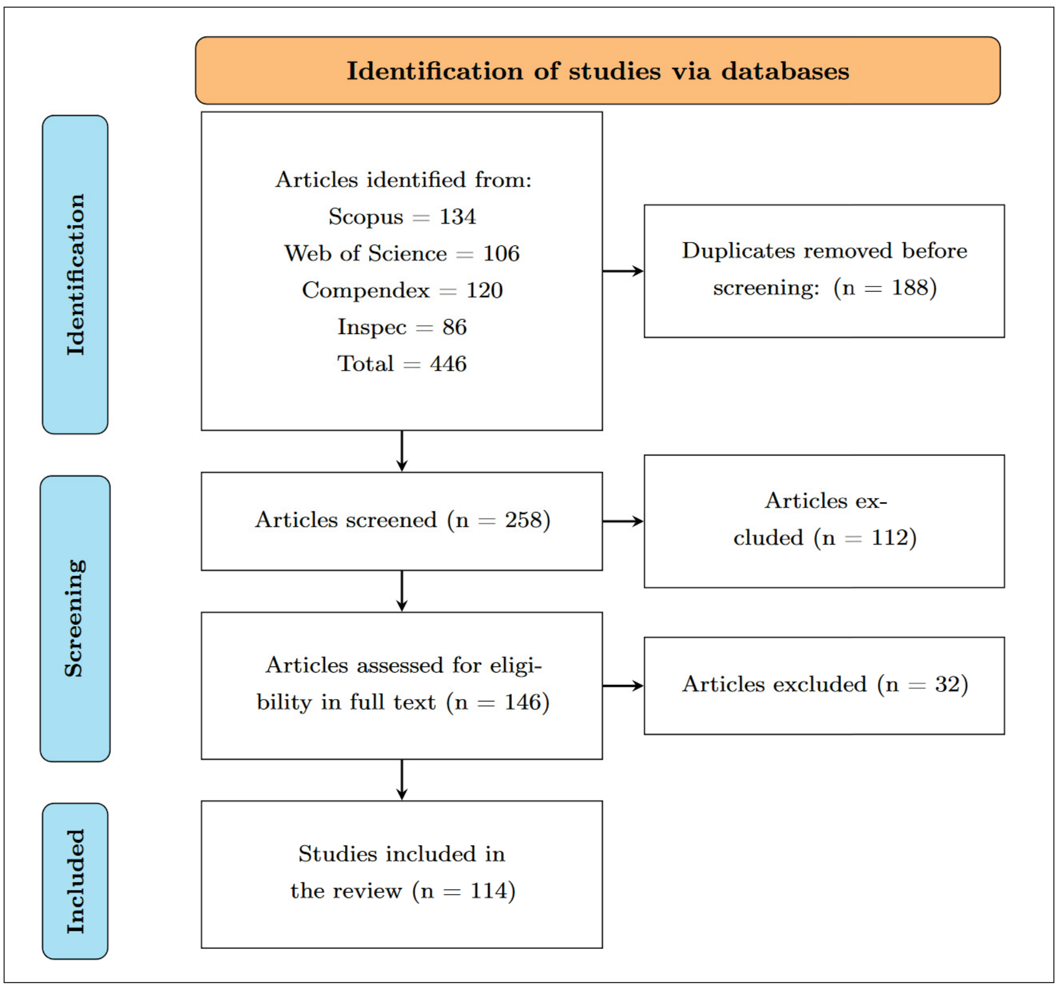

Figure 1.2 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) flow diagram outlining the review process adapted from (Page et al., 2021) and the results

In recent years, publications have increased significantly. More than 83% of the papers have been published between 2019 and 2023. It reflects the increasing attention paid to truck platooning transportation planning. The first paper was published in 2012. In this study, Jaoua et al. (2012) introduced a simulation model for monitoring truck movements in internal haulage networks considering complex traffic behaviors and including platoon formation.

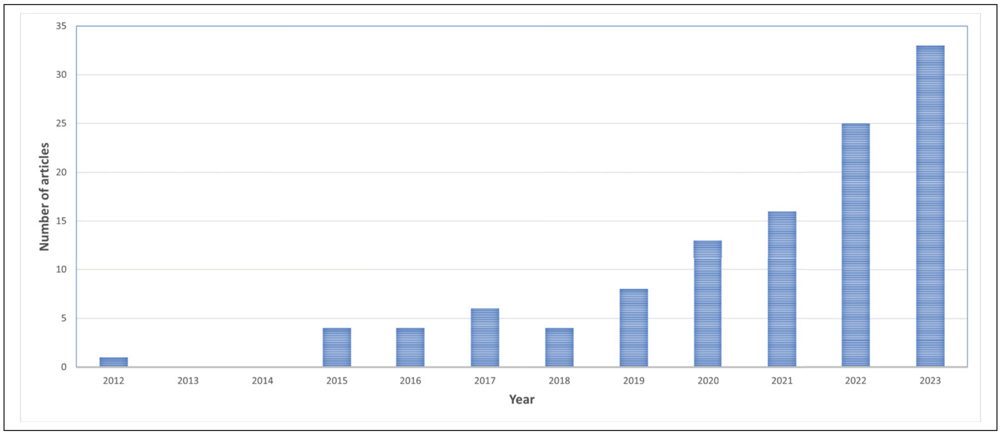

Figure 1.3 Number of articles per year of publication

Table 1.3 provides a breakdown of the number of articles obtained following the three research questions. This table specifies the research question under consideration, the number of articles obtained from Scopus, Web of Science, Compendex, and Inspec databases for each research question, and the total number of articles without duplicates in all databases for each research question and for all of them. We recall that Research question 1 is "What are the transportation planning models proposed to address truck platooning transportation?"; Research question 2 is "What are the collaboration and coordination approaches proposed for transportation using truck platooning?"; Research question 3 is "What are the benefits and challenges related to truck platooning?".

Table 1.3 Number of articles related to the three different research questions obtained from the four databases

Research question	**Scopus**	**Web of Science**	**Compendex**	**Inspec**	**Total number of articles without duplication**
Research question 1	129	99	111	71	175
Research question 2	78	43	68	31	102
Research question 3	79	81	96	63	141
Total number of articles without duplication	134	106	120	86	114

Table 1.4 lists the top journals based on the number of published articles. The table presents the distribution of articles across various journals in transportation and intelligent systems. It highlights the top journals with at least three publications, indicating the frequency of research contributions in them.

Table 1.4 Top journals with at least three articles published

Journal	**Number of articles**
IEEE Transactions on Intelligent Transportation Systems	11
Transportation Research Part B: Methodological	9
Transportation Research Part C: Emerging Technologies	9
Transportation Research Part E: Logistics and Transportation Review	8
International Journal of Intelligent Transportation Systems Research	7
Journal of Transportation Engineering Part A: Systems	7
Journal of Intelligent Transportation Systems: Technology, Planning, and Operations	5
Transportation Science	4
Journal of Advanced Transportation	4
Computers and Industrial Engineering	3
Energies	3

From the 114 articles included in our review, we found six literature review articles. Bhoopalam et al. (2018) focused on truck platooning transportation planning aspects. The paper provides a framework for classifying transportation planning problems related to truck platooning. It surveys relevant OR-based models in the literature and identifies directions for future research. Zhang et al. (2020) provided an overview of research works on fuel savings in truck platooning. The paper reports on methods, contributing factors to fuel consumption, coordination methods to enhance platooning opportunities and control strategies for fuel efficiency. Moreover, this study reviewed 11 articles on optimization methods applied to route planning and speed adjustment. Roukouni et al. (2020) investigated the role of simulation games, to help actors understand the challenges involved, and find solutions interactively. It reviewed a variety of games used in the Port of Rotterdam to facilitate collaboration. Lesch et al. (2022) discussed cooperative driving technology and platoon coordination approaches. A cooperative vehicle has an advantage over an autonomous vehicle since communication enhances each vehicle's perspective and informs them of the intentions of the other vehicles. Wu et al. (2023) provided a review of vehicle group intelligence in a connected environment. They identified knowledge bases and research trends in control architectures, application issues, planning strategies, and communication protocols.

1.3.1 Geographical and industry-specific distribution of the studies

The literature on truck platooning transportation is diverse, reflecting interest in this field from various countries. Figure 1.4 illustrates the number of studies conducted in each country. It is important to note that the classification includes only papers presenting case studies explicitly mentioning the country or region.

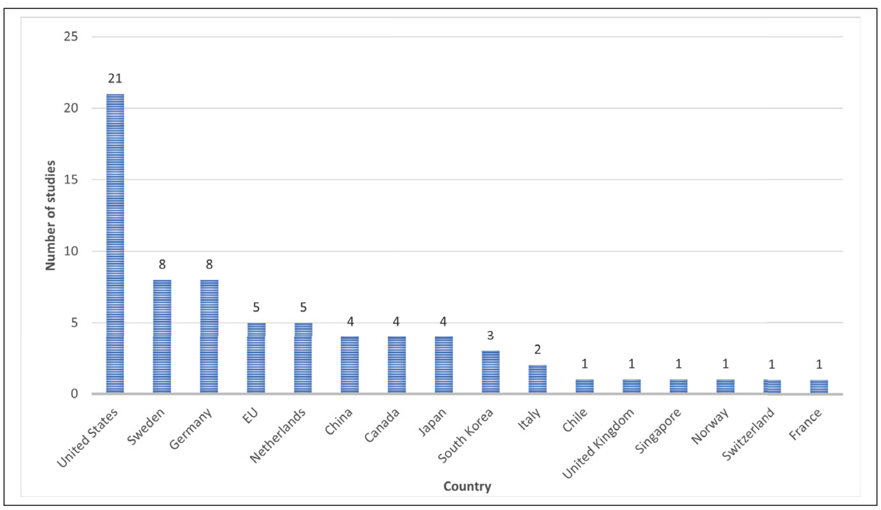

Figure 1.4 Geographical distribution of 70 case studies in the review

The United States (U.S.) is the leading country in truck platooning transportation research, with 21 studies. Sweden and Germany follow with eight studies. Case studies in some papers refer to the European Union (EU) without mentioning specific countries. The EU and the Netherlands contribute five studies. Canada, Japan, and China contributed with four studies each. South Korea and Italy followed with three and two studies respectively. Chile, the United Kingdom, Singapore, Norway, Switzerland, France, and Portugal each contributed with one study.

There are some real-world projects identified in our literature review. EU ENSEMBLE (Schmeitz et al., 2023; Willemsen et al., 2023) is a collaborative project within the European Union. It focuses on improving urban freight transportation efficiency and sustainability. The project explores a number of innovative technologies, including platooning, to optimize city logistics. The project aims to address traffic congestion, GHG emissions, and energy consumption challenges. The KONVOI project in Germany is a project that investigates the technical, economic, and regulatory aspects of platooning by collaborating with academic institutions, research centers, and industry partners. KONVOI aims to provide practical platooning technology for real-world applications, contributing to improved fuel efficiency, reduced emissions, and increased traffic flow efficiency. Energy ITS (Intelligent Transportation Systems) is a research project in Japan that explores various aspects of intelligent transportation technology, including truck platooning (Tsugawa et al., 2016). This project uses advanced technologies to optimize transportation systems for energy efficiency and reduced environmental impact. INTRALOG is a Dutch research project that focuses on developing innovative logistics solutions (Kusumakar et al., 2018). This project explores the integration of various technologies, including platooning to enhance logistics operations, improve supply chain efficiency, and reduce resource consumption. PATH project based in the U.S. aims to advance intelligent transportation systems (Nowakowski et al., 2015). This project explores various technologies, including truck platooning, to improve transportation efficiency, safety, and sustainability. PATH conducts research, testing, and demonstrations to assess the feasibility and benefits of platooning technology on U.S. roads.

In the literature on truck platooning transportation planning, different platooning types and planning levels are considered. These types include different automation levels and planning horizons as discussed in Subsection 1.3.2.

1.3.2 Platooning technology types studied in the literature

Figure 1.5 displays the classification of studies by technology types related to truck platooning, specifically focusing on papers addressing Research Question 1. This classification is essential for identifying trends and gaps in truck platooning transportation planning.

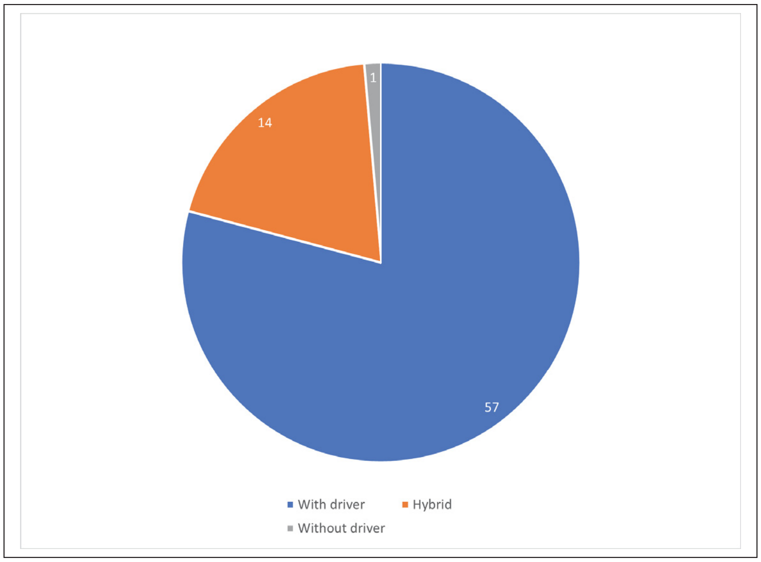

Figure 1.5 Number of studies with different types of truck platooning on papers related to Research Question 1

Truck platooning with a human driver optimizes fuel efficiency and safety by coordinating multiple trucks to travel closely together. In this area, researchers have conducted 57 studies exploring topics such as route planning. Several studies seek to understand how humans can effectively participate in platoon systems. In hybrid platooning, automated driving technology is combined with human intervention. In these studies, researchers investigate autonomous driving and driver input. Although fewer in number, these studies contribute valuable insights into hybrid platooning feasibility and benefits. One of the studies involves fully autonomous truck platooning, where no human driver is present. Only one study has explored this area, addressing challenges related to vehicle-to-vehicle communication and decision-making algorithms. In summary, these studies collectively contribute to optimizing transportation planning for truck platooning, considering factors such as fuel consumption and cost objectives.

1.4 Optimization models for truck platooning transportation planning

Several transportation planning models have been proposed to better manage truck platoon operations. These models aim to minimize travel time, fuel consumption, and costs while considering various constraints, such as delivery schedules, traffic conditions, and vehicle characteristics. Different approaches, such as mathematical optimization, simulation, and heuristics, have been utilized. This section examines the literature to address the research question related to transportation planning models for truck platooning (Research Question 1). As outlined in Research Question 1, we aim to identify and analyze the various problems and models proposed in the literature. We discuss emerging trends and developments in transportation planning models for truck platooning.

We identified and classified 72 papers relevant to Research Question 1. These papers could be classified according to strategic planning (long-term decisions), tactical planning (medium-term decisions), and operational planning (short-term and real-time decisions). Figure 1.6 shows the number of studies according to these planning horizons. We can see the number of studies that address truck platooning at strategic, tactical, and real-time planning is 4, 4, and 3 respectively. In comparison with operational levels, it is not much, and studies at these planning levels require further investigation.

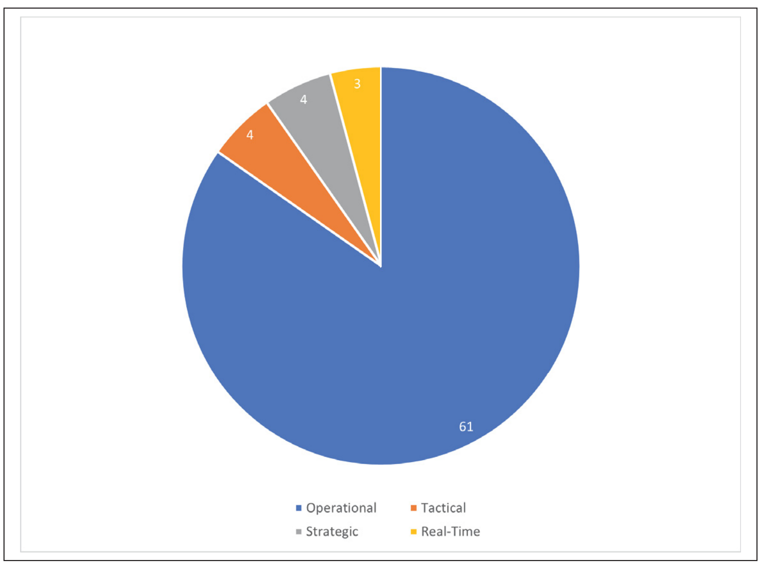

Figure 1.6 Number of studies (related to planning) with different planning horizons

Strategic transportation planning involves high-level decisions that address the integration of truck platooning in the transportation network (Bhoopalam et al., 2018). At this level, the focus is on long-term considerations (SteadieSeifi et al., 2014) such as terminal locations for truck platoons. Strategic decisions impact the entire transportation system and may require collaboration between industry stakeholders, policymakers, and researchers. The main goals include assessing economic benefits, environmental impact, and the feasibility of implementing truck platooning (Alam et al., 2015). Transportation network design and cost-benefit analysis are central to strategic planning (She and Ouyang, 2022).

Tactical planning focuses on medium-term decisions that determine the use of truck platoons (Bhoopalam et al., 2018). This level of planning includes decisions related to fleet composition and flow allocation (SteadieSeifi et al., 2014). Tactical decisions in truck platooning involve optimizing strategies for platoon formation, service level consideration, flow and resource allocation (Scherr et al., 2019). The primary objectives are to allocate trucks to platoons and allocate material flows to platoons to meet delivery deadlines and minimize operational costs (Scherr et al., 2020).

Operational planning deals with short-term decisions to manage day-to-day platoon operations (Bhoopalam et al., 2018). Operational decisions include platoon formation and vehicle routing and scheduling based on data such as time windows and traffic conditions to optimize fuel efficiency, safety, and cost objectives (Zhang, 2023). OR is widely used to formulate and solve operational planning problems. In the modeling part examples are Integer Programming (e.g., Van De Hoef et al. (2018)), Mixed Integer Programming (e.g., Scholl et al. (2023)) and Nonlinear Programming (e.g., Li and Li (2022)). Moreover, examples of solution algorithms include exact algorithms such as Branch-and-Price-and-Cut (You et al., 2023), heuristics like the "greedy heuristic" (Park et al., 2023), and meta-heuristics including Simulated Annealing (Peng and Xue, 2023).

Real-time transportation planning involves making dynamic decisions based on real-time data such as real-time traffic conditions and unexpected events (Li and Li, 2022). Those decisions include adapting platoon formations according to traffic conditions, re-routing platoons to avoid delays, and ensuring driver safety in unpredictable scenarios (Saeednia and Menendez, 2017; Jaoua et al., 2012). The primary objectives are to make rapid decisions to ensure safety, avoid collisions, minimize disruptions to traffic flow, and adjust platoon formation and real-time vehicle routing leading to cost minimization or efficiency maximization.

1.4.1 Strategic planning

Only four studies have investigated strategic truck platooning transportation planning. She and Ouyang (2022) proposed a network design model to optimize the location of dedicated truck platoon lanes and toll pricing in a highway network. The model incorporates multiple factors, including the cost of constructing and maintaining dedicated platoon lanes, the impact of truck platooning on pavement deterioration, and the subsequent costs of road rehabilitation. Watanabe et al. (2021) used a Continues Approximation approach to facility location in hybrid truck platooning in Japan. The study considers optimal location models for platoon formation and explores scenarios for truck platoon deployment.

Xue et al. (2023) addressed the optimal location of platoon formation centers in trucking networks to optimize platoon operations and minimize costs. It proposes an MIP model and a variable neighborhood search algorithm for large-scale problems. Gazran et al. (2023) investigated the possible use of hybrid truck platooning technology in forestry product supply chains. They used a Mixed-Integer Programming (MIP) model to optimize various decisions, including terminal locations, product flows, and routes for ordinary and platoon trucks. The objective is to minimize overall transportation costs while considering backhauling and platooning. According to the study results, a reduction in fuel consumption by 15.6%, a decrease in the number of drivers needed by 3 to more than 30%, and a reduction in costs of 3 to more than 20% could be achieved using hybrid truck platooning.

The information on references, problems, modeling/methods used, objective functions, restrictions /constraints, and decisions considered in the problems of strategic, tactical and operational truck platooning transportation planning literature is summarized in Tables 1.5 - 1.7 respectively. Modeling focuses on constructing representations of problems, while methodology includes the techniques and procedures used to analyze and solve these models. The abbreviations in the table include Linear Programming (LP), Integer Programming (IP), Mixed-Integer Programming (MIP), Nonlinear Programming (NLP), and Continuous Approximation (CA). Furthermore, time refers to time constraints related to the timing of platoon formation, departure, and arrival at specified locations. Table 1.5 summarizes the characteristics of the literature related to strategic planning.

Table 1.5 Characteristics of truck platooning strategic transportation planning studies

Reference	Problem	Modeling/ methodology	Objective function	Restrictions/ constraints	Decisions	Platooning aspects
(Gazran et al., 2023)	Network design and flow allocation considering ordinary and hybrid platoon trucks in forest transportation	MIP / -	Cost minimization (vehicle fixed cost, driver, fuel, terminal location)	Flow conservation, terminal capacity, loading/unloading times, supply and demand	Terminal location, product flow allocation in direct and backhaul routes, number of ordinary and platoon trucks needed	Gradual integration of hybrid platoon trucks into the transportation network
(Xue et al., 2023)	Location problem of platoon formation center	MIP / heuristics	Cost minimization (driver, fuel, hub location)	Supply, demand, node capacity	Node location, flow allocation	platoon formation
(She and Ouyang, 2022)	Truck platooning transportation network design	NLP / bi-level optimization, dynamic programming, meta heuristics	Cost minimization (fuel and pavement rehabilitation)	Road capacity, node flow conservation	Pavement rehabilitation (assessing costs due to deterioration from platoon operations), traffic flow optimization	Converting regular lanes into platoon lanes
(Watanabe et al., 2021)	Network design (node location for truck platooning formation)	CA / -	Travel cost minimization	Supply and demand capacities	Location of platoon formation nodes	platoon formation

The literature review reveals that strategic transportation planning for truck platooning has received relatively less attention than operational and tactical planning. However, few studies have proposed models and methods to address strategic-level decisions. These studies employ various modeling approaches including Mixed-Integer Programming (MIP), Continuous Approximation (CA), and bi-level optimization. The objective functions typically focus on minimizing costs related to fuel consumption, vehicle fixed costs, and infrastructure maintenance, while considering constraints such as capacity limitations (e.g., terminal and road capacity), node flow conservation, and loading/unloading times. Decisions in these models revolve around determining optimal locations, flow allocations, and pavement rehabilitation to enhance the efficiency of truck platooning operations. These studies highlight the importance of considering infrastructure investments, practical scenarios, and industry-specific requirements to facilitate the long-term application and integration of truck platooning technologies into transportation networks.

1.4.2 Tactical planning

Scherr et al. (2019) studied a service network design problem for parcel delivery with hybrid truck platooning. The paper discusses fleet size, mix, and flow allocation decisions, with a focus on coordinating fleets using platooning. Cost savings and coordination strategies are explored based on the transportation network, demand, and fleet mix. Scherr et al. (2020) addressed a similar problem and formulated an IP to determine the fleet mix, schedule services, and make flow allocation decisions for vehicles between nodes. Scherr et al. (2022) discussed a stochastic service network design problem for a platooning service provider that offers towing services between autonomous vehicle areas and autonomous driving zones using platooning for independent autonomous vehicle operators. The authors formulated a two-stage stochastic integer program to address issues related to fleet size, scheduling, and quoting rates to potential customers that take into account their willingness to pay based on the service level received. Table 1.6 shows the characteristics of the literature related to tactical planning.

Table 1.6 Characteristics of tactical truck platooning transportation planning studies

Reference	**Problem**	**Modeling/ methodology**	**Objective function**	**Restrictions/ constraints**	**Decisions**	**Platooning aspects**
(Scherr et al., 2022)	Service network design for hybrid truck platooning in city logistics	MIP / stochastic programming, heuristics	Profit maximization	Supply and demand, node flow conservation, platoon capacity, time windows, service level	Service level assignment to trucks, flow allocation	Platoon formation, platoon size
(Scherr et al., 2020)	Service network design for hybrid truck platooning in city logistics	MIP / heuristics	Cost minimization (driver, travel and vehicle fixed cost)	Supply, demand, node flow conservation, platoon capacity, time windows, service level	Service level assignment to trucks, flow allocation	Platoon formation, platoon size
(Scherr et al., 2019)	Service network design for hybrid truck platooning in city logistics	MIP / -	Cost minimization (driver, travel and vehicle fixed cost)	Supply and demand, node flow conservation, platoon capacity, time windows, service level	Service level assignment to trucks, flow allocation	Platoon formation, platoon size

The literature review reveals studies addressing tactical-level problems and proposing models to enhance truck platooning efficiency. These studies employ MIP, stochastic programming, and heuristics such as search space restriction. The objective functions typically aim to maximize the profit or minimize costs related to drivers and truck operations while considering constraints such as node flow conservation, platoon capacity limitations, service level and time constraints related to earliest departure time from and latest arrival time at a location. Decisions in these models involve service level assignment to trucks, flow allocation, and platoon formation, focusing on minimizing transportation costs or maximizing profit. Overall, the literature on tactical transportation planning for truck platooning demonstrates few papers in developing models and methods to address medium-term challenges. These studies emphasize the importance of optimizing fleet operations to enhance truck platooning systems efficiency.

1.4.3 Operational planning

Larson et al. (2015) focused on maximizing fuel savings in truck platooning by coordinating platoon formation using a distributed network of controllers. This refers to a system where multiple controllers, each responsible for a part of the network or a group of trucks, work together to coordinate the formation and operation of platoons. Larsson et al. (2015) introduced platooning planning with ILP formulations for modeling and solving trucks traveling on road networks which involves optimizing truck routes to ensure they can join and maintain platoons while navigating road networks. It is shown that even with a planar road network (i.e., a simplified model where roads are represented on a flat surface without crossings at different levels), platoon truck routing is an NP-hard problem. Van De Hoef et al. (2016) explores feasible vehicle platooning opportunities for transport assignments which refers to identifying realistic scenarios where trucks can form platoons during their transport assignments. It discusses the use of mobile communication infrastructure to dynamically coordinate platoon formation en route.

Zhang et al. (2017) analyzed platoon departure scheduling under travel time uncertainty. The model aims to minimize costs, including costs that are proportional to travel time (i.e., driver costs and costs related to lost opportunities while driving such as delays in delivery), penalties for missing a schedule, and fuel costs. Van De Hoef et al. (2018) addressed the coordination of a fleet of trucks to enable fuel-efficient platooning and formulated a problem that combines plans for pairs of vehicles to form platoons. Lupi et al. (2020) presented an urban freight distribution system based on automated vehicle platooning and fixed locations where vehicles in platoons split up. The paper presents a methodology to design the proposed transport system developed using two routing algorithms to optimize platoon and single vehicle routes. It also uses a simulator to determine the number of vehicles needed and the schedule of driver activities.

Calvert et al. (2019) evaluated and modeled the traffic flow effects of truck platooning. They explored the potential impact of truck platooning on both sparse and dense traffic flow conditions. Larsen et al. (2019) introduced a model for optimizing truck platoons formed at platooning hubs. It explores various planning and dispatching strategies and assesses their impact on profitability and fuel savings across different scenarios. A dynamic programming-based local search heuristic is used to solve the problem. Bai et al. (2023a) proposed a dynamic programming approach for coordinating large-scale multi-fleet truck platooning in transportation networks. It aims to maximize fleet profits while reducing CO2 emissions through optimized platoon formations. Johansson et al. (2023b) investigated optimal hub-based platoon formation strategies considering decentralized, distributed, and centralized policies. It introduces a coordinator at each hub to determine truck departure times for platooning. Li and Li (2022) focused on trajectory planning for autonomous modular vehicle platooning operations. It explores the optimization of connection routes, which involves physically connected vehicles with zero gaps and extends to automated platooning.

You et al. (2020) addressed the local container drayage problem in transportation (i.e., the problem of transporting shipping containers over distances, for example between ports and facilities such as warehouses and distribution centers.), focusing on hybrid truck platooning. A mathematical model is proposed to capture advantages like using multiple trucks with one driver, coordinating driver activities, and sharing containers among customers. A heuristic method based on an Ant Colony algorithm is introduced to deal with computational challenges. Xue et al. (2021) examined local container drayage problem under the hybrid platooning type. It considers the cost-saving benefits of this mode, including labor and fuel cost reductions. The paper models the problem and develops a Tabu Search heuristic to solve it. Yan et al. (2023) addressed the local container drayage problem with improved truck platooning operations. The study developed an MIP model to optimize drivers' numbers, routes, minimizing operational costs, and solved it using a Simulated Annealing algorithm. Peng and Xue (2023) investigated container drayage platooning in hybrid mode, considering the impact of trucks' loaded and empty state on platoon fuel consumption, and described fuel economy characteristics based on truck sequences within a platoon. An MIP model for truck and driver route planning is developed and the problem is solved using a Simulated Annealing algorithm.

In Noruzoliaee et al. (2021a), a system-level equilibrium model is developed to characterize truck platooning on the U.S. national road network. The model considers the relationship between platoon formation time, truck fuel savings, and effective road capacity. It reveals that platooning can lead to significant fuel savings, increased road capacity, and reduced infrastructure investment needs. Scholl et al. (2023) discussed "E-platooning," which optimizes platoon formation for long-haul transportation using electric trucks. They explored coordinating charging with waiting partner trucks, reducing energy costs, and increasing driving ranges. Alam and Guo (2023) addressed the co-optimization of charging scheduling and platooning for long-haul electric freight vehicles. It aims to maximize freight electrification and platooning benefits by optimizing charging and platooning schedules. The study develops an MIP model to minimize total costs, including charging and delivery-related costs.

Zeng et al. (2022) addressed decentralized truck platooning coordination, to reduce truck operations costs. It proposes a formulation to optimize truck parameters based on a objective function including fuel, operation time and penalty costs. Saeednia and Menendez (2017) introduced an algorithm for forming and modifying truck platoons. It presents a cooperative approach where trucks exchange real-time information to form platoons through consecutive iterations. Bhoopalam et al. (2023a) focused on platoon optimization based on truck pairs and presented a mathematical model for the platoon routing problem with time windows. It aims to develop optimization model for truck platoon formation. Boysen et al. (2018) focused on platooning efficiency, including the impact of technological adoption, maximum platoon lengths, and willingness to wait for partners. Van De Hoef et al. (2019) studied a system for dynamic en-route formation of truck platoons to reduce fuel consumption. Sivanandham and Gajanand (2022) presented a departure time coordination-based heuristic solution for platoon formation. It uses a modal emission model to analyze the influence of speed and platoon size on fuel savings potential.

Abdolmaleki et al. (2021) studied the scheduling of travel itineraries for a set of trucks to facilitate platoon formation and maximize energy savings. It formulates the problem as a minimum-concave-cost network flow problem and proposes solution methods, including an outer approximation algorithm and a dynamic programming-based heuristic. Sun et al. (2021) addressed the potential energy savings of truck platooning in the U.S. National Highway Freight Network. The study used an IP model to schedule trucks for platooning to maximize energy savings. Results suggest that scheduled platooning can save fuel, with factors like platoon size and time flexibility playing crucial roles.

You et al. (2023) addressed the routing of container trucks around a terminal considering multi-trip operations, truck platooning, and fuel cost reduction. The authors propose a Branch-and-Price-and-Cut algorithm with tight linear relaxations to solve this NP-hard problem. The algorithm effectively reduces labor costs and fuel consumption in operations. Xu et al. (2022a) addressed the truck routing and platooning problem by considering drivers' mandatory breaks and other factors like fuel-saving rates, designated relays, and platoon size limits. The goal is to route trucks while maximizing fuel-saving platoons, considering break time, and minimizing fuel consumption. Xu et al. (2022b) addressed the optimization of two-truck platooning with deadlines. The objective is to minimize total fuel consumption through joint optimization of path planning, speed planning, and platooning configurations.

Barua et al. (2023) proposed a platform-based platooning system to maximize truck platoon participation while considering truck stability preferences. Through a two-phase algorithmic approach, it efficiently solves the maximum stable truck platooning participation problem. Yilang Hao and Sun (2023) studied a mathematical framework for jointly optimizing the operation plan of drivers and trucks in hybrid truck platooning. By considering the interdependence between driver schedules and truck routes, it aims to minimize total operation costs while fulfilling delivery demands. A customized Lagrangian Relaxation approach is proposed to tackle large-scale problems efficiently.

Chen et al. (2021) proposed an autonomous truck scheduling problem for container transshipment between two seaport terminals, considering platooning and speed optimization. The paper formulates an MIP model to minimize total operation costs and a column-generation-based heuristic method is developed to address computational challenges. Caballero et al. (2022) explored transportation labor cost reduction via vehicle platooning. Liatsos et al. (2023) discussed a hybrid truck platooning system and presented a model developed to estimate truck caravan cost savings. The model uses linear programming to evaluate different network sizes and examines factors affecting profitability, such as platoon size and driver compensation. Zhang (2023) formulated truck platooning routing as a multi-commodity network flow problem to maximize fuel consumption savings through reduced aerodynamic drag. The study shows that restricting the number of trucks in platooning remains effective and saves fuel.

Pourmohammad-Zia et al. (2023) focused on port transport corridors and proposed a robust optimization approach for platooning vehicles in container pickup and delivery operations. The study aims to minimize time and cost while considering emissions. The model is applied to case studies showing improvements in cost, time efficiency, and emissions reduction. Guo et al. (2022) studied the impact of emerging transport technologies (including truck platoons) on road freight transport's economic and environmental performance, focusing on a port in China. A system dynamics analytical framework is established to assess the effects of the technologies on road profit and GHG emissions under macroeconomic uncertainty on a tactical level. The results show that while the technologies reduce GHG emissions, they result in profit losses. Hatzenbühler et al. (2023) investigated how modular vehicle concepts and consolidation can enhance urban freight and passenger transport efficiency. By forming platoons and integrating different demand types, it addresses routing problems with cost considerations. Results demonstrate significant cost savings of 48% from modularity and 9% from consolidation.

Park et al. (2023) addressed the vehicle routing problem in truck platooning by designing an MIP model. The model considers vehicle deadlines, continuous-time units, fuel reduction rates, traffic congestion, and heterogeneous vehicles. A greedy heuristic is introduced for efficient computation. Marzano et al. (2022) explored the impact of truck platooning on Italy's multimodal freight transport market. The study compares the costs of different freight modes, considering various scenarios with different automation levels. The results indicate that truck platooning can be highly competitive with rail and traditional road transport, especially for medium to long distances. Using an MIP model, Han et al. (2022) investigated truck platoon formation and routing in Japan. They estimated the benefits and formation scenarios of truck platooning with increasing market penetration of platooning technologies. Results show that truck platooning can yield cost and fuel savings of 1.15% and 5.7% respectively. Srisomboon and Lee (2021) proposed heuristic algorithms that aim to optimize fuel efficiency in truck platooning by balancing fuel consumption benefits with minimizing the frequency of position changes among trucks in the platoon. Results show the effectiveness of these algorithms in fuel savings. Table 1.7 illustrates the characteristics of the literature related to operational planning.

Table 1.7 Characteristics of operational truck platooning transportation planning studies

Reference	**Problem**	**Modeling/ methodology**	**Objective function**	**Restrictions/ constraints**	**Decisions**	**Platooning aspects**
(Alam and Guo, 2023)	VRP for electric truck platooning and charging with time windows	MIP / heuristics	Cost minimization (en-route, hub charging and delay)	Time windows, state of charge, capacities of charging stations	Time, charging time	Platoon formation
(Bai et al., 2023a)	VRP for truck platooning with time windows	MIP / dynamic programming	Profit maximization	Time windows	Dispatching	Platoon formation
(Barua et al., 2023)	Maximum stable truck platooning participation	MIP / heuristics	Maximizing truck platooning participation	Time windows	Routing, platooning length and configuration, departure time	Platoon formation
(Bhoopalam et al., 2023a)	Platoon routing with time windows	MIP / heuristics	Cost minimization (fuel)	Time windows	Routing, departure time	Platoon formation
(Hatzenbühler et al., 2023)	VRP for truck platooning	MIP / heuristics	Cost minimization (distance traveled, fleet size, travel time, penalty)	Time windows, capacity, routing	Routing, arrival and loading times	platoon formation
(Johansson et al., 2023b)	VRP for truck platooning with time windows	MIP / dynamic programming, local search	Maximizing total cost savings	Time windows	Dispatching	Platoon formation
(Liatsos et al., 2023)	VRP for truck platooning with time windows	MIP /	Cost minimization (driver, delay)	Supply, demand, flow, time windows	Departure time	Platoon formation, platoon size
(Park et al., 2023)	VRP for truck platooning	MIP / heuristic	Fuel consumption minimization	Balancing, routing, time windows	Routing, arrival time, platooning number	platoon formation

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Characteristics of truck platooning transportation planning studies (continued).

Reference	Problem	Modeling/ methodology	Objective function	Restrictions/ constraints	Decisions	Platooning aspects
(Peng and Xue, 2023)	VRP for truck platooning	MIP / meta-heuristic	Fuel consumption minimization	Supply, demand, capacity	Routing	platoon formation
(Pourmohammad-Zia et al., 2023)	VRP for truck platooning	Bi-objective MIP / robust optimization	Dwell-time and cost minimization	Number of available vehicles	Routing	platoon formation
(Scholl et al., 2023)	VRP for truck platooning with time windows	MIP / meta-heuristic	Cost minimization (energy consumption)	Time windows, routing	Scheduling	platoon formation
(Yan et al., 2023)	VRP for truck platooning	MIP / heuristics	Cost minimization	Supply, demand, capacity	Routing	platoon formation
(Yilang Hao and Sun, 2023)	VRP for truck platooning with time windows	MIP / heuristics	Cost minimization (driver, fuel)	Time windows, routing, platooning constraints	Routing, platoon exchange, driver and truck waiting times	Platoon formation
(You et al., 2023)	VRP for truck platooning	MIP / heuristics	Cost minimization	Supply, demand, capacity	Routing	platoon formation
(Zhang, 2023)	VRP for truck platooning	MIP / -	Cost minimization (fuel)	Routing, detour, platoon formation and size	Routing	platoon formation, platoon size
(Caballero et al., 2022)	VRP for truck platooning	MIP / heuristics	Cost minimization	Supply, demand, capacity	Routing	platoon formation
(Han et al., 2022)	Platoon formation and routing	MIP /	Cost minimization	Capacity, routing	Time, routing	Platoon formation
(Li and Li, 2022)	VRP for truck platooning	NLP / heuristics	Cost minimization	Capacity, time windows	Routing, departure time	Platoon formation
(Sivanandham and Gajanand, 2022)	Platoon formation	MIP / heuristics	Cost minimization	Capacity, platoon size, speed	Platoon formation time	Platoon formation
(Xu et al., 2022a)	VRP for truck platooning	MIP / heuristics	Cost minimization	Drivers' mandatory breaks	Routing	Platoon formation
(Xu et al., 2022b)	VRP for truck platooning	MIP / heuristics	Cost minimization	Drivers' mandatory breaks	Routing	Platoon formation
(Zeng et al., 2022)	VRP for truck platooning with time windows	MIP / heuristics	Cost minimization	Capacity	Routing, scheduling	Platoon formation
(Abdolmaleki et al., 2021)	Truck platooning transportation scheduling and network flow	MIP, MINLP / heuristics	Fuel savings maximization	Capacity, routing, time windows, speed	Schedule, flow allocation	platoon formation
(Chen et al., 2021)	Truck platooning scheduling	MIP / heuristics	Cost minimization	Travel speed	Schedule	Platoon formation
(Noruzoliaee et al., 2021a)	Platoon formation	MIP / heuristics	Fuel savings maximization	Supply, demand, capacity	Time windows	Platoon formation
(Srisomboon and Lee, 2021)	VRP for truck platooning	MIP / heuristics	Fuel savings maximization	Route, time windows	Routing	Truck position in platoon
(Sun et al., 2021)	Platoon routing	IP / heuristics	Minimizing energy consumption	Flow conservation, number of trucks on a link	Departure time, route, and speed choices	Platoon routing
(Xue et al., 2021)	VRP for truck platooning	MIP / meta-heuristic	Cost minimization	Supply, demand, capacity	Routing	Platoon formation
(Lupi et al., 2020)	VRP for truck platooning	MIP / meta-heuristics	Cost minimization	Route, time windows	Routing, scheduling	Platoon formation
(You et al., 2020)	VRP for truck platooning	MIP / meta-heuristics	Cost minimization (driver, travel and truck)	Routing, time	Supply, demand, routing, time windows, detour, flow, node flow conservation	Platoon size

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Characteristics of truck platooning transportation planning studies (continued).

Reference	Problem	Modeling/ methodology	Objective function	Restrictions/ constraints	Decisions	Platooning aspects
(Larsen et al., 2019)	Truck platooning transportation scheduling	MIP / dynamic programming, local search	Cost minimization	Time windows	Dispatching	Platoon formation
(Van De Hoef et al., 2019)	Truck platooning transportation scheduling	MIP / heuristics	Fuel saving maximization	Traffic	Departure time	Platoon formation
(Boysen et al., 2018)	Truck platooning transportation scheduling	MIP / heuristics	Cost minimization	Routing, time windows	Departure time	Platoon length (size)
(Van De Hoef et al., 2018)	Platoon formation, scheduling	IP / heuristics	Fuel saving maximization	Time windows, route, platoon length	Speed	Platoon formation
(Saeednia and Menendez, 2017)	Platoon formation	Mathematical optimization / heuristics	Higher performance	Time windows	Speed	Platoon formation
(Zhang et al., 2017)	VRP for truck platooning with time windows under uncertainty	Convex optimization / -	Cost minimization (travel time, fuel and schedule miss)	Time windows	Scheduling	Platoon formation
(Van De Hoef et al., 2016)	VRP for truck platooning with time windows	MIP / -	Cost minimization	Speed	Departure time, platooning	Platoon formation
(Larson et al., 2015)	Platoon formation and routing	ILP / heuristics	Fuel saving maximization	Routing, detour, flow, node flow conservation, time windows	Routing, platooning, departure time	Platoon formation
(Larsson et al., 2015)	VRP for truck platooning	ILP / heuristics	Fuel minimization	Routing, node flow conservation	Routing, departure time, fuel cost	Platooning routing

Operational transportation planning for truck platooning involves optimizing short-term decisions. The literature review highlights several studies addressing operational-level problems and proposing models to improve truck platooning fuel consumption, cost, and performance. The literature on operational transportation planning for truck platooning shows a growing interest. These studies emphasize the importance of optimizing platoon formation, routing, and other operational aspects such as departure times and speed considerations.

1.4.4 Simulation models for truck platooning transportation planning

Jaoua et al. (2012) presented a simulation framework that combines traffic simulation with discrete event simulation for internal transport systems (i.e., inside a physical boundary). The framework incorporates detailed traffic modeling to simulate truck movement, platoon formation, and congestion in regional haulage networks, such as container terminals and mines for real-time fleet management. Deng (2016) introduced a simulation framework for modeling and analyzing truck platooning by focusing on platoon longitudinal driving behaviors (e.g., acceleration and braking), considering acceleration capabilities. Simulation results demonstrate improvements in traffic efficiency and safety due to increased platooning in traffic flow in operational planning. Saeednia and Menendez (2016) analyzed truck platooning strategies, including speed-up (i.e., the following trucks speed up to keep pace with the leading trucks) and slow-down (i.e., leading trucks slow down so that following trucks can keep up with them). They introduced a platooning strategy that combined these approaches optimally by allowing trucks to form a platoon at the highest possible platooning speed.

Semnarshad et al. (2022) studied the impact of Cooperative Adaptive Cruise Control (CACC) and lane changing on delay and riding comfort. Using traffic simulation, the study evaluates different CACC parameters and cooperative lane-changing effects on average speed and acceleration distributions. Adjusting CACC parameters reduces delay and improves riding comfort in mixed traffic. Hirata and Fukaya (2020) proposed a model that uses truck platooning technology to transport empty trucks to where they are needed based on imbalances in freight demand between cities. The study analyzes the impact of platooning on labor and vehicle costs. Wei et al. (2019) investigated traffic characteristics under a strategy aimed at improving road capacity, for mass evacuation during emergencies considering the effects of trucks on traffic flow. Jo et al. (2019) quantified the benefits of travel time savings resulting from truck platooning in Korean freeway networks. The results suggest annual benefits regarding travel time savings. Haas and Friedrich (2021) proposed a city logistics system based on delivery platoons. Three parameters related to platoon size, and the number of platoon and non-platoon vehicles are analyzed. The number of platoons is the most dominant parameter, affecting waiting time and delay at intersections because of platoon trucks.

Lee et al. (2021) explored the impact of truck platooning on traffic flows. This study uses simulations to assess mobility and safety performance based on truck platoon market penetration rates. Results show that an increased market penetration rate has positive effects on longitudinal safety but negative effects on lateral safety. Sujan et al. (2022) assessed the payback and profitability of truck platooning across the U.S. Interstate highway system. Elbert et al. (2020) used an agent-based simulation model to simulate platoon formation for individual trucks. The model calculates truck waiting times for platooning opportunities. Results show that waiting times relating to platoon formation decrease with an increase in orders and trucks in the network. Haq et al. (2022) studied the minimum distance for executing a safe required when overtaking truck platoons on two-lane highways using simulation and mathematical model for various scenarios involving multiple trucks in platoons.

Chowdhury et al. (2023) investigated the impact of traffic signal prioritization on heavy vehicle platooning in urban areas. The results suggest that signal prioritization can reduce congestion caused by heavy vehicle platooning. Chandra and Thai (2022) focused on freight truck platoon accessibility to their destinations, including the possibility of detours. The findings indicate that platoon accessibility increases on select highway lengths, reaching a maximum and then decreasing. Yuan and Lo (2021) explored traffic flow dynamics, considering different vehicle types, including passenger cars, medium trucks, and heavy trucks. Aboulkacem and Combes (2023) introduced a micro-economic model to forecast truck platooning adoption, considering coordination costs, specialized equipment, network externalities, and system heterogeneity. Table 1.8 shows the characteristics of literature related to simulation approaches.

Table 1.8 Characteristics of truck platooning transportation planning studies with simulation approach

Reference	**Problem**	**Goals**	**Aspects and decisions considered in simulation**	**Platooning aspects**
(Aboulkacem and Combes, 2023)	Micro-economic model to forecast truck platooning adoption	Increasing financial benefits of platooning	Platooning costs, equipment, decisions dependency, heterogeneous road freight transportation system	Platoon matching and formation
(Chowdhury et al., 2023)	Truck platooning traffic modelling	Increasing traffic flow efficiency	Travel time, number of stops, Traffic signal priority	Levels of platooning automation
(Chandra and Thai, 2022)	Truck platooning traffic modelling	Increasing platoon efficiency	Routing, detour	Possibility of detour for trucks forming a platoon
(Guo et al., 2022)	Traffic flow modeling including truck platooning	Improving platooning impact on profit and GHG emissions	Traffic considerations, Speed	Platoon formation
(Haq et al., 2022)	Truck platooning traffic modelling	Improving platooning's impact on traffic flow	Traffic considerations, Speed	Gaps between platoon trucks
(Semnarshad et al., 2022)	Truck platooning traffic modelling	Impacts on delay and riding comfort	Time windows, traffic, Vehicles gap, merging time	Platoon formation
(Yuan and Lo, 2021)	Truck platooning traffic modeling	Analyzing impact of platooning on traffic flow	Moving bottlenecks, Speed	Platoon length (size)
(Elbert et al., 2020)	Calculating waiting times of trucks for platooning possibilities	Cost minimization	Number of orders, traffic flow, Waiting time	Platoon formation
(Sujan et al., 2022)	Truck platooning traffic modelling	Characterizing the payback and profitability	Time, market adoption rates, fuel prices, speed, mileage, fuel benefits, technology costs, traffic impact	Platoon formation, platooning restrictions

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Characteristics of truck platooning transportation planning studies with simulation approach (continued).

Reference	Problem	Goals	Aspects and decisions considered in simulation	Platooning aspects
(Haas and Friedrich, 2021)	Truck platooning traffic modeling	Cost minimization	Platoon size, Travel and waiting time	Platoon formation
(Lee et al., 2021)	Truck platooning traffic modeling	Traffic and safety performance	Traffic flow, Speed	Platoon length and gap
(Hirata and Fukaya, 2020)	Quantifying the impact of truck platooning to transport empty trucks	Improving impact of platooning on traffic flow	Time windows, Scheduling	Platoon formation
(Calvert et al., 2019)	Truck platooning traffic modeling	Performance evaluation	Traffic states, truck gap, platoon sizes, trucks sharing, Routing	Platoon formation
(Jo et al., 2019)	Truck platooning traffic modeling	Quantifying the travel time savings	Capacity, Highway capacity	Platoon formation, platoon size, truck gaps
(Wei et al., 2019)	Truck platooning traffic modeling	Performance evaluation	Traffic, moving bottlenecks, Capacity, flow speed	Platooning lanes
(Saeednia and Menendez, 2016)	Platoon formation	Analysing transportation performance	Time, Speed	Platoon formation
(Deng, 2016)	Truck platooning traffic modeling	Improving platooning impact on traffic flow	Traffic, Speed, acceleration	Platoon formation
(Jaoua et al., 2012)	Truck platooning traffic modeling	Traffic simulation in the internal haulage networks	Traffic, time windows, Dispatching, routing, traffic congestion	Platoon formation

Simulation-based approaches play an important role in understanding the dynamics and improving the performance of truck platooning systems. The literature review reveals 18 studies employing simulation models to address various aspects of truck platooning transportation planning, aiming to improve efficiency, safety, and overall system performance. In general, the literature on simulation-based approaches for truck platooning transportation planning demonstrates a growing interest in developing models to understand and effectively handle various aspects of truck platooning systems. These studies emphasize the importance of simulation in analyzing the impact of platooning on traffic flow, safety, efficiency, and overall system performance.

1.5 Collaboration models for truck platooning

Collaboration in transportation refers to cooperative efforts and coordinated activities among various stakeholders, such as transportation companies, government agencies, suppliers, and customers, to optimize movement within a transportation network (Cruijssen et al., 2007). Collaboration is an opportunity to increase transportation efficiency (for example, by reducing loaded and empty distances). By sharing information and resources, collaboration creates efficiencies, which could reduce costs and increase service levels and market share (Audy et al., 2012). One challenge in collaborations between different parties is establishing a fair distribution of benefits and costs among them (Basso et al., 2019), as an unfair distribution of costs or benefits could prevent companies from collaborating. Collaboration and coordination among multiple actors play a crucial role in successfully implementing truck platooning in transportation.

The literature on conventional truck transportation includes various models and frameworks that address collaboration aspects between different parties (e.g., shippers, carriers, etc.). These models incorporate game theory, coalition formation, and cost/benefit sharing mechanisms (Guajardo and Rönnqvist, 2016). Truck platooning transportation may require collaboration among different parties involved in the transportation system (i.e., truck drivers, freight companies, and other stakeholders). However, challenges such as trust-building, fairness considerations, and effective coordination mechanisms need to be addressed to ensure collaborative truck platooning systems operate effectively. Truck platooning is a collaborative process that introduces new factors, such as coordinating fleets in real-time, ensuring fair sharing of costs and benefits, and building trust between companies. For a successful collaboration, synchronized driving, fuel savings distribution, and shared responsibilities are necessary.

This section is dedicated to answering the research question related to collaboration models in truck platooning transportation (Research Question 2). Collaboration in platooning could be in the form of route planning, where platoon members jointly select the most efficient route (Earnhardt et al., 2022). This involves considerations like traffic conditions, road quality, weather, and the presence of other vehicles along the route (Yi et al., 2023). To maximize platooning advantages, truck drivers collaborate on scheduling departures and arrivals, ensuring coordinated operations (Chen et al., 2023). In cases where platooning includes trucks from different owners or companies, collaboration extends to agreements on cost/benefit sharing. This includes the fair distribution of costs such as fuel, drivers, and maintenance.

Farokhi and Johansson (2015) introduced a congestion game involving cars and trucks to model traffic flow on a road. During various times of the day, they introduce a congestion game to model traffic flow on a road. The platooning capabilities of trucks provide an incentive for them to use the road. Nash equilibrium is used to study the dynamics and equilibrium of this game-theoretic model.

Xing et al. (2022) proposed a secure content delivery service for connected and autonomous trucks based on coalition formation games. It addresses the challenges of limited cache size (data transmission rate) and high deployment costs by using truck platoons. To protect sensitive information and monitor vehicle behaviors, different privacy and trust evaluation models are integrated. A coalition formation game among trucks on the same route is established, demonstrating the scheme's effectiveness through extensive simulations. Bouchery et al. (2022) explores platoon formation from an optimization perspective and uses cooperative game theory to study cost allocations among multiple operators. It presents exact and approximate solution approaches and proposes cost allocation rules for cooperative platooning games. An example based on the Port of Rotterdam is provided to illustrate the findings. The research addresses operational aspects, estimating market penetration, and conducting a factorial analysis. Findings suggest platooning's potential and impact on fuel savings and cost reduction. Results indicate platooning's practical efficiency and highlight considerations for optimal waiting penalties. Furthermore, this study explores cooperative game theory for cost allocation, indicating stable allocations and minimal objections. Earnhardt et al. (2022) focused on incentivized platooning among automated trucks. This study examines mechanisms for encouraging participation. It investigates catch-up and re-routing mechanisms and proposes methods for computing the monetary value of these incentives. To optimize scenarios with proven aggregate benefit, the authors suggest methods for quantifying exchange value including the Shapley value and a bidding approach.

Johansson et al. (2023a) presented a platooning system and coordination approach, where carriers can work together to form platoons. It examines a proportional profit-sharing mechanism (based on the number of vehicles in the platoon) and conducts a simulation study on the Swedish road network to evaluate the potential benefits of platooning under realistic conditions. Chen et al. (2023) studied cost allocation in cooperative autonomous truck platooning among carriers. It considers efficiency and stability conditions in carrier alliance formation to create platooning opportunities. The authors created mathematical programming models to optimize departure times and platoon positions, balancing fuel savings and schedule adherence. By relaxing efficiency and stability conditions simultaneously, they introduced an approximate core concept. Single-objective cost allocation models minimize one condition's violation given the other's, alongside a bi-objective model for cost allocation within the approximate core.

Bai et al. (2023b) modeled a platooning system involving trucks and a third-party service provider that coordinates platoons, shares profits, and charges for services. Government subsidies to incentivize platooning are also considered. Through simulated experiments in Sweden, this paper proposes pricing rules for third-party service providers and evaluates their impact on profits and fuel savings. Government subsidies are given to the third-party service provider, which uses them to increase platooning profits. When platoons are formed, trucks pay service fees for platoon coordination service. The remaining platoon profit is distributed among trucks. Yi et al. (2023) developed a mixed equilibrium model for connected and autonomous vehicle platoons and human-driven vehicles. It considers the effects of platooning, such as improved road capacity and speed differences between platoon trucks and human-driven trucks. The paper explores equilibrium models and proposes an optimal method to mitigate negative effects and promote its adoption. The results show that platooning initially increases travel costs, and the proposed method can effectively reduce platoon interactions with other vehicles, thus promoting wider platooning applications.

Table 1.9 summarizes the literature on collaboration related to truck platooning transportation.

Table 1.9 Characteristics of collaboration in truck platooning transportation studies

Reference	**Problem**	**Modeling/ methodology**	**Objective function**	**Restrictions/ constraints**	**Decision variables**	**Platooning aspects**
(Bai et al., 2023b)	Traffic modelling, cost allocation, pricing related to truck platooning	Simulation, game theory	Cost minimization	-	Pricing under government subsidies	Platoon formation
(Chen et al., 2023)	Cost allocation between truck drivers	Game theory, heuristics	Cost minimization	Time windows	Cost allocation	Platoon formation
(Johansson et al., 2023a)	Platoon formation, profit allocation	Heuristics, game theory	Environmental impact and operational costs minimization	-	Profit allocation	Platoon formation,
(Yi et al., 2023)	Routing, cost allocation	Game theory, stochastic equilibrium	Cost minimization	Road capacity, speed	Routing, cost allocation	Platoon formation

Continued on the next page

Characteristics of collaboration in truck platooning transportation studies (continued).

Reference	Problem	Modeling/ methodology	Objective function	Restrictions/ constraints	Decision variables	Platooning aspects
(Bouchery et al., 2022)	Coalition formation, cost allocation between truck drivers	Game theory	Cost minimization	-	Coalition formation, cost allocation	Platoon formation
(Earnhardt et al., 2022)	Routing, cooperative platooning exchange	Game theory	Fuel cost minimization	Routing	Cost allocation, transportation exchange	Platoon formation
(Xing et al., 2022)	Coalition Formation between truck drivers	Game theory	Fuel cost minimization	-	Coalition Formation	platoon formation
(Farokhi and Johansson, 2015)	Modeling traffic flow at different intervals on a road using a congestion game including platoon trucks.	Game theory	Fuel cost minimization	Time intervals, velocity, traffic flow, tax	Cost allocation	Platoon formation

Collaboration approaches encompass various aspects between truck drivers or carriers participating in platooning. One aspect of collaboration involves route planning, where platoon members jointly select the most efficient route considering factors like traffic conditions, road quality, weather, and the presence of other vehicles or platoons along the route. Moreover, truck drivers collaborate on scheduling departures and arrivals to ensure synchronized operations, optimizing platooning opportunities. In cases where platooning involves trucks from different owners or companies, collaboration extends to agreements regarding cost and benefit sharing. This includes mechanisms for proportional profit-sharing based on the number of vehicles in the platoon, as well as the allocation of costs such as fuel savings, driver costs, and maintenance expenses among participating carriers.

Game theory and coalition formation models are commonly employed to address collaboration and coordination challenges in truck platoon transportation. Overall, collaboration and coordination approaches to truck platooning transportation involve strategic decision-making processes aimed at optimizing route selection, and cost allocation among participating carriers. These approaches leverage game theory, coalition formation, and incentive mechanisms to promote efficient and sustainable transportation systems based on truck platooning.

1.6 Transportation benefits and challenges of truck platooning

This section addresses the research question that explores the benefits and challenges associated with truck platooning transportation planning and collaboration (Research Question 3).

1.6.1 Benefits

The benefits of truck platooning mentioned in the literature could be categorized as follows:

Fuel efficiency: Truck platooning could reduce air drag between vehicles by about 50% through maintaining a close formation, improving fuel efficiency (Jo and Kim, 2022). This leads to cost savings for truck operators through reduced fuel consumption between 4-20% (Alam et al., 2015). Fuel efficiency gains achieved through truck platooning directly contribute to GHG emissions and environmental impact reductions (Guo et al., 2022; Pi et al., 2023; Cheng et al., 2023). In support of this, Paddeu and Denby (2022) investigated the potential for truck platooning to reduce GHG emissions from road freight, presenting scenarios that vary by adoption rates, operational models, and platoon size. The study highlights potential economic and environmental benefits, although there remains high uncertainty regarding adoption rates.

Driver productivity: Platooning technology allows drivers to focus on tasks such as monitoring the road and managing the platoon while reducing the need for constant acceleration and braking (Yang et al., 2023). This increases driver and truck productivity by optimizing their time on the road. Platooning enables in-platoon resting, where drivers can take breaks or rest while their trucks remain in the convoy (Bhoopalam et al., 2023b). This can lead to improved driver well-being and fatigue management. Moreover, in hybrid and automated types, truck platooning can reduce the number of required convoy drivers and decrease operational costs (Xue et al., 2021).

Road capacity and safety: Truck platooning can enhance road capacity by reducing vehicle spacing, allowing more efficient utilization of available road space (van Tilborg et al., 2019). This optimization could decrease highway congestion, leading to smoother traffic flow and improved road capacity. Hurtado-Beltran and Rilett (2021) focused on the impact of truck platooning on highway capacity and found that truck platoons can have a positive effect, with average reductions of 34.3% in passenger car equivalent values compared to other trucks. By minimizing disruptions caused by sudden acceleration and braking, platooning reduces traffic congestion (Chowdhury et al., 2023). Truck platooning also improves road safety by facilitating faster reaction times and coordinated braking among platooning trucks (Faber et al., 2020), leading to a decrease in accidents.

In addition to these benefits, Pająk and Cyplik (2020) studied the contribution of truck platooning to sustainable development, identifying strengths such as enhanced fuel efficiency, reduced GHG emissions, and cost savings for fleet operators. However, the study also highlighted weaknesses, including the high initial investment costs required for implementing platooning technology, the need for infrastructure upgrades, and potential social concerns related to job displacement for drivers, particularly as automation within platooning increases. Similarly, Muratori et al. (2017) examined the potential benefits of platooning in U.S. highway freight transport using connected and automated vehicles, estimating that about 65% of total miles driven by combination trucks could be in platoon formation, resulting in a 4% reduction in total truck fuel consumption. Lastly, Lesch et al. (2022) discussed the benefits of platooning, such as increased road capacity and reduced fuel consumption, while also outlining challenges related to decision-making and geographical scope.

1.6.2 Challenges

Literature on truck platooning transportation identifies the following challenges:

Communication and compatibility: Reliable communication between platooning vehicles and compatibility between different truck platooning systems pose challenges, especially in complex traffic environments (Schmeitz et al., 2023). Coordinating platooning trucks' movements with non-platooning vehicles and ensuring efficient platooning operations present additional challenges (Bishop et al., 2017).

Operational complexity: Coordinating platooning operations in various scenarios (e.g., loading/unloading times, trucks could be at different locations and need to join together to form platoons), modeling optimization at different planning levels, and developing scalable algorithms capable of handling diverse problem sizes and scenarios are essential but challenging tasks (Srisomboon and Lee, 2021). Developing scalable algorithms is challenging because they need to handle the complexity of real-world transportation. These algorithms must balance speed and accuracy to ensure they can be applied across large fleets and multiple scenarios.

Reliability and safety: Ensuring the reliability and safety of platooning systems across different conditions, including varying topologies, roads, weather conditions, and traffic densities, is crucial (Xu et al., 2021; Eitrheim et al., 2022). For example, the breakdown of one truck in a hybrid platoon could lead to the breakdown of the entire platoon.

Safety is presented as both a benefit and a challenge. On the one hand, truck platooning can enhance road safety by improving reaction times, enabling coordinated braking, and reducing traffic disruptions, therefore decreasing the probability of accidents. However, ensuring safety in real-world conditions, such as varying road quality, weather, and traffic density, remains a notable challenge. The breakdown of a single vehicle within a platoon or communication failures can compromise the safety of the entire system. Therefore, while platooning has the potential to improve safety, achieving this requires addressing operational complexities and ensuring robust, reliable systems across different environments.

Infrastructure requirements: Truck platooning may require dedicated equipment and infrastructure elements, such as communication infrastructure and dedicated platooning lanes which entail substantial investment and coordination for implementation (Eitrheim et al., 2022; Kusumakar et al., 2018). For instance, platoons of trucks could lead to queues at loading/unloading centers, which may require special equipment to speed up the process.

Initial investment and collaboration: The initial investment required for implementing truck platooning, including vehicle upgrades, communication infrastructure, and training, could be substantial. Developing business models, incentives, and collaboration among stakeholders are important steps towards successful implementation (Noruzoliaee et al., 2021a; Roukouni et al., 2020).

Willemsen et al. (2023) and Schmeitz et al. (2023) discussed the European ENSEMBLE project which aims to enable safe platooning. They emphasize the need for standardized platooning solutions to facilitate widespread adoption as a challenge. Sindi and Woodman (2021) studied the potential impact of autonomous vehicles on logistics operations. It discusses the barriers to commercial autonomous vehicle implementation, such as lack of standardization and technology direction. The study suggests that autonomous vehicles could reduce maintenance and operational costs, especially for long-haul journeys, ultimately improving efficiency. Eitrheim et al. (2022) studied the opportunities and barriers for truck platooning on rural freight routes in Norway. They investigated factors like low traffic volumes, challenging road conditions, and industry clusters. Juling (2023) examined the advantages and challenges of military truck platooning in Europe. The benefits include fewer drivers, increased crew safety, and reduced resource consumption. Zavvos et al. (2022) addressed challenges including privacy and trust issues in the Internet of Vehicles at the service level. It categorizes privacy concerns into four categories: personal information privacy, multi-party privacy, trust, and consent to share information. Sturm et al. (2021) provided an overview of categorizing objectives and influencing factors for platooning optimization, along with proposed metrics for objective evaluation.

In summary, while truck platooning offers significant benefits in terms of fuel efficiency, driver productivity, road capacity, and safety, it also presents challenges related to communication, compatibility, operational complexity, reliability, infrastructure, workforce implications, and initial investment. Addressing these challenges will be crucial for realizing the full potential of truck platooning in the transportation sector.

1.7 Discussion and research perspectives

This literature review emphasizes planning aspects (e.g., mathematical optimization and simulation methods) in truck platooning. We discuss the challenges and opportunities of platooning in transportation systems. Moreover, our literature review shows an increasing trend in the number of studies related to truck platooning transportation. The majority of papers in this area have been published since 2019, indicating considerable growth in research interest in recent years. The notable increase in academic research also indicates the growing interest in addressing the benefits and challenges of truck platooning technologies in various scenarios.

The literature on planning models for truck platooning reveals a diverse range of approaches, methods, and problem-solving techniques. The studies address various planning levels, from operational to strategic, and employ mathematical optimization models, simulation-based methods, and heuristic algorithms. In comparison to ordinary trucks, truck platooning's transportation planning specifications consider aspects such as platoon formation, detours caused by truck platooning, and their effects on cost. These include fuel and driver costs, cost-sharing between multiple truck owners, etc. Moreover, they include aspects such as different types of platoon trucks and different levels of automation in all areas of the transportation network. Different methods have been used to model and solve these problems. These models aim to optimize truck platooning operations, considering factors such as travel time, fuel consumption, costs, and constraints like delivery schedules, traffic conditions, and vehicle characteristics. Many studies focus on operational planning, utilizing optimization models to address problems such as VRP and platoon formation. Optimization objectives often include minimizing travel time, fuel consumption, and scheduling delays. For instance, studies like Zhang et al. (2017) and Deng (2016) explore travel time uncertainty, seeking to optimize schedules under such uncertainty. Moreover, the literature addresses the impact of platooning on traffic flow and safety. Simulation-based studies, such as Haq et al. (2022), assess the effects of platooning on average speed, acceleration distributions, and safety in mixed traffic conditions. Traffic signal prioritization, as explored in Chowdhury et al. (2023), is also identified as a potential strategy to enhance heavy vehicle platooning in urban areas. Few studies focused on truck platooning and real-time planning (e.g., Li and Li (2022)).

Many planning models consider deterministic parameters such as fixed supply, demand, and travel times. However, in the real world, these parameters are often subject to fluctuations influenced by factors like market trends, economic conditions, and unforeseen events. Future research may explore non-deterministic modeling approaches that consider these uncertain elements. For example, existing planning models often do not consider weather conditions' impact on truck platoon operations. Incorporating weather forecasts into planning could enable the development of strategies that optimize platoon formations and routes based on current and anticipated weather conditions. Reliability aspects need to be considered in truck platooning transportation planning and incorporated into different scenarios. Planning models should analyze routes for their reliability in terms of road quality, traffic patterns, and potential disruptions due to accidents, road closures, or extreme weather conditions which could affect platooning operations' reliability forcing trucks to operate individually, which reduces fuel efficiency and increases travel time. These disruptions also impact communication between vehicles, making it difficult to maintain the benefits of platooning. Regular maintenance of platoon vehicles is crucial for reliability.

Strategic and tactical planning levels are also explored, with studies like Watanabe et al. (2021) and Scherr et al. (2022) considering network design problems. These studies focus on the optimal location of platoon lanes, toll pricing, and fleet coordination to maximize efficiency. A notable aspect is the consideration of emerging technologies. Studies like Scholl et al. (2023) explore the concept of "E-platooning," optimizing platoon formation for long-haul transportation using electric trucks. Another aspect is the integration of autonomous and connected vehicle technologies, as seen in Semnarshad et al. (2022), which evaluates the impact of CACC and cooperative lane changing on traffic dynamics. Furthermore, research explores truck platooning's economic and environmental implications. For example, Guo et al. (2022) uses a system dynamics framework to assess the long-term effects of platooning technologies on profit and GHG emissions.

As the trucking industry faces an ongoing shortage of skilled drivers, effectively allocating available drivers to platoons becomes critical (Lupi et al., 2020). Planning models that optimize the assignment of a limited number of skilled drivers to platooning operations, accounting to factors like experience, fatigue, and shift preferences, can enhance the feasibility and implementation performance of different types of truck platooning. While research often focuses on the operation of platooning fleets, few planning models address the integration of platooning into existing transportation fleets (e.g., Gazran et al. (2023)). Exploring how platooning vehicles interact with ordinary trucks, trains, ships, and other modes of transport could provide insight into optimizing multi-modal logistics networks.

The literature on collaboration models for truck platooning reveals an exploration of some aspects crucial to the successful implementation of collaborative efforts in transportation. Collaboration in this context could include processes such as route planning, scheduling, and cost allocation among partners. These include methods for coordinating platoon activities, such as determining optimal routes, scheduling platoon formations, and allocating costs among partners. Moreover, protocols for communication and information exchange between platoon vehicles are investigated to ensure smooth coordination and synchronization of actions. Decision-making strategies may involve algorithms or heuristics for selecting suitable platooning partners, adjusting convoy configurations based on real-time traffic conditions, and optimizing fuel-saving strategies during platooning operations. These mechanisms, protocols, and decision-making strategies are crucial components of collaborative efforts in truck platooning transportation, aiming to maximize platooning benefits while addressing challenges such as fairness in benefit distribution and cost allocation among participating parties.

One of the challenges highlighted in the literature is the fair distribution of benefits and costs among parties. The literature on collaboration in truck platooning transportation mainly focuses on the short-term planning phase, particularly for "with-driver" platooning. They discuss collaboration between truck drivers to achieve platooning benefits, such as reduced fuel consumption. Simulation-based approaches play a significant role in the literature, providing a virtual environment to test, evaluate, and refine collaborative strategies. These simulations are useful for assessing the impact of different mechanisms, protocols, and decision-making strategies on truck platooning efficiency and safety. The inclusion of international collaboration in the form of studies between the U.S. and the European Union showcases a broader perspective, considering regulatory disparities and technological compatibility issues that might influence collaborative efforts on a global scale. Nevertheless, research is needed to develop comprehensive frameworks that address trust-building, fairness considerations, and the scalability of collaboration models as the number of participating actors increases (Xing et al., 2022).

Game theory integration into collaborative truck platooning systems is a notable trend. By employing concepts such as cooperative game theory, researchers can mathematically analyze and design effective strategies for coalition formation and fair distribution of costs and benefits. This approach not only enhances collaborative efficiency but also ensures stability and fairness: critical components of truck platooning collaboration success. Operational collaboration, with a focus on the immediate planning phase of "with-driver" platooning, emerges as a key area of study. The literature explores aspects such as platoon formation and routing. It recognizes the direct impact of these operational decisions on platooning systems' efficiency and safety. Human factors, communication delays, and conflicts of interest are considered and addressed within the collaborative framework. This reflects a realistic perspective on implementation challenges. In addition to traditional collaboration models, the literature introduces innovative approaches, such as game-based strategies and simulation-based assessments for enhancing sustainable collaboration. These approaches reflect a recognition of the need for creative solutions to overcome potential barriers and engage stakeholders in shaping the future of truck platooning. Examples of these approaches include designing algorithms for optimal coalition formation and conducting simulations to evaluate collaborative strategies' effectiveness in real-world scenarios. These initiatives demonstrate a proactive approach toward overcoming barriers and engaging partners in shaping the future of truck platooning.

Truck platooning transportation would provide potential collaborative opportunities that have yet to be fully explored in the literature. In particular, collaboration among different stakeholders, such as carriers and shippers, remains underexplored. While existing studies focus on operational planning involving truck drivers, studying collaboration between carriers, shippers, and other participants offers a new area of research. Investigating the dynamics of how different companies can work together effectively to optimize not only their operations but also the whole supply chain presents a significant avenue for future exploration. To address these gaps, diverse parties, such as truck drivers, carriers, shippers, and others, must be involved in a collaborative approach. This framework should provide a digital platform where these stakeholders can register, interact, and collaborate for mutual benefit. Such a platform could serve as an interface for information sharing, route optimization, resource allocation, and benefit sharing.

Truck platooning offers a range of benefits in transportation and logistics. Fuel efficiency can be improved by reducing air drag between vehicles. This not only results in cost savings for truck operators but also contributes to a decrease in GHG emissions, aligning with sustainable transportation goals. In the literature, it has been reported that the reduction in fuel consumption (from 4% to more than 20% under different conditions) and GHG emissions (10% on average (Pourmohammad-Zia et al., 2023)) benefits operators and has a positive impact on the environment as well. Operational benefits extend to enhanced road capacity, a critical aspect of traffic management. By reducing vehicle spacing and optimizing road space utilization, truck platooning contributes to smoother traffic flow and increased overall road capacity. The positive impact on road safety is another notable advantage. Coordinated braking among platooning trucks facilitates faster reaction times, leading to fewer accidents. Truck platooning introduces operational efficiencies that benefit driver productivity. With drivers monitoring the road and managing the platoon, the need for constant acceleration and braking is minimized. In-platoon resting becomes feasible, allowing drivers to take breaks or rest while their trucks remain in the convoy, contributing to improved driver well-being and fatigue management. Moreover, in hybrid and automated types, the reduction in required drivers for a convoy reduces operational costs.

Platooning benefits come with challenges that must be addressed. Ensuring reliable and secure communication between platooning vehicles is a fundamental challenge. Maintaining platoon integrity and safety requires the development of robust measures to ensure compatibility between different truck platooning systems. Efficient V2V communication, especially in complex traffic environments, raises challenges for smooth platooning. Other challenges include coordinating platooning trucks' movements with non-platooning vehicles, providing safe control in various situations such as merging and lane changes, and developing methods capable of handling diverse scenarios. The reliability and safety of platooning systems across varying conditions, including different topologies, roads, weather conditions, and traffic densities, is a substantial challenge that requires careful consideration.

Truck platooning also has social implications. The potential impact on the workforce, including job displacement and job requirements changes, is critical. Addressing concerns related to social impacts of automation in trucking are important. Legal and regulatory frameworks need to be adapted to accommodate truck platooning's unique aspects, including liability and operational requirements. Infrastructure requirements add another layer of complexity. Dedicated infrastructure elements, such as V2V systems and potentially specialized platooning lanes, may be necessary to support effective platooning operations. Coordinating the implementation of such infrastructure, along with assessing road networks' suitability for truck platooning, is a complex challenge. The initial investment required for implementing truck platooning, including vehicle upgrades, communication infrastructure, and training, poses a financial challenge. Overcoming market barriers, addressing uncertainty about technology benefits, and fostering collaboration between industry players and regulators are essential steps toward successful implementation.

Truck platooning and transportation planning have made much progress in addressing benefits and challenges, but there are still aspects that need to be explored. One of the future research directions is related to more practical aspects of different industries and the applicability of planning models to truck platooning (e.g., mining, agriculture and forestry). Furthermore, investigating industry-specific applications of truck platooning transportation planning is an avenue of research that holds significant promise. Different industries have varying operational requirements, challenges, and opportunities. Certain industries may be particularly well suited to utilizing truck platooning benefits more effectively due to their unique characteristics. In the forestry sector, where often only forest trucks use transportation routes, truck platooning could be easier to adopt. Therefore it could address challenges such as a shortage of truck drivers and reduce costs. For instance, forest transportation involves mixed loads, where trucks transport different types of wood to mills (e.g., logs, pulpwood, chips). Forests are vast and dispersed, requiring efficient routing across challenging areas. Moreover, loading and unloading often take more time than city logistics, affecting route planning. Forest transportation planning should be synchronized with harvesting schedules to ensure smooth operations. By adapting planning models to specific industries' distinct specifications, researchers can offer more targeted insights and actionable strategies.

1.8 Conclusion

This literature review focuses on truck platooning transportation. It discusses its benefits, challenges, planning models, collaboration strategies, research gaps, and future directions. The analysis highlights the advantages, including heightened fuel efficiency, lower emissions, improved traffic flow, and cost savings. The application of truck platooning to transportation planning in diverse problem contexts, case studies, and further adoption are necessary. Models and methods for optimizing route planning, scheduling, simulation, and resource allocation within truck platooning are presented in this work. To ensure the success of truck platooning systems, collaboration models emphasize the need for effective cooperation between different parties.

The studies cover scheduling, network design, and the broader implications of platooning on traffic flow, and environmental sustainability. Optimization objectives vary but commonly include minimizing travel time, fuel consumption, and operational costs. Simulation-based studies provide a deeper understanding of complex interactions between platooning vehicles and their impact on traffic dynamics. Moreover, studies consider the effects of platooning technologies on economic and environmental factors. As the field progresses, it is essential to address challenges such as uncertainty in travel times, traffic congestion, and the integration of emerging technologies. Future research may also explore the scalability of platooning solutions, considering their implementation in large-scale freight transportation networks.

The literature on collaboration models for truck platooning underscores the critical importance of collaborative efforts in addressing transportation challenges. The emphasis on fairness in the distribution of benefits and costs is a key consideration for maintaining collaboration among participants. Game theory can be used as a powerful tool for modeling strategic decision-making, ensuring stability, and designing fair cost/benefit-sharing mechanisms. The consideration of platoon formation, routing, and addressing practical aspects requires more attention for the successful implementation of collaborative truck platooning systems. Simulation and game-based approaches provide a valuable means of testing and refining collaborative strategies. These approaches demonstrate an understanding of challenges and actively involve various stakeholders in shaping the truck platooning future. Furthermore, collaboration models for truck platooning are not only about optimizing logistics but also about building stable systems.

Challenges include developing models and solution algorithms and ensuring platooning systems' safety and reliability under diverse conditions. Infrastructure requirements and substantial initial investment further complicate truck platoon implementation. Ongoing research and development in this field, as shown by various studies and projects, is key to addressing these challenges and reaching the full potential of truck platooning. Successful implementation requires a comprehensive approach that considers practical, sustainability, and infrastructure aspects. As technology evolves and stakeholders collaborate to overcome challenges, truck platooning has the potential to improve the transportation industry, making it more efficient and sustainable.

CHAPTER 2

OPTIMIZING TRUCK PLATOONING TRANSPORTATION PLANNING: AN APPLICATION TO FORESTRY PRODUCTS SUPPLY CHAINS

Saba Gazran[1,2,3] , Tasseda Boukherroub[1,2,3] , Mikael Rönnqvist[2,3,4] , Marc Paquet[1,2]

[1] Department of Systems Engineering & Numerix Laboratory, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, QC, Canada H3C 1K3
[2] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT),
Université de Montréal, Pavillon André-Aisenstadt, CIRRELT, CP 6128, Succursale Centre-ville Montréal, QC, H3C 3J7, Canada
[3] FORAC Consortium,
1065, av. de la Médecine, Université Laval, Québec, QC, G1V 0A6, Canada
[4] Département de Génie Mécanique,
1065, av. de la Médecine, local 1504, Université Laval, Québec, QC, G1V 0A6, Canada

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Abstract

The Fourth Industrial Revolution offers new opportunities for improving the efficiency and agility of supply chain operations such as transportation. This study explores the impact of integrating truck platooning technology in forestry products supply networks. Companies need to know how and where to use truck platooning in transportation networks to get optimum benefits from truck platooning in supply chains. To this end, a Mixed-Integer Linear Programming (MILP) model was developed. Decisions to be made include the selection of the potential terminal locations, the number of ordinary and platooning trucks needed in the transportation network, the origin and destination of products, and their flow in direct and backhaul routes. The objective is to minimize the overall transportation cost including terminal location costs, fixed costs for ordinary and platoon trucks, fuel, and driver costs. A total of 27 randomly generated instances are used to test the optimization model. We considered several scenarios to analyze different combinations of using or not backhauling, having or not truck platoons in the network, and allowing or not the truck platoons to visit the forest areas. The results show that the potential savings of combining the two types of trucks are in the range of 1%–12% in the scenarios in

which truck platooning transportation is allowed only between terminal and mill nodes. This savings could reach more than 20% when the truck platoons are allowed to visit forest areas, depending on how many forest areas are visited. The number of drivers can be reduced by 3% to more than 30%. In addition, using truck platooning and backhauling together could reduce fuel consumption by 15.6% on average.

Keywords: Truck platooning, transportation planning, backhauling, network design, forest supply chain

2.1 Introduction

Transportation is an essential part of supply chains and represents a notable proportion of the costs in many industries. In countries like Canada and Sweden, transportation cost is about one-third of the total raw material cost in the forest industry (Frisk et al., 2010). Since the 2008 economic crisis, companies have been searching for solutions to reduce their costs and governments and companies have consequently tried to find solutions to perform their supply chain processes more efficiently. Additionally, in transportation, it is essential to pay attention to critical environmental issues, such as GHG emissions. In Canada, transport activities were responsible for 30% of greenhouse gas (GHG) emissions in 2019 (Government of Canada, 2021). Moreover, transportation companies are facing truck driver shortage in some countries (Kelso, 2018); for instance, in the US and Canada truck driver shortage is a serious problem especially in some areas such as the forest sector. These issues could be addressed by different approaches such as systematic and global optimizations, collaboration, information sharing between companies, and deploying connected, autonomous, and electric vehicles (Speranza, 2018; Porter et al., 2015).

Thanks to recent technological advancements known as Industry 4.0 or the Fourth Industrial Revolution, it is expected that semi-autonomous and autonomous trucks will be seen on the roads in the near future, which will transform transportation. Fourth Industrial Revolution (Industry 4.0) incorporates technologies such as Internet of Things (IoT), artificial intelligence, and cloud computing (Xu et al., 2018). Industry 4.0 leads to more integrated, connected, and autonomous systems that are being implemented all over the world (Alessandra et al., 2018). The National Highway Transportation Safety Administration of the United States Department of Transportation has outlined five different levels of progressive automation, starting from a base level (Level 0) of no automation, to Level 5 corresponding to full self-driving automation (United States Department of Transportation, National Highway Traffic Safety Administration, 2016). Connected vehicle technologies allow creating an integrated network of vehicles and infrastructure systems where individual vehicles can communicate with other vehicles (V2V communication) and other infrastructures (V2I communication) (Mahmassani, 2016). At present, industries like mining and farming have adopted autonomous vehicle technology (Bertoncello and Wee, 2015). For instance, Rio Tinto already has a fleet of self-driving haul trucks in its Australian mines (Jamasmie, 2018).

One of the new technologies in the autonomous vehicles area is truck platooning. Truck platooning could improve transportation by contributing to addressing the challenges of driver shortage, high costs, and GHG emissions. Bhoopalam et al. (2018) describes a truck platoon as a group of virtually connected trucks that use automated driving technology to drive closely behind each other. The benefits of truck platooning include cost savings, reduced emissions (reduced fuel consumption due to reduced air drag), and increased road capacity utilization (Maiti et al., 2017).

There are three types of truck platooning with different transportation automation levels. Bhoopalam et al. (2018) proposed the following classification: human-driven platooning with in-platoon resting (automation level 3), hybrid platooning (automation level 4), and driver-less platooning (automation level 5). The first one is the case when drivers are at the wheels of all vehicles forming the platoon. In the second case, only the leading truck has a driver. In the third type, there is no driver in any truck of the platoon. The first type can only benefit from fuel consumption reduction, while the second type can contribute to address driver shortage issues, costs reduction, and fuel consumption reduction.

The problem of truck platooning transportation planning is quite a new research area. This problem could be investigated at strategic, tactical, or operational levels. Strategic planning deals with the effects of truck platooning on long-term decisions in transportation, e.g., the structure of the transportation network, and the investments in infrastructures and vehicles to be made. Tactical truck platooning transportation planning concerns mid-term decisions, e.g., material flow between the network's nodes. Operational truck platooning transportation planning deals with short-term decisions, e.g., day-to-day vehicle scheduling problems.

Most studies on truck platooning transportation planning in the literature have considered the operational level. Larson et al. (2013) is one of the first papers that appeared in this research area. This study initiated the scheduling of truck platoons with flexible routing decisions. Larson et al. (2016) used truck platooning problem features like the maximum length of a detour to decrease the problem's size. Larsson et al. (2015) introduced a truck platooning routing problem, defined in a given line part of the road network in real-time. They suggested an integer linear programming model (ILP) for the problem formulation and two heuristics to solve the model. Zhang et al. (2017) investigated departure time scheduling and freight platoon planning while considering travel time uncertainty. Noruzoliaee et al. (2021b) developed a platoon formation model of automatic truck platooning with the presence of normal vehicles. They considered the relation between platoon formation time, truck fuel savings, and improvement in road capacity in the transportation network.

Nourmohammadzadeh and Hartmann (2016) presented a Mixed Integer Programming (MIP) model for the platoon formation problem. The inputs include a set of trucks, their origin and destination, ultimate times for pickup and delivery, the road network structure, and the fuel-saving factor for the trucks in a platoon. You et al. (2020) studied the hybrid truck platooning combined with what is called the Local Container Drayage Problem. The study concluded that by increasing platoon size and/or coordinating container sharing between customers, the new transportation model could potentially result in lower labor costs. In another research, Xue et al. (2021) studied the Local Container Drayage Problem with a focus on the fuel-saving effect of platooning and developed a heuristic algorithm to solve large-sized problems. Abdolmaleki et al.

(2021) focused on scheduling a given collection of platoon trucks to optimize fuel savings on a time-expanded network. Larsen et al. (2019) presented a model for the problem of platoon formation at a hub that aims to minimize the total travel cost of the whole system through fixed routes. Johansson et al. (2021b) studied how vehicles could coordinate in a transportation network. In this study, vehicles travel along predetermined routes, and they form platoons by waiting at hubs to connect with other vehicles.

There is a limited number of studies in the literature that consider tactical transportation planning with truck platoons. Scherr et al. (2018) proposed a service network design solution for parcel delivery with truck platooning and formulated this problem as an MIP. The authors identified a two-tier city logistics scenario where autonomous trucks in different regions satisfy customer demands by the guidance of trucks with drivers. In another work, Scherr et al. (2019) studied a related problem. They considered heterogeneous vehicles in which autonomous vehicles can only drive in feasible zones but require control elsewhere by driver leaders in the platoons. This model determines the size and mix of the fleet of vehicles and also the flows in the network. Recently Scherr et al. (2020) investigated a similar problem with an improved formulation and faster solution methodology.

A recent study conducted by Watanabe et al. (2021) indicates that a location for forming platoons of trucks is needed in order to facilitate the automated operation of truck connections in a platoon. In their study, the researchers describe the present status of truck platooning in Japan and present a numerical experiment that uses a continuous approximation model to determine the optimal location for truck platooning formation. We found no other study in the literature that addresses the problem of facility location in the context of truck platooning transportation planning. In addition, Watanabe et al. (2021) proposed a different approach than a Mixed Integer Linear Programming (MILP) model that we propose in this work. Moreover, to the best of our knowledge, there are no studies in the literature dealing with forestry products transportation planning using truck platoons.

In recent years, the first Canadian truck platooning technology experiments in the forest industry have been conducted by FPlnnovations organization and its partners in the province of Quebec. The different phases of technical and road testing such as acceleration, steering, and braking were successful. FPInnovations is working on further improvements such as exposing the system to weather conditions that are typical of Canadian operations. Furthermore, the tests will assess how the autonomous system reacts to the road and environmental conditions. It is expected that truck platoons will be introduced in the forestry sector in the near future. Therefore, in order to efficiently use this technology and benefit from its advantages, it should be carefully integrated with existing transportation technologies (ordinary trucks). At this level, providing an appropriate truck platooning transportation plan to employ in the forestry sector is essential, and this is the purpose of our research.

Truck platooning could lead to even more cost-efficiency in transportation. The first step of introducing truck platooning in the forestry sector is to study how we can integrate it with existing normal (ordinary) trucks in transportation and in which part of the network. It is therefore a gradual integration of this technology. Moreover, as part of this gradual integration, we must address strategic and tactical planning before moving on to operational planning.

The objectives of this paper are as follows:

- Our study analyzes the integration of truck platooning in transportation planning in the forestry sector, which is a promising sector for adopting this technology. To the best of our knowledge, it is the first time that a research work has studied truck platooning integration in transportation planning in this sector. The proposed model considers both truck platoons and ordinary trucks. Therefore, the model includes different parameters (fuel consumption, driver cost, loading and unloading time capacities, etc.) to capture the specifics of the two different types of trucks. Decisions to be made include the network design (terminals to open and forest areas to visit), product flows in direct and backhaul routes for ordinary and platoon trucks, and the number of ordinary and platoon trucks to use in the transportation network.
- Our study investigates the gradual integration of truck platoons in the transportation network, as this technology is relatively new. This is reflected in the various scenarios and realistic

instances studied: we consider networks with diverse average transportation distances between nodes, vary the accessibility level of truck platoons to forest area nodes, and analyze scenarios with or without backhauling. By doing this, we identify under which conditions integrating truck platoons in forestry transportation is most profitable. We also measure the impact of introducing truck platooning in all the scenarios in terms of: 1) total transportation cost, 2) the number of drivers needed, and 3) fuel consumption savings.

The remainder of this paper is organized as follows: In Section 2.2, the research problem is described. Section 2.3 presents the mathematical formulation of the problem. Section 2.4 presents the break-even distance for platoon trucks. Section 2.5 shows the case study, scenarios, and instances used to test the model. Section 2.6 reports the numerical results and presents our discussion. Section 2.7 gives our conclusions and future research directions.

2.2 Problem description

Forest planning problems cover a varied range of processes, including raw material products transportation (El Hachemi et al., 2013) on which our study focuses. Typically, the distances between supply and demand areas are long. As an example, in the province of Quebec in Canada, the average distance is approximately 150 km and transportation accounts for about 30% of the total wood cost (Rix et al., 2015). Therefore, raw material transportation in the upstream supply chain should be organized as efficiently as possible. Usually the upstream forest supply chain transportation network contains supply nodes (forest areas) from which forest products are harvested and transported to demand points (mills). Products can be sent directly from the supply areas to demand nodes. In some cases, the transportation network contains terminal nodes, storage or sorting yards in which products are first stored or sorted and then sent to the demand nodes. In our case, terminals are considered as transshipment nodes for truck platoons, when they are not allowed to visit the forest areas. In fact, in the first stages of implementing truck platooning technology, opportunities for platooning in the forest areas will likely be limited until the technology is fully functional in these areas. Initially, platooning would be restricted to terminals. Therefore, we study two cases for truck platoons: 1) using terminals for loading the truck platoons in case they are not allowed to visit the forest areas and 2) transporting forest products directly from forest areas to mills in case truck platoons are allowed to visit the forest areas. In addition, in this study, because mills are typically not located in cities (but rather in remote forestry regions), we avoid operating truck platooning in the cities. The aim is to answer the following questions:

- Which terminals among the potential ones should be used in the transportation network (in situations requiring using terminals)?
- How many ordinary and platoon trucks are needed in the transportation system over the planning horizon to fulfill the demand?
- What is the quantity of product flows that should be transported in each part of the network and by which type of trucks?
- Which direct and backhauling routes need to be selected for each type of truck?

Usually, a truck moves loaded from an origin node to a destination node and then returns back empty to the origin. An efficiency increase could be achieved if routes include more than one loaded trip on backhaul routes, in which a truck that has transported one load takes another load on its way back. Backhauling could significantly improve transportation efficiency (Forsberg et al., 2005; Epstein et al., 2007; Carlsson and Rönnqvist, 2007). For instance, Epstein et al. (2007) demonstrated that backhauling could result in cost savings of between 2% and 20%. Therefore, it is also interesting to investigate backhauling in our problem. An interesting question is how to assign routes to different types of trucks (platoon trucks and ordinary trucks). This involves combining the network link flows in order to create efficient backhauls for either ordinary trucks or platoon trucks.

In transportation planning, it is important to consider both fixed and variable transportation costs. We consider the fixed cost for opening a given terminal and for having ordinary and platoon trucks. The main variable costs in the transportation system include fuel costs and driver costs. The tactical plan determines the terminal locations, the flows in the direct and backhaul routes for each truck type, and the number of vehicles of each type used in the transportation network. Products can either be sent directly from the supply to demand nodes or through terminal nodes.

We assume that the terminals could be used to collect the forest products from multiple forest areas and supply multiple demand points.

The main assumptions of the studied problem are as follows:

- The planning horizon is one year.
- The network design and transportation planning decisions are centralized.
- The transporter company employs two types of vehicles; ordinary and platoon trucks.
- We consider a fixed cost over the planning horizon for purchasing each type of truck and we assume that a truck will be in operation for five years. By estimating the cost of buying a new truck and the remaining value for a truck after five years, we calculate the discounted cost per year for ordinary and platoon trucks.
- A system of truck platoons uses only one human driver (at the wheels of the leading truck) for all the trucks in the platoon (driver cost is shared between all trucks in the platoon).
- During transportation all trucks in a platoon are always together and we do not investigate the platoon formation problem.
- We assume truck platooning is fuel-efficient, so each truck in a platoon consumes less fuel (Bhoopalam et al., 2018).
- The quality of roads in forest areas is lower than other roads in transportation networks and it takes more time and fuel for a truck to transport products in these areas.
- There are multiple types of products (e.g., saw-logs, pulp-logs, etc.) supplied from forest areas to mills and terminals.
- Each harvest node has a limited and known supply amount for each product type in the planning horizon.
- Demand is known for each mill and each product type in the planning horizon.
- Potential terminal nodes have limited product inflow capacities (inventory decisions are not included in the problem).

2.3 Mathematical formulation

We formulate the problem as a Mixed-Integer Linear Program (MILP) where the objective function minimizes the total cost which includes fixed location costs of terminals, fixed truck costs, and also fuel and driver costs. Sets, parameters and decision variables, the objective function and the constraints are described in the next paragraphs:

2.3.1 Sets

Table 2.1 presents sets used for defining the problem.

Table 2.1 Sets

Set	Description
F	Set of supply (forest areas) nodes
S	Set of potential terminal nodes
M	Set of demand (mills) nodes
$N = F \cup S \cup M$	Set of all nodes
E	Set of all edges
$G = (N, E)$	Network graph
P	Set of all product types
R_O	Set of all direct routes for each product type for ordinary trucks, $R_O = \{\{i, j, p\} : i, j \in N, i \neq j, p \in P\}$.
B_O	Set of backhaul routes for ordinary trucks, $B_O = \{\{i_1, j_1, p_1, i_2, j_2, p_2\} : i_1, i_2, j_1, j_2 \in N, p_1, p_2 \in P\}$.
R_L	Set of all direct routes for each product type for truck platoons, $R_L = \{\{i, j, p\} : i, j \in N, i \neq j, p \in P\}$.
B_L	Set of backhaul routes for truck platoons, $B_L = \{\{i_1, j_1, p_1, i_2, j_2, p_2\} : i_1, i_2, j_1, j_2 \in N, p_1, p_2 \in P\}$.
$R_{O_{ip}}$,$R_{L_{ip}}$	Set of direct routes that pass node i with product p for ordinary and platoon trucks respectively.
R_{O_p}, R_{L_p}	Set of direct routes with product p for ordinary and platoon trucks respectively.
$B_{O_{ip}}$,$B_{L_{ip}}$	Set of backhaul routes that pass node i with product p for ordinary and platoon trucks respectively.
B_{O_p}, B_{L_p}	Set of backhaul routes with product p for ordinary and platoon trucks respectively.

The direct routes are defined as a set in which i is the starting node, j is the end node, p is the product type. Backhaul routes are characterized as a set where i_1 and i_2 are the first and second supply nodes, j_1 and j_2 are the first and second demand nodes, with p_1 and p_2 product types in first and second loaded transportation.

2.3.2 Parameters

The parameters used in the model are given as follows:

$T:$ duration of the planning horizon (weeks).

$f_s:$ fixed opening cost of terminal s (Canadian Dollars (CAD)).

$q_s:$ inflow capacity of terminal s (tons).

$f^{VO}:$ fixed cost of each ordinary truck in the planning horizon (CAD).

$f^{VL}:$ fixed cost of each truck platoon system (with n trucks) in the planning horizon (CAD).

$g_{fp}:$ the supply capacity (tons) of forest area f for product type p.

$d_{mp}:$ the demand amount (tons) of mill m for product type p.

$c_r^{AO}:$ transportation cost for direct route r for ordinary trucks (CAD).

$c_k^{BO}:$ transportation cost for backhaul route k for ordinary trucks (CAD).

$c_r^{AL}:$ transportation cost for direct route r for truck platoons (CAD).

$c_k^{BL}:$ transportation cost for backhaul route k for truck platoons (CAD).

$e_r^{AO}:$ total time per ton for an ordinary truck transportation on direct route r.

$e_k^{BO}:$ total time per ton for an ordinary truck transportation on backhaul route k.

$e_r^{AL}:$ total time per ton for a truck platoon transportation system on direct route r.

$e_r^{BL}:$ total time per ton for a truck platoon transportation system on backhaul route k.

h^O : total available hours for an ordinary truck in the planning horizon.

h^L : total available hours for a truck platoon (containing n truck) in the planning horizon.

w^O: load capacity of an ordinary truck (tons).

w^L: load capacity of a platooning truck (tons).

w^{DO}: driver cost per hour for ordinary trucks (CAD).

w^{DL}: driver cost per hour for a platoon of n trucks (CAD).

t_r^{AO}: total trip time in direct route r for ordinary trucks, which consist of one loaded and one empty trip (hours).

t_r^{AL}: total trip time in direct route r for truck platoons, which consist of one loaded and one empty trip (hours).

t_k^{BO}: total trip time in backhaul route k for ordinary trucks. Backhaul routes consist of two loaded and two empty trips (hours).

t_k^{BL}: total trip time in backhaul route k for truck platoons. Backhaul routes consist of two loaded and two empty trips (hours).

l^O: loading time for ordinary trucks (hours).

u^O: unloading time for ordinary trucks (hours).

n: number of trucks in a platoon.

l^L: loading time for truck platoons (= $n \times l^O$) (hours).

u^L: unloading time for truck platoons (= $n \times u^O$) (hours).

f^O, f^L: fuel consumption (liter per kilometer) for each ordinary truck and each truck in a platoon respectively.

c^f: fuel cost (CAD) per liter.

d_r^{AO}, d_r^{AL}: total distance in direct route r for ordinary and platoon trucks respectively (km).

d_k^{BO}, d_k^{BL}: total distance in backhaul route k for ordinary and platoon trucks respectively (km).

Total transportation time for an ordinary truck or a truck platoon on direct route r or backhaul route k is calculated based on transportation time in the route (t_r^{AO}, t_r^{AL}, t_r^{BO} and t_r^{BL}) in addition to the loading (l^O and l^L) and unloading (u^O and u^L) times. Total transportation time per ton for an ordinary or platooning truck on direct route r or backhaul route k is calculated by dividing the total time by the capacity of the truck (w^O and w^L). The driver cost (w^{DO} and w^{DL}) depends on the time driver spends driving and loading/unloading in each route. Therefore, it can be calculated by multiplying hourly driver cost by the total time for each route. Moreover, the fuel cost depends on the driving kilometers in each route. Therefore, it can be calculated by multiplying fuel cost per liter (c^f) by fuel consumption per kilometer for trucks (f^O and f^L) by the total driving kilometers in each route (d_r^{AO}, d_r^{AL}, d_k^{BO} and d_k^{BL}).

2.3.3 Decision variables

Table 2.2 shows all the decision variables used in the mathematical model.

Table 2.2 Decision variables

Variable	**Definition**
y_i	$= \begin{cases} 1, & \text{if terminal } i \text{ is opened} \\ 0, & \text{otherwise.} \end{cases}$
x_r^{AO}	= Product flow in direct route r for ordinary truck transportation.
x_k^{BO}	= Product flow in back-haulage route k for ordinary truck transportation.
x_r^{AL}	= Product flow in direct route r for truck platoon transportation.
x_k^{BL}	= Product flow in back-haulage route k for truck platoon transportation.
z^O	= Total number (integer) of ordinary trucks needed in the transportation network.
z^L	= Total number (integer) of truck platoons needed in the transportation network.

2.3.4 Objective function and constraints

The objective function (TC) and constraints of the mathematical model are the following:

$$\min TC = \sum_{i \in S} f_i y_i + \sum_{r \in R_O} c_r^{AO} x_r^{AO} + \sum_{k \in B_O} c_k^{BO} x_k^{BO} + \sum_{r \in R_L} c_r^{AL} x_r^{AL} + \sum_{k \in B_L} c_k^{BL} x_k^{BL} + f^{VO} z^O + f^{VL} z^L \tag{2.1}$$

$$s.t: \sum_{r \in R_{O_{ip}}} x_r^{AO} + \sum_{k \in B_{O_{ip}}} x_k^{BO} + \sum_{r \in R_{L_{ip}}} x_r^{AL} + \sum_{k \in B_{L_{ip}}} x_k^{BL} \leq g_{ip} \qquad \forall i \in F, p \in P \tag{2.2}$$

$$\sum_{r \in R_{O_{ip}}} x_r^{AO} + \sum_{k \in B_{O_{ip}}} x_k^{BO} + \sum_{r \in R_{L_{ip}}} x_r^{AL} + \sum_{k \in B_{L_{ip}}} x_k^{BL} = d_{ip} \qquad \forall i \in M, p \in P \tag{2.3}$$

$$\sum_{r \in R_{O_{ip}}} x_r^{AO} + \sum_{k \in B_{O_{ip}}} x_k^{BO} + \sum_{r \in R_{L_{ip}}} x_r^{AL} + \sum_{k \in B_{L_{ip}}} x_k^{BL} -$$

$$\sum_{r \in R_{O_{i'p}}} x_r^{AO} - \sum_{k \in B_{O_{i'p}}} x_k^{BO} - \sum_{r \in R_{L_{i'p}}} x_r^{AL} - \sum_{k \in B_{L_{i'p}}} x_k^{BL} = 0 \qquad \forall i, i' \in S, p \in P \tag{2.4}$$

$$\sum_{r \in R_{O_i}} x_r^{AO} + \sum_{k \in B_{O_i}} x_k^{BO} + \sum_{r \in R_{L_i}} x_r^{AL} + \sum_{k \in B_{L_i}} x_k^{BL} \leq q_i y_i \qquad \forall i \in S \tag{2.5}$$

$$\sum_{r \in R_O} e_r^{AO} x_r^{AO} + \sum_{k \in B_O} e_k^{BO} x_k^{BO} \leq h^O z^O \tag{2.6}$$

$$\sum_{r \in R_L} e_r^{AL} x_r^{AL} + \sum_{k \in B_L} e_k^{BL} x_k^{BL} \leq h^L z^L \tag{2.7}$$

$$y_i \in \{0, 1\} \qquad \forall i \in S \tag{2.8}$$

$$z^O, z^L \geq 0, integer \tag{2.9}$$

$$x_r^{AO}, x_k^{BO}, x_r^{AL}, x_k^{BL} \geq 0 \qquad \forall r \in R_O, R_L, k \in B_O, B_L \tag{2.10}$$

The objective function TC (equation 2.1) minimizes total costs of terminal location, direct and backhaul flows for ordinary and platooning trucks, and also the fixed costs of the fleet for ordinary and platoon trucks over the planning horizon. Constraint set (2.2) restricts the amounts for each product type that can be supplied from each forest area. Constraint set (2.3) guarantees that the demand for each product type in each mill is satisfied. Constraint set (2.4) is the flow balance at terminal nodes which indicates that the amounts of input flow to each terminal must be equal to the amounts of output flows for each product type. Constraint set (2.5) is the inflow capacity for each terminal node. Under constraint sets (2.6) and (2.7), the number of ordinary and platoon trucks multiplied by their available hours must be greater than or equal to the total amount of time needed to carry out products in ordinary and platoon transportation, respectively.

The remaining constraint sets (2.8-2.10) define the binary, integer, and non-negative decision variables respectively.

In Section 2.4, we use the break-even distance to estimate the minimum transportation distance ensuring economic feasibility for truck platooning.

2.4 Break-even distance

Fuel cost, driver cost, and fixed cost (i.e., price for a truck over a period) are the most important factors to consider in order to calculate the break-even distance. We consider the distance between supply and demand points as x and assume that the average speed for an ordinary truck is v_O and for a truck in a platoon is v_L. For a truck in a platoon system (with n trucks) and an ordinary truck traveling from node A to node B, the transportation costs can be calculated as follows:

$$
\begin{aligned}
TC_O &= f^{VO} + (\frac{x}{v_O} + l_O + u_O) \times w^{DO} + c^f \times f^O \times x \\
&= (\frac{w^{DO}}{v_O} + c^f \times f^O) \times x + f^{VO} + (l_O + u_O) \times w^{DO}
\end{aligned} \tag{2.11}
$$

$$
\begin{aligned}
TC_L &= f^{VL} + (\frac{x}{v_L}) \times \frac{w^{DL}}{n} + (l_L + u_L) \times w^{DL} + c^f \times f^L \times x \\
&= (\frac{w^{DL}}{n \times v_L} + c^f \times f^L) \times x + (f^{VL} + (l_L + u_L) \times w^{DL})
\end{aligned} \tag{2.12}
$$

By equalizing TC_O and TC_L, we can calculate the break-even distance (x) as follows:

$$x = \frac{(f^{VL} - f^{VO}) + ((l_L + u_L) \times w^{DL} - (l_O + u_O) \times w^{DO})}{(\frac{w^{DO}}{v_O} - \frac{w^{DL}}{n \times v_L}) + c^f \times (f^O - f^L)} \tag{2.13}$$

Based on parameters in Table 2.4, the break-even distance when $n = 3$, is about 100 km. We considered the case with three trucks in the platoons. A larger number of trucks in a platoon is more cost-efficient (in terms of transport driver costs) in longer distances but at the same time, it leads to more loading and unloading time.

2.5 Case study

In this section, the mathematical model is solved and the results (solutions and analysis) are presented. We built a case study based on 27 randomly generated realistic instances (Quebec case) and consider six different scenarios (sub-section 2.5.1).

2.5.1 Scenarios

In order to analyze potential benefits (cost savings, reduction of the number of drivers and fuel consumption) by using truck platooning, we have defined six main scenarios. The scenarios are built based on the level of accessibility to forest areas for truck platoons and the combination of using direct and backhaul routes for ordinary and platoon trucks in the transportation network. The six scenarios are as follows:

- **Scenario S01:** considers only ordinary trucks and direct transportation between all nodes in the transportation network. This is our base-case scenario.
- **Scenario S02:** considers only ordinary trucks and direct transportation as well as backhaul transportation between all nodes in the transportation network.
- **Scenario S03:** considers direct transportation between all nodes for ordinary trucks and direct truck platooning transportation between terminals and mills. Truck platoons are not allowed to visit any forest area.

- **Scenario S04:** considers direct and backhaul transportation between all nodes for ordinary trucks and direct and backhaul transportation for platoon trucks between terminals and mills. Platoon trucks are not allowed to visit any forest area.
- **Scenario S05:** considers direct transportation between all nodes for ordinary trucks and direct transportation for platoon trucks between terminals, mills, and a limited number of forest areas. Backhauling is not considered in this scenario.
- **Scenario S06:** considers direct and backhaul transportation between all nodes for ordinary trucks and direct and backhaul transportation for platoon trucks between terminals, mills, and a limited number of forest areas.

Depending on the number of forest areas allowed to be visited by the truck platoons, scenarios S05 and S06 are further divided into four sub-scenarios. In sub-scenario *a*, truck platoons can only transport products from one forest area. The truck platoons could transport products from three and five forest areas, respectively, in sub-scenarios *b* and *c*. Finally, truck platoons could transport products from all forest area nodes in sub-scenario *d*. Scenarios S05d and S06d are optimistic scenarios that have been introduced to show what the effects of truck platooning would be if the technology is fully operational in forest areas.

Scenario S01 is considered as the base case scenario and results (total cost, fuel consumption and the number of drivers) generated by other scenarios are compared to the results obtained in scenario S01.

2.5.2 Instance generation

We generated 27 instances that we classified in 9 groups, each group contains three instances. These instances vary in the number of nodes, products, and node locations. The number of forest areas, potential terminals, mills, and product types are fixed for all instances in each group. All the details are shown in Table 2.3.

Table 2.3 Number of nodes and product types in the generated network instances

Group	**Instances**	$\|F\|$	$\|S\|$	$\|M\|$	$\|P\|$
1	I01, I02, I03	10	8	6	2
2	I04, I05, I06	10	8	6	3
3	I07, I08, I09	10	8	6	4
4	I10, I11, I12	15	12	9	2
5	I13, I14, I15	15	12	9	3
6	I16, I17, I18	15	12	9	4
7	I19, I20, I21	20	16	12	2
8	I22, I23, I24	20	16	12	3
9	I25, I26, I27	20	16	12	4

For all the forest nodes we assume that the first 10 km of forest roads have higher fuel consumption and transportation time. The X and Y coordinates of the nodes in the randomly generated networks were defined with integer coordinates between 0 and 370 kilometers resulting in average distances between forest areas and mills between 162 - 215 km. The average transportation distances between forest areas and mills are between 70 - 161 km in scenario S01, which is similar to average transportation distances in upstream forest supply chains in the province of Quebec in Canada (Rix et al., 2015). As an example, Figure 2.1 shows a network with 10 forest areas, 8 terminals, and 6 mills.

Data used are given in Table 2.4. These data come from multiple sources, such as FPInnovations regarding the number of trucks used in a platoon, the cost of drivers, and the capacity of trucks. Truck prices are based on the average prices provided by transportation organizations' websites (e.g., www.autotrader.ca). Loading and unloading time of trucks and fuel savings for truck platoons are based on the literature (El Hachemi et al., 2013; Larson et al., 2013). Furthermore, fuel consumption and fuel cost come from Canadian government websites (e.g., www.nrcan.gc.ca).

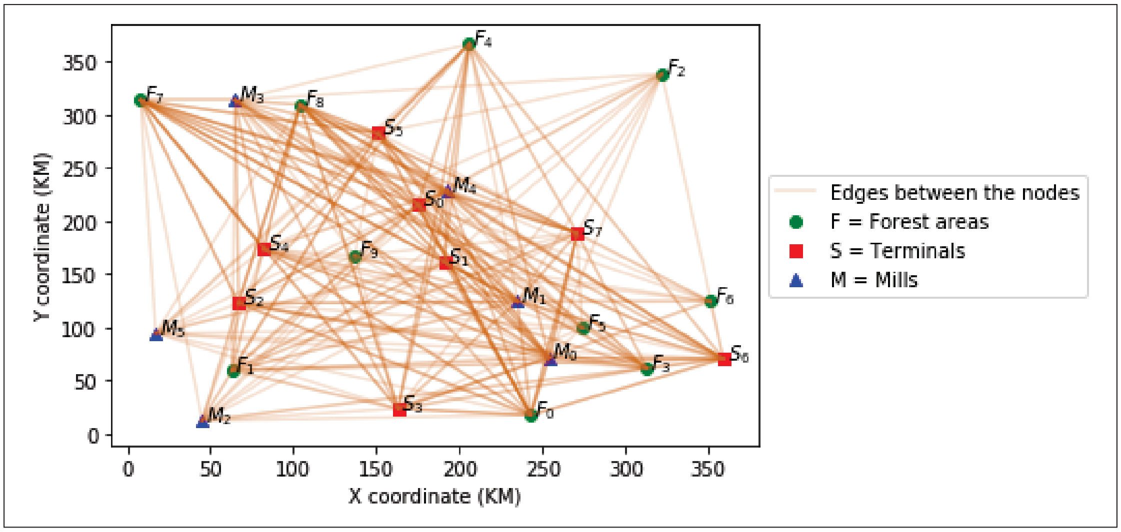

Figure 2.1 An example of a network with 10 forest areas, 8 terminals, and 6 mills

Table 2.4 Parameter values in the case study

Parameter	Value	Reference	Parameter	Value	Reference
T	52 weeks	-	h^O	40 hours	Expert from Chantiers Chibougamau company
n	3	FPInnovations www.fpinnovations.ca	h^L	40 hours	Expert from Chantiers Chibougamau company
w^O	40 tons	FPInnovations	$f^O \times c^f$	$= 0.4 \times 1$ CAD	www.nrcan.gc.ca
w^L	40 tons	FPInnovations	$f^L \times c^f$	$= 0.36 \times 1$ CAD	www.nrcan.gc.ca; (Larson et al., 2013)
l^O	1/3 hour	(El Hachemi et al., 2013)	w^{DO}	30 CAD per hour	Expert from Chantiers Chibougamau company
u^O	1/3 hour	(El Hachemi et al., 2013)	w^{DL}	30 CAD per hour	Expert from Chantiers Chibougamau company
l^L	1 hour	$l^L = n \times l^O$	f^{VO}	20,000 CAD	www.autotrader.ca
u^L	1 hour	$u^L = n \times u^O$	f^{VL}	60,000 CAD	www.autotrader.ca

We assume that the cost of buying a new truck is 120,000 CAD and it will be in operation for five years. The remaining value for a truck after five years is 20,000 CAD, therefore the discounted cost per year is 20,000 CAD. Also, we assume that when we buy three trucks to form a platoon, we can buy them with a rebate such that the fixed cost including the automation technology cost is equivalent to buying one ordinary truck. The estimation of the technology cost would be 10,000 - 15,000 CAD in the planning horizon (The North American Council for Freight Efficiency, 2016). We also assume this amount is equivalent to the rebate obtained when buying a platoon of three trucks. The platoon trucks will be bought in groups of three and ordinary trucks will not be bought in groups of three; therefore we do not assume that there will be a rebate in the case of ordinary trucks.

In order to generate the routes for platoon trucks, we took into account some limitations (based on the scenarios). We change our route generation according to different scenarios for both types of direct and backhaul routes. For instance, in scenarios S03 and S04, the direct and backhaul flows for truck platoons are limited between mills and terminal nodes. In scenarios S05 and S06, forest area nodes could be added to truck platooning potential routes.

Our optimization model is solved based on the 27 instances using 64-bit Gurobi version 9.0 on a laptop with an Intel Core i7-7700 @ 2.80 GHz and 16 GB of RAM running 64-bit Microsoft Windows 10. Python is used to generate the random instances and prepare the data. The model was created by using Gurobi's Python environment in 64-bit Anaconda3 6.0.3 Jupyter.

2.6 Numerical experiments and results

This section is divided into four parts. In Subsection 2.6.1, we present the cost savings obtained for the different scenarios and groups of instances. Next in Subsection 2.6.2, we examine how much truck platooning could affect the number of needed drivers and the amount of fuel consumption. In Subsection 2.6.3, we perform a sensitivity analysis regarding the fixed cost parameter of platooning trucks. Finally, Subsection 2.6.4 discusses the results.

2.6.1 Results

The number of decision variables and constraints of the optimization model varies in the different scenarios and instances. The number of constraints in scenarios S01 and S02 is between 57 and 209. The number for scenarios S03 to S06 is between 122 and 210. This is because of the constraint related to the number of platoon trucks needed in scenarios S03 to S06. Scenarios S01 and S02 in all the instances have one integer variable (which indicates the number of ordinary trucks to be used) whereas scenarios S03 to S06 have 2 integer variables (which indicate the number of ordinary and platoon trucks to be used). We recall that in scenarios S01 and S02 we only have ordinary trucks and in scenarios S03 to S06 we have both types of trucks. The number of binary variables in each scenario is equal to the number of potential terminal nodes in the instances (8, 12, and 16). Scenario S01 results in between 217 and 1192 continuous variables in the 27 instances and these numbers go up for scenarios S03 and S05 with 1.25 to 2 factors. Since scenarios S02, S04, and S06 consider both direct and backhaul flows between the nodes the number of variables increases significantly compared to scenarios S01 and S03, and S05 respectively. In our instances, scenarios S02, S04, and S06 have more than 380,000, 400,000, and 760,000 continuous variables in the largest instances respectively. Table 2.5 shows the number of constraints and decision variables and solving time for different scenarios in all instances.

Table 2.5 Solving time, the number of constraints, and decision variables for all scenarios and instances

Scenarios	Interval of the number of constraints	Interval of the number of decision variables			Interval of solution times (seconds)
		Continues	Integer	Binary	
S01	57 - 209	217 - 1192	1	8 - 16	0.1 - 0.3
S02	57 - 209	18127 - 565165	1	8 - 16	2 - 53.8
S03	58 - 210	273 - 1544	2	8 - 16	0.3 - 0.5
S04	58 - 210	18715 - 59597	2	8 - 16	2.1 - 108.1
S05	58 - 210	296 - 2384	2	8 - 16	0.3 - 0.5
S06	58 - 210	18218 - 1053162	2	8 - 16	2.4 - 653

The solver takes less than one second for all of the instances of scenarios S01, S03, and S05. For scenario S02, the solution time ranges from 2 to 54 seconds, while the solution time ranges from 2 to 108 seconds for scenario S04 and 2 to 653 seconds for scenario S06. This is due to the fact that in scenarios S02, S04, and S06, the number of variables has increased substantially.

The results in terms of optimal cost are shown in Table 2.6. The first column shows the instance groups, and the second column shows the average optimal cost for each instance group in scenario S01 (in million Canadian Dollars). The other columns show the average cost-saving percentages of all other scenarios compared to scenario S01 for each instance group.

Table 2.6 Optimal cost-saving results for each scenario compared to scenario S01 obtained for each instance group

Group	S01 (M CAD)	Average optimal cost savings % of each instance group for each scenario										
		S02	S03	S04	S05				S06			
					a	b	c	d	a	b	c	d
1	14.099	6.0	3.5	8.0	5.0	9.4	12.6	25.2	9.1	13.6	16.4	29.3
2	19.341	5.4	3.3	6.4	4.1	7.6	13.5	25.6	8.3	11.7	17.1	29.2
3	22.425	9.3	4.5	11.2	4.7	8.5	14.9	26.0	12.7	16.3	21.0	32.5
4	18.365	2.6	2.2	3.9	3.9	5.8	9.3	24.4	5.6	7.0	10.8	26.2
5	32.710	4.1	4.9	7.8	6.1	9.0	12.5	26.0	9.2	11.5	15.1	28.8
6	28.220	6.7	2.1	8.0	3.0	5.7	10.5	25.3	8.7	11.6	15.3	29.9
7	22.730	4.7	2.2	5.7	2.8	5.1	8.2	23.4	6.5	8.7	11.8	26.5
8	32.401	3.2	2.3	5.0	4.0	5.3	8.5	24.1	6.7	8.0	11.0	26.3
9	34.100	7.8	3.3	9.2	4.4	6.4	8.6	24.7	9.8	13.0	15.0	30.0

Figure 2.2 illustrates the average cost savings of different scenarios compared to scenario S01. The average cost savings of scenarios S02, S03, and S04 compared to scenario S01 are 5.4%, 3.2%, and 7.2% respectively. However, when there are more forest areas that can be visited by platoon trucks, the savings increase significantly (to more than 20%), both for direct and backhaul transportation.

Results show that backhauling leads to savings in transportation distances in scenarios S02 compared to S01 and in scenario S04 compared to S03. Comparing the results of scenarios S03 and S04 with those of S01 and S02 reveals that truck platooning leads to more transportation distances. This is because truck platoons can only transport between terminals and mills and cannot go directly between forest areas and mills in these scenarios. Therefore, using truck platooning requires first transporting materials from forest areas to terminals by ordinary trucks, then shipping products from terminals to mills by truck platoons, which results in longer transportation distances.

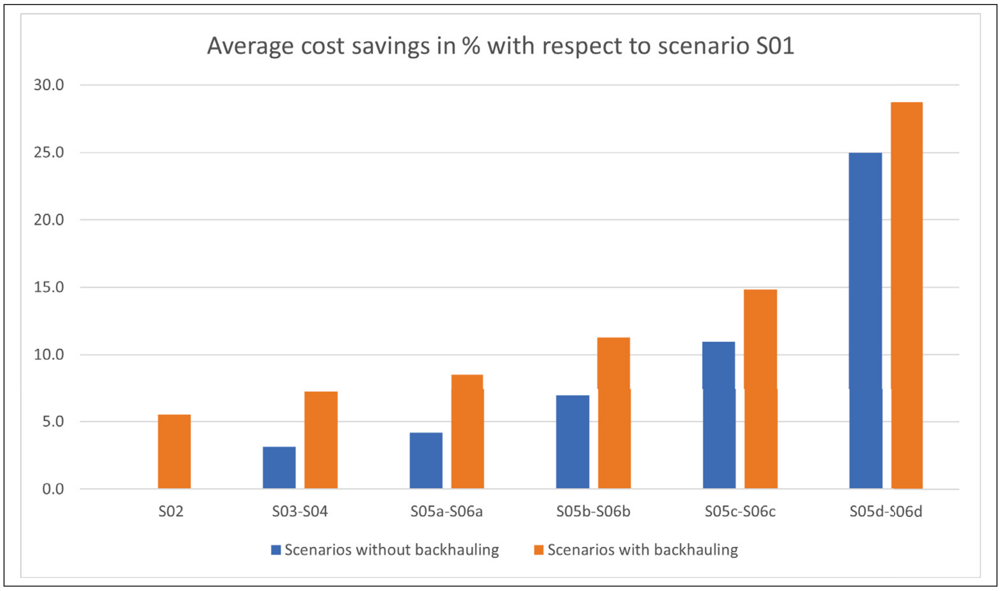

Figure 2.2 Average cost savings percentage for all instances and different scenarios

Within scenarios involving truck platooning, higher average transportation distances lead to higher cost savings. This effect is more noticeable particularly when the average transportation distances are longer than break-even distances. Therefore, truck platooning has better effects in larger network and longer transportation distances. This could be explained by the fact that higher loading and unloading times for truck platoons make them more efficient in longer distances. In scenario S05, this relation is higher compared to scenario S03, and in scenario S06, it is higher compared to scenario S04. The system would need to perform an extra loading and unloading at terminal nodes in scenarios S03 and S04 in order to utilize platoon trucks, and transportation distances would be greater.

2.6.2 Analysis of fuel consumption and number of drivers needed

In this study, the fuel consumption calculation is based on the number of kilometers of transportation multiplied by fuel consumption rate of the trucks (liters/km). The results in terms of fuel consumption are shown in Table 2.7. The first column shows the instance groups. The other columns show the fuel-saving in percentage of the different scenarios compared to scenario

S01 for each group of instances. The saving in fuel consumption in scenarios S02, S03, S04, S05, and S06 is due to lower transportation distances and the use of truck platoons. If we use truck platooning without backhauling (scenario S05) the maximum fuel savings would be 10% compared to scenario S01. The percentage is lower in scenario S03 with an average of 0.9% savings with respect to scenario S01. This is due to the fact that in order to use truck platoons in this scenario we need to first locate a terminal and transport materials by ordinary trucks to the terminal locations and then send the materials to mills by truck platoons. This leads to low usage of the number of truck platoons and higher transportation distances which further leads to higher fuel consumption. We can see that average fuel savings increases to 1.5%, 2.5%, 4.0%, and 9.4% in scenarios S05a, S05b, S05c, and S05d respectively.

Table 2.7 Fuel-saving results for each scenario compared to scenario S01 obtained for each instance group

Group	**Average fuel consumption savings % of each instance group in each scenario**										
	S02	**S03**	**S04**	**S05**				**S06**			
				a	**b**	**c**	**d**	**a**	**b**	**c**	**d**
1	6.5	0.2	6.8	1.6	3.0	4.8	9.7	7.0	9.3	10.4	18.2
2	6.4	0.3	6.8	1.4	2.6	4.7	9.6	7.0	8.0	9.8	15.1
3	10.1	1.2	10.5	1.7	3.1	5.4	9.8	11.7	13.0	14.0	19.0
4	2.8	0.3	2.9	1.8	2.0	3.4	9.5	4.7	4.6	5.8	12.6
5	4.4	1.8	5.1	2.4	3.4	4.6	10.0	6.1	6.6	7.8	13.9
6	7.2	1.5	8.0	1.0	2.3	4.0	9.6	7.6	8.9	9.9	16.5
7	5.8	0.6	6.2	0.8	1.6	2.9	8.7	5.9	6.5	7.5	14.4
8	3.6	0.7	4.1	1.5	2.0	2.9	8.8	4.5	4.9	5.8	13.2
9	8.2	1.1	8.4	0.9	2.3	3.2	8.9	9.1	10.3	11.1	17.6

The results of scenarios with backhauling is different. The fuel-saving of scenario S02 is 6.1% on average for all 27 instances, which is higher than scenarios S03 and S05a. This saving comes from lower transportation distances. In scenarios S04 and S06, the saving in fuel consumption comes from both lower transportation distances and lower fuel consumption of truck platoons.

The difference between S02 and S04 is 0.4% and again it is due to the fact that in scenario S04 truck platoons are limited to being used between terminal and mill nodes and therefore transportation distances are higher. The average savings compared to scenario S01 are 7.1%, 8.0%, 9.1%, and 15.6% in scenarios S06a, S06b, S06c, and S06d respectively.

In the transportation system, both platooning and backhauling affect the number of human drivers needed. The results in terms of number of drivers are shown in Table 2.8. The first column shows the instance groups. The other columns show the driver reduction in percentage of the different scenarios compared to scenario S01 for each group of instances. Using truck platooning without backhauling would reduce the number of drivers needed by an average of 11.1% in scenario S03. In comparison with scenario S01, in scenario S04, there is an average savings of 13.3% in number of drivers needed. When the number of mills delivered by truck platoon grows, we can observe that the average reductions in the number of drivers needed in scenarios S06a, S06b, S06c, and S06d, are 14.7%, 21.2%, 29.7%, and 58.9% respectively.

Table 2.8 Driver decrease results for each scenario compared to scenario S01 obtained for each instance group

Group	**Average reduction % in the number of drivers needed of each instance group in each scenario**										
	S02	**S03**	**S04**	**S05**				**S06**			
				a	**b**	**c**	**d**	**a**	**b**	**c**	**d**
1	5.4	2.0	5.4	12.5	21.8	30.3	57.6	15.7	25.1	31.2	59.3
2	5.1	8.1	9.4	11.7	18.9	32.7	58.0	14.3	22.1	33.5	59.8
3	8.8	16.2	18.1	14.2	23.6	35.2	58.5	19.1	28.6	39.8	61.6
4	2.4	5.5	10.0	13.1	17.9	24.8	56.4	11.8	15.8	27.7	57.5
5	3.8	19.6	21.3	17.7	23.1	31.0	58.8	18.5	24.0	31.9	60.1
6	6.2	13.8	17.5	7.8	14.5	24.5	57.4	13.2	19.6	28.9	59.8
7	4.3	10.3	11.9	11.3	15.3	20.8	55.0	11.7	17.6	23.6	56.3
8	2.9	13.1	13.7	11.4	14.5	21.9	56.0	13.9	16.4	23.9	57.0
9	7.4	11.2	12.7	10.4	18.3	22.9	57.0	14.6	21.7	27.0	59.3

The situation differs for scenarios that involve backhauling. The reduction in the the number of drivers needed in scenario S02 (results from shorter transportation distances) is higher than the reductions achieved in scenarios S03 and S05a. The lower number of drivers needed in scenarios S04 and S06 compared to scenario S02 is due to both shorter travel distances and lower number of drivers needed in truck platoons. As a result of shorter travel distances, driving hours are reduced, which in turn reduces the number of drivers needed.

2.6.3 Sensitivity analysis

We perform a sensitivity analysis to investigate how truck platooning fixed costs affect their cost-effectiveness in the transportation network as illustrated in Figure 2.3. This analysis is conducted on instance I01 in scenarios S04, S06a, S06b, S06c, and S06d in which we use truck platooning with backhauling in the transportation. The horizontal axis represents the increased percentage in truck platooning fixed cost parameter and the vertical axis shows the total resulting transportation cost in different scenarios. Optimal cost in scenario S02 is 12.7 million CAD. The first column of the graph has a value of 0, which shows the fixed cost with no increase. In the following columns, the fixed cost for a platoon truck is increased by 10%, 20%, 30%, 40%, 50%, and in the final column, this cost is doubled. As the platooning fixed cost increases, the transportation cost increases and at some point (depending on the scenario) truck platoons are no longer used in the optimal solutions due to their higher fixed cost.

For example in scenario S04, more than 30% increase in truck platooning fixed cost results in using only ordinary trucks in the optimal solution. This happens in scenario S06 and its sub-scenarios from about 110%. As a result, when we increase the truck platooning fixed cost of instance I01 in scenarios S04, and S06 by more than mentioned percentages (30% and more than 110%) the optimal cost is equal to 12.7 million CAD which is the optimal cost of scenario S02.

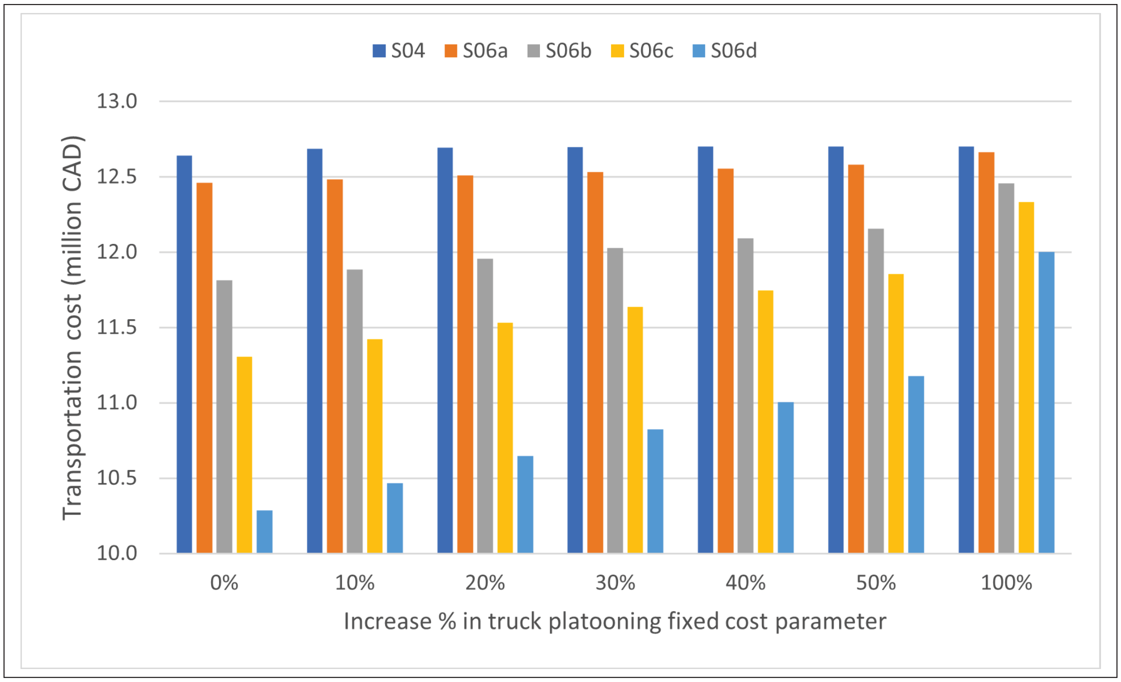

Figure 2.3 Sensitivity analysis for fixed cost of platoon trucks (based on instance I01) in scenarios S04, S06a, S06b, S06c, and S06d

2.6.4 Discussion

This study focused on truck platooning transportation integrated with ordinary trucks in the upstream forest supply chain. Different scenarios reflecting progressive integration of truck platooning in the transportation network have been analyzed. In scenarios S01 and S02, we have considered only ordinary trucks with direct and backhauling transportation. Scenarios S03 and S04 include truck platooning transportation, but we consider truck platoons only between mills and terminals for transporting products. Finally, in scenarios S05 and S06, we allow the truck platoons to visit one forest area (S05a, S06a), three forest areas (S05b, S06b), five forest areas (S05c, S06c), and all forest areas (S05d, S06d).

Three main factors affect the results. The first factor is the average used transportation distance between the nodes. More dense networks would use less truck platooning because in those cases the average distance is less than the break-even distance. This is observed in the results of scenarios S03 to S06. For example, if the average distances between nodes increase, using truck platooning becomes more efficient. The loading and unloading process for platoon systems leads to more waiting time because each truck has to wait until all the trucks in the platoon complete their loading/unloading operation before they start their transportation conjointly. For instance, if it takes 20 minutes to load/unload an ordinary truck, it will take one hour (3×20 minutes = 60 minutes) for a platoon of three trucks to load/unload.

Therefore, using truck platoons for small distances would not be very efficient and cannot make much more savings in comparison to scenario S02. The lowest cost savings for scenario S03 are obtained in instances with an average distance lower than the break-even distance.

The second factor that affects the results is backhauling for ordinary and platoon trucks in the transportation network. According to the literature, backhauling in forest transportation typically results in cost savings of between 2%-20% (Carlsson and Rönnqvist, 2007; Frisk et al., 2010), which are consistent with our results for scenario S02. In all the instances, the optimal cost for scenario S02 is lower than scenario S01, by 0.84% to 11.17%, and the optimal cost for scenario S03 is lower than scenario S01, between 0.22% and 7.47%. The product destinations in scenarios S02 and S04 may differ from scenarios S01 and S03. The number of backhauls highly depends on the number of origins and destination nodes and their locations and also the number of products and their amounts in the transportation network. Furthermore, the cost structure of the backhauls is important. In the literature, backhaul savings in some cases are defined on distances, while in others, for example, the savings are specifically defined based on a rebate for a distance reduced. Our calculation of the backhauling cost is based on the distance between the nodes without considering rebates.

The advantage of backhauling is that it allows covering a longer distance while keeping the total loaded and empty transportation at a lower level. Overall transportation distances decrease when backhauling is used. Backhauling could add from 0.5% to 9.2% cost savings to truck platooning depending on the scenarios and the instances. In the scenarios where there are only ordinary trucks or all truck types could visit all the nodes, finding efficient backhauls are easier. In this study, in scenarios where truck platoons could not transport products from all forest area nodes, there is a limitation on the number of efficient backhauls that could be used by truck platoons.

In studies that reported on tactical truck platooning transportation planning, cost savings are in the range of 9%-17% (Scherr et al., 2018) and 2%-20% (Scherr et al., 2019). These studies determined the number and mix of autonomous and manual vehicles, as well as the flows of the products across the network in the context of two-tier city logistics network. While manual vehicles are allowed to drive anywhere in a network in these studies, autonomous vehicles are only allowed to drive in autonomous vehicle zones, which may cover specific streets or areas in the city network. Using platooning, autonomous vehicles could follow manual vehicles to leave these zones, but in these studies, the limitation is in a district called the automated regions, in our study, the limitation concerns the number of forest areas that could be visited by the platoon trucks (ranging from zero to all forest areas).

The third factor that affects the results is the level of accessibility of the platoon trucks to the forest areas. In all the instances, the optimal cost for scenarios S05 and S06 decreases significantly by allowing more forest areas to be visited by the platoon trucks. The cost savings results could increase by more than 20% in these scenarios. The effect of backhauling could lead to an additional 5% cost savings in S06 with respect to S05 on average.

Based on the results, on average, scenario S02 leads to higher cost savings than scenario S03. This shows that if truck platoons use is limited between terminals and mills, in general the effect of these trucks in only direct transportation is lower than ordinary trucks with backhauling. It is more beneficial to combine truck platooning transportation with backhauling in scenarios with limited truck platooning transport only between terminals and mills. If truck platoons are allowed to transport through forest areas, the situation changes and truck platoons become more cost-efficient. To summarize, the percentage of platooning cost savings depends on three main factors:

- Average used transportation distances between nodes in the network.

Results show that a network with larger average transportation distances between nodes leads to more cost savings over one-year horizon.

- Backhauling opportunities.

  Truck platooning and backhauling together enhance the efficiency of the transportation system. Also, the location of terminal nodes affects the backhauling opportunities for ordinary and platoon trucks.

- Number of forest areas allowed to be visited by platoon trucks.

  The transportation network is more cost-effective if platoon trucks could travel to more forest areas.

Truck platooning would reduce the number of drivers needed by an average of between 11.1% (in scenario S03) to 58.9% (in scenario S06d). The percentages vary depending on the scenarios. This results from the lower number of drivers needed in truck platoons and also shorter travel distances resulting from backhauling. The number of drivers needed decreases if truck platoons are able to transport products from a larger number of forest areas.

As for fuel savings, the results show that in scenarios with truck platooning without backhauling the average savings range between 0.8% (in scenario S03) and 10% (in scenario S05d). Low transportation distances and the use of truck platoons result in lower fuel consumption in scenarios with truck platoons and backhauling. These scenarios save between 6.2% (in scenario S04) and 15.6% (in scenario S06d) on average compared to scenario S01. The fuel savings are higher if more forest areas could be visited by truck platoons in the transportation network.

The model and scenarios investigated in this study could be used in different decision-making situations. The first one is before implementing truck platooning technology by determining whether it could reduce total transportation costs, fuel consumption, and the number of drivers required when it is combined with ordinary trucks and how many of each type are needed. In addition, it shows how the transportation network could benefit from the gradual integration of nodes that can be visited by the platoon trucks (i.e., forest areas). Furthermore, the model could be used as a planning tool once the technology is implemented.

We assumed the platooning technology costs and the purchasing rebates cancel out, leaving the cost for a platoon truck equal to the cost for an ordinary truck. It would result in fewer platoon trucks being used in the case where truck platooning fixed costs are higher. Our sensitivity analysis revealed that using platoon trucks could have cost benefits even with higher fixed cost from 30% to more than 170% depending on the scenario.

2.7 Conclusions and future work

Recently, with the advent of the Fourth Industrial Revolution, integrated, connected, and autonomous systems such as truck platoons are expected to be used in transportation in various industrial sectors. For instance in the forestry sector, in order to reduce transportation costs, fuel consumption and contribute to addressing driver shortage issue, transportation companies are currently considering using truck platooning to enhance their transportation system.

In previous optimization studies of truck platooning transportation, the operational planning problem was investigated, including platoon formation, scheduling, and routing. But strategic and tactical planning has not been studied sufficiently. Our work contributes to addressing this gap. More precisely, this study examined truck platooning gradual integration into forest transportation networks with the objectives of reducing fuel consumption, the number of human drivers required, and total transportation costs.

By analysing different scenarios, we could determine the factors that impact most cost savings. The results show that combining ordinary and platoon trucks and also using backhauling leads to substantial savings in the transportation system over a one-year planning horizon. On average 5.4% cost savings can be achieved by using backhauling, 3.1% by using a combination of ordinary and platoon trucks in direct routes, and 7.2% by integrating both truck platoons and backhauling. When truck platooning transportation is allowed in forest areas, savings could reach more than 20%. Additionally, the results show that, on average, truck platooning could lead to 1%-10% lower fuel consumption compared to the base scenario and with backhauling the fuel consumption savings could reach 19%. Our results show that on average truck platooning could lead to from 3% to more than 30% lower human drivers if the technology is used with backhauling.

When there is a long distance between the origin and destination nodes, truck platooning becomes very efficient. Terminals considered in this study do not perform sorting operations, so to increase the efficiency of the transportation system, one way could be by having instead sorting yards near forest areas. Considering sorting and storage operations could be a relevant research direction to analyze how truck platooning can reduce costs in these situations.

Finally, in the case where the transportation fleets belong to multiple companies, it could be interesting to examine how to share the cost savings or benefits between them. There are many models on cost sharing in the literature, but truck platooning has some specifics like fuel and driver savings which make this problem interesting to study.

CHAPTER 3

COLLABORATION BETWEEN CARRIER COMPANIES USING TRUCK PLATOONING: AN APPLICATION IN THE FORESTRY INDUSTRY

Saba Gazran[1,2,3] , Tasseda Boukherroub[1,2,3] , Mikael Rönnqvist[2,3,4]

[1] Department of Systems Engineering & Numerix Laboratory, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, QC, Canada H3C 1K3
[2] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT),
Université de Montréal, Pavillon André-Aisenstadt, CIRRELT, CP 6128, Succursale Centre-ville Montréal, QC, H3C 3J7, Canada
[3] FORAC Consortium,
1065, av. de la Médecine, Université Laval, Québec, QC, G1V 0A6, Canada
[4] Département de Génie Mécanique,
1065, av. de la Médecine, local 1504, Université Laval, Québec, QC, G1V 0A6, Canada

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Abstract

This study explores collaboration between different carrier companies where at least one is equipped with hybrid truck platooning technology (one driver operates a platoon of trucks). Collaboration could help carrier companies share resources and reduce costs. First, a tactical transportation planning problem is formulated as a Mixed-Integer Linear Programming (MILP) model. Using a mix of ordinary and platoon trucks for collaboration, this model aims to minimize transportation costs. The decisions to be made include choosing direct and backhaul routes for both types of trucks in the transportation network and potential terminal nodes to activate. The results show that using truck platooning in collaboration could lead to cost savings ranging between 0.5% and 19% (compared to only using ordinary trucks) depending on the level of collaboration and coverage between the transportation networks of the companies involved. Second, we study the cost-sharing problem to ensure fair cost-saving allocation between the companies. We compare the results of four cost-sharing methods used in a two-step cost allocation process. The first step allocates the cost savings obtained from collaboration using only ordinary trucks. The second step allocates additional cost savings due to platoon trucks. The results show the Shapley value method produces the best allocations.

Keywords: Truck platooning; transportation planning; collaboration; cost allocation; forest industry; cooperative game theory

3.1 Introduction

Transportation plays an essential role in the economic development of various industries around the world. For many companies, transportation significantly impacts their competitive advantage. However, the transportation sector is facing important issues such as high costs and negative environmental impacts (e.g., high GHG emissions). For example, regarding costs, in the forestry sector in countries such as Canada and Sweden, transportation costs account for about one-third of raw material costs (Frisk et al., 2010). Different approaches could be used to enhance the efficiency of transportation, such as information sharing between companies, optimization, collaboration, and the deployment of electric, connected and autonomous vehicles (Porter et al., 2015; Speranza, 2018). As an example, optimizing transportation planning could reduce the need for trucks and drivers which leads to reduced costs and GHG emissions (less fuel consumption) (Gazran et al., 2023).

In the near future, semi-autonomous, autonomous, and virtually connected trucks are expected to be on the road as a result of recent technological advancements. Indeed, throughout the world, Industry 4.0 is leading to a shift toward more connected, autonomous, and integrated systems (Alessandra et al., 2018). Vehicle automation consists of five levels, starting with no automation (Level 0) to fully autonomous vehicles (Level 5) (United States Department of Transportation, National Highway Traffic Safety Administration, 2016). In connected vehicle systems, individual vehicles interact with other vehicles and with surrounding infrastructures (Mahmassani, 2016). Truck platooning technology is one of these autonomous and connected vehicle systems.

Truck platooning refers to a group of virtually connected trucks moving closely behind each other, assisted by an automated technology. Truck platooning offers advantages including lower transportation costs and fuel consumption, and reduced reliance on human drivers (Maiti et al., 2017). According to Bhoopalam et al. (2018), there are three types of truck platooning based on the level of automation: human-driven platooning, hybrid platooning, and driverless platooning. The first one is the case when drivers are present at every vehicle in the platoon, in the second type, only the first truck has a driver and in the third one, none of the vehicles has a driver.

Collaboration is another opportunity that could enhance transportation efficiency. There are two main approaches: vertical and horizontal collaboration (Mason et al., 2007). Vertical collaboration occurs between members of the same supply chain at different levels such as collaboration between suppliers, manufacturers, distributors, and retailers. Horizontal collaboration occurs between partners or competitors at similar levels (e.g., product transportation) but operating in different supply chains. Collaboration in transportation can lead to lower loaded and empty transportation distances and therefore to reduced costs. Collaboration creates efficiencies through information and resource sharing, costs could be decreased as well as service level and market share could be increased (Audy et al., 2012).

Collaborating companies can make their transportation operations more efficient, for instance, by planning routes together, sharing capacity, or exchanging orders (order sharing) (Verdonck et al., 2013). Changing the origins or destinations of product transportation could provide cost-saving opportunities as well. As an example, if a supply node of a company is closer to a demand node of another company and vice versa, swapping the destinations could lower transportation distances. Collaboration benefits carriers the most when their customers are concentrated rather than geographically distributed, and when their vehicles must travel long distances (Fernández et al., 2016). When implementing collaboration between companies, establishing a fair distribution of the resulting benefits/costs between them is one of the biggest challenges (Basso et al., 2019) since an unfair distribution of costs or benefits could prevent companies from entering the collaboration.

Since owning resources requires a substantial capital investment (e.g., vehicles), and idling them is expensive, companies collaborate and build coalitions to share those resources and the required investments (Agarwal and Ergun, 2010). In this regard considering collaboration between companies willing to invest in truck platooning could be an effective strategy to share the investment costs. Indeed, although platooning offers many benefits, it may require substantial investments. In addition, truck platooning will likely become an important step toward fully automated trucks in the future (Bouchery et al., 2022). Therefore multiple businesses involved in truck platooning logistics operations, such as individual truck owners or companies, could benefit from working together. Furthermore, platooning advantages could be effectively achieved if multiple companies with or without platooning technology collaborate effectively to utilize their resources. Transportation planning and cost/benefit sharing between different parties need to be investigated in this context to make sure that the collaboration is beneficial and viable for all of them.

This study contributes to the literature on collaborative transportation planning where ordinary and platoon trucks are both used in the transportation network. Through sharing resources (i.e., trucks and terminals) and order exchange, this study seeks to evaluate the collaboration benefits (i.e., cost savings) when truck platoons are introduced in the transportation network and recommends the best cost-sharing methods in this context. We modify the Mixed-Integer Linear Program (MILP) model proposed in (Gazran et al., 2023). This new model considers collaboration between a set of companies of which at least one uses truck platoons. The model is formulated in the context of forest product transportation in the upstream supply chain. The model's results are used to identify the cost savings resulting from collaboration when using or not truck platoons in the transportation network. Four allocation methods are then considered to determine how the cost savings made could be shared between the different companies involved in the collaboration. We design a two-step allocation process for sharing the cost savings with and without platooning in separate steps. First, the cost savings obtained when only using ordinary trucks, and second, the additional cost savings obtained due to platoon trucks.

The tactical transportation optimization model proposed by Gazran et al. (2023) is modified to determine the minimum (optimal) total transportation cost when different companies form a coalition and collaborate. The four allocation methods studied are proportional allocations

(Guajardo et al., 2016), the Shapley value (Shapley, 1997), the Alternative Cost Avoided Method (ACAM) (Tijs and Driessen, 1986), and the Equal Profit Method (EPM) (Frisk et al., 2010). We evaluate the results of the collaborative transportation model and the cost-sharing methods based on a set of generated instances (based on the characteristics of transportation in the forestry sector in the province of Quebec, Canada).

The remainder of this article is organized as follows: Section 3.2 presents a brief literature review. In Section 3.3, the research problem is described. Section 3.4 formulates the problem of collaborative transportation planning where both ordinary and truck platoons are used and presents the four cost allocation methods as well as the two-step allocation process mentioned above. Section 3.5 presents our case study instances used to solve the optimization model. Section 3.6 presents results and a discussion. Section 3.7 summarizes our conclusions.

3.2 Literature review

Transportation planning using truck platoons is a relatively new research area. This problem is being investigated in the literature at the strategic, tactical, and operational levels. The majority of studies have focused on the operational level. Larson et al. (2013) studied truck platoon scheduling with routing decisions. This work was among the first publications in this research area. Since then, a variety of aspects have been investigated in the literature such as the maximum length of a detour for platoon formation (Larson et al., 2016), truck scheduling (Zhang et al., 2017; Abdolmaleki et al., 2021), and platoon formation planning (Noruzoliaee et al., 2021a; Larsen et al., 2019). Some studies focused on tactical and strategic levels such as service network design (Scherr et al., 2019, 2020) and locating facilities in which platoons can be formed (Watanabe et al., 2021). Gazran et al. (2023) proposed an optimization model to integrate hybrid platoon trucks with ordinary trucks in the upstream forest supply chain.

Recently, the number of studies on collaborative transportation has grown significantly (Guajardo et al., 2016). Guajardo and Rönnqvist (2016) provided a review on cost-sharing methods in the context of collaboration in freight transportation. Gansterer and Hartl (2018) surveyed collaborative vehicle routing and related optimization models. Basso et al. (2019) investigated challenges encountered in implementing horizontal collaboration in practice. Pan et al. (2019) surveyed horizontal collaboration in freight transportation and implementation issues. Aloui et al. (2021) reviewed studies that considered sustainability aspects through horizontal collaboration in freight transportation.

Collaborative transportation is investigated in vast areas of application. In the forestry sector, Frisk et al. (2010) examined how eight forest companies collaborated to obtain more efficient truckload shipments through resource sharing, change of destinations, and backhauling. Audy et al. (2011) studied collaboration between four Canadian wood furniture manufacturers. The authors conducted a sensitivity analysis of the cost reductions required to persuade companies to join the coalition using a cost-allocation method. The authors proposed a new method combining ACAM and EPM. Through locating distribution centers across two-echelon networks, Verdonck et al. (2016) examined the economic benefits of horizontal collaboration between companies. They also investigated cost allocation methods including the Shapley value method, EPM, and ACAM to share costs among companies.

We found a few papers that study collaboration and cost-sharing problems in a transportation network using truck platooning. Johansson et al. (2018) investigated the problem of platoon matching (i.e., during platoon formation, vehicles are divided into smaller groups and then grouped into platoons) by considering a group of trucks with different destinations but the same starting point. Different fleet owners operate the vehicles, and their communication is modeled as non-cooperative games where the actions of the vehicles are their departure times. The authors demonstrate that this game has a Nash equilibrium (Facchinei and Kanzow, 2010), and propose an algorithm for determining it. Sun and Yin (2021a) designed a mechanism for sharing profits among the trucks (drivers) of a platoon based on an auction process that specifies leader-follower positioning and benefits. The vehicle types are the same, but the willingness to pay for less driving time differs among participants. In another study, a multi-agent system is proposed by Sun and Yin (2021b) that accounts for differences in fuel savings between the platoon vehicles. In this study, a decentralized platooning system is proposed for vehicles with multiple brands and different drivers. A dynamic platoon formation process is used in this decentralized system, as opposed to the previous study which used a central controller to form platoons all at once.

By using hubs to form truck platoons, Johansson et al. (2021a) examined multi-fleet platoon planning in transport networks with fixed routes and a waiting time cost at the hubs. Trucks could stop and wait at hubs to form platoons with others. Each hub has a coordinator responsible for planning departure times and platoon members for arriving trucks. When platoons are formed within fleets, they can increase profits by reducing fuel consumption. To calculate fleet profit, platooning benefits and waiting time at hubs are included. Bouchery et al. (2022) studied two problems related to truck platooning transportation planning. They studied platoon formation optimization and formulated an optimization problem that has similarities with lot-sizing models. They proposed exact (Dynamic Programming) and approximate solutions. They applied cooperative game theory including the Shapley value and an approximation game (the game that is defined by approximate characteristic functions) to share the cost between the participants.

We conclude that the literature on collaborative truck platoon transportation planning and cost-sharing presents some gaps. First, one area that has not been studied is the integration of platoon trucks with ordinary trucks in the transportation network at the strategic and tactical planning level, particularly in the context of collaboration between different carriers (horizontal collaboration). Second, the hybrid type of truck platooning where the platoon of trucks has only one driver is not investigated in collaborative transportation planning and cost-sharing approaches have not been studied in this type of platooning. Hybrid truck platooning has a different cost structure compared to with-driver platooning. The with-driver type can reduce fuel consumption and costs while the hybrid type can also address issues related to driver shortage and reduce further transportation costs (driver costs). The loading and unloading operations for these types of trucks might also differ. For example, in hybrid platooning, since only the first truck has a driver, the driver needs to wait until all trucks are loaded or unloaded before moving, whereas in with-driver platooning, trucks could move after loading/unloading or join together afterward. Furthermore, to the best of our knowledge, no studies exist in the literature addressing the problems of collaborative transportation planning using truck platoons and cost-sharing in forestry.

3.3 Problem description

Forest supply chain planning involves many processes, including the transportation of raw materials. In upstream forest supply chains, roundwood is picked up from supply nodes (forest areas) and shipped to demand nodes (mills). The transportation network can also include terminal nodes where products are stored or sorted and transshipped to consumer mills. Due to the poor quality of the roads in forest areas, trucks have to spend more time and consume more fuel for transporting the products in the forest areas. Generally in upstream forest transportation, trucks move loaded from one node to another and return empty to the origin. Using a backhaul route that combines two direct routes can decrease the unloaded distances (Carlsson and Rönnqvist, 2007) and therefore, reduce the costs.

The terminals in this study are used as transshipment points for truck platoons if they are unable to operate in forest areas. Indeed, truck platooning opportunities will likely be limited in forest areas during the early phases of implementing truck platooning technology, then gradually expand to other areas as the technology becomes more widespread. Therefore, the following two cases are considered for truck platoons: first loading the trucks at terminals if forest areas cannot be accessed by truck platoons; and second, transporting forest products directly to mills when truck platoons are able to access forest areas. Companies willing to use truck platoons can purchase the platooning technology and equip their fleet with it. The company can convert all or a part of ordinary trucks into platoon trucks or use them separately. By investing in platooning technology, the company will have the same transportation capacity and number of trucks.

This study aims to minimize transportation costs and determine the best cost-saving allocations through the use of truck platooning and establishing collaboration between different carriers. We consider horizontal collaboration between carriers where the companies jointly use their vehicles and terminal nodes and can exchange their transportation orders and deliver to different destinations in the transportation network depending on the level of collaboration. We consider the case where multiple carrier companies operate independently in their own supply chains. Each supply chain includes supply, demand, and potential terminal nodes and each carrier owns a specified number of trucks. We assume that a subset of companies (at least one) are willing to invest in platooning technology such that they can convert their trucks into truck platoons. The carrier companies intend to collaborate to reduce their transportation costs. We consider that collaborative transportation plans are made jointly by all companies. Our study aims to address the following two questions:

1. How does horizontal collaboration affect transportation efficiency in the context of ordinary and platoon trucks?
2. How should the transportation costs be shared among collaborating companies when cost savings result from the use of ordinary and platoon trucks?

Regarding the first question, we propose a tactical transportation planning model taking into account the use of ordinary and platoon trucks, direct and backhaul routes, and collaboration between companies. The companies operate with the objective of reducing their overall costs as a result of their collaboration. Collaborating companies need to decide which terminals to use and what product flow allocation to different parts of the transportation network on direct and backhaul routes using ordinary and platoon trucks. The focus here is to quantify the benefits (cost savings) of collaboration resulting from resource sharing (including truck platoons) and changing transportation destinations between different companies. Since the companies focus on reducing their overall costs through collaboration, cost savings represent the benefit of collaboration. To answer the second question, we evaluate different methods for allocating costs among the collaborating companies and propose a two-step allocation process that considers cost savings resulting from using only ordinary trucks, and additional cost savings resulting from using truck platooning.

In collaborative transportation planning, decisions to be made are: among the potential terminals, which ones should be used in the transportation network (in case terminals are required)? Which type of truck should be used to transport which quantity of products in each part of the network on direct and backhaul routes? Also, we want to evaluate the impact of different scenarios defined by the level of collaboration and the number of accessible forest areas for truck platoons on the total transportation cost.

Our assumptions are as follows:

- We only consider one period in the planning horizon (e.g., one year).
- The decisions are made jointly by all companies.
- During the planning horizon, there are enough trucks available for each company to handle their product transportation when working alone, and the number of trucks for each company remains the same when they join the collaboration.
- A platoon of trucks once formed, cannot be split during transportation and requires only one driver for all the trucks in the platoon (hybrid platooning type).
- During the planning horizon, each company has a specific assigned supply, demand, potential terminal nodes, and trucks.
- Inflow capacity at the potential terminal nodes is limited.
- Each supply and demand node in the planning horizon has a predetermined supply and demand amount for each product type (e.g., saw logs and pulp logs).
- Ordinary trucks could transport products in all parts of the transportation network whereas platoon trucks can operate in only parts or in all parts of the transportation network depending on the number of forest areas they could access.
- The variable transportation cost is calculated as the sum of fuel and driver costs on the direct and backhaul routes.
- We consider a fixed cost for purchasing platooning technology for each truck in the planning horizon. By dividing the fixed cost by the number of operating hours of the trucks in the planning horizon we calculate the variable technology cost per hour for the truck platoons. This means that there are no fixed costs in the mathematical model other than those related to opening the terminals.

Collaboration types considered

Three different collaboration types are considered:

(i) **Non-collaboration transportation planning**, in which each company makes its own decisions (each company solves its transportation planning problem within its supply chain). In this collaboration type, carriers in different supply chains work separately and do not share anything.

(ii) **Semi-collaboration transportation planning**, in which transportation planning decisions are jointly made (trucks and terminals are shared and companies are involved in joint transportation planning). In this collaboration type, products from all origin nodes belonging to a carrier's supply chain to all destination nodes belonging to the same supply chain can be supplied by all carrier companies. In addition, the carriers can share their terminals. The savings are obtained from backhauling and truck platooning.

(iii) **Full-collaboration transportation planning**, where the transportation plan is jointly made and orders are also shared. In this collaboration type, all products from all origin nodes to all destination nodes can be supplied by more than one carrier. In the full-collaboration type, there is the possibility to exchange order destinations between carriers. This method is also called wood bartering since it changes destinations between supply and demand nodes is allowed. The savings are obtained from changing the destinations of the products (it could lead to reductions in loaded transportation distances), backhauling, and integrating truck platoons with ordinary trucks. Full-collaboration transportation planning is studied in works such as (Frisk et al., 2010).

Figures 3.1a, 3.1b and 3.1c illustrate the product flow in three supply chains (green, red, and blue) in non-collaboration, semi-collaboration, and full-collaboration types respectively. Circles and squares represent supply and demand nodes respectively. An arrow shows that there exists a product flow from a supply node to a demand node. Each color is assigned to a carrier company. The non-collaboration type only allows products to be transported from supply to demand nodes of a given supply chain using the vehicles of the carrier operating in that supply chain. It is possible to transport products from supply to demand nodes in the same supply chain using vehicles of any carrier in the semi-collaboration type. In the full-collaboration type, all vehicles could carry the products between any supply node and any demand node in the transportation network.

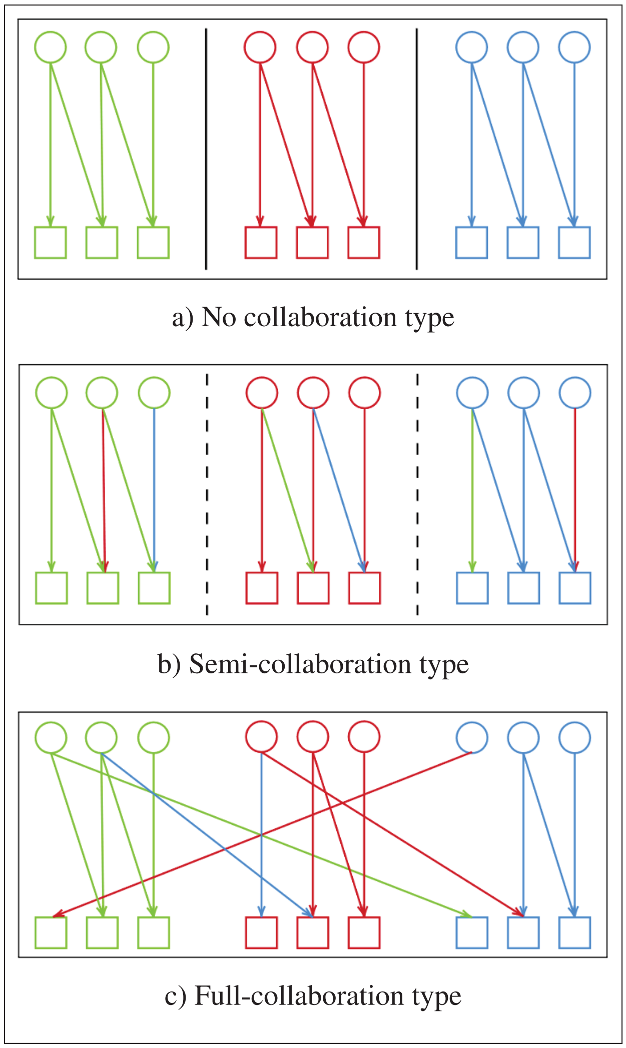


Figure 3.1 An illustration of product flows in different collaboration types

Figures 3.2a, 3.2b and 3.2c show an example of loaded and empty transportation flows in non-, semi-, and full-collaboration types respectively. Circles and squares represent supply and demand nodes respectively. Each color is assigned to a carrier company. In these figures, solid and dashed lines show loaded and empty transportation flows respectively. It can be seen that empty transportation distances are lower in the semi-collaboration type compared to the no-collaboration type. For instance, in the no-collaboration type transportation between supply and demand nodes 4 (blue company), 5 (green company), and 6 (blue company) is done on direct routes by trucks owned by each company. In the semi-collaboration type, a backhaul route is created between supply and demand nodes 4 and 5 (transported by trucks of the red company) which leads to lower empty transportation distances compared to the no-collaboration type. In the full collaboration type, since the destinations of transportation could be swapped between the companies, there are three direct routes between supply and demand nodes 4 (transported by trucks of the red company), supply node 5, and demand node 6 (transported by trucks of the blue company) and supply node 5, and also demand node 5 (transported by trucks of the blue company). These transportations lead to lower empty and loaded transportation distances compared to the two other types.

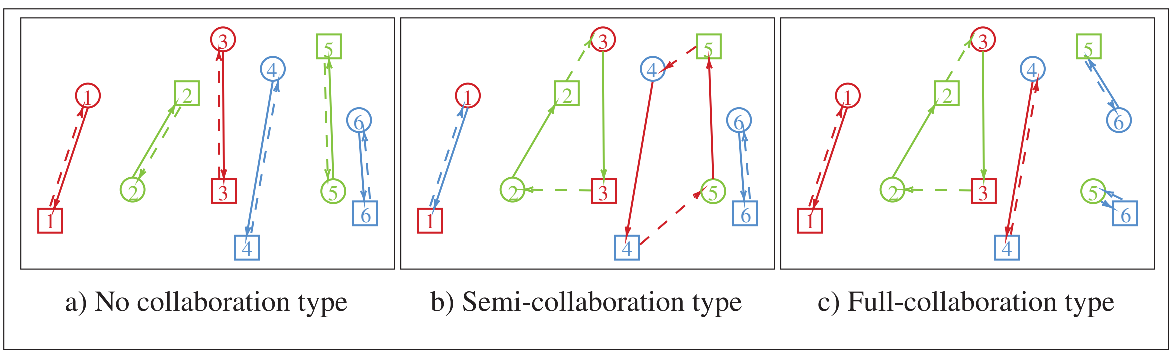


Figure 3.2 An example of loaded and empty transportation in different collaboration types

3.4 Problem formulation

This section presents mathematical formulations of the problem of collaborative transportation planning (subsection 3.4.1) and the problem of cost-sharing (subsection 3.4.2).

3.4.1 Mathematical formulation of the collaborative transportation planning problem

The mathematical model proposed in this study (collaboration model) is adapted from the model proposed by Gazran et al. (2023) in which the objective function minimizes the total cost including the variable transportation cost and vehicles and terminal fixed cost. In the collaboration model, we consider variable transportation and technology costs as well as the terminal location fixed cost. Moreover, we consider platooning technology cost as a variable cost that is dependent on how much they are used in the planning horizon. The objective is to minimize total fixed and variable costs. The fixed costs include costs related to terminal opening. Variable costs consist of transportation costs between forest areas, terminals, and mills on direct and backhaul routes using ordinary and platoon trucks and technology costs required to convert ordinary trucks into platoon trucks. While Gazran et al. (2023) considered the number of ordinary and platoon trucks as decision variables, this model considers them as parameters.

In the definition of sets, parameters, and variables, we use the letters A and B to refer to direct and backhaul routes, respectively. Moreover, we use the letters O and L to refer to routes that could be used by ordinary and platoon trucks, respectively. In the following, we describe the sets, parameters, decision variables, constraints, and objective function of the mathematical model:

Sets

J: set of companies involved in the collaboration.

J_1: set of companies involved in the collaboration with ordinary and platoon truck fleets.

J_2: set of companies involved in the collaboration with only ordinary truck fleets.

F: set of supply nodes (forest areas) belonging to different companies.

S: set of potential terminal nodes belonging to different companies.

M: set of demand nodes (mills) belonging to different companies.

N: set of all nodes belonging to different companies.

E: all edges between the nodes of different companies.

$G = (N, E)$: graph of the network.

P: all product types

R_O: all direct routes for ordinary trucks for different product types.

$R_O = \{\{i, i', p, j\} : i, i' \in N, i \neq i', p \in P, j \in J\}$.

B_O: all direct routes for platoon trucks for different product types.

$B_O = \left\{\left\{i_1, i_1', p_1, i_2, i_2', p_2, j\right\} : i_1, i_2, i_1', i_2' \in N, p_1, p_2 \in P, j \in J\right\}$.

R_L: all backhaul routes for ordinary trucks for different product types.

$R_L = \{\{i, i', p, j\} : i, i' \in N, i \neq i', p \in P, j \in J_1\}$.

B_L: all backhaul routes for ordinary trucks for different product types.

$B_L = \left\{\left\{i_1, i_1', p_1, i_2, i_2', p_2, j\right\} : i_1, i_2, i_1', i_2' \in N, p_1, p_2 \in P, j \in J_1\right\}$.

R_{O_j}, R_{L_j}: all direct routes used by ordinary and platoon trucks of company j.

B_{O_j}, B_{L_j}: all backhaul routes used by ordinary and platoon trucks of company j.

$R_{O_{ip}}$,$R_{L_{ip}}$: all direct routes passing node i carrying product p by ordinary and platoon trucks.

$B_{O_{ip}}$,$B_{L_{ip}}$: all backhaul routes passing node i carrying product p by ordinary and platoon trucks.

$R_{O_i'}, R_{L_i'}$: all direct routes that deliver products to node i by ordinary and platoon trucks.

$B_{O_i'}, B_{L_i'}$: all backhaul routes that deliver products to node i by ordinary and platoon trucks.

Parameters

Following is a list of parameters used in the model.

T: planning horizon (weeks).

f_s: costs associated with opening each terminal s (in case that cost is in Canadian dollars (CAD)).

q_s : inflow capacity (tons) of terminal s.

f^P: variable cost of platooning technology for a truck (in case that cost is in $\frac{CAD\$}{hour}$). It is based on the total fixed cost for one planning horizon divided by the hours available in the planning horizon.

g_{fp} : supply quantity (tons) of forest node f for product p.

d_{mp} : demand quantity (tons) of mill m for product p.

n_j^V: total number of trucks (ordinary and platooning) belonging to company j.

c_r^{AO}: cost of direct transport (route r) for ordinary trucks in Canadian dollars (in case that cost is in CAD).

c_r^{BO} : cost of backhaul transport (route r) for ordinary trucks in Canadian dollars (in case that cost is in CAD).

c_r^{AL}: cost of direct transport (route r) for platoon trucks in Canadian dollars (in case that cost is in CAD).

c_r^{BL}: cost of backhaul transport (route r) for platoon trucks in Canadian dollars (in case that cost is in CAD).

e_r^{AO}: transport time for one ton by an ordinary truck using a direct route r.

e_r^{BO}: transport time for one ton by an ordinary truck using a backhaul route r.

e_r^{AL}: transport time for one ton by a truck platoon using a direct route r.

e_r^{BL}: transport time for one ton by a truck platoon using a backhaul route r.

h_j : hours available for a truck of company j in the planning horizon.

w: the truck's load capacity (tons).

w^{DO}: hourly driver cost for an ordinary truck (in case that cost is in CAD).

w^{DL}: hourly driver cost for a platoon of n trucks (in case that cost is in CAD).

t_r^{AO}: total transportation time (hours) on direct route r using ordinary trucks.

t_r^{AL}: total transportation time (hours) on direct route r using platoon trucks.

t_r^{BO}: total transportation time (hours) on backhaul route r using ordinary trucks.

t_r^{BL}: total transportation time (hours) on backhaul route r using platoon trucks.

l^O: loading time (hours) of an ordinary truck.

u^O: unloading time (hours) of an ordinary truck.

n: number of trucks in a platoon.

l^L: loading time (hours) of a platoon truck (= $n \times l^O$).

u^L: unloading time (hours) of a platoon truck (= $n \times u^O$).

f^O, f^L: fuel consumption rate (liters per km) of an ordinary truck and each truck in the platoon respectively.

c^f: cost (in case that cost is in CAD) per liter of fuel.

d_r^{AO}, d_r^{AL}: total distances (km) for direct route r transported by ordinary and platoon trucks.

d_r^{BO}, d_r^{BL}: total distances (km) for backhaul route r transported by ordinary and platoon trucks.

The total travel time of an ordinary truck or a truck platoon on a direct or backhaul route is computed based on transportation and loading and unloading times. By dividing the overall time by the truck's capacity, the total travel time per ton can be calculated using an ordinary or platoon truck on a direct or backhaul route. The time spent driving, loading, and unloading along each route must be taken into account when calculating the driver's cost. Therefore, this amount is calculated by multiplying the hourly rate of the driver by the total amount of time he spends on each route. Furthermore, fuel cost is determined based on the number of kilometers on each route. Thus, it would be computed by multiplying the fuel cost for each liter by the amount of fuel consumption for each kilometer for trucks. This would be multiplied by the whole driving kilometers on each route.

Decision variables

The decision variables utilized in the mathematical model are as follows.

$$y_i = \begin{cases} 1, & \text{if terminal } i \text{ is selected} \\ 0, & \text{otherwise.} \end{cases}$$

x_r^{AO} = The flow of products by ordinary truck transport through a direct route r.

x_r^{BO} = The flow of products by ordinary truck transport through a backhaul route r.

x_r^{AL} = The flow of products by platoon truck transport through a direct route r.

x_r^{BL} = The flow of products by platoon truck transport through a backhaul route r.

Objective function and constraints

$$\min TC = \sum_{i\in S} f_i y_i + \sum_{r\in R_O} c_r^{AO} x_r^{AO} + \sum_{r\in B_O} c_r^{BO} x_r^{BO} + \sum_{r\in R_L} (c_r^{AL} + f^P e_r^{AL}) x_r^{AL} + \sum_{r\in B_L} (c_r^{BL} + f^P e_r^{BL}) x_r^{BL} \tag{3.1}$$

$$s.t: \sum_{r\in R_{O_{ip}}} x_r^{AO} + \sum_{r\in B_{O_{ip}}} x_r^{BO} + \sum_{r\in R_{L_{ip}}} x_r^{AL} + \sum_{r\in B_{L_{ip}}} x_r^{BL} \le g_{ip} \qquad \forall i \in F, p \in P \tag{3.2}$$

$$\sum_{r\in R_{O_{ip}}} x_r^{AO} + \sum_{r\in B_{O_{ip}}} x_r^{BO} + \sum_{r\in R_{L_{ip}}} x_r^{AL} + \sum_{r\in B_{L_{ip}}} x_r^{BL} = d_{ip} \qquad \forall i \in M, p \in P \tag{3.3}$$

$$\sum_{r\in R_{O_{ip}}} x_r^{AO} + \sum_{r\in B_{O_{ip}}} x_r^{BO} + \sum_{r\in R_{L_{ip}}} x_r^{AL} + \sum_{r\in B_{L_{ip}}} x_r^{BL} - \sum_{r\in R_{O_{i'p}}} x_r^{AO} - \sum_{r\in B_{O_{i'p}}} x_r^{BO} - \sum_{r\in R_{L_{i'p}}} x_r^{AL} - \sum_{r\in B_{L_{i'p}}} x_r^{BL} = 0 \qquad \forall i, i' \in S, p \in P \tag{3.4}$$

$$\sum_{r\in R_{O'_i}} x_r^{AO} + \sum_{r\in B_{O'_i}} x_r^{BO} + \sum_{r\in R_{L'_i}} x_r^{AL} + \sum_{r\in B_{L'_i}} x_r^{BL} \le q_i y_i \qquad \forall i \in S \tag{3.5}$$

$$\sum_{r\in R_{O_j}} e_r^{AO} x_r^{AO} + \sum_{r\in B_{O_j}} e_r^{BO} x_r^{BO} \le h_j n_j^V \qquad \forall j \in J_2 \tag{3.6}$$

$$\sum_{r\in R_{O_j}} e_r^{AO} x_r^{AO} + \sum_{r\in B_{O_j}} e_r^{BO} x_r^{BO} + \sum_{r\in R_{L_j}} e_r^{AL} x_r^{AL} + \sum_{r\in B_{L_j}} e_r^{BL} x_r^{BL} \le h_j n_j^V \qquad \forall j \in J_1 \tag{3.7}$$

$$y_i \in \{0, 1\} \qquad \forall i \in S \tag{3.8}$$

$$x_r^{AO}, x_r^{BO}, x_r^{AL}, x_r^{BL} \geq 0 \qquad \forall r \in R_O, R_L, B_O, B_L \tag{3.9}$$

Objective function TC minimizes the total cost (terminal opening, cost of direct and backhaul transportation, and technology costs for platoon trucks) over the planning horizon. Constraint set (3.2) expresses the maximum amount of each product type that is allowed to be supplied from each forest node. Constraint set (3.3) ensures that the volume of demand associated with each type of product in each mill is fulfilled. Constraint set (3.4) states that the input flow amounts to each terminal node need to be equal to the output flow amounts for each type of product. Constraint set (3.5) provides the total amount of inflow that is allowed at each terminal. Based on constraint sets (3.6) and (3.7), the time required to transport products by ordinary and platoon trucks across the transportation network has to be lower than or equal to the available time capacity of ordinary and platoon trucks. Constraints (3.8-3.9) represent the binary and non-negative decision variables respectively.

With this model, it is possible to obtain optimized transportation costs with and without platooning for various collaboration types and possible coalitions. It is also possible to calculate the optimized transportation cost of each carrier before collaboration using a non-collaborative version of the model. In other words, the model then becomes a transportation planning model for a single carrier without collaboration. The model can also calculate the total optimal cost for any coalition by considering only its members. Therefore the model can be used to analyze three different collaboration types described in Section 3.3.

3.4.2 Formulation of the problem of cost/benefit allocation

We study the problem of cost-sharing between companies after transportation planning is optimized by investigating four different methods. These include two proportional methods based on cost and volume respectively, the ACAM, the Shapley value solution concept, and the EPM. We use a two-step allocation process as the cost savings can come from two different sources: 1) collaboration using only ordinary trucks and wood bartering and 2) collaboration using platoon trucks. Therefore, we propose a two-step allocation process to allocate the cost savings resulting from these two different sources. In other words, we share the savings resulting from collaboration using only ordinary trucks and wood bartering in the first step and then the savings resulting from collaboration using truck platooning in the second step. The two-step approach is used only in collaboration cases involving truck platooning. We compare the properties and results of the different methods in terms of providing a fair allocation where the allocation to each company depends on its contribution to cost savings at each step.

We define a cooperative game including a set of players or companies ($N' = \{1, 2, ..., n\}$) and a characteristic function ($C : 2^n \rightarrow \mathbb{R}$) that assigns a value (cost) to each sub-coalition ($S' \subset N'$). Collaboration can lead to cost savings for players in coalition S' and it is assumed that $C(\phi) = 0$. The grand coalition is defined as the set N'. The main objective in cooperative game theory consists in dividing the total cost $C(N')$ among the players $i \in N'$. We define an allocation vector by $z = \{z_1, ..., z_i, ..., z_n\} \in \mathbb{R}$, where z_i shows the cost allocated to company i. A cost allocation that divides the total costs among the companies is called efficient. An individual rational cost allocation ensures that no company pays more than its stand-alone cost. A rational cost allocation ensures that no subset of companies pays more than their stand-alone cost by quitting and starting their own collaboration. The core of the game is defined as cost allocations that satisfy efficiency, individual rationality, and rationality conditions.

The following are the parameters and decision variables of the cost-sharing problem (in the EPM method, as EPM is a linear optimization model).

Parameters:

$C(\{j\})$: stand-alone cost of company $j \in N'$.

$C(S')$: cost of collaborative planning for sub-coalition $S' \subset N'$ (optimized cost obtained from solving the MILP model).

$|S'|$: the number of coalition members for $S' \subset N'$.

$D(\{j\})$: the total demand (tons) for all product types of demand nodes associated with company $j \in N'$.

Variables:

z_j: cost allocated to company $j \in N'$.

f': a variable that measures the difference in relative savings between a pairwise of participants.

The following paragraphs present briefly each method.

3.4.2.1 Proportional methods

In proportional methods which are based on stand-alone cost and volume, the collaborating companies (players) share the cost based on individual stand-alone costs and the volumes they need to transport. Although it is simple to calculate, understand and apply, proportional allocation cannot ensure stable cost sharing (Guajardo and Rönnqvist, 2016). It is because the allocation may not be in the core and the companies may not get the allocation based on their contribution to the collaboration (Özener et al., 2013).

- Proportional allocations based on stand alone costs is calculated as follows:

$$z_j = \frac{C(\{j\})}{\sum_{i \in N'} C(\{i\})} C(N') \qquad \forall j \in N' \tag{3.10}$$

- Proportional allocations based on transported product volumes is calculated as follows:

$$z_j = \frac{D(\{j\})}{\sum_{i \in N'} D(\{i\})} C(N') \qquad \forall j \in N' \tag{3.11}$$

3.4.2.2 Alternative Cost Avoided Method (ACAM)

According to ACAM (Tijs and Driessen, 1986), the total cost to be shared includes two components: separable costs and nonseparable costs. Separable costs are allocated to each company, then non-separable costs are split between them based on weights. In equation (3.12), $m'(j)$ is the marginal (separable) cost of company $j \in N'$ and in equation (3.13), $g'(N')$ is the non-separable cost of coalition N'. In equation (3.14), w'_j is savings gained by company j by joining the grand coalition rather than working alone (the stand-alone cost of company j minus its marginal cost). ACAM assigns to player j, a cost z_j based on equation (3.15).

$$m'(j) = C(N') - C(N' \setminus \{j\}) \qquad \forall j \in N' \tag{3.12}$$

$$g'(N') = C(N') - \sum_{j \in N'} m'(j) \tag{3.13}$$

$$w'(j) = C(\{j\}) - m'(j) \qquad \forall j \in N' \tag{3.14}$$

$$z_j = m'(j) + \frac{w'(j)}{\sum_{i \in N'} w'(i)} g(N') \qquad \forall j \in N' \tag{3.15}$$

3.4.2.3 Shapley value solution concept

Shapley value solution concept (Shapley, 1997) is an approach that gives a unique solution to the cost allocation problem. It assigns a value to each player (company) in a collaboration based on their marginal contribution to the collaboration benefits. Equation (3.16) considers all possible coalitions and calculates the average marginal contribution of each player over all possible combinations of players. Each player is rewarded for its contribution, regardless of the order in which it participated. The cost assigned to player (company) j is as follows:

$$z_j = \sum_{S' \subseteq N' : j \in S'} [\frac{(|N'| - |S'|)!(|S'| - 1)!}{|N'|!}].[C(S') - C(S' \setminus \{j\})] \qquad \forall j \in N' \tag{3.16}$$

3.4.2.4 Equal Profit Method (EPM)

The goal of this method (Frisk et al., 2010) is to find an allocation that minimizes the maximum difference between relative savings between pairs of players (companies). The mathematical formulation is as follows:

$$\min f' \tag{3.17}$$

$$s.t : f' \geq \frac{z_i}{C(\{i\})} - \frac{z_j}{C(\{j\})} \qquad \forall i, j \in N' \tag{3.18}$$

$$\sum_{j \in S'} z_j \leq C(S') \qquad \forall S' \subset N' \tag{3.19}$$

$$\sum_{j \in S'} z_j = C(N') \tag{3.20}$$

$$z_j \in \mathbb{R} \qquad \forall j \in N' \tag{3.21}$$

$$f' \in \mathbb{R} \tag{3.22}$$

Objective function (3.17) minimizes the largest difference between costs allocated to players (companies). Constraint set (3.18) measures participants' relative savings based on their pairwise differences. Constraint set (3.19) presents the individual and group rationality conditions for all coalitions of players (companies) which indicates that the sum of the allocated cost to each player (company) in a sub-coalition needs to be lower or equal to the sub-coalition cost. Constraint (3.20) relates to the efficiency condition. Constraints (3.19) and (3.20) are stability constraints.

3.4.2.5 Properties of the allocation methods

There are some desirable properties of collaboration that have been identified in the literature (Tijs and Driessen, 1986; Guajardo and Rönnqvist, 2016; Verdonck et al., 2016), as described below:

- **Efficiency.** In the grand coalition, all players (companies) share the total cost.
- **Individual rationality.** players (companies) will only pay an amount that is equal to or less than the costs they would pay if they were operating alone without any collaboration with other players.
- **Symmetry.** The benefit/cost should be equal for two players (companies) with the same contribution.
- **Stability.** The core of the allocation solution is a set of allocations that satisfy efficiency and individual rationality criteria. Since no sub-coalition can benefit from moving away from the grand coalition (rationality), stability is provided by allocations within the core.
- **Dummy.** The collaborative savings should not be allocated to players (companies) that add no value (in terms of cost savings) to the coalition.
- **Additivity.** When two cost-sharing games are combined, the allocations they receive under the two separate games should equal the sum of the allocations for the combined game.

The properties of the Shapley value method, ACAM, EPM, and proportional methods are listed in Table 3.1.

Table 3.1 Properties of the cost-sharing methods (adapted from Verdonck et al. (2016))

Property	**Shapley**	**EPM**	**ACAM**	**Proportional methods**
Efficiency	✓	✓	✓	✓
Individual rationality	✓	✓		
Symmetry	✓	✓	✓	✓
Stability		✓		
Dummy	✓			
Additivity	✓			

3.4.2.6 Proposed two-step sharing allocation process

In our transportation planning problem, we could distinguish two types of collaboration effects (synergies): the effect of collaboration when using only ordinary trucks and when using both ordinary and platoon trucks. The first one is due to the decrease in transportation distances through collaborative backhauling and swapping the destination of products (wood bartering) when possible. The second one is the contribution of platooning to collaboration. In the two-step approach, we consider the non-collaboration with no platooning use in the transportation network as the base case. Therefore, in the base case, the coalition cost is equal to the sum of the stand-alone costs of the companies when they do not use platooning. Next, we assume that we have collaboration between companies that do not use truck platooning. Finally, we assume that platoon trucks are used in the collaboration. The cost allocation in the first and second steps of the approach could be based on the Shapley value method, EPM, ACAM, or proportional methods. To ensure consistency we use the same allocation method in both steps. The following are the parameters and decision variables used in our approach:

$C^0(s')$: The cost of the companies within set s' in the base situation (without platooning and without collaboration).

$C^1(s')$: The cost of coalition s' in step 1 (without platooning and with collaboration).

$C^2(s')$: The cost of coalition s' in step 2 (with platooning and with collaboration).

$O^1(s')$: The cost savings of coalition s' resulting from collaboration in step 1.

$O^2(s')$: The cost savings of coalition s' resulting from collaboration in step 2.

z_j^{O1}: The cost saving allocated to company $j \in N'$ in step 1.

z_j^{O2}: The cost saving allocated to company $j \in N'$ in step 2.

The procedure of the two-step allocation approach proposed is as follows:

- Step 1.

  1. Calculate the cost savings resulting from collaboration without platooning for each sub-coalition:

$$O^1(s') = C^0(s') - C^1(s'), \forall s' \in S' \tag{3.23}$$

  2. Allocate the cost savings to the companies by using proportional methods, EPM, Shapely method, and ACAM: $z_j^{O1}, \forall j \in N'$

- Step 2.

  1. Calculate the cost savings resulting from collaboration and from using of platooning for each sub-coalition:

$$O^2(s') = C^1(s') - C^2(s'), \forall s' \in S' \tag{3.24}$$

  2. Allocate the cost savings to the companies by using the same method used in step 1 for consistency: $z_j^{O2}, \forall j \in N'$

- Calculate the final allocated costs based on the cost savings allocated to each company i:

$$z_j = C^0(\{j\}) - z_j^{O1} - z_j^{O2}, \forall j \in N' \tag{3.25}$$

3.5 Case study

Our case study is based on 30 generated instances that reflect the characteristics of transportation of forest products (upstream supply chain network) in the province of Quebec (Canada). There are three companies considered in the case study, one of which uses platooning technology. The instances differ from each other based on the level of coverage of the supply, terminal, and demand nodes of the three different companies' transportation networks and also the level of accessibility of truck platoons to the forest areas. When there is a high level of node coverage level, there would be significant overlap between the nodes of the different companies' transportation networks. In contrast, when there is a low node coverage, the overlap between the nodes of the different companies' transportation network would be low (see Figure 3.3 for some examples).

In order to analyze the potential benefits of using truck platooning and collaboration, we have considered six scenarios. These scenarios are based on the type of collaboration and the type of trucks used (ordinary, or ordinary and platoon trucks) and all consider backhauling. The scenarios are presented in Table 3.2:

Table 3.2 The different scenarios considered in our study

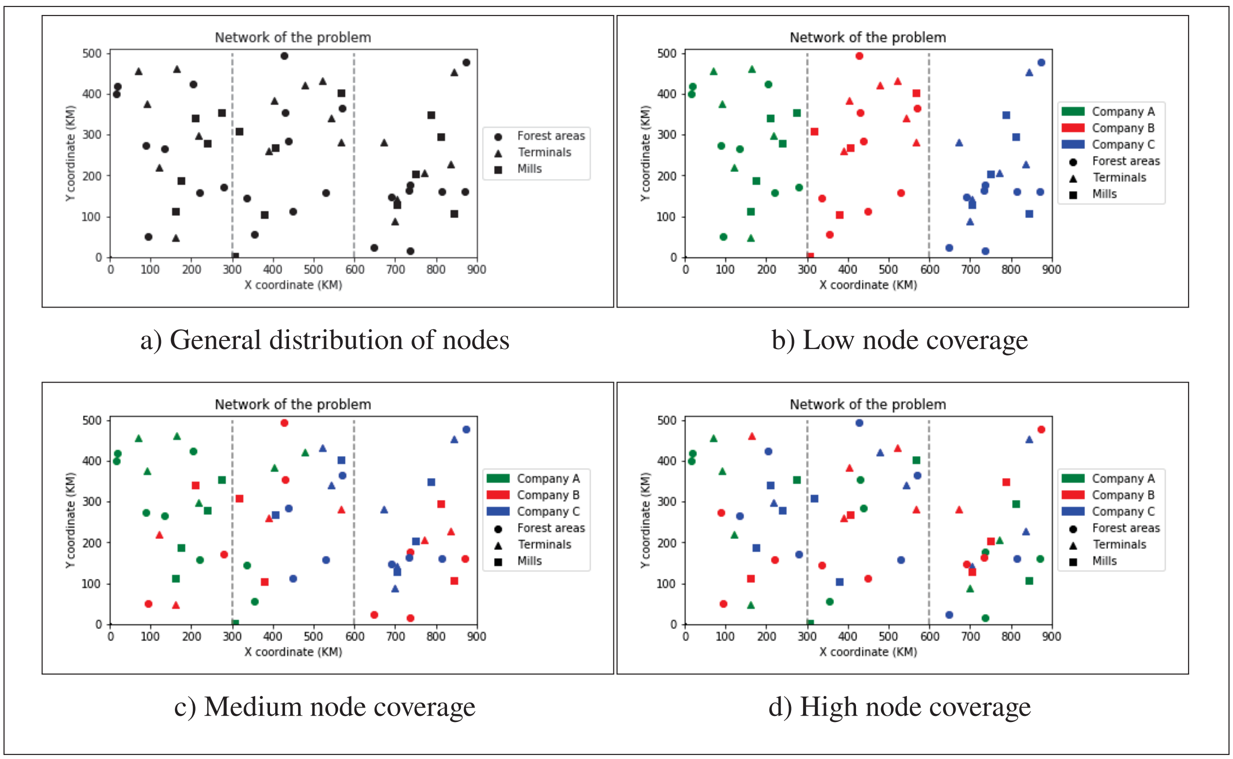
Scenarios	**Type of collaboration**	**Type of trucks**
1	No-collaboration	Ordinary
2		Ordinary and platoons
3	Semi-collaboration	Ordinary
4		Ordinary and platoons
5	Full-collaboration	Ordinary
6		Ordinary and platoons

In this case study we consider a planning horizon (T) of one year or 52 weeks; each week (h) consists of 40 hours. The other parameter values used in the case study are as follows: the load capacity of trucks (w) is considered to be 40 tons, and the platoon size (n) is 3. Moreover, the loading and unloading time for ordinary trucks is 20 minutes, and 1 hour for truck platoons. Each truck consumes 0.4 liters of fuel per kilometer, each liter of fuel costs 1.5 CAD, and every truck in a platoon saves 10% of fuel per kilometer. Furthermore, the salary of the truck drivers is 30 CAD per hour. In addition, we assume that each company owns 150 trucks (this number is estimated based on feasible solutions for companies working alone in all instances). The case study uses data obtained from several sources. Fuel savings by truck platoons and trucks loading/unloading times are derived from the literature (Larson et al., 2013; El Hachemi et al., 2013). Moreover, the fuel consumption rate and fuel price are based on official Canadian government websites (e.g., www.nrcan.gc.ca). The estimated platooning technology cost for a truck is about 5,000 CAD in the planning horizon (one year) (The North American Council for Freight Efficiency, 2016).

Truck platooning transportation could initially be used in limited areas of the transportation network (i.e., none, some, or all forest areas). Consequently, we consider two situations: using platoon trucks only between terminals and mills (if they cannot visit forest areas) and using truck platoons for transporting products directly from the forest areas to mills if it is allowed. Since truck platooning is a relatively new technology, the first stage of its implementation could be restricted to limited areas, and its integration into the transportation network could be gradual. Taking this into account, we have considered different possibilities where truck platoons could initially transport products between terminals and mills and then gradually could access forest areas. We generate the routes for platoon trucks accordingly. In the first case, truck platoons are limited to direct and backhaul routes between mills and terminals, and in the other cases, forest areas could be included in truck platoon potential routes (e.g., truck platoons could visit 1, 3, or all forest areas of each company).

All instances include a total of 24 forest areas, 18 potential terminals, and 15 mills. We consider three carrier companies and assign one-third of the forest areas, terminals, and mills to each one. All instances are created first by generating forest areas and mills in 0-500 by 0-900 km rectangular and terminals in 20-480 and 20-880 km rectangular. These dimensions are based on the size and configuration of upstream forest supply chain nodes in the province of Quebec.

The initial coordination of the nodes is generated randomly, then the nodes are assigned to each carrier in three different settings: low coverage, medium coverage, and high coverage. In the low coverage case, nodes of the same company are located in proximity to each other, while nodes with different colors have low spatial proximity to each other. Therefore, in low coverage, nodes of different colors have a small amount of overlap with each other. As coverage increases to medium and high, the level of overlap between nodes of different colors increases accordingly. Figure 3.3a illustrates the general location of the nodes. As coverage increases from low to high, the overlap between nodes of different colors increases.



a) General distribution of nodes

b) Low node coverage

c) Medium node coverage

d) High node coverage

Figure 3.3 Supply, demand, and terminal node distributions in instances with different node coverage levels for three companies (identified in red, blue, and green).

In the low coverage instances (Figure 3.3b) the nodes of company A (green) are located on the left side of the node configuration and the nodes of companies B (red) and C (blue) are on the middle and right side respectively. In the medium coverage instances (Figure 3.3c) nodes of company A are on the left side, the nodes of company C are on the right part and those of company B have coverage with both of them. In the high coverage instances (Figure 3.3d), the nodes of each company are rather scattered throughout the entire node configuration.

3.6 Results and discussion

Here we describe the results of our experiments. The optimization models are solved using 64-bit Gurobi 9.0 on a laptop powered by Intel Core i7-7700 @ 2.80 GHz and 16 GB RAM that runs 64-bit MS Windows 10. The data is prepared and generated using Python. Jupyter 64-bit Anaconda3 6.0.3 was used to build the models using Gurobi's Python environment. First, we present the results of the collaborative transportation optimization model. Second, we present the results of the cost allocation methods.

3.6.1 Results of the collaborative transportation optimization model

The collaborative transportation optimization model can provide solutions that are at least as good as non-collaborative solutions in terms of optimization cost. The improvement in outcomes results from increased efficiency and collaboration between the multiple companies involved in the transportation. For each instance, we solved the model considering each possible sub-coalition.

Table 3.3 presents the results for semi- and full-collaboration scenarios. The first column indicates the network coverage level (low, medium, and high). The second and third columns present collaboration type (semi- and full-collaboration) and whether platooning is used (jointly with ordinary trucks) or not, respectively. The fourth column shows the number of fixed forest areas truck platoons are allowed to visit (in case truck platooning is used). The next five columns present the optimal cost of the different sub-coalitions generated by the optimization model (in millions of Canadian dollars). The final column shows the average cost-saving (in %) of the grand coalition compared to the related grand coalition without collaboration and platooning. In addition, when companies B and C (which only have ordinary trucks) do the transportation alone at different coverage levels, the resulting costs (in million CAD) are as follows: low coverage:

Cost({B})=7.711, Cost({C})=7.076; medium coverage: Cost({B})=13.200, Cost({C})=9.848; high coverage: Cost({B})=13.237, Cost({C})=13.057.

Table 3.3 The total cost obtained for scenarios 3, 4, 5, and 6

Coverage level	Collaboration type	Type of trucks	# forest areas	Cost of the different sub-coalitions (in million CAD)					Cost savings of the grand coalition
				{A}	{A,B}	{A,C}	{B,C}	{A,B,C}	
Low	Semi-collaboration	Ordinary	-	9.206	16.917	16.282	14.787	23.993	0.00%
		Ordinary and platoons	0	9.141	16.852	16.101	14.787	23.812	0.75%
			1	8.846	16.413	15.638	14.787	23.206	3.28%
			3	8.127	15.103	14.650	14.787	21.627	7.94%
			8	6.796	12.849	12.285	14.787	19.663	18.05%
	Full-collaboration	Ordinary	-	9.206	16.727	16.282	14.787	23.804	0.79%
		Ordinary and platoons	0	9.141	16.723	16.101	14.787	23.683	1.29%
			1	8.846	16.350	15.638	14.787	23.143	3.54%
			3	8.127	14.949	14.650	14.787	21.473	8.67%
			8	6.796	12.693	12.285	14.787	19.489	18.77%
Medium	Semi-collaboration	Ordinary	-	9.511	21.085	19.359	21.752	29.841	8.35%
		Ordinary and platoons	0	9.418	20.912	18.926	21.752	29.364	9.81%
			1	9.217	20.509	18.226	21.752	28.676	11.93%
			3	8.488	18.478	16.670	21.752	26.163	16.08%
			8	7.003	16.499	14.847	21.752	25.094	22.93%
	Full-collaboration	Ordinary	-	9.511	19.058	19.197	18.130	25.299	22.30%
		Ordinary and platoons	0	9.418	18.775	18.709	18.130	24.842	23.70%
			1	9.217	18.379	18.019	18.130	24.064	26.06%
			3	8.488	16.178	16.514	18.130	21.799	28.74%
			8	7.003	14.714	14.710	18.130	20.860	35.93%
High	Semi-collaboration	Ordinary	-	14.003	25.692	25.357	21.785	34.643	14.03%
		Ordinary and platoons	0	13.737	25.200	24.908	21.785	34.482	14.43%
			1	13.435	24.597	24.204	21.785	33.506	16.85%
			3	11.526	21.686	21.737	21.785	30.722	21.17%
			8	10.053	20.617	20.371	21.785	29.543	26.69%
	Full-collaboration	Ordinary	-	14.003	22.097	21.264	15.344	25.359	37.07%
		Ordinary and platoons	0	13.737	22.010	21.002	15.344	25.120	37.66%
			1	13.435	20.955	20.446	15.344	24.246	39.71%
			3	11.526	18.828	18.474	15.344	21.718	42.23%
			8	10.053	17.407	16.586	15.344	20.679	48.68%

The total costs are reduced from 0.75% to 48% depending on the semi- or full- collaboration scenario. Collaboration leads to lower transportation distances while truck platooning results in less fuel consumption and requires a lower number of drivers compared to ordinary trucks. The highest cost-saving percentage occurs in the network with high node coverage and the possibility for truck platoons to visit all forest areas. The savings are between 0%-14% for semi-collaboration scenarios and 0%-37% for full-collaboration scenarios without truck platooning. They range from 0.75%-27% for semi-collaboration and 0.79%-48% for full-collaboration with truck platooning. In semi-collaboration, savings come from backhauling and truck platooning while in full-collaboration they result from backhauling, truck platooning, and the possibility of changing the destination of supplied products from one company to another, i.e., wood bartering. According to the results, truck platoons increase cost savings when there is a possibility of visiting more forest areas. Moreover, we can see that cost-savings increase in networks with medium and high node coverage levels.

The highest cost savings occur in high node coverage instances, which is reasonable since companies operate in common regions and therefore have more opportunities to collaborate. We can see that the contribution of truck platoons is noticeable even in the case of low node coverage where collaboration with ordinary trucks does not lead to significant cost savings. For example, in the low-coverage instances, truck platoons contribute between 0.75%-18% and 0.5%-17.93% to the cost savings depending on the number of forest areas they are allowed to visit in semi- and full-collaboration scenarios respectively. The savings are between 1.46%-14.58% and 0.4%-13.63% in the medium coverage instances. The contribution of truck platooning to cost savings in high-coverage instances is between 0.4%-12.66% and 0.59%-11.61%.

3.6.2 Results of the cost allocation process

The transportation costs need to be divided fairly among the collaborating companies (e.g., based on how much contribution each company has made to the cost savings) to ensure the viability of the collaboration. A fair allocation in this problem can be viewed as an allocation that takes into account both the contributions of companies collaborating without and with truck platooning. The idea is to quantify how much each company's participation reduces total costs with and without platooning and then distribute the savings accordingly. The cost savings resulting from collaboration (obtained by using the optimization model, see subsection 3.6.1) are allocated to carrier companies by using the proportional method, Shapley value method, ACAM, and EPM in the traditional or two-step approach. The latter is used only in collaboration cases that involve truck platooning.

Tables (3.4-3.8) present the results of these different cost-sharing methods for scenarios with and without platooning and in semi- and full-collaboration (for instances in which truck platoons could visit one or all forest areas). In these tables, the first to fourth columns show the collaboration type, companies involved, and the stand-alone cost of each company (when they do not collaborate). In the other columns, the % shows the allocated cost savings to each company by each method. In these tables "Co." stands for company, Cost* is stand-alone cost, % shows allocated cost saving percentage and f'% represents f' value in percentage in EPM. Table 3.4 shows the cost-allocation results based on the traditional approach in semi- and full-collaboration without platooning.

Table 3.4 Cost-sharing results in semi- and full-collaboration scenarios without platooning

Coverage level	**Collaboration type**	**Co.**	**Cost***	**Cost allocated to each company based on different methods (in million CAD)**										
				Proportional based on				**Shapley**	**%**	**EPM**	**f'%**	**%**	**ACAM**	**%**
				Cost	**%**	**Volumes**	**%**							
Low	**Semi-collaboration**	A	9.206	9.206	0.00	7.998	13.13	9.206	0.00	9.206	0.00	0.00	9.206	0.00
		B	7.711	7.711	0.00	7.998	-3.72	7.711	0.00	7.711		0.00	7.711	0.00
		C	7.076	7.076	0.00	7.998	-13.02	7.076	0.00	7.076		0.00	7.076	0.00
	Full-collaboration	A	9.206	9.133	0.79	7.935	13.81	9.111	1.03	9.103	1.12	1.12	9.111	1.03
		B	7.711	7.650	0.79	7.935	-2.90	7.616	1.23	7.624		1.12	7.616	1.23
		C	7.076	7.021	0.79	7.935	-12.13	7.076	0.00	7.076		0.00	7.076	0.00
Medium	**Semi-collaboration**	A	9.511	8.717	8.35	9.947	-4.58	8.766	7.83	8.717	0.00	8.35	8.772	7.77
		B	13.200	12.098	8.35	9.947	24.65	11.807	10.55	12.098		8.35	11.788	10.70
		C	9.848	9.026	8.35	9.947	-1.01	9.268	5.89	9.026		8.35	9.280	5.76
	Full-collaboration	A	9.511	7.390	22.30	8.433	11.33	8.095	14.89	7.390	0.00	22.30	8.208	13.70
		B	13.200	10.257	22.30	8.433	36.12	9.406	28.75	10.257		22.30	9.250	29.92
		C	9.848	7.652	22.30	8.433	14.37	7.799	20.80	7.652		22.30	7.841	20.38
High	**Semi-collaboration**	A	14.003	12.039	14.03	11.548	17.53	13.080	6.59	12.859	8.97	8.17	13.300	5.02
		B	13.237	11.380	14.03	11.548	12.76	10.910	17.57	10.967		17.15	10.809	18.34
		C	13.057	11.225	14.03	11.548	11.56	10.653	18.41	10.818		17.15	10.534	19.32
	Full-collaboration	A	14.003	8.812	37.07	8.453	39.64	10.851	22.51	10.015	13.16	28.48	11.404	18.56
		B	13.237	8.330	37.07	8.453	36.14	7.507	43.28	7.725		41.64	7.280	45.00
		C	13.057	8.217	37.07	8.453	35.26	7.001	46.38	7.620		41.64	6.675	48.88

Table 3.5 presents the cost-allocation results based on the traditional approach in semi- and full-collaboration with platooning and with the possibility for truck platoons to visit one forest area of each company.

Table 3.5 Cost-sharing results in semi- and full-collaboration scenarios with the possibility for truck platoons to visit one forest area of each company

Coverage level	Collaboration type	Co.	Cost*	Cost allocated to each company based on different methods (in million CAD)										
				Proportional based on				Shapley	%	EPM	f'%	%	ACAM	%
				Cost	%	Volumes	%							
Low	Semi-collaboration	A	8.846	8.686	1.81	7.735	12.55	8.632	2.41	8.686	0.00	1.81	8.632	2.41
		B	7.711	7.571	1.81	7.735	-0.32	7.639	0.93	7.571		1.81	7.639	0.93
		C	7.076	6.949	1.81	7.735	-9.31	6.935	2.01	6.949		1.81	6.935	2.01
	Full-collaboration	A	8.846	8.662	2.07	7.714	12.79	8.601	2.77	8.662	0.00	2.07	8.601	2.77
		B	7.711	7.551	2.07	7.714	-0.05	7.608	1.34	7.551		2.07	7.608	1.34
		C	7.076	6.930	2.07	7.714	-9.01	6.935	2.00	6.930		2.07	6.935	2.00
Medium	Semi-collaboration	A	9.217	8.191	11.12	9.559	-3.71	7.995	13.26	8.191	0.00	11.12	7.993	13.28
		B	13.200	11.732	11.12	9.559	27.59	11.750	10.99	11.732		11.12	11.733	11.12
		C	9.848	8.752	11.12	9.559	2.94	8.932	9.30	8.752		11.12	8.950	9.11
	Full-collaboration	A	9.217	6.874	25.42	8.021	12.97	7.275	21.06	6.874	0.00	25.42	7.373	20.00
		B	13.200	9.845	25.42	8.021	39.23	9.323	29.38	9.845		25.42	9.181	30.45
		C	9.848	7.345	25.42	8.021	18.55	7.466	24.18	7.345		25.42	7.510	23.74
High	Semi-collaboration	A	13.435	11.331	15.66	11.169	16.87	12.137	9.66	11.722	4.39	12.75	12.346	8.10
		B	13.237	11.164	15.66	11.169	15.62	10.828	18.20	10.967		17.15	10.737	18.88
		C	13.057	11.012	15.66	11.169	14.46	10.542	19.26	10.818		17.15	10.422	20.18
	Full-collaboration	A	13.435	8.199	38.97	8.082	39.84	9.963	25.84	8.901	7.90	33.74	10.478	22.01
		B	13.237	8.078	38.97	8.082	38.94	7.313	44.75	7.725		41.64	7.081	46.50
		C	13.057	7.968	38.97	8.082	38.10	6.969	46.63	7.620		41.64	6.687	48.79

Table 3.6 provides the cost-allocation results based on traditional sharing approaches in semi- and full-collaboration with platooning and the possibility for truck platoons to visit all forest areas of all companies.

Table 3.6 Cost-sharing results in semi- and full-collaboration scenarios with the possibility for truck platoons to visit all forest areas

Coverage level	Collaboration type	Co.	Cost*	Cost allocated to each company based on different methods (in million CAD)										
				Proportional based on				Shapley	%	EPM	f'%	%	ACAM	%
				Cost	%	Volumes	%							
Low	Semi-collaboration	A	6.796	6.192	8.90	6.554	3.56	5.615	17.38	5.471	15.78	19.50	5.330	21.57
		B	7.711	7.024	8.90	6.554	15.00	7.323	5.02	7.378		4.32	7.456	3.30
		C	7.076	6.447	8.90	6.554	7.38	6.724	4.98	6.814		3.71	6.876	2.83
	Full-collaboration	A	6.796	6.137	9.71	6.496	4.42	5.531	18.62	5.490	15.25	19.23	5.274	22.40
		B	7.711	6.962	9.71	6.496	15.75	7.239	6.11	7.204		6.58	7.342	4.78
		C	7.076	6.390	9.71	6.496	8.20	6.718	5.07	6.795		3.98	6.872	2.89
Medium	Semi-collaboration	A	7.003	5.848	16.50	8.365	-19.44	4.831	31.01	5.719	5.61	18.34	4.696	32.95
		B	13.200	11.023	16.50	8.365	36.63	11.383	13.77	10.780		18.34	11.340	14.10
		C	9.848	8.223	16.50	8.365	15.06	8.880	9.83	8.595		12.72	9.058	8.02
	Full-collaboration	A	7.003	5.380	23.18	7.695	-9.88	5.049	27.90	5.100	12.18	27.17	5.295	24.39
		B	13.200	10.141	23.18	7.695	41.70	9.857	25.33	9.614		27.17	9.175	30.50
		C	9.848	7.565	23.18	7.695	21.86	8.179	16.94	8.372		14.99	8.616	12.51
High	Semi-collaboration	A	10.053	8.171	18.72	9.848	2.04	8.386	16.58	8.171	0.00	18.72	8.565	14.80
		B	13.237	10.759	18.72	9.848	25.60	10.685	19.28	10.759		18.72	10.600	19.92
		C	13.057	10.613	18.72	9.848	24.58	10.472	19.80	10.613		18.72	10.378	20.52
	Full-collaboration	A	10.053	5.720	43.10	6.893	31.43	6.413	36.21	5.720	0.00	43.10	6.927	31.09
		B	13.237	7.531	43.10	6.893	47.92	7.384	44.22	7.531		43.10	7.178	45.77
		C	13.057	7.429	43.10	6.893	47.21	6.883	47.28	7.531		42.32	6.574	49.65

Co.: company, Cost*: stand-alone cost, %: allocated cost saving percentage, f'%: f' value in percentage in EPM.

In order to check if the cost allocations provide collaboration stability, it is necessary to test whether or not the cost-sharing methods are consistent for individual and group rationality. Without allocation solutions in the core, companies might quit the collaboration. All experiments show that the grand coalition is stable and contains feasible core solutions. A stable grand coalition does not have any coalitions of companies that would leave and act independently.

By analyzing the results of traditional cost allocation methods (Tables 3.4-3.6), we observe that many solutions based on the proportional allocation method are not in the core (e.g., instances with medium coverage in semi-collaboration with and without platooning). This method often fails to satisfy core stability. Moreover, we could see some negative allocated savings when using the volume-based proportional method (e.g., in Tables 3.5 and 3.6) which indicates a higher cost than the stand-alone cost for the company. In some instances, the results of the cost-based proportional allocation method are the same as the EPM results (e.g., in Table 3.6, semi-collaboration and high coverage), i.e., cases where f'% is equal to zero. In general, the proportional method mostly does not result in stable solutions and does not consider adequately the contributions of companies to the collaboration.

Three main factors have a major impact on the cost allocation results: First, the collaboration type affects the total cost of the collaboration and consequently, the cost allocated to the companies involved. Since the cost savings calculated by the transportation planning model are higher in full-collaboration than in semi-collaboration, the savings allocated to companies also will be higher in full-collaboration. Second, the cost-allocation results are dependent on the number of forest areas that could be visited by truck platoons. When the truck platoons visit more forest areas, the cost-savings for all companies increase. Third, the cost savings allocation depends on the node coverage level of a given company with the others (e.g., in medium coverage company B which has coverage with both companies A and B obtains high cost-savings). In this situation, there are more backhaul possibilities between the nodes of the company and the others, therefore the company contributes more to cost reduction.

By analyzing the allocations calculated using the Shapley value method, the ACAM, and the EPM for all instances (Tables 3.4-3.6), the following observations can be made. The cost allocations based on EPM are in the core because core constraints are integrated into the EPM formulation. Therefore, the feasible EPM solution reflects the stability of the coalition. In instances with medium coverage in semi- and full-collaboration, and also in instances with high coverage in semi- and full-collaboration, we can see similar results for ACAM and Shapley value but different ones for EPM. This is due to the principle of EPM, which is to equalize the relative savings between companies as much as possible.

The cost allocations based on ACAM for all instances and scenarios are in the core. Cost allocations based on Shapley value, except two solutions (i.e., instances with low coverage in semi- and full-collaboration and with the possibility for truck platoons to visit all forest areas in Table 3.6), are in the core. The results of Shapley value and ACAM are similar in most instances and most of the savings are allocated to the companies that contribute more to the cost-savings. In most of the allocations obtained, company A, which would own the platooning technology, gets most of the savings because it contributes the most to the grand coalition and sub-coalitions in terms of cost savings. In the medium coverage instances, company B, whose nodes have coverage with those of companies A and C, is allocated considerable cost-savings. In these instances, the average transportation distances of company B are higher than those of the other companies.

The cost-saving allocated to the three companies (Tables 3.4-3.6), range between 0% and more than 20%. The costs allocated to the companies vary based on the method used, especially the Shapley value and ACAM methods. Companies in semi-collaboration and with low and medium coverage obtain similar results i.e., cost savings obtained with the different methods are close to each other. Moreover, large differences are observed when companies operate in networks with high coverage and within full-collaboration. Table 3.5 shows that in full-collaboration, the allocated cost savings range between 25%-47%, 33%-42%, and 22%-49% for Shapley methods, EPMs, and ACAMs respectively.

Regarding the number of forest areas that truck platoons could visit, Gazran et al. (2023) found that the more possibilities for truck platoons to visit a higher number of forest areas, the more opportunities for cost savings would be obtained. Moreover, we found in collaborative transportation that this could also lead to higher cost savings allocations for the different companies involved in the collaboration. In particular, this is the case for companies with truck platooning technology, which usually contributes the most to the sub-coalitions' cost savings.

The differences between the highest and lowest cost-saving allocations to the companies based on the EPM method are close to each other in the cases of low and medium coverage (Tables 3.4-3.6). This allocation may be helpful in the early stages of collaborations, where similar cost-saving allocations for all companies may be more suitable for initiating the collaboration (Ramaekers et al., 2017). In most cases, the company with platooning technology would prefer using the Shapley value method (e.g., low and medium coverage levels in Tables 3.5 and 3.6). This allocation method favors the company with platooning technology by assigning them a larger savings percentage compared to the ACAM and the EPM methods because the company with platooning technology contributes the most to cost savings.

Table 3.7 shows the cost-allocation results based on the two-step approach in semi- and full-collaboration when platooning and with the possibility for truck platoons to visit one forest area of each company. The cells in the table filled with "-" indicate instances where the EPM method has an empty core in the second step.

Table 3.7 Two-step approach cost-sharing results in semi- and full-collaboration scenarios with the possibility for truck platoons to visit one forest area of each company

Coverage level	Collaboration type	Co.	Cost*	Cost allocated to each company based on different methods (in million CAD)					
				Shapley	%	EPM	%	ACAM	%
Low	Semi-collaboration	A	6.796	6.192	8.90	6.554	3.56	5.615	17.38
		B	7.711	7.024	8.90	6.554	15.00	7.323	5.02
		C	7.076	6.447	8.90	6.554	7.38	6.724	4.98
	Full-collaboration	A	6.796	6.137	9.71	6.496	4.42	5.531	18.62
		B	7.711	6.962	9.71	6.496	15.75	7.239	6.11
		C	7.076	6.390	9.71	6.496	8.20	6.718	5.07
Medium	Semi-collaboration	A	7.003	5.848	16.50	8.365	-19.44	4.831	31.01
		B	13.200	11.023	16.50	8.365	36.63	11.383	13.77
		C	9.848	8.223	16.50	8.365	15.06	8.880	9.83
	Full-collaboration	A	7.003	5.380	23.18	7.695	-9.88	5.049	27.90
		B	13.200	10.141	23.18	7.695	41.70	9.857	25.33
		C	9.848	7.565	23.18	7.695	21.86	8.179	16.94
High	Semi-collaboration	A	10.053	8.171	18.72	9.848	2.04	8.386	16.58
		B	13.237	10.759	18.72	9.848	25.60	10.685	19.28
		C	13.057	10.613	18.72	9.848	24.58	10.472	19.80
	Full-collaboration	A	10.053	5.720	43.10	6.893	31.43	6.413	36.21
		B	13.237	7.531	43.10	6.893	47.92	7.384	44.22
		C	13.057	7.429	43.10	6.893	47.21	6.883	47.28

Co.: company, Cost*: stand-alone cost, %: allocated cost saving percentage.

Table 3.8 gives the cost-allocation results based on the two-step approach in semi- and full-collaboration when using platooning and with the possibility for truck platoons to visit all forest areas of all companies.

Table 3.8 Two-step approach cost sharing results in semi- and full-collaboration scenarios with the possibility of truck platoons to visit all forest areas

Coverage level	Collaboration type	Co.	Cost*	Cost allocated to each company based on different methods (in million CAD)					
				Shapley	%	EPM	%	ACAM	%
Low	Semi-collaboration	A	6.796	5.615	17.38	4.875	28.26	5.330	21.57
		B	7.711	7.323	5.02	7.711	0.00	7.456	3.30
		C	7.076	6.724	4.98	7.076	0.00	6.876	2.83
	Full-collaboration	A	6.796	5.531	18.62	4.796	29.43	5.252	22.73
		B	7.711	7.239	6.11	7.616	1.23	7.374	4.36
		C	7.076	6.718	5.07	7.076	0.00	6.862	3.02
Medium	Semi-collaboration	A	7.003	4.831	31.01	3.858	44.91	4.361	37.73
		B	13.200	11.383	13.77	12.294	6.86	11.589	12.21
		C	9.848	8.880	9.83	8.942	9.20	9.144	7.15
	Full-collaboration	A	7.003	4.307	38.50	-	-	3.816	45.51
		B	13.200	9.115	30.95	-	-	9.296	29.58
		C	9.848	7.437	24.48	-	-	7.747	21.33
High	Semi-collaboration	A	10.053	8.386	16.58	7.758	22.83	8.324	17.20
		B	13.237	10.685	19.28	10.982	17.03	10.707	19.11
		C	13.057	10.472	19.80	10.802	17.27	10.512	19.49
	Full-collaboration	A	10.053	6.413	36.21	-	-	6.716	33.19
		B	13.237	7.384	44.22	-	-	7.278	45.01
		C	13.057	6.883	47.28	-	-	6.685	48.80

Co.: company, Cost*: stand-alone cost, %: allocated cost saving percentage.

The two-step EPM has limitations since it does not provide a feasible solution in the second step in some instances (e.g., high coverage levels in Table 3.7 and medium and high and full-collaboration in Table 3.8). When the second step provides a solution within the core, the two-step EPM method results in more cost savings for the company equipped with the platooning technology which has the most contribution in terms of total cost savings in the second step. In some cases, the two-step EPM does not lead to any results because the solution does not exist (empty core) in the second step. Examples are instances with high coverage, semi- and full-collaboration where truck platoons could visit one forest area (Table 3.7) and instances with medium and high coverage, and full-collaboration where truck platoons could visit all forest areas (Table 3.8).

Consider, for example, the cost of sub-coalitions in the instance with high coverage, full-collaboration, and the possibility of platoon visits to all forest areas (Table 3.3). Although the sub-coalition costs C^0, C^1, and C^2 are in the core and are stable, the cost savings resulting from platooning O^2 are not in the core. In this case, the cost savings of platooning in sub-coalition $\{$A, B$\}$ are higher than in those obtained by the grand coalition. This is because collaboration when using only ordinary trucks C^1 led to significant savings (14.937 million CAD) and truck platooning contribution could not save much more in the grand coalition (4.68 million CAD). The total savings in the grand coalition is 19.617 million CAD. The savings of collaboration with ordinary trucks in sub-coalition $\{$A, B$\}$ is 5.143 million CAD, and the contribution of platooning and the total savings in this sub-coalition are 4.69 and 9.833 million CAD respectively. A similar situation happens in the instance with medium coverage, full-collaboration, and the possibility for trucks to access all forest areas in sub-coalition $\{$A, C$\}$. Overall, this situation happened in the second step for EPM in 9 out of 24 instances indicating that the second step lacks solutions in the core and the reason is that collaboration with ordinary trucks alone already leads to substantial savings.

In most instances, the Shapley value solution concept leads to better results since it considers the contributions of companies in the collaboration to the total cost savings. In particular, the results reveal that the Shapley method has the same results in both approaches (traditional and two-step) because of the additivity property. The additivity property is an important characteristic of the Shapley method, which states that the cost allocated to a company in a collaboration consisting of two or more cooperative games is equal to the sum of the costs allocated in each of the sub-collaborations. In our problem, the first cooperative game is collaboration without platooning and the second one is when platooning technology enters the collaboration. In the second step of the two-step approach when using the Shapley value method, even though the solutions might not be in the core it takes into account the contribution of platooning when the company equipped with the technology joins the collaboration. Therefore, the best recommendation for the collaborating companies would be to use the Shapley method. The solutions of this method are in the core in most cases (except for 2 out of 24 instances). As for the ACAM method in low coverage cases, the results of the traditional and two-step approaches are the same. The results for medium and high coverage levels are not the same and the two-step approach when using ACAM allocates a higher amount of savings to the company equipped with platooning technology which has the most contribution in the second step.

In summary, the cost savings resulting from collaboration depends on the following three aspects:

The collaboration type. Total cost savings in full-collaboration are higher than in semi-collaboration because in full-collaboration the product destinations could be changed between the different companies and this leads to lower transportation distances. However, the contribution of truck platoons to semi-collaboration is higher compared to full-collaboration. That is because in full-collaboration when only ordinary trucks are used they could already save considerable costs. Moreover, since the transportation distances are higher in semi-collaboration and truck platoons have better efficiency in longer distances, their contribution is higher in this scenario.

The number of forest areas that truck platoons could visit. Overall, the cost savings increase as truck platoons can visit a higher number of forest areas. This is because truck platoons could be more efficient when they are not restricted (terminals are not needed in this case, and therefore no cost is needed to open them) and perform more efficiently over long transportation distances as described in (Gazran et al., 2023).

The node coverage level. Truck platooning could lead to considerable cost savings even at low node coverage levels. However, the cost savings improve with higher node coverage levels. There is a higher backhauling opportunity for ordinary and platoon trucks in both semi-collaboration and full-collaboration situations in high node coverage situations. Moreover, there are a greater number of wood bartering opportunities for different companies at higher node coverage levels in full-collaboration.

3.6.3 Discussion

The results of this study show that multiple carriers equipped with platooning technology (at least one company) could achieve substantial cost savings through collaboration. Collaboration in transportation would enable companies to use the platooning fleet capability to its full potential.

Companies could assign more efficient routes for ordinary and platoon trucks which enable them to reduce transportation distances. According to the results, the savings are highly dependent on the collaboration type, node coverage, and the number of forest areas that truck platoons can visit. The collaboration with platoon trucks leads to better cost savings in instances with larger networks (where average transportation distances are higher). This is consistent with the findings of Gazran et al. (2023), who showed that truck platoons are more efficient in networks with longer average transportation distances.

The cost saving that platoon trucks add to collaboration when using only ordinary trucks is between 0.75%-19%. In instances where the use of ordinary trucks only can provide low cost savings, truck platooning can achieve significant additional savings. Moreover, the average savings of truck platooning in semi-collaboration is higher than those achieved in full-collaboration. This is explained by two facts. First, the transportation destinations of products in full-collaboration change based on lower transportation distances. This leads to high-cost savings. Second, the average transportation distances are lower in full-collaboration compared to semi-collaboration.

Maintaining the collaboration requires an allocation method that takes into account companies' contributions to the collaboration. Simple allocation methods like proportional methods based on volume or cost may be preferred in practice because of their convenience of calculation and interpretation (Guajardo et al., 2016). Nevertheless, these methods often produce non-core solutions, which could not ensure the collaboration stability and continuity over time (Özener et al., 2013). There are only two cases where stability was not achieved by using the Shapley value method. Among the allocation methods investigated in this paper, ACAM and EPM provide stable solutions in all instances. Stability is guaranteed in EPM if there is a feasible solution and the method benefits all companies in providing the most equal relative cost savings allocations. Initial equal allocations can encourage cooperation in the early stages of a horizontal collaboration (Ramaekers et al., 2017). In most cases, the Shapley value method and ACAM methods lead to comparable cost-sharing solutions.

The cost savings could be divided into two categories: cost savings resulting from collaboration based on only ordinary trucks and wood bartering, and those resulting from truck platooning. Therefore we proposed a two-step based cost allocation approach. The results provide useful insights for the companies involved in the collaboration. For example, if a company's transportation network presents a high coverage level with other companies' networks, it would be beneficial for them to first explore the potential of collaboration based on ordinary trucks. Second, this company could study the potential of including platooning in the collaboration and decide how cost allocation should be performed according to cost savings made in both steps. Therefore, companies could use the two-step approach to identify the cost savings resulting from collaboration based on ordinary trucks and on truck platooning separately.

Investment in platooning technology could be challenging and raise questions about truck platoon transportation planning. It could also raise questions about collaboration with other companies to use the technology most efficiently. Moreover, this research could guide the collaborating companies on how to create a fair cost-sharing process that considers the contributions of both collaboration when using only ordinary trucks and collaboration when using both ordinary and platoon trucks. The two-step approach could lead to a better understanding of the contributions of the different companies involved in the collaboration in separate steps and provides allocations based on these contributions.

Another aspect that could affect the results of transportation optimization and cost-sharing is technology costs. The company that owns the technology could benefit from declaring higher technology costs to other companies. In order to prevent unequal situations in which non-common information is not properly shared between the collaborating companies, there needs to be a transparent and fair mechanism for information sharing between the collaborating companies.

For the cost-sharing results, although EPM has stable allocations and leads to similar cost-saving compared to other methods, the Shapley value method is more advantageous because its results are the same as those obtained in the two-step approach. In general, higher cost savings are allocated to companies with platooning technology and companies with better node distribution since they contribute more to the coalition's cost savings.

Truck platoons are more efficient at long transportation distances, which is an opportunity for companies with platooning technology to collaborate with other companies. Indeed, if companies without platooning technology have longer transportation distances than companies owning this technology, it would be an opportunity for all of them to reduce their transportation costs by collaborating, particularly in scenarios where wood bartering is not possible. In addition, if other companies that do not own platooning technology have more opportunities for platoon trucks to transport products directly from the forest areas to the mills, it would be advantageous for companies equipped with this technology to collaborate with the former ones to reduce the total cost of all companies. Therefore, thanks to collaboration truck platoons could be used more efficiently in the transportation network and the total transportation costs would decrease significantly.

3.7 Conclusions

Collaborative truck platooning transportation planning is promising to reduce transportation costs and increase efficiency. With the utilization of hybrid platooning technology, only the lead truck has a driver who controls the convoy, which reduces fuel consumption as well as driver costs. The utilization of platooning technology in the logistics industry has gained considerable attention in recent years, and collaboration between companies can further improve its benefits. However, to achieve effective collaboration between companies, there is a need for optimal planning and an appropriate cost/benefit allocation mechanism. Moreover, investing in platooning technology could be challenging and raise questions regarding the best transportation planning and collaboration with other companies. Therefore, companies need new decision-making tools to support them in their planning and decision process. This research provides such decision-making tools to support companies interested in investing in truck platooning technology and collaborating with other companies.

In this paper, we studied collaboration between different carrier companies in transportation networks in the forestry sector by using a mix of ordinary and platoon trucks. First, we calculated the cost savings resulting from collaborative transportation for all possible coalitions. For this purpose, an MILP model was used to optimize the transportation costs (tactical planning). Second, we studied the important question of how to share the benefits of collaboration among the companies. By applying different cost-sharing methods including the Shapley value, ACAM, and EPM, the total cost saving was allocated to the companies. Based on the fact that in our problem collaboration benefits come from both ordinary and platoon trucks a two-step cost allocation approach was proposed.

The transportation planning model leads to total cost savings ranging between 0.75% and 48% depending on the type of collaboration (semi- or full- collaboration). A saving of 0.75%-19% is obtained when platoon trucks are used together with ordinary trucks. Therefore, truck platooning could lead to significant cost savings. Due to the fact that full-collaboration allows product destinations to be changed between companies, the total cost savings in full-collaboration are higher than in semi-collaboration. This is because full collaboration reduces the total transportation distances even further. In semi-collaboration, truck platoons lead to higher cost savings in comparison to full-collaboration. This is due to the fact that in full collaboration using only ordinary trucks already saves a considerable amount of costs and the transportation distances are higher than in semi-collaboration where truck platoons have better efficiency. Moreover, with a larger number of forest areas visited by truck platoons, the total cost savings increase. Truck platooning could result in considerable cost savings even at low node coverage levels, but in general, the cost savings improve as the node coverage (overlap between the nodes) among different companies increases.

Regarding collaborative transportation planning using ordinary and platoon trucks, we have two types of collaboration benefits: the benefit of collaboration when platoon trucks are not considered in the transportation network and the benefit of using platooning technology. We proposed a two-step based sharing approach to allocate the total cost savings between the companies. In the first step, we identified the cost savings of collaboration when using only ordinary trucks and determined the cost savings allocated to each company. In the second step, we performed another cost allocation approach proposed, which aims to share the cost savings resulting from using truck platoons. In most scenarios and instances, the Shapley value method produces the best results. Various cost savings were allocated among the three companies, ranging from 0% to more than 20%. Based on the methods used companies received different costs. The collaboration type affects the total cost of the collaboration and consequently, the cost allocated to the companies involved. In full-collaboration rather than in semi-collaboration, the savings allocated to companies will also be higher. More forest areas visited by truck platoons lead to more savings for all companies. Also, the company contributes more to cost reduction at high node coverage levels because the company has more backhaul possibilities between its nodes and the others.

As possible future research directions, it would be interesting to study operational and collaborative transportation planning involving the use of platoon trucks. It would be possible in that case to consider supply and delivery time windows and restrictions on the number of drivers available in short-term planning. There is also greater flexibility provided by a platoon of trucks in operations since they could transport products together as a system, or they could be used for picking up and delivering driverless trucks to supply and demand nodes in order to load/unload them when they are separated from other trucks.

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusions

Truck platooning has gained increasing attention due to its potential to improve transportation by reducing costs and addressing critical challenges such as driver shortage and GHG emissions. This thesis aimed to review the literature on truck platooning transportation planning and developed strategic-tactical planning models to optimize transportation using truck platooning technology, specifically focusing on the forestry sector. The findings reveal potential for considerable cost reduction, fuel consumption savings, and improved labor use by adopting truck platooning. The thesis presents three interconnected articles.

The first paper provides a systematic review on truck platooning transportation planning, outlining current advancements, benefits, challenges, and existing planning models. The literature review demonstrated that about 80% of total papers were published since 2019, indicating the growing interest in this topic and the necessity for a comprehensive review. This paper highlights a number of critical gaps in the existing literature, which justify the subsequent research contributions presented in papers 2 and 3. One of the key findings is the lack of strategic-tactical planning models specific to the forestry sector. While many studies focus on the operational aspects of truck platooning, there is a noticeable absence of models that address the integration of platooning into long- and mid-term planning models. Another major gap identified is the limited research on the combined use of ordinary and platoon trucks within the same transportation network. Most existing models do not consider interactions between different types of vehicles. By identifying these gaps and challenges, the literature review underscores the need for innovative models that efficiently integrate truck platooning into transportation planning. Papers 2 and 3 directly address these issues by developing strategic-tactical planning models for the forestry sector and exploring the collaborative use of platoon and ordinary trucks. These contributions aim to enhance transportation networks' efficiency and sustainability, providing practical solutions to the challenges highlighted in the literature review.

The second paper develops a model for planning and analyzing the integration of truck platooning in the forestry sector. It aims to develop an optimization model at the tactical planning level that incorporates both ordinary and platoon trucks, focusing on reducing transportation costs while taking into account the characteristics of truck platooning. The integration of truck platooning to forestry transportation, as analyzed through our MILP model, demonstrates improvements in cost efficiency, fuel consumption, and the need for truck drivers. Our model evaluates various scenarios to understand the impact of different levels of truck platooning adoption. These improvements are due to platooning's benefits, including reduced fuel consumption and driver costs. Moreover, backhaul opportunities and optimized routes reduce transportation distances. The results indicate that using a mix of ordinary and platoon trucks can lead to 3% to more than 20% cost savings. Specifically, platoon trucks reduce fuel consumption by 1-16%. Furthermore, the deployment of platoon trucks reduces the number of drivers needed, contributing to address the driver shortage issue in the industry. A reduction of 10% to more than 50% could be achieved in the number of required drivers. Cost savings are particularly relevant for long-distance transportation defined as routes longer than about 100 kilometers which is common in the forestry sector. Using truck platoons over long transportation distances leads to cost savings, where the per-unit transportation cost decreases as the distance increases, making truck platooning an effective solution to the forestry industry's logistical challenges.

The third paper addresses the collaborative aspect of using truck platooning, exploring how different carrier companies can work together to maximize the benefits of platooning technology. There is a heterogeneous operational environment in this study since some companies are equipped with platoon trucks and others are not. The paper tackles a strategic-tactical transportation planning problem where cost-sharing mechanisms are examined to ensure an equitable distribution of costs among collaborating carriers in the forestry industry. By addressing these mechanisms, the study highlights the benefits of collaboration among carrier companies using truck platooning technology. It demonstrates how companies with and without platoon trucks can effectively collaborate to achieve mutual benefits. Using truck platooning in collaboration, 1-19% cost savings (which exceed those achieved with ordinary trucks alone) can be achieved. By developing models that facilitate collaborative planning and cost-sharing, we provide an approach to efficiently integrate truck platooning and share the resulting benefits. The transportation planning model incorporates collaborative backhauling. This allows companies to optimize their routes maximizing the utilization of both ordinary and platoon trucks and reducing overall transportation costs. The cost-sharing models use cooperative game theory to design fair cost-sharing mechanisms, ensuring that cost savings from collaboration are equitably distributed among all participating companies. The models allocate costs based on each company's contribution to collaboration with and without platooning. The application of cooperative game theory in this research provides robust and fair allocation models that ensure stability, therefore making long-term collaboration possible.

This research enhances the application of truck platooning by developing decision-support models that academic researchers and industry planners can use to optimize transportation and improve efficiency. The models provide a basis for integrating truck platooning into existing transportation networks, offering efficiency and sustainability benefits. However, it is important to acknowledge our research limitations. For instance, the number of trucks in a platoon is always considered to be three, which may not reflect all real-world scenarios where different platoon sizes could be more efficient. Moreover, our models only consider terminal nodes as transshipment nodes. In practice, these nodes could serve multiple functions, such as sorting, which would require modified modeling.

4.2 Further research

Research in truck platooning transportation, particularly in the forestry sector, presents some promising avenues. We identified three key research perspectives that could significantly advance the field:

- Operational planning of hybrid truck platooning in forestry: Future research should focus on the operational planning level, where both ordinary and platoon trucks work together, building on previous studies but incorporating short-term levels of planning such as platoon formation and scheduling. In hybrid truck platooning, the first truck has a human driver, and there are multiple operational possibilities. All trucks in the platoon can transport together, or the first truck can pick up or deliver other trucks along its route. This includes developing models and algorithms that dynamically consider the number of trucks in the different platoons, and allocate trucks and drivers between ordinary and platoon operations to determine which trucks and drivers need to be in which operation at which time to improve efficiency. The key lies in using short-term data to respond to day-to-day conditions. The allocation problem will focus on determining the optimal distribution of truck types and drivers across various routes and schedules. Moreover, factors such as load distribution between trucks, constraints on the number of trucks in a platoon, speed limitations on different routes, and coordination between trucks and drivers to maximize operational efficiency could be considered. Considering a limited number of available drivers on different shifts adds another layer of complexity, which can be addressed by developing models that optimize driver assignments based on shift availability, skills, and preferences. Investigating the impact of different platoon configurations and the integration of hybrid platooning in daily operations can minimize costs, reduce delays, and improve transportation systems' flexibility. This research could provide optimization and simulation models that incorporate short-term constraints providing a deep analysis of short-term optimal strategies.

- Uncertainty in parameters: Developing models that account for uncertainty in key parameters is crucial for truck platooning implementation. Future research should focus on creating optimization models that incorporate stochastic elements such as fuel consumption, loading/unloading time, road conditions, and unforeseen disruptions (e.g., weather conditions). Using the methodologies developed in this thesis, we propose exploring the following approaches to handling uncertainty. First, extend the MILP model by incorporating stochastic programming techniques which involve defining multiple scenarios for uncertain parameters and optimizing the transportation plan across all scenarios. For example, different fuel consumption rates can be considered based on historical data and future projections. This allows the model to plan for best, worst, and average-case scenarios. Next, develop robust optimization models that handle parameter uncertainty without explicit probability distributions with a focus on creating solutions that remain feasible and effective under a wide range of conditions. By using these techniques, the models can account for variations in loading/unloading times and road conditions, ensuring reliability and performance. Considering uncertainty through these methodologies will help in designing robust and reliable truck platooning transportation solutions that maintain high-performance levels even under varying and unpredictable conditions. This approach builds on the foundational work of this thesis.
- Electric truck platooning: Future research could consider the integration of electric trucks into platooning operations as a possible future integration towards more sustainable forest transportation. Electric trucks present unique challenges and opportunities, such as the need for recharging facilities, recharging time considerations, and charging session scheduling. Developing models that incorporate these elements is crucial for optimizing electric truck use in platoons that consider both truck platooning and electric truck characteristics. Specific research directions could include developing models and algorithms to minimize electric truck charging time. This involves creating efficient recharge schedules that align with truck routes and driver shift patterns. This ensures that trucks are charged without significant delays to

operations. Moreover, identifying optimal locations for charging stations in the transportation network. It involves analyzing the spatial distribution of routes and determining where to install power infrastructure to support platoon operations. Furthermore, the scheduling of truck operations should include recharging sessions. Platoons of electric trucks must be able to complete their routes efficiently by balancing charging needs with delivery schedules and route planning.

These research perspectives could help pave the way for more efficient planning of truck platooning transportation in the forestry sector and beyond. This would enhance operational performance, sustainability, and adaptability in dynamic working conditions.

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