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Optimal Platoon Formation and Stable Benefit Allocation in Mixed-Energy Truck Fleets under Size Limitations ⋆

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Abstract: In this paper, we investigate cooperative platoon formation and benefit allocation in mixed-energy truck fleets composed of both electric and fuel-powered trucks. The central challenge arises from the platoon-size constraint, which limits the number of trucks permitted in each platoon and introduces combinatorial coupling into the search for optimal platoon formation structures. We formulate this problem as a coalitional game with bounded coalition sizes and derive a closed-form characterization of the optimal coalition structure that maximizes the fleet-wide platooning benefit. Building on this structure, we develop a type-based least-core payoff allocation scheme that guarantees stability within the coalition-structure core (CS-core). For cases in which the CS-core is empty, we compute the least-core radius to determine the minimal relaxation required to achieve approximate stability. Through numerical studies, we demonstrate that the proposed framework consistently achieves the highest total platooning benefit among all feasible formation configurations while providing stable benefit allocations that outperform existing baseline methods.

Keywords: Electric vehicles, mixed-energy truck platooning, coalition structure.

1. INTRODUCTION

Road freight electrification has emerged as a pivotal pathway for decarbonizing the transport sector in response to growing concerns over fossil fuel depletion and accelerating climate change (Link et al., 2024; Bai et al., 2025b). Compared with conventional fuel-powered trucks (FPTs), electric trucks (ETs) offer substantial advantages, including higher energy efficiency, zero tailpipe emissions, and reduced maintenance and operating costs, contributing to a cleaner and more sustainable freight transportation system. To accelerate ET adoption, governments and private investors have introduced a range of supportive initiatives, such as purchase subsidies, carbon taxation policies, large-scale charging infrastructure development, and the development of optimal charging strategies (Bai et al., 2023b). As freight carriers progressively incorporate ETs into their fleets, traditional FPT fleets are gradually transforming into *mixed-energy truck fleets* that contain both FPTs and ETs. This transition phase is expected to persist until road freight transportation is fully electrified.

Truck platooning is an advanced cooperative driving technique in intelligent transportation systems and has been well developed over the past few decades (Tsugawa et al., 2016). By leveraging vehicle-to-vehicle communication and automated cruise control, platooning enables trucks to travel in closely coordinated formations safely and seamlessly. The shorter inter-vehicle gaps and reduced aerodynamic drag, particularly for trailing trucks, yield multiple benefits, including increased road capacity, mitigated traffic congestion, enhanced driving safety (Axelsson, 2016), and reduced operational costs (Bai et al., 2023a). While the leading truck typically receives negligible energy savings, each follower can achieve a 10%-20% reduction in energy consumption (Van De Hoef et al., 2017), leading to substantial cost savings. In mixed-energy truck fleets, although platooning remains advantageous, the magnitude and nature of the benefits, such as energy consumption patterns and cost savings, vary significantly across vehicle types, making the formation of profitable platoons and stable benefit allocation scheme design more difficult.

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Forming platoons requires coordination among trucks, which can be achieved through various strategies, such as planning delivery routes to maximize the overlapping road segments (Meisen et al., 2008), regulating trucks' velocity to merge into platoons, and scheduling waiting times at midway hubs (Wang et al., 2025). These coordination mechanisms fundamentally rely on which trucks choose to cooperate and how the resulting benefits are shared among participants. In particular, identifying appropriate platoon partners determines the total platooning benefit that can be achieved, whereas the benefit allocation scheme governs how this benefit is distributed among individual trucks, shaping their incentives to cooperate.

Although platoon formation and incentive-design schemes have been extensively explored for homogeneous FPT platoons, effective solutions for mixed-energy truck fleets remain limited. For instance, Johansson and Mårtensson (2019) developed benefit-distribution models for the platoon matching problem, treating vehicles as strategic agents that independently adjust their departure times to maximize individual platooning gains. These interactions are formulated as a non-cooperative game, with Nash equilibrium used to characterize the stable platoon configuration. Similarly, Sun and Yin (2019) addressed the problem by first maximizing the total platooning profit and then allocating benefits so that no vehicle has an incentive to deviate from its assigned platoon. However, these studies assume homogeneous vehicle characteristics, overlooking the imbalanced cost savings in mixed-energy fleets. Recently, Chen et al. (2023) studied cost allocation among multiple carriers by optimizing vehicle departure times to minimize total operational cost while ensuring approximate core stability. Nevertheless, it considers only grand-coalition platooning while not accounting for the practical platoon size constraints.

This paper investigates the problem of optimal platoon formation and benefit allocation in a mixed-energy truck fleet comprising FPTs and ETs. Due to safety and technological constraints, the size of each platoon is bounded. We address the problem within a game-theoretic framework and develop a payoff allocation scheme to ensure stability of the coalition structure. The major contributions are:

- We model the strategic interactions among trucks in forming mixed-energy platoons as a coalitional game and establish necessary and sufficient conditions for the existence of a feasible coalition structure under any fleet compositions and platoon size limits.
- We derive optimality conditions for identifying the platoon formation and leader selections that maximize the total platooning benefit attainable by the fleet. An efficient algorithm to construct the optimal coalition structure is developed accordingly.
- Under the optimal coalition structure, we design a type-based least-core payoff allocation scheme that lies in the coalition-structure core (CS-core) whenever the CS-core is nonempty. In addition, it minimizes the least-core radius when the CS-core is empty, thus ensuring maximal formation stability.

Finally, simulation studies validate the theoretical findings and demonstrate the superior stability performance of the proposed framework. We note that this work extends our recent study in (Bai et al., 2025a), which addressed stable payoff allocation in mixed-energy truck platoons but did not take platoon size limitations into account.

Notation: Let $\mathbb{R}$, $\mathbb{R}_+$, and $\mathbb{N}$ denote the sets of real numbers, positive real numbers, and non-negative integers, respectively. The cardinality of a set $\mathcal{S}$ is denoted by $|\mathcal{S}|$. The ceiling operator $\lceil y \rceil$ gives the smallest integer greater than or equal to y, while the floor operator $\lfloor y \rfloor$ returns the largest integer less than or equal to y.

2. PRELIMINARIES AND PROBLEM FORMULATION

This section formally presents the mixed-energy truck platoon formation problem within a coalitional game framework. First of all, some key concepts are introduced (Saad et al., 2009; Béal et al., 2013).

Definition 1. (Coalitional game). A coalitional game with transferable utility is a pair $(\mathcal{N}, v)$, where
(1) $\mathcal{N}=\{1,2,\ldots,N\}$ with $N\in\mathbb{N}$ is a finite set of players;
(2) $v: 2^{\mathcal{N}} \to \mathbb{R}$ is a characteristic function, which assigns a real value $v(\mathcal{S})$ to each coalition $\mathcal{S}\subseteq\mathcal{N}$ with $v(\emptyset)=0$.
The game has transferable utility if the value $v(\mathcal{S})$ can be freely distributed among members of the coalition $\mathcal{S}$.

Definition 2. (Coalition structure). For a coalitional game $G=(\mathcal{N}, v)$, $\mathcal{P}=\{\mathcal{S}_1,\ldots,\mathcal{S}_P\}$ with $\mathcal{S}_m\neq\emptyset$ for $m=1,\ldots,P$, is called a coalition structure (i.e., a partition of $\mathcal{N}$) if
(a) $\mathcal{S}_m\cap\mathcal{S}_\ell=\emptyset$, $\forall\mathcal{S}_m,\mathcal{S}_\ell\in\mathcal{P}$, $m\neq\ell$ (disjoint coalitions);
(b) $\bigcup_{m=1}^{P}\mathcal{S}_m=\mathcal{N}$ (complete coverage).

Definition 3. (Payoff vector). Given a coalitional game $G=(\mathcal{N}, v)$ and a coalition structure $\mathcal{P}$, a vector $x=[x_1,\ldots,x_N]^\top\in\mathbb{R}^N$ is referred to as a payoff vector if
(a) $x_i\geq v(\{i\})$, $\forall i\in\mathcal{N}$ (individual rationality);
(b) $\sum_{i\in\mathcal{S}_m}x_i=v(\mathcal{S}_m)$, $\forall\mathcal{S}_m\in\mathcal{P}$ (coalitional efficiency).

In the above definitions, each subset $\mathcal{S}\subseteq\mathcal{N}$ is known as a *coalition*, and the set $\mathcal{N}$ is known as the *grand coalition*. The characteristic function $v(\mathcal{S})$ represents the total value (i.e., payoff) that can be achieved by all players in $\mathcal{S}$ through cooperation in game $G=(\mathcal{N}, v)$.

Definition 4. (CS-core). Consider a coalitional game $G=(\mathcal{N}, v)$ and a coalition structure $\mathcal{P}=\{\mathcal{S}_1,\ldots,\mathcal{S}_P\}$. The CS-core is the set of all feasible payoff vectors $x=[x_1,\ldots,x_N]^\top\in\mathbb{R}^N$ such that no coalition external to $\mathcal{P}$ can profitably deviate. Formally,

$$\text{CS-core}(\mathcal{P}) = \Big\{x\in\mathbb{R}^N \,\big|\, \sum_{i\in\mathcal{S}_m}x_i=v(\mathcal{S}_m),\ \forall\mathcal{S}_m\in\mathcal{P}, \text{ and} \sum_{i\in\mathcal{C}}x_i\geq v(\mathcal{C}),\ \forall\mathcal{C}\subseteq\mathcal{N}\Big\}. \quad (1)$$

Throughout this paper, we consider a hub-based platoon formation game denoted by $G_p=(\mathcal{N}, v)$, where trucks departing from an origin hub are grouped into platoons heading to the same destination hub. The set of players (i.e., trucks) is denoted as $\mathcal{N}=\{1,\ldots,N\}=\mathcal{N}_e\cup\mathcal{N}_f$, where $\mathcal{N}_e$ and $\mathcal{N}_f$ represent the sets of ETs and FPTs, respectively. Each truck $i\in\mathcal{N}$ is associated with a type $T_i\in\{e,f\}$, indicating if it is an ET or FPT. The platoon size limitation is captured by $M\in\mathbb{N}$, with $2\leq M<N$.

Extensive field tests and experimental studies have indicated that follower trucks of the same type and load receive similar platooning benefits, while the benefit to the leader is significantly smaller and can be neglected (Van De Hoef et al., 2017). For this reason, we denote by $\epsilon_e, \epsilon_f \in \mathbb{R}_+$ the operational cost savings per travel time unit in platoons for an ET and FPT follower, respectively, and assume the leader obtains zero benefit. Since ETs generally incur lower cost savings than FPTs, we consider $\epsilon_e \leq \epsilon_f$.

The characteristic function $v(\mathcal{S})$ of game G_p is defined as the maximum platooning benefit attainable by all trucks in the coalition $\mathcal{S} \subseteq \mathcal{N}$ via optimally assigning the leader role in $\mathcal{S}$. Specifically, let $S = |\mathcal{S}| = S_e + S_f$, where $S_e = |\mathcal{S} \cap \mathcal{N}_e|$ and $S_f = |\mathcal{S} \cap \mathcal{N}_f|$ denote the numbers of ETs and FPTs in $\mathcal{S}$, respectively. Then, $v(\mathcal{S})$ is denoted as

$$\begin{aligned} v(\mathcal{S}) &:= \max_{L \in \mathcal{S}} v(\mathcal{S}, L) \\ &= \begin{cases} 0, & \text{if } S = 0, \\ \epsilon_e(S_e - 1) + \epsilon_f S_f, & \text{if } 1 \leq S \leq M, S_e \geq 1, \\ \epsilon_f(S_f - 1), & \text{if } 1 \leq S \leq M, S_e = 0, \end{cases} \end{aligned} \tag{2}$$

where $L \in \mathcal{S}$ denotes the leader truck of the coalition (i.e., platoon) $\mathcal{S}$. Note that, given $\epsilon_e \leq \epsilon_f$, $v(\mathcal{S})$ is maximized by selecting an ET as the platoon leader whenever $S_e \geq 1$.

In mixed-energy truck fleets, the fleet manager aims to maximize the total platooning benefit by presenting an optimal coalition structure $\mathcal{P}^*$ subject to the platoon size limitation. However, individual trucks, often owned by different operators, may prioritize their own gains over the fleet-wide outcome. To maximize fleet-wide benefits while ensuring stable platoon formation and sustained cooperation among heterogeneous trucks, it is essential to address the following key questions:

(i) What is the optimal coalition structure of game G_p so that each coalition satisfies the platoon-size limit M while maximizing the total platooning benefit?
(ii) Under the optimal coalition structure $\mathcal{P}^*$, how to allocate the platooning benefits among all participants so that the payoff vector lies in the CS-core?

3. OPTIMAL PLATOON FORMATION

In this section, we provide solutions to problem (i) by developing an efficient method to identify the optimal coalition structure of G_p. We first establish conditions that ensure the existence of feasible coalition structures.

Lemma 1. (Feasibility condition). Let $\mathcal{N}$ be a set of $N \geq 2$ players and let M be an integer satisfying $2 \leq M < N$. A coalition structure $\mathcal{P} = \{\mathcal{S}_1, \ldots, \mathcal{S}_P\}$ that forms a partition of $\mathcal{N}$ and satisfies $2 \leq |\mathcal{S}_m| \leq M$ for all m exists if and only if there exists an integer $P \geq 1$ such that

$$\left\lceil \frac{N}{M} \right\rceil \leq P \leq \left\lfloor \frac{N}{2} \right\rfloor. \tag{3}$$

Proof: Recall that $2 \leq M < N$. We prove the necessity and sufficiency of the feasibility condition, respectively.

($\Rightarrow$) Necessity: Suppose there exists a feasible coalition structure $\mathcal{P} = \{\mathcal{S}_1, \ldots, \mathcal{S}_P\}$ such that $2 \leq |\mathcal{S}_m| \leq M$ for all m. Summing the coalition sizes yields

$$N = \sum_{m=1}^{P} |\mathcal{S}_m|.$$

Since each coalition satisfies $|\mathcal{S}_m| \geq 2$, we have $N \geq 2P$. In addition, as $|\mathcal{S}_m| \leq M$, we obtain $N \leq MP$. Therefore, $2P \leq N \leq MP$ holds, which is equivalent to

$$\left\lceil \frac{N}{M} \right\rceil \leq P \leq \left\lfloor \frac{N}{2} \right\rfloor.$$

($\Leftarrow$) Sufficiency: Assume that there exists an integer $P \geq 1$ satisfying (3), i.e., $2P \leq N \leq MP$. We will show that N trucks can be partitioned into P platoons whose sizes lie in $[2, M]$ and sum to N. We discuss two cases:

Case (1) $M = 2$. In this case, $2P \leq N \leq 2P$ forces $N = 2P$. Thus, the only feasible coalition structure consists of P platoons, each of size 2.

Case (2) $M \geq 3$. Let us start with P platoons of size 2, which corresponds to $2P$ trucks in total. The remaining number of trucks is denoted as

$$r = N - 2P \geq 0.$$

From $N \leq MP$, we obtain $r \leq (M-2)P$. Next, we distribute these r trucks across the P platoons by adding at most $(M-2)$ trucks to each. Define that

$$q := \left\lfloor \frac{r}{M-2} \right\rfloor, \quad s := r - q(M-2).$$

Thus, $0 \leq s < M-2$. We increase the sizes of q platoons from 2 to M by adding $(M-2)$ trucks to each. If $s > 0$, increase one additional platoon from size 2 to $2+s$, and all other platoons remain at size 2. This construction yields q platoons of size M, one platoon of size $2+s \in \{3, \ldots, M-1\}$ if $s > 0$, and all other platoons of size 2. Consequently, all platoon sizes lie in $[2, M]$. The total number of trucks is

$$2P + q(M-2) + s = 2P + r = N.$$

Thereby, a feasible partition of N trucks into P platoons exists. Since every platoon contains at least two trucks, a leader can be designated for each. This proves the feasibility condition in Lemma 1. ■

Lemma 1 establishes conditions under which a feasible coalition structure exists under the platoon size constraint. In particular, the lower bound on P in condition (3) guarantees that no platoon exceeds the size limit M, while the upper bound ensures that every platoon contains at least two trucks so that no truck fails to join a platoon. On this basis, we present the optimal platoon formation structure for the game G_p through the following results.

Theorem 1. (Optimal platoon formation). Let $N_e = |\mathcal{N}_e|$ and $N_f = |\mathcal{N}_f|$ denote the numbers of ETs and FPTs in $\mathcal{N}$, with $N_e + N_f = N$. Suppose the feasibility condition in Lemma 1 holds. Then:

(a) The optimal coalition structure of game $G_p = (\mathcal{N}, v)$, i.e., the one that maximizes the total platooning benefit, is obtained by forming the smallest number of feasible platoons, denoted as P^*, which equals

$$P^* = \begin{cases} \left\lceil \dfrac{N}{M} \right\rceil, & \text{if } M \geq 3, \\ \dfrac{N}{2}, & \text{if } M = 2 \text{ and } N \text{ is even.} \end{cases} \tag{4}$$

(b) Let L_e^* and L_f^* be the numbers of ET and FPT leaders assigned to the P^* platoons, which are determined by

$$L_e^* = \min\{N_e, P^*\}, \quad L_f^* = P^* - L_e^*. \tag{5}$$

Proof: Consider any feasible coalition structure $\mathcal{P} = \{\mathcal{S}_1, \ldots, \mathcal{S}_P\}$ with $2 \le |\mathcal{S}_m| \le M$, and denote as L_e, L_f the numbers of ET and FPT leaders, respectively, satisfying

$$L_e + L_f = P, \quad 0 \le L_e \le N_e, \quad 0 \le L_f \le N_f.$$

The numbers of ET and FPT followers are denoted as

$$F_e = N_e - L_e, \quad F_f = N_f - L_f.$$

In line with the characteristic function given in (2), the total platooning benefit under coalition structure $\mathcal{P}$ is

$$\begin{aligned} V(\mathcal{P}) &= \sum_{m=1}^{P} v(\mathcal{S}_m) \\ &= \epsilon_e(N_e - L_e) + \epsilon_f(N_f - L_f) \\ &= \underbrace{\big(\epsilon_e N_e + \epsilon_f N_f\big)}_{\text{Constant in } \mathcal{P}} - \big(\epsilon_e L_e + \epsilon_f L_f\big). \end{aligned} \tag{6}$$

Thus, maximizing $V(\mathcal{P})$ over all feasible platoon coalition structures is equivalent to minimizing $(\epsilon_e L_e + \epsilon_f L_f)$ subject to the feasibility constraints on P, L_e and L_f. Below, we prove results (a) and (b), respectively.

(a) For any fixed P, we have

$$\epsilon_e L_e + \epsilon_f L_f \ge P \cdot \min\{\epsilon_e, \epsilon_f\}.$$

By (6), the total benefit $V(\mathcal{P})$ is nonincreasing in P. Therefore, maximizing $V(\mathcal{P})$ requires selecting the smallest feasible number of platoons. From Lemma 1, when $M = 2$, a feasible partition exists if and only if N is even. In this case, the number of platoons is uniquely determined by $P = N/2$. When $M \ge 3$, as the interval $\big[\lceil N/M \rceil, \lfloor N/2 \rfloor\big]$ is nonempty, a feasible partition exists for every N, and the minimum feasible number of platoons is

$$P_{\min} = \left\lceil \frac{N}{M} \right\rceil. \tag{7}$$

This proves (4) in part (a).

(b) Under the optimal coalition structure $\mathcal{P}^*$, $P = P^*$ is fixed. By (6), maximizing $V(\mathcal{P})$ is equivalent to solving

$$\begin{aligned} \min_{L_e, L_f} \quad & \epsilon_e L_e + \epsilon_f L_f \\ \text{s. t.} \quad & L_e + L_f = P^*, \ 0 \le L_e \le N_e, \ 0 \le L_f \le N_f. \end{aligned}$$

Since $\epsilon_e \le \epsilon_f$, and

$$\epsilon_e L_e + \epsilon_f L_f = \epsilon_f P^* + (\epsilon_e - \epsilon_f) L_e,$$

the objective is minimized by choosing the maximum possible L_e. Thus, $L_e^* = \min\{N_e, P^*\}$. The remaining platoons must then be led by FPTs, so $L_f^* = P^* - L_e^*$. This establishes part (b) and completes the proof. ∎

Theorem 1 reveals that the total platooning benefit is maximized when the fleet forms the minimum number of feasible platoons. For any feasible problem, the optimal platoon formation can be constructed by Algorithm 1.

Algorithm 1 Construct the Optimal Platoon Formation

Input: Truck set $\mathcal{N} = \mathcal{N}_e \cup \mathcal{N}_f$; platoon size limit $N > M \ge 2$ satisfying Lemma 1.
Output: Optimal platoon formation structure $\mathcal{P}^*$.

Compute P^*, L_e^*, and L_f^* according to Theorem 1.
Select L_e^* trucks from $\mathcal{N}_e$ and L_f^* trucks from $\mathcal{N}_f$ to form the leader set $\mathcal{L}^* = \{L_1, \ldots, L_{P^*}\}$.
Initialize $\mathcal{P}^* \leftarrow \emptyset$ and $\mathcal{F} \leftarrow \mathcal{N} \backslash \mathcal{L}^*$.
for $m = 1$ to $P^* - 1$ **do**
    Create platoon $\mathcal{S}_m \leftarrow \{L_m\}$.
    while $|\mathcal{S}_m| < M$ **do**
        Select an arbitrary follower $i \in \mathcal{F}$.
        $\mathcal{S}_m \leftarrow \mathcal{S}_m \cup \{i\}$; $\mathcal{F} \leftarrow \mathcal{F} \backslash \{i\}$.
    end while
    $\mathcal{P}^* \leftarrow \mathcal{P}^* \cup \{\mathcal{S}_m\}$.
end for
Create the last platoon $\mathcal{S}_{P^*} \leftarrow \{L_{P^*}\}$.
while $|\mathcal{S}_{P^*}| < M$ **and** $|\mathcal{F}| > 0$ **do**
    Select an arbitrary follower $i \in \mathcal{F}$.
    $\mathcal{S}_{P^*} \leftarrow \mathcal{S}_{P^*} \cup \{i\}$; $\mathcal{F} \leftarrow \mathcal{F} \backslash \{i\}$.
end while
if $|\mathcal{S}_{P^*}| = 1$ **then**
    Select any index $q \in \{1, \ldots, P^* - 1\}$ with $|\mathcal{S}_q| > 2$.
    Select an arbitrary follower $j \in \mathcal{S}_q \backslash \{L_q\}$.
    $\mathcal{S}_{P^*} \leftarrow \mathcal{S}_{P^*} \cup \{j\}$; $\mathcal{S}_q \leftarrow \mathcal{S}_q \backslash \{j\}$.
end if
$\mathcal{P}^* \leftarrow \mathcal{P}^* \cup \{\mathcal{S}_{P^*}\}$.
return $\mathcal{P}^*$.

4. TYPE-BASED LEAST-CORE PAYOFF ALLOCATION SCHEME

While $\mathcal{P}^*$ maximizes the fleet-wide platooning benefit, trucks owned by different operators may prioritize their individual gains. To achieve stable allocations among trucks, we develop below a type-based payoff allocation scheme under $\mathcal{P}^*$ that maximizes coalition stability. Based on the CS-core of a general coalitional game given in Definition 4, we specialize the concept to the platoon formation game G_p and introduce the notion of the least-core.

Definition 5. (CS-core of G_p). Consider the game $G_p = (\mathcal{N}, v)$ under the coalition structure $\mathcal{P}^* = \{\mathcal{S}_1, \ldots, \mathcal{S}_{P^*}\}$ determined by Theorem 1. A payoff vector $x = [x_1, \ldots, x_N]^\top \in \mathbb{R}^N$ is said to be feasible under $\mathcal{P}^*$ if

$$\sum_{i \in \mathcal{S}_m} x_i = v(\mathcal{S}_m), \quad \forall \mathcal{S}_m \in \mathcal{P}^*. \tag{8}$$

The CS-core of G_p associated with $\mathcal{P}^*$ is defined as

$$\begin{aligned} &\text{CS-core}(\mathcal{P}^*) \\ &= \Big\{ x \in \mathbb{R}^N \,\big|\, \sum_{i \in \mathcal{S}_m} x_i = v(\mathcal{S}_m), \forall \mathcal{S}_m \in \mathcal{P}^*, \text{ and} \\ &\qquad \sum_{i \in \mathcal{C}} x_i \ge v(\mathcal{C}), \forall \mathcal{C} \subseteq \mathcal{N}, \text{with } 2 \le |\mathcal{C}| \le M \Big\}. \end{aligned} \tag{9}$$

Definition 6. (Least-core of G_p). Consider the game $G_p = (\mathcal{N}, v)$ under the coalition structure $\mathcal{P}^* = \{\mathcal{S}_1, \ldots, \mathcal{S}_{P^*}\}$ determined by Theorem 1. A payoff vector $x = [x_1, \ldots, x_N]^\top \in \mathbb{R}^N$ is said to be ε–feasible if

$$\sum_{i \in \mathcal{S}_m} x_i = v(\mathcal{S}_m), \quad \forall \mathcal{S}_m \in \mathcal{P}^*, \tag{10a}$$

$$\sum_{i \in \mathcal{C}} x_i \ge v^*(\mathcal{C}) - \varepsilon, \quad \forall \mathcal{C} \subseteq \mathcal{N}, \text{with } 2 \le |\mathcal{C}| \le M, \tag{10b}$$

where $v^*(\mathcal{C})$ denotes the maximal value attainable by $\mathcal{C}$, as given in (2). The least-core radius of G_p under $\mathcal{P}^*$ is then defined as

$$\begin{aligned} \varepsilon^* = \ & \min_{x \in \mathbb{R}^N, \ \varepsilon \ge 0} \ \varepsilon \\ & \text{s. t.} \quad x \text{ is } \varepsilon\text{–feasible}. \end{aligned} \tag{11}$$

Accordingly, the set

$$\text{LC}(G_p, \mathcal{P}^*) = \big\{ x \in \mathbb{R}^N \,|\, x \text{ is } \varepsilon^*\text{–feasible} \big\} \tag{12}$$

is known as the least-core of G_p associated with $\mathcal{P}^*$.

Remark 1. The quantity ε^* represents the minimal uniform relaxation of the coalition-stability constraints required to sustain $\mathcal{P}^*$ against all admissible deviations. If $\varepsilon^* = 0$, then the CS-core of G_p under $\mathcal{P}^*$ is nonempty. If $\varepsilon^* > 0$, the value of ε^* quantifies the least amount of relaxation needed to achieve approximate stability, with smaller values indicating a higher degree of stability for the optimal platoon structure.

In what follows, we present a type-based payoff allocation scheme under the optimal platoon formation $\mathcal{P}^*$, where each ET and FPT receives a uniform payoff x_e and x_f, respectively. To handle both CS-core stable and unstable scenarios within a unified framework, the scheme is designed to maximize the achievable CS-core stability.

Let $\mathcal{P}^*$ be the optimal coalition structure of G_p determined by Theorem 1. Consider the type-based payoff allocations

$$x_i = \begin{cases} x_e, & \text{if } T_i = e, \\ x_f, & \text{if } T_i = f. \end{cases} \tag{13}$$

Proposition 1. Define $(x_e^*, x_f^*, \varepsilon^*)$ as an optimal solution of the following problem:

$$\min_{x_e, x_f, \varepsilon \geq 0} \quad \varepsilon \tag{14}$$

$$\text{s. t.} \quad x_e N_e + x_f N_f = \epsilon_e (N_e - L_e^*) + \epsilon_f (N_f - L_f^*), \tag{14a}$$

$$x_e C_e + x_f C_f \geq v^*(\mathcal{C}) - \varepsilon, \quad \forall \mathcal{C} \subseteq \mathcal{N},\ 2 \leq |\mathcal{C}| \leq M, \tag{14b}$$

$$x_e, x_f \in \mathbb{R}_+, \tag{14c}$$

where C_e and C_f denote the numbers of ETs and FPTs in coalition $\mathcal{C}$ with $C_e + C_f = |\mathcal{C}|$. Let $x^* \in \mathbb{R}^N$ be the induced payoff vector, with $x_i^* = x_e^*$ and $x_i^* = x_f^*$. Then:
(a) If $\varepsilon^* = 0$, then x^* lies in the CS-core of G_p under $\mathcal{P}^*$.
(b) If $\varepsilon^* > 0$, x^* minimizes the least-core radius over all allocations of the form (13).

Proof: The efficiency constraint (14a) ensures that x is feasible under $\mathcal{P}^*$. If $\varepsilon^* = 0$, all stability constraints satisfy

$$x_e^* C_e + x_f^* C_f \geq v^*(\mathcal{C}), \quad \forall \mathcal{C} \subseteq \mathcal{N},\ 2 \leq |\mathcal{C}| \leq M.$$

Thus, $x^* \in$ CS-core$(\mathcal{P}^*)$ by Definition 4. If $\varepsilon^* > 0$, solving the optimization problem (14) minimizes the maximal stability violation over all type-based allocations. By the definition of the least-core radius, x^* attains the minimum least-core radius among all allocations of the form (13). ■

5. NUMERICAL STUDY

5.1 Optimality of the Platoon Formation

We consider a mixed-energy truck fleet at a hub with the truck set $\mathcal{N} = \{1, \ldots, 9\}$, where the ET set is $\mathcal{N}_e = \{1, 2, 3\}$ and the FPT set is $\mathcal{N}_f = \{4, \ldots, 9\}$. The platoon size is constrained by $M = 4$. Following the realistic platooning benefit evaluation (Bai et al., 2025b), the parameters are set as $\epsilon_f = 0.07$ and $\epsilon_e = 0.048$ dollars per kilometer.

As the feasibility condition in Lemma 1 is satisfied, we proceed to construct the optimal platoon structure. Applying Theorem 1 and Algorithm 1, we have

$$P^* = \left\lceil \frac{N}{M} \right\rceil = \left\lceil \frac{9}{4} \right\rceil = 3, \quad L_e^* = 3, \quad L_f^* = 0.$$

Thus, an optimal platoon coalition that maximizes the total platooning benefit of the fleet is obtained as

$$\mathcal{P}^* = \{\{1, 4, 5, 6\}, \{2, 7, 8\}, \{3, 9\}\}.$$

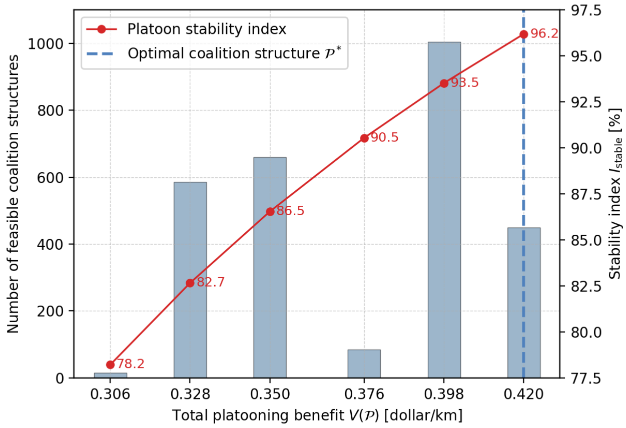

Fig. 1. Comparison of the total platooning benefit and stability index in different feasible coalition structures.

The total benefit achieved by the fleet under $\mathcal{P}^*$ is

$$V(\mathcal{P}^*) = 6\epsilon_f = 0.42 \text{ dollar/km}.$$

To demonstrate the optimality of $\mathcal{P}^*$, we show in Fig. 1 the total platooning benefit attained by all feasible coalition structures. The x-axis represents the total benefit of each feasible coalition, while the y-axis shows the number of coalition structures achieving the corresponding benefit. The results show that the proposed platoon formation structure $\mathcal{P}^*$ achieves the largest total platooning benefit across all feasible configurations, thereby validating the optimality of the proposed formation approach.

To further evaluate the stability of each feasible coalition structure $\mathcal{P}$ under the type-based least-core allocation, we introduce the following *platoon stability index*:

$$I_{\text{stable}}(\mathcal{P}, x) := \left(1 - \frac{\varepsilon^*(x)}{V(\mathcal{P})}\right) \times 100\%, \tag{15}$$

where $V(\mathcal{P}) = \sum_{\mathcal{S}_m \in \mathcal{P}} v(\mathcal{S}_m)$ is the platooning benefit of $\mathcal{P}$, and $\varepsilon^*(x)$ is the least-core radius corresponding to the optimal allocation, representing the minimum relaxation required for the CS-core of G_p under $\mathcal{P}$ to be nonempty. By solving the problem in Proposition 1, the optimal type-based least-core payoff allocation under $\mathcal{P}^*$ is

$$x_e^* \approx 0.032, \quad x_f^* \approx 0.054,$$

with the least-core radius $\varepsilon^*(x^*) \approx 0.016$. The resulting stability indices are shown on the right y-axis of Fig. 1. As shown, the proposed allocation scheme under the optimal coalition structure $\mathcal{P}^*$ attains the highest stability index among all other feasible coalition structures, demonstrating its superior stability performance.

5.2 Comparison with Baseline Allocation Schemes

We evaluate the stability of the proposed allocation scheme by comparing it against the following baseline allocation methods under the optimal coalition structure $\mathcal{P}^*$:

- **Fleet-based Equal Split (F-ES):** Each truck equally shares $V(\mathcal{P}^*)$, regardless of its type or role.
- **Platoon-based Equal Split (P-ES):** All trucks in each platoon $\mathcal{S}_m \in \mathcal{P}^*$ receive an equal share of the benefit $v(\mathcal{S}_m)$, independent of their type or role.
- **Follower-only (FO):** Only followers in each platoon $\mathcal{S}_m \in \mathcal{P}^*$ share the total benefit $v(\mathcal{S}_m)$ equally, while the platoon leader receives no benefit.

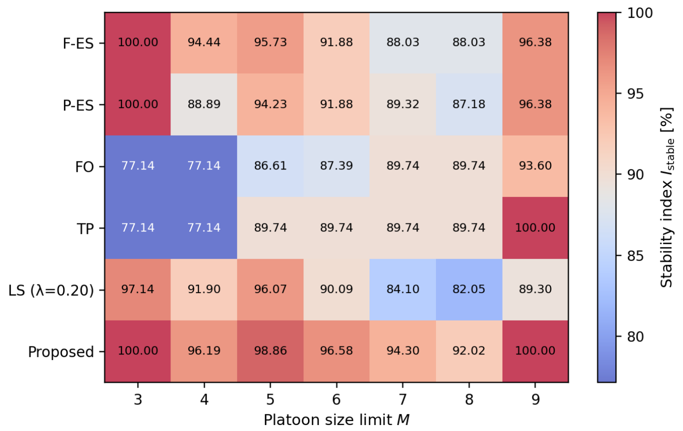

Fig. 2. Comparison of the stability index in different payoff allocation schemes under $\mathcal{P}^*$ with different size limits.

- **Type-proportional (TP):** For any truck $i \in \mathcal{S}_m \in \mathcal{P}^*$, the allocation is

$$x_i = \begin{cases} 0, & \text{if } i = L_m, \\ v(\mathcal{S}_m)\dfrac{\epsilon_{T_i}}{\sum_{j\in\mathcal{S}_m\setminus\{L_m\}}\epsilon_{T_j}}, & \text{otherwise.} \end{cases}$$

- **Leader-Subsidy (LS):** Let $\lambda \in (0,1]$. For any truck $i \in \mathcal{S}_m \in \mathcal{P}^*$,

$$x_i = \begin{cases} \lambda\, v(\mathcal{S}_m), & \text{if } i = L_m, \\ (1-\lambda)\dfrac{v(\mathcal{S}_m)\epsilon_{T_i}}{\sum_{j\in\mathcal{S}_m\setminus\{L_m\}}\epsilon_{T_j}}, & \text{otherwise.} \end{cases}$$

Fig. 2 shows the stability indices of the proposed method and the baseline methods under the optimal coalition structure $\mathcal{P}^*$, with $\lambda = 0.2$ and $M = 3, \dots, 9$. It shows that the FO and TP schemes yield lower stability indices across most settings, indicating that assigning zero benefit to leaders undermines coalition stability. The F-ES and P-ES schemes show comparable stability performance, offering moderate stability. While the least-core radius $\varepsilon^*(x)$ of our method is nonzero for some cases (e.g., $M = 4, \dots, 8$), the proposed allocation scheme consistently achieves the highest stability index in all scenarios, showing good stability and robustness against deviations.

6. CONCLUSION

In this paper, we addressed the platoon formation problem for a mixed-energy truck fleet comprised of both FPTs and ETs while taking into account platoon size constraints. We modeled the strategic interactions among trucks in a coalitional game framework and established conditions to ensure the feasibility and optimality of the coalition structure. On this basis, we developed an efficient algorithm to construct the optimal platoon formation, achieving the maximal fleet-wide platooning benefit. Moreover, a type-based least-core payoff allocation scheme was developed under the optimal platoon formation that maximizes the coalition stability. Extensive numerical studies demonstrated that the proposed platoon formation structure achieves the highest total benefit, and the developed allocation scheme outperforms existing baseline methods. As for future work, we would extend this framework to multi-hub platoon formation and coordination, enabling applications to mixed-energy truck platooning in large-scale road transportation.

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