Level-1 truck platooning optimisation: methodology and network-wide solutions

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1 Introduction

Truck platooning (TP) is defined as the linking of two or more trucks in convoy, with different levels of automation, potentially disrupting the road freight industry and the freight modal competition (Bhoopalam et al., 2018; Marzano et al., 2022). Level-1 TP (TP1) is characterized by a fully manned platoon, with real-world estimates of average fuel saving and emissions in the 8%-14% range, thanks to reduced aerodynamic drags.

Truck drivers can join or leave TP1 convoys opportunistically (online, or on-the-fly), or a third-party TP manager can optimize their overlapping based on pre-trip requests (offline, or pre-trip), given flexibility in departure/arrival times by truck drivers. The network-wide logic of a TP manager is non trivial, and represents the research question tackled by the paper.

Several papers attempted to optimise TP manager operations, a problem proven to be NP-hard by Larsson et al. (2015). Van de Hoef et al. (2015a, 2015b) developed a first-order fuel model to get optimal convoys, taking into account speed-dependent fuel consumption and platooning decisions, in the form of a partitioning-around-medoids (PAM) algorithm. Luo et al. (2018) proposed a coordinated platooning optimisation – involving scheduling, routing, and speed selection – in the form of a mixed-integer linear problem, solved heuristically by partitioning the set of vehicles first and then sub-optimising their routing. Larsen et al. (2019) optimised truck platoons to/from a single hub, under static and dynamic dispatching strategies, respectively with an integer linear programming (ILP) and a mixed ILP (MILP) approach. Luo and Larson (2022) proposed an iterative decomposition-based heuristic for centralized planning, with a two-step solution of the routing problem first and then scheduling, eventually improved by Zhao and Leus (2023). Johansson et al. (2022) treated the hub-based platoon coordination as a non-cooperative platoon coordination game, proving the existence of a Nash equilibrium. Johansson et al. (2023a) studied optimal hub-based platooning at hubs along a corridor and compared decentralized, distributed, and centralized policies. Bai et al. (2023) proposed a distributed multi-fleet platooning framework, based on scheduling discretized waiting times at hubs, solved by dynamic programming. A similar approach was followed by Johansson et al. (2023), who proposed a platooning architecture based on service, strategic, tactical, and operational layers.

Overall, the review of the literature offers some approaches to optimise TP operations, however none of them applicable to real-world networks with multiple origin-destination points. In fact, the capability of managing TP operations can be primarily offered by highway managers and/or by relevant freight network integrators, both looking for a system-wide optimisation. Enabling such capabilities to system-wide networks is the primarily research concern of this paper.

2 Methodology

2.1 Problem formulation

The paper tackles the problem of optimising network-wide TP1, leveraging a graph-based formulation of the problem. The problem can be conveniently formulated on a daily basis for pre-trip/offline TP1, that is with all trip requests for day d+1 available at the end of day d, seeking to optimise their overlapping in platoons. It can be also straightforwardly adapted to opportunistic/online platooning, in a rolling horizon formulation that considers only requests available until that moment. The problem is solved in the light of a road network manager, usually an highway/motorway manager, that can adjust the departure/arrival times of TP requests to maximise their overlapping in platoons, given an upper bound on the maximum deviation between posted and offered departure/arrival times.

The main inputs of the procedure are therefore: a network wherein TP1 can take place; a list of pre-trip truck platooning requests R for all origin-destination pair *o-d* in the network; with corresponding desired departure and arrival times t_{ro} and t_{rd} respectively $\forall r \in$R. Assignment to platoons might imply deviations in departure and arrival times, that are assumed to be accepted by truck drivers up to maximum thresholds t_{omax} and t_{dmax} respectively. The problem is further complicated by considering that a truck entering the network operated by the TP manager might join and leave many different platoons along its journey.

Given the inherent complexity of the problem, the paper proposes a formulation based on the optimal partitioning of graphs. In particular, a graph G is built, with as many nodes as the cardinality of R, such that each node represents a trip request. Two nodes i and j belonging to G are connected by an edge ij if trip requests corresponding to i and j can be coupled in a platoon. This occurs formally if (a) the overlapping of the paths of the two trips i and j exceeds a minimum overlapping threshold v_{min}, and (b) the difference between the expected arrival times of the two trucks at the first common link of their respective paths does not exceed the sum of the maximum departure time shifts for trips i and j. The weight of each edge ij equals the fuel savings of a follower truck in a platoon for a length corresponding to the overlapping of paths underlying trip requests i and j.

The paper proves formally that a feasible platooning p is represented by an e-disjoint subgraph $V_p \subseteq G$ with two characteristics: (a) completeness, i.e. a clique; (b) a number of nodes R_p less than the maximum platoon size M. Edges $l \in V_p$ can have different weights w_l, because the overlapping of truck paths might vary across pairs of trucks in the platoon, due to their possibly different origins and destinations. Letting L_{p,R_p-1} be the set of combinations of $R_p - 1$ edges belonging to V_p, of reduced size, identifying the platoon p, the contribution of p to the objective function is:

$$F_p = \max_{\mathrm{L}_{p,R_p-1}} \left\{ \sum_{l=1..\mathrm{Vp}-1} w_l \right\}$$

It is worth noting that this framework, not only allows for considering platoons formed by vehicles travelling between different OD pairs, but also to consider the possibility for a given vehicle to join and leave many different platoons along its journey. This can be done by including zero-weight edges in the initial graph G even connecting trips without path overlap as long as temporal constraints are respected. Such edges, representing a hypothetical platooning possible if one vehicle continued beyond its destination reaching another within the threshold of deviations in departure time, do not affect the objective function but only the clique topology, allowing for representing all types of platooning.

The problem of listing all k-cliques in a graph, i.e. all cliques of given size k, is solved through a parallel implementation of the iconic algorithm of Chiba and Nishizeki (1985). The proposed implementation overcomes the limits of a sequential graph processing by means of a node-parallel architecture which does not rely on a directed acyclic graph (as in Danisch and Balalau, 2018). The results of a computational performance comparison between the proposed node-parallel implementation and the algorithm in Danisch and Balalau (2018) are also discussed.
Once all cliques are listed, the truck platooning problem consists in selecting a set of e-disjoint cliques which maximize the objective function. The resulting integer linear optimization problem (ILP) is solved by means of a branch-and-bound algorithm and a proposed column-generation heuristics, and performance tradeoffs between the two are discussed.

3 Case study and results

The proposed approach has been tested on the challenging test site of the Milano-Napoli A1 motorway in Italy, for a length of about 900 km and 97 entries/exits. Real truck trip data (entrance and exit stations and entrance time) for an entire day together with dynamic travel times, have been provided by the motorway operator Autostrade per l'Italia.

Thresholds t_{omax} and t_{dmax} have been set as linear piecewise increasing functions of travel time, from zero for 1 hours or less of travel time up to 30 minutes for trips of more than 5 hours.
Numerical experiments will be carried out assuming different market penetration rates of the system (from 5% to 30%), in order to test the model under different levels of complexity and evaluate the possible environmental and economic impacts.

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