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Platform-based Platooning to Connect Two Autonomous Vehicle Areas

Nadia Pourmohammad-Zia, Frederik Schulte, Rudy R. Negenborn

Abstract—Autonomous vehicles (AVs) have been successfully applied in closed environments such as ports and industrial zones, while their operation in open areas has a long way to go. The current research is initiated to overcome this limitation by the introduction of platooning as a transfer mode. It investigates a container transportation problem between a port and an industrial area where the platform facilitates collaborative transportation. Both zones are appropriate for automated driving, whereas their connecting route is not. Different carriers are present at the port, and each transportation task can be done either by a truck or an AV. The platform not only operates as the interface between demand points and carriers but also provides a platooning service to move AVs through non-autonomous roads. It specifies the transportation schedules and service fees based on which the carriers will decide whether to use AVs or trucks for each transportation task. This is modeled as a Stackelberg competition, transformed into a conventional mixed-integer model, and solved to optimality. The approach enables demand and resource pooling between the port and industrial area. Numerical results show that the successful application of AVs highly depends on platoon formation costs and regulations.

Keywords - Autonomous Vehicles (AVs), Platooning, Platform, Container Transportation, Game Theory

I. INTRODUCTION

While the transportation sector is expected to undergo a tremendous change by the advent of autonomous vehicles (AVs), their widespread operation has not come to pass yet. The development of essential infrastructures plays the role of a barrier to this transformation. There remains much to be done to bring AVs into open areas and public roads. To overcome the mentioned limitation, this research introduces platooning as a transfer mode between two AV-ready areas.

A platoon is a string of virtually linked vehicles that travel closely behind each other using automated driving technology [1]. The leading vehicle of a platoon is human-driven, followed by the rest of the vehicles which plan their maneuvers based on the actions of the leading vehicle. Such a structure suggests that the following vehicles do not necessarily need drivers and can be autonomous. Accordingly, platooning has the potential to move AVs outside of confined controlled areas.

In this paper, a platform-based container transportation problem between a port and demand points in an industrial area is studied. Both zones are appropriate for automated driving, whereas the route connecting the zones is not. Different carriers are present at the port which join a platform to carry out delivery tasks and each task can be done either by a truck

or an AV. The platform operates as an intermediary between demand points and carriers. It also provides a platooning service to move AVs through non-autonomous roads. Firstly, the platform specifies the transportation schedules and service fees of the carriers. Then, based on these decisions, the carriers decide whether to use AVs or ordinary trucks for each delivery task. This interactive decision-making process is modeled as a two-level constrained Stackelberg competition.

Automated driving technologies are widely used in container terminals of large ports [2] and designing a scheme under which they are also applied out of these closed environments can be regarded as a breakthrough in drayage operations. Introducing platooning as a "transfer mode" in the context of drayage operations is a novel feature of this study. Developing a platform-based setting which enables resource and demand pooling between the origin and destination and modeling it in the form of a constrained Stackelberg competition rather than a centralized optimization scheme to plan the collaboration, are further contributions of this paper.

Section II gives a review of the related literature. The proposed model is introduced in section III. The solution procedure is outlined in section IV. Section V provides numerical results and sensitivity analysis. Finally, conclusions and future research directions are presented in section VI.

II. LITERATURE REVIEW

This research mainly builds on two streams of literature: platform-based collaborative transportation and platooning.

A. Platform-based collaborative transportation

A high portion of existing works has focused on conceptual frameworks and social impacts of platforms, while the study on operational decisions and planning problems in collaborative transportation and logistics networks is still in its preliminary stage. We mainly focus on recent papers in this category and refrain from covering other mentioned directions.

Implementing an appropriate pricing strategy has a key impact on the success of transportation platforms that has been the motivation for several studies on optimal pricing in taxi hailing [3], [4], and [5], crowdsourced delivery [6] and [7], ride sourcing [8], and on-demand service [9] and [10] platforms.

There is a strong demand for efficient logistics systems in B2B e-commerce where transportation platforms can play a key role. Zhang et al. [11] investigate an e-commerce logistics

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The authors are with the Department of Maritime & Transport Technology, Delft University of Technology, The Netherlands (corresponding author to provide phone: +31 15 2781640; e-mail addresses: n.pourmohammadzia@tudelft.nl, f.schulte@tudelft.nl, and r.r.negenborn@tudelft.nl).

network with multiple logistics service providers (LPSs) in a platform-based collaboration. Demands are allocated to LPSs in an attempt to maximize the profit of the system. Individual rationality is incorporated to provide the partners with enough joining incentives. Zhang et al. [12] propose a relatively similar structure to minimize the costs of the logistics network system.

Behrend et al. [13] propose a collaborative setting for capacitated item-sharing and crowd shipping problem where a platform performs the transportation of consumers' requested items. Ma et al. [14] develop a facility location problem with regional demand. They optimize the location of potential gasoline stations for a platform in presence of time bounds.

B. Platooning

Platooning is capable of bringing various gains in the freight transportation sector including fuel cost reductions, road safety, and increased road capacity. Motivated by these benefits, platooning has gained growing interest during these years.

Bhoopalam et al. [1] review developments in the area until 2018 and provide problem classifications, objectives, and solution approaches. A high portion of the papers has focused on technical and technological aspects of platooning such as string sequence and stability, speed profile, signal timing, longitudinal control, and intra-platoon communications which are not the focus of this research. Readers are referred to Liang et al. [15] and Zhong et al. [16] for studies in these directions.

The literature on operational and planning decisions of platooning in the logistics is still confined. Zhang et al. [17] develop a model for platoon coordination and scheduling intending to minimize traveling fuel cost and schedule miss penalties. They show that platooning is less advantageous on networks with converging routes. Nourmohammadzadeh and Hartman [18] study a relatively similar problem where detours are admissible to enable platooning.

Platoon formation is an interactive decision-making process that can be illustrated through game theory. Calvo and Mathar [19] incorporate cooperative game theory to optimize the platoon formation decisions. They define a joint global utility function to minimize total travel costs and congestion tax and use Shapely Value to allocate total cost to individuals. Johansson et al. [20] analyze the problem from another point of view. They consider that vehicles belong to different fleets and are reluctant to form coalitions. They model the problem as a non-cooperative game.

Scherr et al. [21] investigate a parcel delivery problem in a heterogeneous infrastructure where AVs drive in feasible zones and need guidance by ordinary vehicles in others. This is the only research that has focused on this capability of platooning. The authors discretized time by using a time-expanded network to handle the complexity of the problem and incorporated a centralized scheme to optimize the system.

All in all, studies on platooning and platform-based collaboration in freight transportation are still in their infancy. There are limited papers in the area and much needs to be done to investigate the impact of platforms and platoons on operational decisions of logistics networks. Platforms have been mostly handled by a centralized optimization system,

neglecting the interactive decision making among the partners and their powers. Fuel cost is the center of attention in platooning problems and other benefits of platooning remain almost unfolded. To the best of our knowledge, platooning as a transfer mode to move driverless vehicles (AVs) in a heterogeneous vehicle area has been regarded by only one paper (Scherr et al. [21]) in a problem for which time is discretized and a centralized optimization scheme is applied.

III. MODEL DEVELOPMENT

Carriers deliver full containers from a port to companies in an industrial zone. The problem is modeled as a graph $G(V, A)$ where $V = \{a\} \cup B \cup \{c\}$ is the set of vertices including container terminal (a : initial start and c : final return) and demand points (B); $A = \{(i, j) | i = a, j \in B \text{ or } i \in B, j = c\}$ is the set of linking arcs. The set of potential platoons, which projects the available drivers and leading vehicles of each platoon string, is distinguished by P . $K = K_1 \cup \dots \cup K_l \cup \dots \cup K_L$ is the union of the vehicles (including available AVs and trucks) of the carriers and F is the set of carriers.

The vehicles belong to different carriers and each delivery task can be done either by a truck or an AV. So, two modes are considered for each vehicle ($n=1,2$; 1 representing an AV and 2 a truck). A truck travels directly from the container terminal to its targeted demand point to deliver a container. On the other hand, an AV has to join a platoon at the container terminal, travel to the zone, disjoin the platoon at the platoon pooling area of the zone, and then travel to its demand point. Similarly, on the way back to the port, it needs to join the initial platoon at the pooling zone. In order to form a platoon, a human-driven leading vehicle should be assigned to each string. These vehicles and their drivers belong to the platform. The activities for each vehicle mode in vertices and arcs of the graph and their corresponding time are listed in Tables I and II respectively.

The platform operates as the interface between demand points and carriers. It also provides AVs with platooning

TABLE I. ACTIVITIES OF VERTICES

Vertex	$n=1$	$n=2$
$i = a$	Load the full container (tl) Join platoon (tj)	Load the full container (tl)
$i \in B$	Unload the full container (tl) Unpack the full container (tu_i) Load the empty container (tl)	Unload the full container (tl) Unpack the full container (tu_i) Load the empty container (tl)
$i = c$	Disjoin the platoon (tj) Unload the empty container (tl)	Unload the empty container (tl)

TABLE II. ACTIVITIES OF ARCS

Arc		$j \in B$	$j = c$
$i = a$	$n=1$	Travel from i to P.P (tp_i) Disjoin platoon (tj) Travel from P.P to j (tp_j)	-
	$n=2$	Travel from i to j (tr_{ij})	-
$i \in B$	$n=1$	-	Travel from i to j (tr_{ij})
	$n=2$	-	Travel from i to P.P (tp_i) Wait for the initial platoon (tw_i) Join platoon (tj) Travel from P.P to j (tp_j)

P.P: Platoon pooling area in industrial zone

service. It specifies the transportation schedules and service fees intending to minimize its total cost which includes service fees and platoon formation costs. Then, based on these decisions, the carriers will determine whether to use AVs or trucks for each task so that their profits are maximized. This interactive decision-making process is modeled as a two-level constrained Stackelberg competition where the platform is the leader and the carriers are the followers. The remainder of the notations which are used to formulate the model are as follows:

Parameters

CL	Platoon formation cost
d_i	Number of demanded containers at $i \in B$
UB	Maximum allowed number of AVs in a platoon
LB	Minimum possible number of AVs in a platoon
T_i^n	Total time of activities of vertex i for mode n
T_{ij}^{kn}	Total time of activities of arc (i,j) for vehicle k of mode n
TA_i	Lower bound for admissible service time at vertex i
TB_i	Upper bound for admissible service time at vertex i
LS_i^{kn}	Lowest acceptable fee for vehicle k of mode n serving i

Decision variables

x_{ij}^{kn}	1: if vehicle k of mode n travels from i to j 0: otherwise
v_p^k	1: if vehicle (AV) k joins platoon p 0: otherwise
σ_p	1: if platoon p is formed 0: otherwise
ST_i^{kn}	Time when vehicle k of mode n starts to service vertex i
STP_p	Time when platoon p starts to form at the origin
LT_i^k	Time when vehicle (AV) k arrives at the platoon pooling zone after serving vertex i
LTP_p	Time when all vehicles (AVs) of platoon p arrive at platoon pooling zone after serving their vertices
tw_i^k	Waiting time of AV k serving point i at platoon pooling zone
W_i^{kn}	Service fee announced to vehicle k of mode n for serving vertex i
RW_i^{kn}	Service fee paid to vehicle k of mode n for serving vertex i
z^{kn}	1: if vehicle k decides to use mode n 0: otherwise
γ_{ip}^k	1: if AV k serving i moves in platoon p back to container terminal 0: otherwise
M_1, \dots, M_{12}	Large numbers providing upper bounds for their respective equations

A. Optimization model of the platform

$$P_1: \min \sum_{n=1,2} \sum_{k \in K} \sum_{i \in B} RW_i^{kn} + CL \sum_{p \in P} \sigma_p \quad (1)$$

Subject to:

$$\sum_{n=1,2} \sum_{k \in K} x_{aj}^{kn} = d_j \quad \forall j \in B \quad (2)$$

$$\sum_{j \in B} x_{aj}^{kn} = z^{kn} \quad \forall k \in K, n = 1, 2 \quad (3)$$

$$x_{al}^{kn} - x_{lc}^{kn} = 0 \quad \forall l \in B, k \in K, n = 1, 2 \quad (4)$$

$$\sum_{j \in B} x_{aj}^{k1} = \sum_{p \in P} v_p^k \quad \forall k \in K \quad (5)$$

$$\sum_{k \in K} v_p^k \leq UB \sigma_p \quad \forall p \in P \quad (6)$$

$$\sum_{k \in K} v_p^k \geq LB \sigma_p \quad \forall p \in P \quad (7)$$

$$STP_p \leq M_1 \sigma_p \quad \forall p \in P \quad (8)$$

$$ST_a^{k1} = \sum_{p \in P} (STP_p v_p^k) \quad \forall k \in K \quad (9)$$

$$ST_j^{kn} \geq (ST_i^{kn} + T_i^n + T_{ij}^{kn}) x_{ij}^{kn} \quad \forall i, j \in V, k \in K, n = 1, 2 \quad (10)$$

$$LT_i^k = (ST_i^{kn} + T_i^1 + tp_i^k) x_{ic}^{k1} \quad \forall i \in B, k \in K \quad (11)$$

$$LTP_p = \max_{k \in K} \left(\sum_{i \in B} LT_i^k v_p^k \right) \quad \forall p \in P \quad (12)$$

$$tw_i^k = \sum_{p \in P} (LTP_p - LT_i^k) (v_p^k x_{ic}^{k1}) \quad \forall i \in B, k \in K \quad (13)$$

$$TA_i \sum_{j \in V} x_{ij}^{kn} \leq ST_i^{kn} \leq TB_i \sum_{j \in V} x_{ij}^{kn} \quad \forall i \in V, k \in K, n = 1, 2 \quad (14)$$

$$W_j^{kn} \leq M_2 \sum_{n=1,2} x_{aj}^{kn} \quad \forall j \in B, k \in K, n = 1, 2 \quad (15)$$

$$W_j^{kn} \geq LS_j^{kn} \sum_{n=1,2} x_{aj}^{kn} \quad \forall j \in B, k \in K, n = 1, 2 \quad (16)$$

$$RW_j^{kn} = W_j^{kn} x_{aj}^{kn} \quad \forall j \in B, k \in K, n = 1, 2 \quad (17)$$

$$x_{ij}^{kn}, v_p^k, \sigma_p \in \{0, 1\} \quad \forall i, j \in V, k \in K, p \in P, n = 1, 2 \quad (18)$$

$$ST_i^{kn}, LT_i^k, tw_i^k, W_i^{kn}, RW_i^{kn} \geq 0 \quad \forall i \in V, k \in K, p \in P, n = 1, 2 \quad (19)$$

The objective function (1) minimizes the total service fee paid to the carriers and platoon formation costs. Platoon formation cost expresses the cost of assigning a human-driven leading vehicle and its driver to each string. Constraint (2) ensures that the demand of each point is fully satisfied. Constraint (3) expresses that the mode of a vehicle leaving the port is chosen by the carrier. Constraint (4) is the flow constraint. Constraint (5) implies that an AV can leave the port only if it joins a platoon. Constraints (6) and (7) confine the number of vehicles in a platoon. Constraint (8) specifies a platoon's start time. Constraint (9) implies that the start time of an AV is equal to the start time of its platoon. Consistency of service time is guaranteed by constraint (10). Constraint (11) specifies the time an AV arrives at the platoon pooling zone after serving a demand point. Constraint (12) determines the time that all AVs of a platoon arrive at the platoon pooling zone. The waiting time of each AV in the platoon pooling zone is obtained by (13). Time windows are represented by (14). Constraint (15) guarantees that the platform announces service fees to a vehicle, only if that demand point is planned to be served by the vehicle. Constraint (16) ensures that the minimum acceptable service fee of each vehicle is respected. Constraint (17) determines the service fee paid to each vehicle. Constraints (18) and (19) imply the type of variables.

Constraints (9)-(13) and (17) are non-linear and are linearized as follows:

$$ST_a^{k1} \leq STP_p + M_3(1 - v_p^k) \quad \forall k \in K, p \in P \quad (20)$$

$$ST_a^{k1} \geq STP_p - M_3(1 - v_p^k) \quad \forall k \in K, p \in P \quad (21)$$

$$ST_j^{kn} \geq ST_i^{kn} + T_i^n + T_{ij}^{kn} - M_4(1 - x_{ij}^{kn}) \quad \forall i, j \in V, k \in K, n = 1, 2 \quad (22)$$

$$LT_i^k \leq ST_i^{kn} + T_i^1 + tp_i^k + M_5(1 - x_{ic}^{k1}) \quad \forall i \in B, k \in K \quad (23)$$

$$LT_i^k \geq ST_i^{kn} + T_i^1 + tp_i^k - M_5(1 - x_{ic}^{k1}) \quad \forall i \in B, k \in K \quad (24)$$

$$LT_i^k \leq M_6 x_{ic}^{k1} \quad \forall i \in B, k \in K \quad (25)$$

$$LTP_p \geq \sum_{i \in B} LT_i^k - M_7(1 - v_p^k) \quad \forall k \in K, p \in P \quad (26)$$

$$LTP_p \leq M_8 \sum_{k \in K} v_p^k \quad \forall p \in P \quad (27)$$

$$x_{ic}^{k1} + v_p^k \geq 2\gamma_{ip}^k \quad \forall i \in B, k \in K, p \in P \quad (28)$$

$$x_{ic}^{k1} + v_p^k \leq \gamma_{ip}^k + 1 \quad \forall i \in B, k \in K, p \in P \quad (29)$$

$$tw_i^k \leq LTP_p - LT_i^k + M_9(1 - \gamma_{ip}^k) \quad \forall i \in B, k \in K, p \in P \quad (30)$$

$$tw_i^k \geq LTP_p - LT_i^k - M_9(1 - \gamma_{ip}^k) \quad \forall i \in B, k \in K, p \in P \quad (31)$$

$$tw_i^k \leq M_{10} \sum_{p \in P} \gamma_{ip}^k \quad \forall k \in K, p \in P \quad (32)$$

$$RW_j^{kn} \geq W_j^{kn} - M_{11}(1 - x_{aj}^{kn}) \quad \forall j \in B, k \in K, n = 1, 2 \quad (33)$$

Where constraints (20) and (21) are linearized forms of (9), constraint (10) is linearized by (22), constraints (23)-(25) are linearized forms of (11), constraint (12) is linearized by (26) and (27), constraint (13) is linearized by (28)-(32), and finally constraint (33) is the linearized version of constraint (17).

B. Optimization model of the carriers

For each carrier $l \in F$ we have:

$$P_2: \max \sum_{n=1,2} \sum_{k \in K_l} \left(\sum_{i \in V} W_i^{kn} - \sum_{j \in V} C_{ij}^{kn} x_{ij}^{kn} \right) z^{kn} \quad (34)$$

Subject to:

$$\sum_{n=1,2} z^{kn} = 1 \quad \forall k \in K_l \quad (35)$$

$$z^{kn} \in \{0,1\} \quad \forall k \in K_l, n = 1, 2 \quad (36)$$

The objective function (34) maximizes the total profit obtained by the vehicles of each carrier. Constraint (35) ensures that each vehicle is chosen to be an AV or truck. Finally, constraint (36) implies the type of variables.

C. Two-level Stackelberg problem

The two-level Stackelberg model is summarized as:

$$\min \quad (1)$$

Subject to:

$$(2)-(8), (14)-(16), (18)-(19), (20)-(33)$$

$$\max \quad (34)$$

Subject to: (35)-(36)

IV. SOLUTION APPROACH

Multi-stage games are solved through backward induction. Firstly, the problem of the follower is solved to obtain its best response for different actions of the leader. Taking this as the input, the procedure steps backward to determine the best response for the leader. To optimize the problem of the carriers with respect to the actions of the platform, problem P_2 is substituted by its optimal decision rules:

$$\sum_{i \in V} W_i^{k1} - \sum_{j \in V} C_{ij}^{k1} x_{ij}^{k1} - \sum_{i \in V} W_i^{k2} + \sum_{j \in V} C_{ij}^{k2} x_{ij}^{k2} \geq -M_{12}(1 - z^{k1}) \quad \forall k \in K_l, l \in F \quad (37)$$

$$\sum_{i \in V} W_i^{k1} - \sum_{j \in V} C_{ij}^{k1} x_{ij}^{k1} - \sum_{i \in V} W_i^{k2} + \sum_{j \in V} C_{ij}^{k2} x_{ij}^{k2} \leq M_{12}(1 - z^{k2}) \quad \forall k \in K_l, l \in F \quad (38)$$

$$\sum_{n=1,2} z^{kn} = 1 \quad \forall k \in K_l, l \in F \quad (39)$$

$$z^{kn} \in \{0,1\} \quad \forall k \in K_l, l \in F, n = 1, 2 \quad (40)$$

Inequalities (37) and (38) guarantee that the mode of each vehicle is selected such that the profit is maximized. Then, the problem is transformed into the following single-level mixed-integer programming (MIP) optimization model:

$$P_3: \min \quad (1)$$

Subject to:

$$(2)-(8), (14)-(16), (18)-(19), (20)-(33), (37)-(40)$$

Firstly, the model of the platform is linearized applying constraints (20)-(33). Then, the models of the carriers are transformed into constraints (37)-(40) that converts the two-level Stackelberg model into the above single level MIP (P_3) which can be solved by existing mathematical optimization software such as Gurobi, Cplex, and GAMS.

V. COMPUTATIONAL EXPERIMENTS

We consider container deliveries from the Port of Rotterdam to the companies in an industrial area located in city of Rotterdam known as Heijplaat. Due to its features and infrastructure, the area seems to be a promising potential candidate for automated driving purposes. The MIP model is coded in IBM ILOG CPLEX Optimization Studio 12.7 and the experiments are carried out on a computer with Intel® Core i7-8650U CPU 1.9 GHz, 2.11 GHz, and 7.88 GB memory available.

A. Experiments setting

The proposed problem is confined to assign the carriers to the demand points and therefore, can be seen as a variant of generalized assignment problem with further constraints. It belongs to the class of NP-hard problems for which the computational time increases sharply as the size of the problem gets larger. As an instance adding one delivery point with four demands, to the five existing demand points and increasing the size of k by four to meet these demands, increases the computation time by 537%. Accordingly, we have considered a sufficiently sized example which can be solved in a reasonable time while efficiently illustrating the features of the problem and our case study.

There exist 17 companies in Heijplaat among which six companies receive relatively considerable numbers of import containers from the Port of Rotterdam. We assume that three carriers serve these companies and have 12, 10 and 13 vehicles (of two modes) to fully meet the demands which are (5,6,5,7,8,4) containers in a day. The distance between the port and Heijplaat is 40 km. Distances are transformed into travel time by considering speeds of 70 km/h (Trucks) and 55 km/h (AVs) in the linking area and 20 km/h (Trucks) and 15 km/h (AVs) within the zone. It should be noted that these speeds are experimental choices regarding our case and can vary for different problem settings. Travel costs are proportional to distances and are higher for trucks due to higher fuel costs. The rates are considered 1 and 0.9 monetary units per kilometer for trucks and AVs, respectively. Moreover, the labor cost of each truck and platoon formation cost are 50 and 150 monetary units, respectively. The number of admissible AVs in a platoon is confined to (2,4).

B. Results

The transportation schedules are provided in Fig. 2.

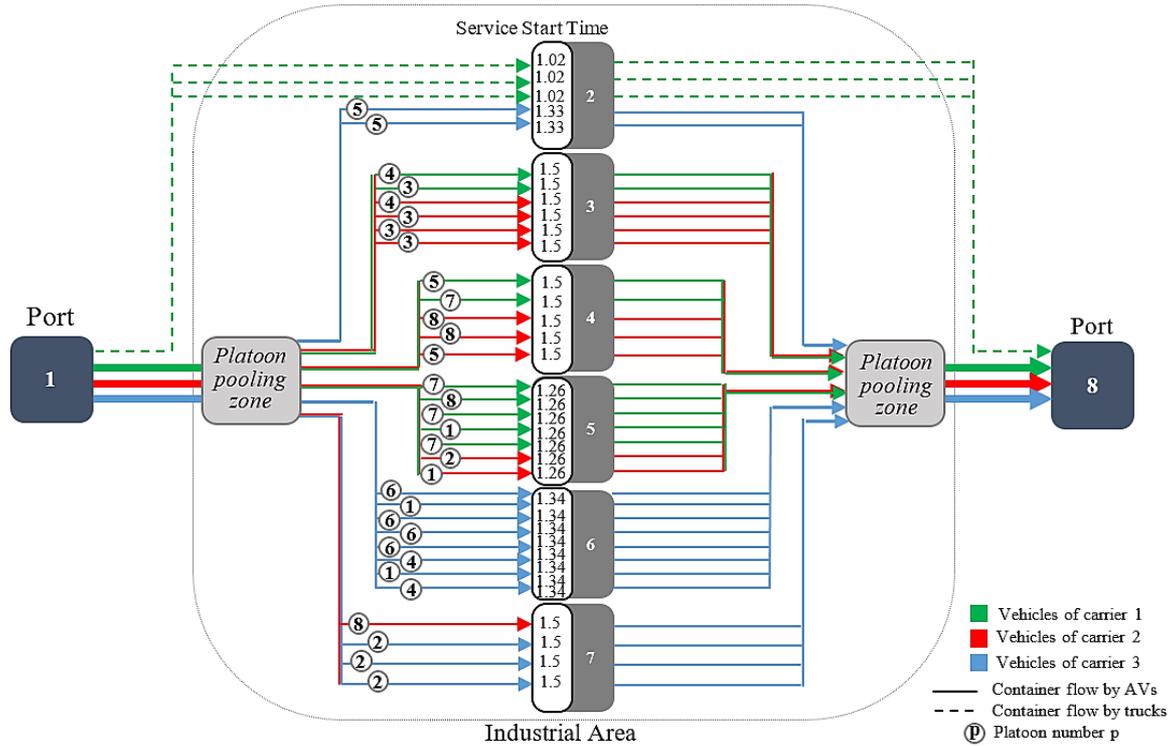


Figure 1. Schematic representation of the results

The optimal cost of the platform is 3850.9 monetary units and service fees account for 69% of this amount. The optimum revenues obtained from all vehicles of each carrier are 276.8, 249.79 and 369.33, respectively. The computation time is 124.31 sec.

As illustrated in Fig. 2, 32 AVs and three trucks are used to carry out the delivery tasks. Eight platoons are formed to move these 32 AVs indicating that all of the platoons contain their maximum possible number of AVs in a string which is four in our problem. This is economically rational as it minimizes platoon formation costs. Then, it can be concluded that as long as the time windows are respected, the system tends to maximize the number of AVs in each platoon.

Since the travel costs of trucks are higher than AVs, their minimum acceptable service fees (LS_i^{kn}), under which the vehicle is still willing to carry out a transportation task, are also higher. Then, as long as platoon formation costs are compensated, the system prefers to use AVs rather than trucks. For the mentioned 32 vehicles, the announced service fees are selected in a way that: 1-Minimum acceptable fees are respected, 2-The service fees of AVs are lower than trucks, and 3-The profit of the carriers are higher if they use AVs. As an instance, consider four AVs of carrier 3 in platoon 6 which serve demand point 6. The announced service fees and profits for each mode (AV or truck) of these vehicles are provide in Table III.

TABLE III. COMPARISON BETWEEN TWO MODES OF VEHICLES

Vehicles	W_6^{k1}	W_6^{k2}	$Profit^{k1}$	$Profit^{k2}$
23,25,26,28	75.01	127	28.64	28.63

The minimum acceptable service fees of these vehicles are 60 for AVs and 127 for trucks. So, if the trucks are used, the platform should pay at least 268 monetary units more to these vehicles. On the other hand, by choosing AVs, the platform bears 150 monetary units platoon formation cost which is still lower than 268. So it is beneficial to specify the service fees in a way that, the carriers choose to use AVs. As depicted in Table III, the announced service fees of AVs are 75.01 that are higher than their minimum acceptable fees and the announced service fees of trucks are equal to their minimum acceptable threshold. Consequently, the profits are higher when using AVs which leads to the selection of mode one.

Consider three trucks of carrier 1 serving demand point 2. Their announced service fees and profits are provide in Table IV. The minimum acceptable service fees of these vehicles are 63 for AVs and 120 for trucks. So, if the trucks are used, the platform should pay 171 monetary units more to these vehicles. On the other hand, by choosing AVs, the platform bears 150 monetary units platoon formation cost and has to raise their service fees at least by 10.8. Then, it should invest 182.4 monetary units more which is higher than 171. Therefore, it is beneficial for the platform to specify the service fees in a way that, these vehicles are chosen to be trucks. As Table IV displays the profits are higher when using trucks which leads to the selection of mode two.

The platoon formation cost and maximum possible number of AVs in a string, play a key role on the mode of the

TABLE IV. COMPARISON BETWEEN TWO MODES OF VEHICLES

Vehicles	W_2^{k1}	W_2^{k2}	$Profit^{k1}$	$Profit^{k2}$
2, 5, 9	63	120	13	23.8

A sensitivity analysis on these two parameters is carried out to investigate this impact. The number of AVs (trucks), platoons and total cost of the platform are provided in Table V for different values of these input parameters.

TABLE V. SENSITIVITY ANALYSIS ON CL AND UB

Parameter	Changes	Number of AVs (trucks)	Number of platoons	Total cost of the platform
CL	-50 %	35 (0)	9	3186.3
	-25 %	35 (0)	9	3523.8
	+25 %	24 (11)	6	4149.3
	+50 %	0 (35)	0	4260.6
UB	-50 %	0 (35)	0	4260.6
	-25 %	21 (14)	7	4223.8
	+25 %	35 (0)	7	3561.38
	+50 %	35 (0)	6	3411.3

As CL increases, forming a platoon becomes less economical. With a 25% increase in CL , the number of applied AVs decrease from 32 to 24 suggesting that forming a platoon is more expensive than using trucks for these eight vehicles. The rise in the total cost by the increase in CL is totally expected; as platoon formation cost accounts for approximately one third of the total cost. By decreasing the maximum allowable number of AVs in a string, more platoons are required to be formed for the same number of AVs leading to a rise in platoon formation costs. Thus, again the number of applied AVs decrease. This implies that platooning decisions are highly influenced by related regulations. Accordingly, comprehensive studies on platooning regulations are prerequisites for the success of platooning in the real-world.

VI. CONCLUSION

In this paper, a platform-based container transportation problem between a port and an industrial area is investigated. Both zones are appropriate for automated driving, whereas their connecting route is not. The platform not only operates as the intermediary between demand points and carriers but also provides platooning service to move AVs through non-autonomous roads. It specifies the transportation schedules and service fees of the vehicles. Based on these decisions, the carriers decide whether to use AVs or ordinary trucks. This interactive decision-making process is modeled as a two-level constrained Stackelberg competition. The two-level constrained model is transformed into a one-level MIP model by backward induction. The developed structure is illustrated through numerical results where delivery from the Port of Rotterdam to an industrial area located in the city of Rotterdam known as Heijplaat is considered. The approach enables demand and resource pooling between the port and industrial area. It is shown that maximum possible number of AVs in a string plays a key role on the platooning decisions which emphasizes the impact of platooning regulations on the widespread application of automated driving. The results also imply that if platoon formation costs are managed, AVs can considerably enhance the efficiency of drayage operations. The benefits of the proposed setting may create incentives for establishing new companies in the respective industrial zones and their further development.

Developing an exact or heuristic solution approach seems to be a promising future direction as it can handle larger sizes of the problem. The flow of export containers to the port can also be regarded which projects a more practical setting. Studying the impact of other factors such as time and string length on platooning costs is another promising future direction.

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