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Modular Vehicle Routing on Railways: Opportunities for Intermodality

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Abstract— **This paper explores the enhancement of rail-based, intermodal freight transport systems through the integration of modular vehicles (MVs), aiming to boost the flexibility of this form of transport and its integration into the mobility-as-a-service framework. This study specifically addresses a specific variant of the Pickup and Delivery Problem (PDP) tailored to railway logistics, by developing mathematical models for the Pickup and Delivery Modular Vehicle Routing Problem (PDMVRP) with platooning. This model focuses on the operational challenges associated with routing and platooning of MVs on the railways. A case study conducted within a railway context assesses the efficacy of our model, demonstrating its potential to reduce transportation costs and improve railway capacity utilization, thereby advancing modular vehicle operations in railway environments.**

I. INTRODUCTION

Shifting freight transport from road to more environmentally friendly modes such as rail is acknowledged as a key approach for reducing emissions in this sector. However, over the last ten years, there has been a noticeable decline in this transition, which can be associated with higher flexibility of road transport, amongst others. A recent study finds that there are significant underutilized capacities in passenger trains and suggests that integrating light freight can free up road capacities and improve (urban) livability and accessibility[1]. Therefore, there is a pressing need to evolve rail-based, intermodal freight systems for greater adaptability and seamless integration into the mobility-as-a-service concept, leveraging the existing infrastructure. This shift not only increases rail's share in transport of freight, but also optimizes the existing infrastructure utilization. The railway sector is actively pursuing innovations [2], [3], e.g. in automatic operation and vehicle-to-vehicle communication technologies such as virtual coupling, paving the way for modular vehicles (MVs) integration in the rail systems.

Given the potential of modular vehicles on the road in terms of efficiency, operation cost reduction and better balance of supply and demand (Guo et al. [23], Zhang et al. [24], Xia et al. [21]), this paper aims at extending their application to the railway system. In the context of this paper, modular vehicles are autonomous wagons capable of moving on the railway infrastructure which can connect to the modular vehicles on the road, either directly and without transshipment or via load transfer. Similar concepts are developed/under development such as Rinspeed Snap and microSNAP[4], Mercedes Benz Vision Urbanetic[5], DLR U-shift[6] and Continental BEE[7], and in Pods4Rail European project [2]. DB cargo's m^2 freight wagon concept is another enabling technology [8]. This expands the application of modular vehicles across modes, however, in itself presents operational and logistic complications that have motivated this research. The issue at hand comprises a dual challenge involving interconnected planning and scheduling subproblems. These are specifically tied to meeting demand requirements for pick-up and delivery, as well as efficiently scheduling modular vehicles within the railway system. The primary focus of this paper is on addressing the former problem, which provides the input for the latter. From the operational perspective, the system has one principal consideration: planning the movements of MVs on the railway network to ensure fulfilling of the demand, considering intermodality constraints in connecting road and rail, thus enabling a seamless transport of freight from their origin to their destination utilizing the railway infrastructure. This includes accounting for platooning capabilities and incorporating distinct time windows for MVs and requests, as well as interfacing with road transport (more details explained in section III).

The paper is organized as follows: Section II provides a detailed examination of previous studies and identifies existing gaps in the literature. Section III outlines the specific issues and assumptions that form the basis of this research. Section IV details the mathematical model. Section V describes a concise case study undertaken to test the efficacy of the proposed model. The final section, Section VI, synthesizes the key outcomes of the investigation and proposes avenues for further exploration.

II. LITERATURE REVIEW

Modularity refers to a group of modular vehicles (MVs), sometimes referred to as Pods, that can operate independently or in connection (as in platoons) on road and rail networks to meet the freight demand. The configuration of MV platoons, including their joining or leaving, can be adjusted during operation [9].

Planning the movement of MVs to fulfill the demand focuses on a specific variant of the broader PDVRP framework initially introduced by Desrochers et al. [10], Dumas et al. [11], and Savelsbergh et al. [12]. They model the process of request pickup and delivery along a route. Jodeau et al. [13] firstly investigated the optimization of a rail-road PDVRP as an example of combined railway and road passengers transport , but only a single railway line and no platooning are considered, both of which are addressed in our work. Other key features related to PDVRP such as vehicle

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capacities, pickup and delivery locations, time windows, and the presence of single or multiple depots are all considered in this work.

Studies on the MVs transportation system can be broadly divided into two road and rail applications. In the rail sector, Chen et al. [14], [15] delved into MVs scheduling along urban rail corridors, taking into account station-wise docking to uncover reduced operational costs and enhanced vehicle utilization when contrasted with conventional fixed-formation operations. Shi et al. [16], [17] investigated the application of MVs for variable-capacity operations in urban rail corridors, revealing substantial reductions in operational costs. Lin et al. [18] developed an optimization model that adjusts capacity and module allocation for passengers and freight in urban rail transit, significantly reducing operational costs through efficient station-wise docking. On the road transport side, Wu et al. [20] implemented a two-stage optimization model for MVs at intersections, reducing passenger transfers and travel time while maintaining energy use akin to traditional buses. Khan et al. [19] tested a bus-splitting strategy using MVs, finding it more than doubled travel cost savings compared to traditional stop-skipping strategies. Xia et al. [21] addressed timetabling and dynamic capacity for a Beijing bus line's modular bus system, enhancing cost-efficiency and demand matching. Tian et al. [22] developed a nonlinear mixed-integer model for optimal scheduling and platoon formation of MVs, significantly cutting costs for passengers and operators. For the interest in the PDVRP using MVs on roads: Zhang et al. [24] demonstrated cost and operational benefits in modular buses through dynamic platooning for varied trip lengths. Guo et al. [23] improved on-demand bus services using a two-phase optimization for modular autonomous electric vehicles, enhancing accessibility and efficiency. Fu et al. [25] significantly reduced travel costs and improved service times in demand-responsive transit with MVs using a mixed integer linear model. For combined freight and passenger transport, Chen et al. [26] and Hatzenbühler et al. [27] explored MVs that switch between passenger and freight tasks, while Hatzenbühler et al. [28] optimized MVs platooning with a pre-departure scheduling model.

This study contributes to the PDVRP in the railway transport context by acknowledging the possibility of multiple pickups or deliveries at the same station and multiple visits by the same vehicle, a significant deviation from traditional PDVRP. Unlike existing research on modular vehicles and platooning [28], [23], which often treats platoons as static entities in demand assignment, this work addresses the movement of individual MVs, allowing for station-wise platoon formation changes instead of only at depots or shunting yards and route adjustments. Additionally, tracking the movement of each individual MV and its corresponding onboard load, rather than the complete modular train sets, allows for extension of this modeling framework to the consideration of the dynamics of the system and its resilience. While prior studies mainly focus on road transport, this research is pioneering in applying these concepts to railway freight transport.

The literature on MVs in rail has largely concentrated on operational issues within single rail line. In contrast, this study expands to network-level challenges and integrates VRP to facilitate pickup and delivery services previously unexplored.

To address these research gaps, this paper introduces a mathematical model for the Pickup and Delivery Modular Vehicle Routing Problem (PDMVRP) tailored for the railway setting, especially at the intersections of road and rail networks, enhancing the understanding of modular vehicle operations within railway environments. Particularly, we complement the related studies to virtual-coupling of modular wagons by incorporating an operational perspective of this technology at the network level.

III. Problem description and assumptions

In the context of an intermodal transport system, MV $e \in P$ moves on the railway network represented by a space-time graph consisting of a set of space-time vertices. Each vertex A represents a specific location in both space and time within the railway network. For each MV, the point of entry to the railway network is associated with an in-service time t_e^p and out-of-service time t_e^d denoting the time when containers are transferred to the railway network from road and back to road to catch up their next transport plans on road, and is pre-loaded with H_e, showcasing the road-rail interface (intermodality).

Note that, for each MV, only the times associated with arrival from road, departure from railway, and en-route pick up and delivery times are specified. The detailed scheduling is for now not considered due to added complexity.

Additionally, certain unpacked freight requests $r \in R$, specified by pickup/delivery time windows $[t_r^{p1}, t_r^{p2}]$, $[t_r^{d1}, t_r^{d2}]$, quantity q_r, and origin o_r, and destination d_r, are serviced by MVs that pick up and deliver the freight during these windows. Platoon formation at stations, which reduces transport costs, is a key feature: longer platoons are more cost-efficient, attributed to decreased energy usage and optimized railway capacity[29].

Figure 1 demonstrates the operation of the Pickup and Delivery Modular Vehicle Routing Problem (PDMVRP) within a railway context. In case of using detachable wagons, loads are transferred to the railway network in pre-loaded containers that may be transferred directly from the road MVs to the railway network. This, if synchronised properly, eliminates the storage of containers at the transfer stations. The remaining empty capacity of these containers may be used for pick-up and delivery purposes on the railway. Alternatively, freight can be directly loaded onto the MVs on the railway. In this figure, containers are transferred to detachable wagons on railway network via stations 1 and 2 from road, each preloaded with parcels corresponding to their colors (blue and black). These stay on the MV and exit the railway network to their final destinations. Concurrently, two additional parcels, grey and yellow, need to be transported from station 1 to 4 and station 2 to 3, respectively fulfilled

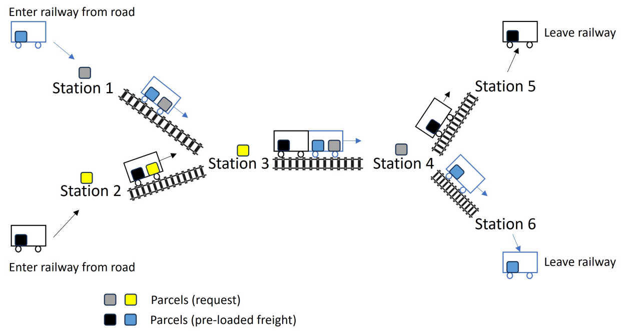

Fig. 1. Modular vehicle on railway

by the blue and the black MV. Upon meeting at station 3, two MVs form a platoon while black MV also facilitates the delivery of the yellow parcel. Travelling from station 3 to 4 in a platooned formation, MVs reach station 4, where the grey parcel is delivered by the blue MV. Following this, the MVs leave platoon arrangement and proceed independently to their onboard containers' respective egress points from the railway network, stations 5 and 6.

The foundational assumptions include: each timeslot permits only a single MV or platoon per uni-directional track (i.e., from station i to j), with a timeslot's length as the minimum headway; platoon configurations can be modified at any station, and sequence of MVs in platoon is not considered assuming that MVs can use idle railway tracks at station for overtaking and reshuffling; MVs, pre-loaded with freight, have defined in-service/out-of-service times, origins, and destinations; in case of direct transfer of containers, the flat wagons are readily available for transshipment; and a unique MV size and capacity is considered; station capacity in terms of storage space and number of tracks is not taken into account; longer MV platoons result in lower transport costs per km; the freight requests are assumed to be identical standard parcels; there are always two uni-directional railway tracks between each pair of stations.

IV. Mathematical model

To address the complex temporal-spatial features of the PDMVRP problem in the railway context, a discrete space-time modelling approach is adopted. A two dimensional railway network is constructed comprising a set of space-time vertices A. These vertices are defined by space-time tuples (i, j, t), signifying the movement of the MV e from station i to station j at the specific timeslot t. The operational timeframe of the railway system is segmented into equal-duration intervals $t \in T$, facilitating a granular analysis of movements and scheduling within the network. A distinctive feature of this model is the incorporation of two types of time windows, catering to both the MV $e \in P$ and freight requests $r \in R$. The MVs operate within a strict time window $[t_e^p, t_e^d]$ ending at a designated endpoint d_e. While freight requests are also assigned hard time windows for pickup $[t_r^{p1}, t_r^{p2}]$ and delivery $[t_r^{d1}, t_r^{d2}]$, the model introduces flexibility by allowing for the potential rejection of requests, albeit with an incurred penalty cost.

Notations

P: set of MVs/pre-loaded containers e from road
o_e: starting station of MV $e \in P$
d_e: ending station of MV $e \in P$
t_e^p: in-service time of MV $e \in P$, representing the time when containers are ready to be transferred from road to railway
t_e^d: out-of-service time of MV $e \in P$, representing the time when containers are ready to be transferred back to road
R: set of (non-containerized) requests r at station i
o_r: origin station of request $r \in R$
d_r: destination station of request $r \in R$
q_r: quantity of request $r \in R$
$[t_r^{p1}, t_r^{p2}]$: pickup time window of request $r \in R$, each request can only be picked up at timeslot $t \in \{t_r^{p1}, t_r^{p1}+1, ..., t_r^{p2}\}$
$[t_r^{d1}, t_r^{d2}]$: delivery time window of request $r \in R$, each request can only be delivered at timeslot $t \in \{t_r^{d1}, t_r^{d1}+1, ..., t_r^{d2}\}$
N_s: set of existing railway tracks between stations, $(i, j) \in N_s$
N: set of station indices, $i \in N$
T: $(0, 1, 2...t, t+1...TT)$, set of operation timeslot t of the railway system
A: set of time-space vertices consisting of (i, j, t) where $(i, j) \in N_s, t \in T$
$t_{i,j}$: travel time between stations i and j, $t_{i,j} = 1$ if $i = j$
$l_{i,j}$: travel distance between stations i and j, $l_{i,j} = 0$ if $i = j$
H_e: on-board load of MV (the associated container) $e \in P$ at its point of entry into the railway network
t_s: the service time needed at stations when picking up or delivering goods
C: capacity of MV (parcels)
μ: maximum size of platoon (e.g. limited by station capacity)
w_1: transport cost (euro/km)
w_2: penalty cost (euro/parcel)
β: platoon cost saving rate

Decision variables

$y_{i,j,t,e}$: 1 if MV $e \in P$ moves from i to j at t, $\forall (i, j, t) \in A$
$S_{t,e,r}$: 1 if request $r \in R$ is picked up by a MV $e \in P$ at t, $\forall t \in T$
$D_{t,e,r}$: 1 if request $r \in R$ is delivered by a MV $e \in P$ at t, $\forall t \in T$
$z_{i,j,t,e,v}$: 1 if MV $e \in P$ moves in platoon with MV $v \in P$ from i to j at t

Other variables

$Q_{t,e}$: load of MV $e \in P$ at t
$k_{i,j,t,e}$: the number of MVs that the MV $e \in P$ is traveling with, in platoon, on $(i, j, t) \in A$

Objective function:

Minimize the total transport cost:

$$min \sum_{(i,j,t)\in A}\sum_{e\in P} w_1 l_{i,j}(y_{i,j,t,e}-\beta k_{i,j,t,e}) \tag{1}$$

and unsatisfied demand penalty cost:

$$min \quad w_2 \sum_{r\in R}(q_r - \sum_{e\in P}\sum_{t=t_r^{p1}}^{t_r^{p2}} S_{t,e,r} q_r) \tag{2}$$

Constraints:

1. Intermodality (interface with road):
Each MV can only move on one link $(i,j)\in N_s$ at $t\in T$:

$$\sum_{(i,j,t)\in A} y_{i,j,t,e} \leq 1, \forall t\in T, e\in P \tag{3}$$

The MV $e\in P$ stays at its origin station o_e until reaching in-service time t_e^p denoting the time when containers transfers from road to railway take place:

$$y_{i,j,t,e}=1, \quad \forall i=o_e, i=j, e\in P, t\in T, t<t_e^p \tag{4}$$

$$\sum_{(i,j,t)\in A} y_{i,j,t,e}=1, \quad \forall i=o_e, e\in P, t=t_e^p=0 \tag{5}$$

The MV $e\in P$ should reach its destination d_e when reaching its out-of-service time t_e^d, and after its out-of-service time the MV $e\in P$ will stay there until the end of time horizon TT , denoting their leaving from railway network:

$$y_{i,j,t,e}=1, \forall i=d_e, i=j, e\in P, t\geq t_e^d \tag{6}$$

2. Freight request-MV assignment:
Since the value of delivery variable $D_{t,e,r}$ depends on the value of pickup variable $S_{t,e,r}$(if request is picked up, it must be dropped off as stated in constraint 10), only $S_{t,e,r}$ is constrained in equations 9:
Each request $r\in R$ can be picked up and delivered by at most one MV $e\in P$:

$$\sum_{e\in P}\sum_{t\in T} S_{t,e,r}\leq 1, \forall r\in R \tag{7}$$

$$\sum_{e\in P}\sum_{t\in T} D_{t,e,r}\leq 1, \forall r\in R \tag{8}$$

Each request $r\in R$ can only be picked up within its time window:

$$S_{t,e,r}=0, \forall r\in R, e\in P, t\in T/\{t_r^{p1}, t_r^{p1}+1..., t_r^{p2}\} \tag{9}$$

The request $r\in R$ picked up by a MV $e\in P$ must be delivered by the same MV $e\in P$ within its delivery time window:

$$\sum_{t=t_r^{p1}}^{t_r^{p2}} S_{t,e,r} = \sum_{t=t_r^{d1}}^{t_r^{d2}} D_{t,e,r}, \forall r\in R, e\in P \tag{10}$$

When t is not within the operation period of MV $e\in P$, they cannot pick up or deliver any request:

$$\begin{aligned} &S_{t,e,r}=D_{t,e,r}=0, \forall r\in R, e\in P,\\ &t\in T/\{t_e^p, t_e^p+1..., t_e^d-1\}\end{aligned} \tag{11}$$

When request r is picked up or delivered by MV e at a station i which is the location for pickup o_r or delivery d_r at timeslot t_1, MV e must visit and stay there for at least a period of t_s which is the service time:

$$\begin{aligned} &y_{i,j,t,e}\geq S_{t_1,e,r}, \forall (i,j,t_1)\in A, e\in P, r\in R, i=o_r, i=j,\\ &t\in\{t_1, t_1+1..., t_1+t_s-1\}\end{aligned} \tag{12}$$

$$\begin{aligned} &y_{i,j,t,e}\geq D_{t_1,e,r}, \forall (i,j,t_1)\in A, e\in P, r\in R, i=d_r, i=j,\\ &t\in\{t_1, t_1+1..., t_1+t_s-1\}\end{aligned} \tag{13}$$

After staying at the service station for a period of t_s, at timeslot t_1+t_s, MV e can leave:

$$\begin{aligned} &\sum_{(i,j,t)\in A|t=t_1+t_s} y_{i,j,t,e}\geq S_{t_1,e,r}, \forall t_1\in T, i=o_r, e\in P,\\ &r\in R\end{aligned} \tag{14}$$

$$\begin{aligned} &\sum_{(i,j,t)\in A|t=t_1+t_s} y_{i,j,t,e}\geq D_{t_1,e,r}, \forall t_1\in T, i=d_r, e\in P,\\ &r\in R\end{aligned} \tag{15}$$

3. Vehicle routing:
MVs flow conservation at station i:

$$\begin{aligned} &\sum_{(i,j,t)\in A} y_{i,j,t,e} = \sum_{(j,i,t-t_{j,i})\in A} y_{j,i,t-t_{j,i},e}, \forall e\in P,\\ &i\in N, t\in T, t\geq 1\end{aligned} \tag{16}$$

4. MV capacity:
For each MV/preloaded container $e\in P$, they have pre-load H_e inside:

$$Q_{0,e}=H_e, \forall e\in P \tag{17}$$

Onboard load conservation of MV $e\in P$ at $t\in T$:

$$\begin{aligned} &Q_{t,e}=Q_{t-1,e}+\sum_{r\in R}(q_r S_{t-1,e,r}-q_r D_{t-1,e,r})\\ &,\forall e\in P, t\in T, t\geq 1\end{aligned} \tag{18}$$

The load of MV at any time should not exceed its capacity:

$$0\leq Q_{t,e}\leq C, \forall e\in P, t\in T \tag{19}$$

5. Platooning:
MV $e\in P$ and MV $v\in P$ can form platoon at station i heading to station j at timeslot t, only when they both will run on $(i,j,t)\in A$:

$$\begin{cases} z_{i,j,t,e,v}\leq y_{i,j,t,e}\\ z_{i,j,t,e,v}\leq y_{i,j,t,v}\\ z_{i,j,t,e,v}\geq y_{i,j,t,e}+y_{i,j,t,v}-1\end{cases} \tag{20}$$
$$,\forall (i,j,t)\in A, i\neq j, e\in P, v\in P, e\neq v$$

Before and after the MV e's in-service time t_e^p and out-of-service time t_e^d, MV e can not join any platoon moving from i to j at t:

$$\begin{aligned} &z_{i,j,t,e,v}=0, \forall e\in P, v\in P, e\neq v, (i,j)\in N_s,\\ &t\in T/\{t_e^p, t_e^p+1..., t_e^d-1\}\end{aligned} \tag{21}$$

Number of MVs that MV $e \in P$ are traveling with in platoon at $(i, j, t) \in A$, which is calculated based on the platooning decision variable $z_{i,j,t,e,v}$ indicating if MV e and MV v are platooned at (i, j, t):

$$k_{i,j,t,e} = \sum_{v \in P} z_{i,j,t,e,v}, \forall (i, j, t) \in A, e \in P \tag{22}$$

The size of platoon should not exceed its maximum when moving between different stations $i \neq j$:

$$k_{i,j,t,e} + 1 \leq \mu, \forall (i, j, t) \in A, e \in P, i \neq j \tag{23}$$

V. CASE STUDY

The proposed model is implemented for a small railway network, comprising 8 train stations in triangles (indexed 0 to 7) interconnected by 11 railway tracks(2 bi-directional tracks each) depicted as lines, as depicted in Figure 2. The travel time required to traverse each railway track is indicated adjacent to it.

Subsequently, Table II present information regarding the availability of MVs, including their origin/destination stations, in-service time, out-of-service time, as well as pre-loaded freight. Additionally, freight demand details, such as origin/destination stations, pickup/delivery time windows, and quantities, are outlined in Table I. Specifically, the scenario encompasses 8 MVs (indexed from 0 to 7) and 5 requests (indexed from 0 to 4).

Demand request r	0	1	2	3	4
Origin station, o_r	5	1	2	2	4
Destination station, d_r	6	0	0	3	8
Earliest pickup timeslot, t_r^{p1}	5	2	7	9	3
Latest pickup timeslot, t_r^{p2}	6	3	8	10	4
Earliest delivery timeslot, t_r^{d1}	13	9	10	12	10
Latest delivery timeslot, t_r^{d2}	14	10	11	13	11
Quantity, q_r	7	8	7	6	6

TABLE I
FREIGHT DEMAND

MV e	0	1	2	3	4	5	6	7
Starting station, o_e	5	6	1	4	4	4	5	6
Ending station, d_e	6	3	0	5	8	3	6	8
In-service timeslot, t_e^p	5	0	1	10	4	6	9	1
Out-of-service timeslot, t_e^d	14	12	10	14	13	13	14	14
Pre-loaded freight, H_e	9	6	11	6	11	11	8	10

TABLE II
MVS' AVAILABILITY INFORMATION

Parameters	Value
Service time, t_s	1
Maximum platoon size, μ	3
Platoon cost saving rate, β	0.2
Transport cost (€/km), w_1	10
Unserved demand penalty cost (€/parcel), w_2	50
Load capacity (parcels), C	20

TABLE III
PARAMETERS

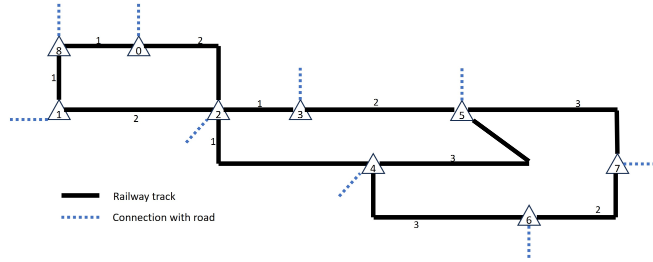

Fig. 2. Intermodal railway network

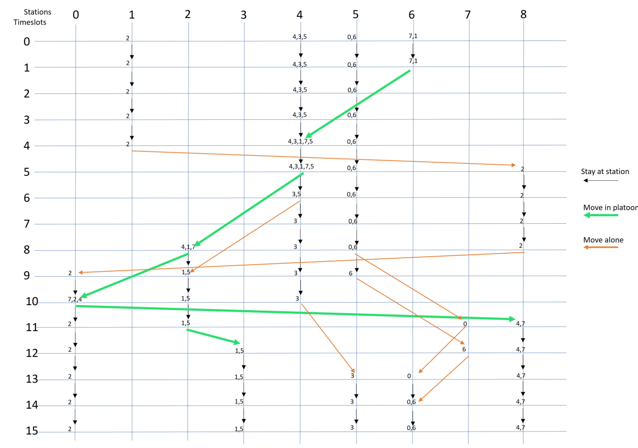

Fig. 3. Movement of MVs

All pertinent experimental parameters are shown in Table III. Experiments are executed utilizing Gurobi on a 13th Gen Intel(R) Core(TM) i7-1365U processor.

Figure 3 illustrates the movement of MVs in a space-time network, with horizontal axis marking stations and timeslots shown on the vertical axis. Green arrows denote platoon movements, black arrows signify station halts, and orange arrows indicate individual movements, with each number corresponding to a specific MV. Notably, five movements are depicted in platooned arrangement (green arrows). For example, MVs 4, 1, and 7 travel in a platoon from station 4 to station 2, departing at timeslot 5.

Additionally, four requests (requests 0, 1, 3, and 4) are satisfied by MVs 0, 2, 5, and 4, respectively. The fluctuation of MVs' load with assigned pickup tasks(only MVs 0,2,4 and 5) is displayed in Figure 4. For instance MV 0 picks up request 0 with a quantity of 7 at its origin station 5 during timeslot 5 within the request's pickup time window [5,6]. Subsequently, as depicted in the figure, MV 0's load increases by 7 from 9 to 16 during timeslot 6. Furthermore, after delivering request 0 to its destination at station 6 during timeslot 13, MV 0's load decreases back to 9 during timeslot 14.

A sensitivity analysis regarding maximum platoon sizes of 1, 2, and 3 is conducted, with the results summarized in Table V. Firstly, it is evident that longer platoons lead to reduced transport costs due to associated reductions in energy consumption. Moreover, overall capacity utilization can also be reduced if MVs can move in platoons. This is because

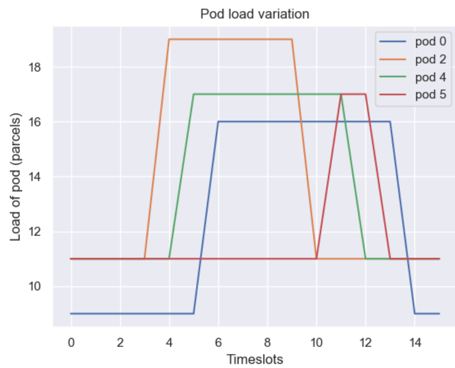

Fig. 4. Variation of pods' load with assigned pickup and delivery tasks

Max_platoon size, μ	1	2	3
Total cost (€)	2400	2140	2080
Capacity utilization	5.11%	3.7%	3.7%

TABLE IV
IMPACTS OF PLATOON SIZE

on the railway, only one MV or platooned MVs is allowed to depart on a rail uni-directional track during each timeslot to fulfill safety requirements. Consequently, with the same number of MVs, the total timeslots utilized are reduced.

VI. CONCLUSIONS

This paper presents a mathematical model designed specifically for addressing the pickup and delivery modular vehicle routing problem within a railway context. Through a case study, the findings suggest that the adoption of Modular Vehicles (MVs) within railway operations holds promise for reducing transport costs and optimizing railway capacity utilization.

Future research endeavors may explore the development of intermodal transport systems incorporating MVs and addressing potential disruptions, encompassing both road and rail networks. Additionally, further investigations could consider the integration of MV operations with railway scheduling processes, more detailed railway infrastructures and a real case study, offering a more holistic approach to enhancing transportation efficiency across multiple modes of transport.

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