Railway Infrastructure Capacity Evaluation of Modular Rail Pods under ETCS Level 2 Signalling System

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Abstract

Rail Pods are an emerging concept of modular self-propelled rail vehicle which can interchangeably move freight and transport for a more customer-oriented rail service. Pods are envisaged to operate on-demand with the possibility of forming platoons by either physically or virtually coupling at stations. In such a context, it is essential to quantify the actual service capacity of rail pod platooning, taking into account heterogeneous convoy structures and infrastructure constraints such as signalling rules and block occupation. This study extends UIC Code 406/blocking time theory to applied to Pod platoons, proposing a novel optimization model that integrates traction, cruising, and braking speed profiles alongside safe separation constraints. This approach enables coordinated optimization of cruising speeds across various platoon structures to minimize track capacity consumption. The model is applied to a case study considering the ETCS Level 2 signalling system. The results obtained for such a case study illustrate the ability of the proposed model to identify operational speed and composition of rail pods' platoons which lead to capacity effective use of the existing infrastructure. The proposed method provides potentials for a more flexible allocation of modular rail cars based on demand configuration.

Keywords: Capacity Evaluation; Pods4rail; Modular rail platoons; Optimized speed configuration; ETCS Level 2 signalling system

1 Introduction

Delivering customer-oriented rail services requires greater system flexibility and seamless operations, prompting the development of innovative operational paradigms. Pods4Rail, an EU-funded project developing a next-generation modular and smart railway system, introduces autonomously driven, reconfigurable self-propelled rail cars (Pods) with freight or passenger capability. Operating on existing infrastructure, Pods are designed to function either independently or dynamically form platoons via coupling or decoupling mechanisms. This dynamic platooning capability enables the adjustment of their structure to meet variable transport demands, thereby enhancing overall system efficiency through increased flexibility (for more details, see Pods4Rail, 2024[7]).

Pods operations are subject to a dual constraint system. At the transport service level, arrival and departure times at key nodes must strictly adhere to predefined time windows. At the physical operational level, constraints include both inherent infrastructure parameters (e.g., maximum platoon length, speed and acceleration thresholds) and dynamic safety spacing requirements. These constraints ensure both the punctuality of transport services and the safety and stability of system operations.

Capacity evaluation is a key challenge when introducing novel transport modes compatible with existing infrastructure. UIC 406 analytical method is the most widely used capacity model providing solid methodological and comparative work on static railway capacity, using headway/braking curve formulas and UIC code validation based on given timetable [3, 9]. Non-timetabled operational concepts have also been proposed to enhance flexibility, executing dynamic decision-making through techniques like Reinforcement Learning [2].While the underlying capacity evaluation principles of these approaches align well with the operational logic of Pods, a critical limitation lies in the implicit assumption that all trains are homogeneous—characterized by standardized lengths, masses, and performance profiles. This assumption becomes inadequate in the context of Pod systems, which are characterized by variable platoon sizes leading to dynamic headways. As a result, conventional capacity indicators—such as the number of trains per hour—fail to accurately reflect the true utilization or throughput of such flexible and modular operations.

Rail transit is shifting from fixed consists to flexible platooning, driven by key technologies like Virtual Coupling (VC) [1, 8] and digital automatic coupling [6]. These technologies provide the conditions for Pods platoon operation. While the Pods4Rail project has explored conceptual architecture and demand-driven scheduling for Pods systems [4, 5], significant gaps remain in capacity performance analysis. Especially, parameter variations (e.g., platoon length changes), heterogeneous platoons, and how these unique Pod features integrate with existing infrastructure and ensure the safe separation.

This study addresses critical knowledge gaps by analyzing how platoon structures, and coordinated speed interactions affect capacity consumption under ETCS Level 2 system. It incorporates operational constraints related to signaling, train separation, speed transitions, and heterogeneous platoon characteristics, and establishes essential foundations for implementing Pods systems on existing infrastructure and provides essential inputs for scheduling studies. The paper is organized as follows. Section 2 presents the problem statement, introducing the concept of Pods, Pod platoons and their structure. Section 3 extends blocking time theory and the UIC 406 capacity model to develop a capacity occupancy model for Pod platoons. Based on this, a nonlinear optimization model is designed to determine the optimal coordinated cruising speeds for platoons, minimizing infrastructure occupancy while maintaining safety margins. Simulation results are presented in Section 4, and Section 5 concludes the paper.

2 Problem Statement

The modular transport unit system, referred to as Pods, consists of two core components (as shown in Figure 1): Transportation Units (TUs) and Carriers. TUs serve as modular, demand-responsive loading container units that can be autonomously decoupled from and reattached to Carriers. This design enables the seamless transfer of loaded TUs across different transport modes, including rail and road, thereby facilitating efficient intermodal operations. Carriers act as mobile service terminals, with their dispatching strategies adhering to the spatio-temporal pickup and delivery requirements of the TUs. Upon assembly at designated operating stations, TUs and a Carrier form a complete Pod.

As illustrated in Figure 2, rail corridors equipped with the Pods system must accommodate multiple heterogeneous platoons, each capable of dynamically adjusting its length through coupling and decoupling operations. A platoon traverses an ordered sequence of fixed block sections, where each block is released only after the physical tail of the platoon clears the section.

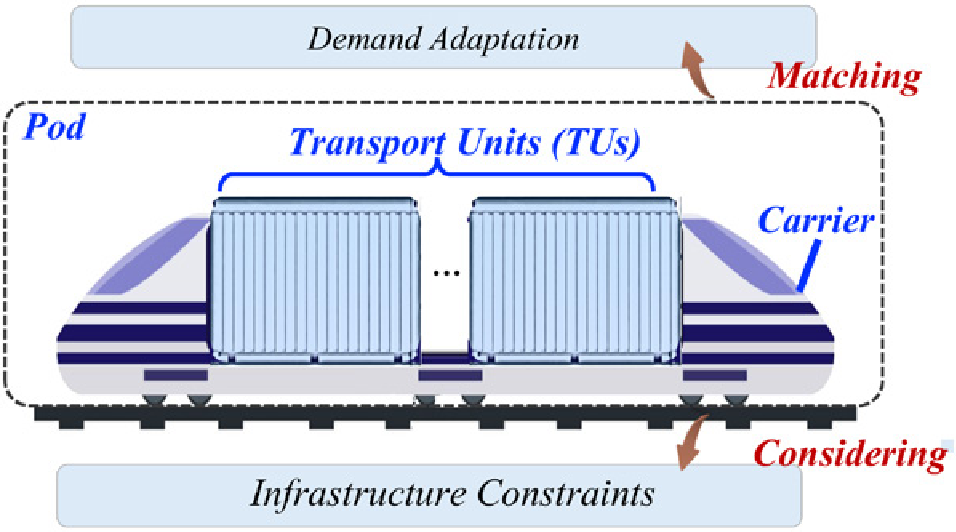


Figure 1: Pods architecture with Transportation Units (TUs) and Carriers

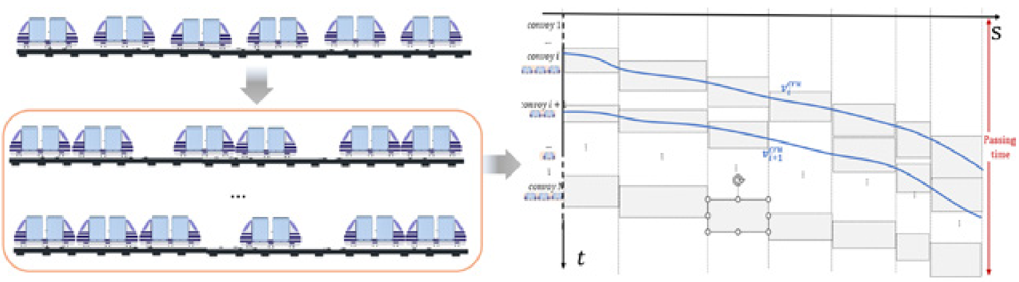


Figure 2: Block Occupancy Diagram for Heterogeneous Pod Platoon Traffic

Let $\mathscr{P} = \{P_1, P_2, \ldots, P_N\}$ denote the set of rail pod platoons involved in a demand request. This system $P_i \in \mathscr{P}$ is characterized by the following features:

- **Formation Type** $\mathscr{P}$: Defines the platoon structure, such as a single Pod, a short platoon, or a long platoon, which determines platoon operation attribute.
- **Speed Profile Conditions**: The motion of each platoon must comply with a predefined traction–cruise–braking trajectory. For a given platoon P_i, selecting an optimal cruising speed v_i is essential to minimize block occupancy across multiple blocks, even if theoretical optimal speeds might vary per block.
- **Platoon traffic Interaction**: Due to heterogeneous platoon characteristics, the optimal performance of heterogeneous Pod Platoons is interdependent, necessitating the calculation of coordinated cruising speeds.

Therefore, evaluating the performance of a given Pod Platoons Traffic requires minimizing infrastructure capacity consumption by coordinately optimizing the cruising speeds of all constituent platoons.

3 Model Formulation

3.1 Notions and Assumptions

The notations used in this paper are formally defined in Table1

The proposed method modeled under these fundamental assumptions, aligned with ETCS Level 2 signaling system operational specifications:

- Constant acceleration/deceleration profiles during traction (a_{tra}) and braking (a_{bra}) phases.
- Static platoon composition maintaining fixed pod count (n) throughout operational cycles
- All single pods are identical in terms of physical dimensions and mass. That is, each pod has the same length, weight, and performance characteristics.

3.2 Infrastructure occupation model

The blocking-time theory quantifies infrastructure occupation by defining the total duration a train renders a block section unusable goverde2013railway, bevsinovic2017microscopic, wang2020evaluating. However, this framework assumes fixed train lengths and a dispatching pattern, which limits its applicability to dynamically formed and reconfigurable pod platoons. Based on this, we extend the basic model to account for platoon composition with variable lengths and internal spacing. Fig. 3 illustrates the spatio-temporal blocking profiles for a pod platoon operating under two typical scenarios: (a) cruising and (b) station approach and departure. In each subfigure, the top part presents the speed profile across segmented infrastructure blocks, while the bottom part visualizes the corresponding block occupation timeline.

For cruising segments (Fig. 3 (a)), the block occupation time for a pod platoon is gov-

Table 1: Symbol Definitions with Classification

Symbol	**Definition**	**Unit**
Parameters (System Constants)		
L_{tlen}	Single Pod vehicle length	m
S_{vc}	Virtual coupling safety spacing	m
a_{bra}	Maximum braking deceleration	m/s²
a_{tra}	Maximum traction acceleration	m/s²
v_{sat}	Station speed limit	m/s
L_{sec}	Track section signaling length	m
L_{pla}	Station approach protection zone length	m
L_{over}	Platform throat overlap length	m
L_j^{total}	Cumulative position before block j (sum of preceding blocks)	m
L_{sat}	Station cumulative position k	m
T_r	Route establishment time	s
T_{free}	Block release delay time	s
T_D	Mandatory dwell time at platform	s
n_i	Number of Pods in platoon i	-
T_D	Mandatory dwell time at platform	s
t_{couple}	Setting time for forming platoon	s
α_j	Block type indicator (0:station,1:track)	-
Intermediate Variables (Calculated)		
$T^{\text{sat}}(n)$	Station blocking time for n-Pod platoon	s
T_{ap}	Approach braking time ($v_i^{\text{cru}}/a_{\text{bra}}$)	s
T_{pass}	Block traversal time	s
T_{sm}	Safety margin time behind last Pod	s
T_{tlen}	Train length passage time	s
T_{over}	Station throat clearance time	s
$v_{i,j}^{\text{in}}$	Platoon i entry speed at block j	m/s
$v_{i,j}^{\text{out}}$	Platoon i exit speed at block j	m/s
L_{platoon}	Total platoon length ($nL_{\text{tlen}} + (n-1)S_{vc}$)	m
d_{bra}	Braking distance ($(v_i^{\text{cru}})^2/(2a_{\text{bra}})$)	m
$t_{N,M}$	Total block occupation time for last platoon	s
$T_{i,j}^{\text{pass}}$	Platoon i passing time at block j	s
Decision Variables (Optimizable)		
$h_{\text{min}}^{(i-1,j)}$	Minimum headway between platoon $i-1$ and i at block j	s
v_i^{cru}	Optimized cruising speed of platoon i	m/s

erned by:

$$T^{\text{line}}(n) = T_r + \frac{v_i^{\text{cru}}}{a_{\text{bra}}} + \frac{L_{\text{sec}} + nL_{\text{lenP}} + (n-1)S_{intra} + L_{\text{sm}}}{v_i^{\text{cru}}} + T_{\text{clear}} \tag{1}$$

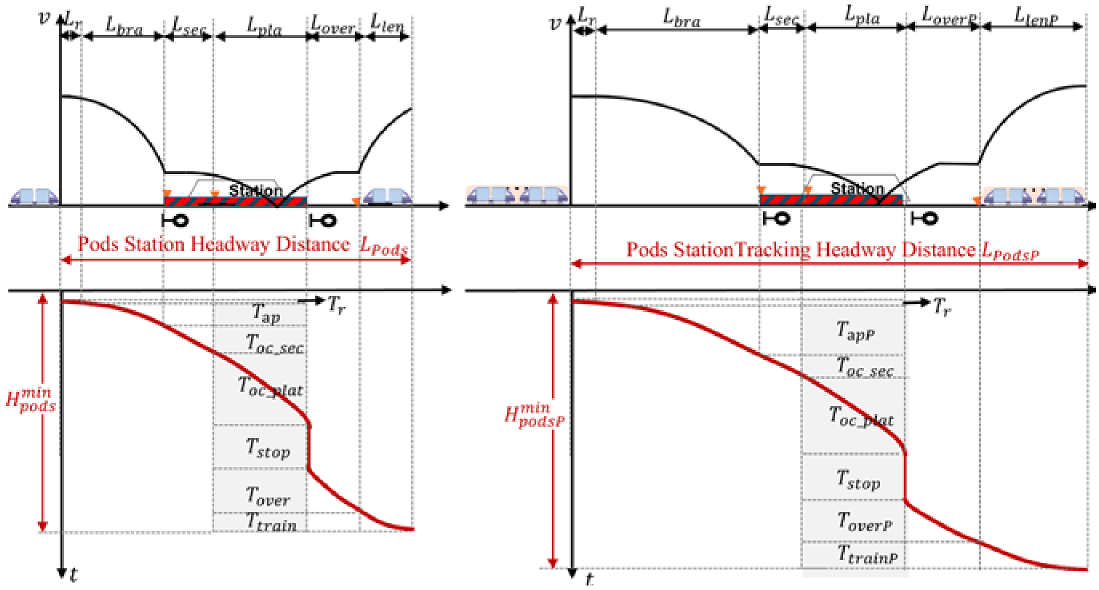


Figure 3: Block Occupancy Diagram for Heterogeneous pod Platoon Traffic

Here, nL_{lenP} represents the total physical length of the pod platoon, while $(n-1)S_{intra}$ denotes the safety separations between adjacent pods in the platoon. In contrast, other components, such as reaction time T_r, approaching time, and release delay, are governed by the real-time coordination system and are considered independent of the platoon size.

This formulation indicates that the primary length-dependent terms are nL_{lenP} and $(n-1)S_{intra}$, which directly prolong the time required for complete clearance of a block. Accordingly, the model captures how larger platoon formations lead to extended occupation, critical for capacity estimation and control design.

For station segments (Fig. 3 (b)), additional components must be considered, including dwell time and constrained acceleration profiles. The blocking time of a pods platoon is:

$$T^{\text{sat}}(n) = T_r + \frac{v_i^{\text{cru}}}{a_{bra}} + \frac{L_{pla} - \frac{(v_i^{\text{cru}})^2}{2a_{bra}}}{v_i^{\text{cru}}} + T_D + [T_{lapP}(n) + T_{tlenP}(n)] + T_{rel} \tag{2}$$

When generalized to an n-pod platoon, the time required to fully clear the station throat increases proportionally to the platoon length. To ensure safe operations and avoid conflicts, the station overlap length must be correspondingly extended. Given the allowable station speed and the overlap length, the rear-end passing time of the pod platoon through the station and overlap sections is computed as follows:

$$T_{\text{lapP}}(n)+T_{\text{lenP}}(n)=\begin{cases}\sqrt{\dfrac{2\left(nL_{\text{len}}+(n-1)S_{\text{intra}}+L_{\text{over}}\right)}{a_{\text{tra}}}}, & v_i^{\text{cru}}\geq Vcrit\\ \dfrac{2a_{\text{tra}}\left(nL_{\text{len}}+(n-1)S_{\text{intra}}+L_{\text{over}}\right)+(v_i^{\text{cru}})^2}{2a_{\text{tra}}v_i^{\text{cru}}}, & v_i^{\text{cru}}<Vcrit\end{cases} \tag{3}$$

where $Vcrit$ denotes the critical velocity defined by:

$$Vcrit=\sqrt{2a_{\text{tra}}\left(nL_{\text{len}}+(n-1)S_{\text{intra}}+L_{\text{over}}\right)}.$$

Compared to cruising segments, station areas exhibit higher sensitivity to platoon length due to the complexity of station throat sections and overlap track areas. Capturing this effect through an extended formulation is crucial to accurately evaluate infrastructure capacity under operational and signalling constraints.

3.3 Capacity Optimization Model

As illustrated in the previous section, the capacity consumed by a given pods' service schedule is measured by the total time the infrastructure is occupied. Thus, a capacity-effective schedule aims to minimize such an infrastructure occupation. Assuming a fixed start time for the rail pods' service, this translates into reducing the time at which the last platoon in a schedule cycle clears the considered infrastructure. Given a section composed of M blocks, the objective is to calculate the capacity consumption of N pod platoons, where each platoon consists of n pods. The objective function is defined as:

$$\min\ T_{\text{pass}}=t_{N,M}-t_{1,1} \tag{4}$$

where, the total passing time $t_{N,M}$ is computed through an iterative process over platoon movements and block transitions.

- For each block j, the earliest time at which platoon i can enter is determined by the minimum headway from the preceding platoon:

$$t_{i,j}=t_{i-1,j}+h_{\min}^{(i-1,j)} \tag{5}$$

- The passing time of a platoon from consecutive blocks is determined as::

$$t_{i,j} = t_{i,j-1} + T^{\text{pass}}_{i,j-1} \tag{6}$$

The passage time $T^{\text{pass}}_{i,j}$ of platoon i through block j is important for evaluating infrastructure capacity, especially under the Pods system with heterogeneous platoons. Modeling the movement of these mixed-structure platoons is essential, accounting for variations in formation length, distinct acceleration/deceleration profiles, and the time cost associated with coupling process.

$$T^{\text{pass}}_{i,j} = \begin{cases} (n_i - 1)t_{\text{couple}} + T_{\text{stop}} + f_{\text{sta}}(l_j), & \text{Station operation} \\ f(v_{\text{in}}, v_{\text{out}}, l_j), & \text{Acceleration/Deceleration} \\ \dfrac{l_j}{v^{\text{cru}}_i}, & \text{Cruising} \\ \dfrac{l_j}{\max(|v_{\text{in}}|, 0.1)}, & \text{Other cases} \end{cases} \tag{7}$$

where

$$v^{\text{out}}_{i,j} = \begin{cases} v_{\text{tar}}, & \text{if } v_{\text{out}} \text{ reached} \\ \sqrt{|v^2_{\text{in}} \pm 2al_j|}, & \text{otherwise} \end{cases}$$

The Pods platoons operation process is governed by the following constraints defined for all trains $i \in \mathscr{I}$ and block segments $j \in \mathscr{J}$:

$$v^{\text{in}}_{i,j+1} = v^{\text{out}}_{i,j}, \qquad \forall i \in \mathscr{I},\ j \in \{1, \ldots, J-1\} \tag{8}$$

$$t_{1,1} = 0 \tag{9}$$

$$V_{\min} \leq v^{\text{in}}_{i,j},\ v^{\text{out}}_{i,j} \leq V_{\max}, \qquad \forall (i,j) \in \mathscr{I} \times \mathscr{J} \tag{10}$$

$$v^{\text{cru}}_i \geq v_{\text{sat}}, \qquad \forall i \in \mathscr{I} \tag{11}$$

$$h^{(i-1,j)}_{\min} \geq T^{\text{block}}_{i,j}, \qquad \forall i \in \mathscr{I} \setminus \{1\},\ j \in \mathscr{J} \tag{12}$$

Speed continuity requires that platoon i's output speed at block j equals its input speed at block $j+1$, as shown in Eq. (8). Eq. (9) indicates that the lead platoon departs from the first block at time zero, establishing a temporal reference. The speeds are constrained within the operational limits $[V_{\min}, V_{\max}]$, as shown in Eq. (10), and the cruising speed v^{cru}_i must be no less than the station limit v_{sat}, according to Eq. (11).

The minimum time headway $h_{\min}^{(i-1,j)}$ is imposed to maintain safe separation by ensuring that it exceeds the block occupation time of the preceding platoon, as stated in Eq. (12). The term $T_{i-1,j}^{\text{block}}$ represents the blocking time of platoon $i-1$ at block j.

The non-linear coupling between vehicle speed, time consumption, and headway constraints creates nonconvex solution space. This complexity hinders the direct application of standard optimization solvers such as CPLEX or Gurobi. However, observing that the objective function's complexity is contrasted by a relatively small number of constraints, we apply a hybrid Interior Point - Augmented Lagrangian strategy to solve the model.

4 Analysing capacity impacts of rail pods' platoon formation and operational speed

Simulation cases are provided in this section considering the ETCS level 2 signalling system to illustrate the effectiveness of the proposed approaches.Six Pods with varying platoon structures were selected to verify the proposed model. Other related parameters can be approximated in table 2.

Table 2: Simulation Parameters for Case Study

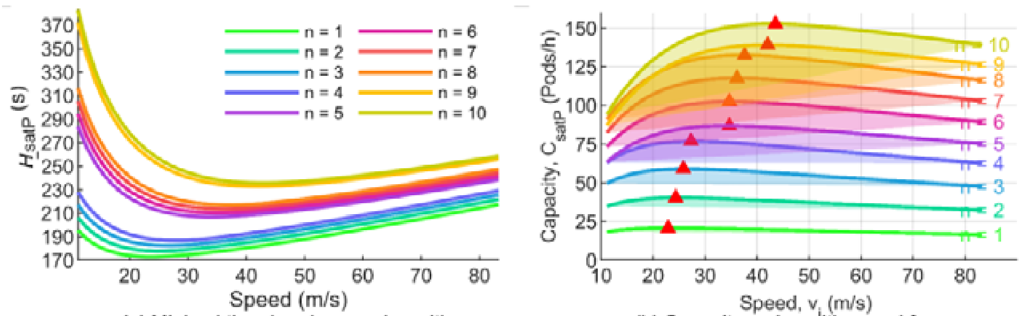
Structural		**Dynamic**		**Operational**	
Symbol	Value (Unit)	Symbol	Value (Unit)	Symbol	Value (Unit)
M	6 (-)	a_{bra}	1.0 (m/s²)	v_{sat}	20 (m/s)
L_{tlen}	100 (m)	a_{tra}	0.8 (m/s²)	$v_{\max}$	60 (m/s)
S_{vc}	30 (m)			$v_{\min}$	20 (m/s)
Geometric		**Control**		**Time**	
L_{sec}	[1000,1500×4,1000] (m)	T_r	4 (s)	T_{stop}	30 (s)
L_{pla}	100 (m)	T_{rel}	3 (s)	t_{couple}	120 (s)
L_{over}	50 (m)	α_j	[0,1,1,1,1,0] (-)		
L_{sm}	200 (m)				

4.1 Analysis of the relation capacity-cruising speed for uniform pod platoons

First, consider a homogeneous platoon configuration, where each platoon consists of the same number of Pods, resulting in equal platoon lengths. Under a uniformly block section length configuration, the minimum tracking time headway equals the block occupation time, leading to a line headway defined as $H^{\text{block}} = T^{\text{block}}$. The corresponding line capacity is derived from the UIC standard as follows:

$$C_{\text{block}} = \frac{3600}{H^{\text{block}}} \tag{13}$$

Based on this formulation, analysis is conducted on the relationship between speed, tracking interval, and capacity within the station blocking section under homogeneous platoon flow conditions. As shown in Figure 4, the approach area of the station imposes additional restrictions on the separation of the train due to the need for precise stopping and a longer blockage time.



(a) Minimal time headway varies with speed for platoon with n Pods
(b) Capacity varies with speed for platoon with n Pods

Figure 4: Optimal Speed Matching under Maximum Capacity and Headway

Results indicate that the station capacity is not directly proportional to speed or platoon length. The station capacity is much smaller than the section capacity, so when trains enter a section, there is some space to adjust the platoon formation through speed variation. When a train cluster forms platoons of different configurations, there will be varying supply rates within the time window for pods transportation.

4.2 Capacity analysis of heterogeneous pod platoons for optimised cruising speeds

To further evaluate the impact of heterogeneous platoon configurations on infrastructure capacity, we consider all possible platoon arrangements composed of 6 Pods under a fixed infrastructure setup. By modeling all integer partitions of 6 Pods, a total of 32 distinct platoon structures are generated, ranging from a single long platoon to multiple shorter, evenly distributed platoons. Figure 5 illustrates the infrastructure occupation time corresponding to each configuration. The X-axis represents the total track occupation time, while the Y-axis indexes the specific platoon structures.

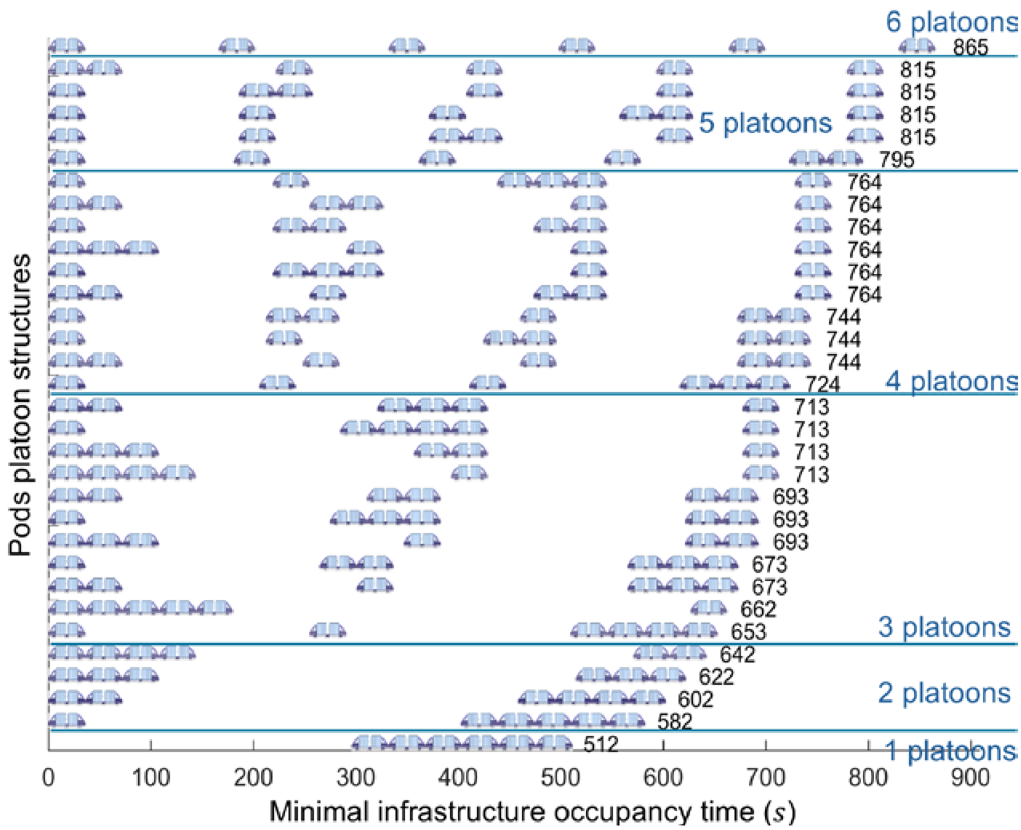


Figure 5: Minimum infrastructure occupation time for heterogeneous platoons

The comparison reveals that platoon structure has a significant influence on infrastructure consumption. The optimal platoon configuration can improve system efficiency by up to 40.8%. These findings highlight the importance of structural design in platoon scheduling and provide a quantitative basis for future optimization in dynamic platoon management strategies. Results suggest that, in the absence of platform length constraints, forming larger platoons can significantly enhance line throughput and infrastructure utilization.

Even with the same number of platoons using the Pods set, variations in platoon length configuration can lead to significant differences in infrastructure occupation. For instance, a `2-3-1` structure and a `1-1-4` structure both consist of three platoons, where numbers indicate the number of Pods included in each platoon, but their temporal occupation across the blocking sections differ due to the order and size distribution of the platoons.

To investigate this effect, Figure 6 presents the block time occupation and optimal cruise speed configurations under `2-3-1` and `1-1-4` structures. The horizontal axis denotes the cumulative length of the blocks, while the rectangular blocks represent the minimum safe separation time required by each block. The upper part of Figure 9 shows the safety separation and speed trajectory of the block, and the lower part shows its coordinated speed configuration. The curved lines represent the coordinated speed profiles computed for each platoon. Each group of lines corresponds to one platoon, and the number of lines in each group reflects the number of Pods within that platoon.

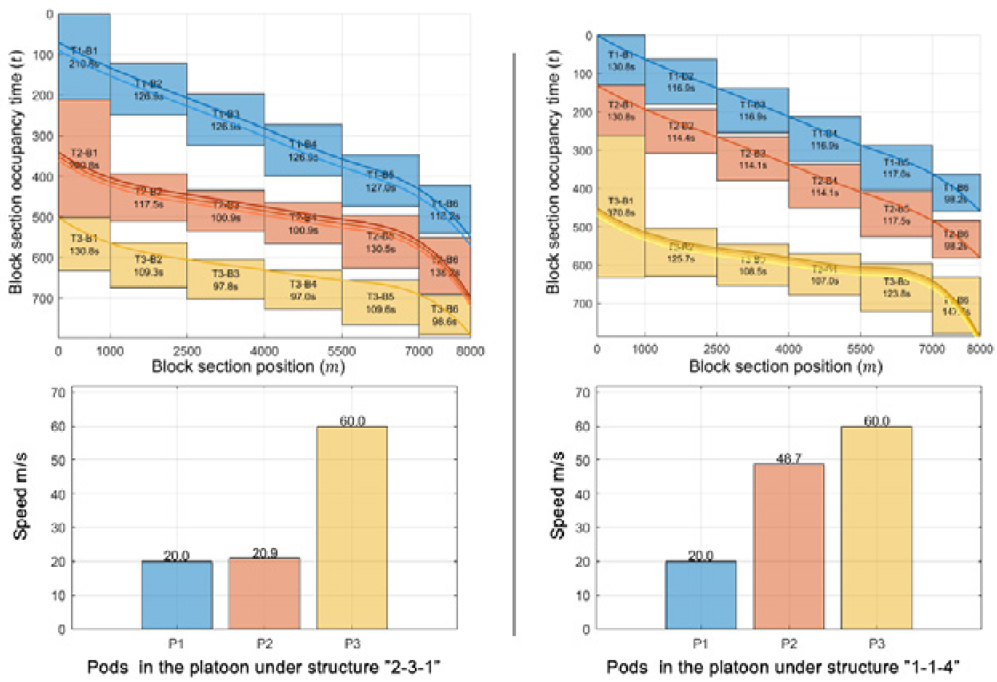


Figure 6: Minimum occupation time for heterogeneous platoons with optimal speed

The simulation results indicate that optimal velocity configurations can minimize block occupation time under different platoon layouts. The departure block, which includes additional time for platoon formation, often becomes the bottleneck in overall capacity consumption. This visualization highlights how structural layout and coordinated velocity planning jointly impact infrastructure usage, reinforcing the need for formation and speed co-optimization in platoon scheduling.

Interestingly, the optimal solutions do not require all trains to operate at maximum speed. Instead, a trend emerges where leading platoons are assigned relatively higher speeds, while trailing platoons operate at reduced velocities. This "fast-front, slow-rear" coordination effectively minimizes tracking gaps and optimizes infrastructure utilization. Moreover, the optimal cruise speed is not linearly proportional to platoon size. Longer platoons do not necessarily result in higher optimal speeds, highlighting the importance of joint optimization between structural layout and speed planning for capacity enhancement.

Further analysis was conducted to investigate the impact of platoon coupling time on infrastructure occupation and optimal platoon structure. The results, summarized in Table 3, indicate a near-linear increase in total occupation time with increasing coupling time.

Table 3: Impact of Platoon Coupling Time on Infrastructure Occupation

CouplingTime (s)	0	30	60	90	120	150	180	210
Occupation (s)	249	399	549	699	849	902	902	902
Structure	6	6	6	6	6	[1,1,1,1,1,1]		

When the coupling time exceeds a threshold (e.g., 150 seconds), the optimizer consistently selects the most uniform platoon structure (e.g., [1,1,1,1,1,1]), suggesting that structure-based optimization becomes ineffective. This is because the extended coupling time dominates the total occupation time, rendering any benefit from structural variation negligible. These findings imply that excessive coupling durations can negate the benefits of platoon-based structural planning. Therefore, the operational time window for platoon formation acts as a limiting factor in capacity optimization. This provides a quantitative reference for setting pick-up and delivery time constraints in Pods systems.

5 Conclusion

The Pods system offers higher flexibility for Customer-oriented rail services and seamless operations. The scheduling time windows must be carefully configured by considering infrastructure, especially under the safety constraints imposed by signaling systems. The dynamic nature of Pods—featuring variable platoon lengths and dispatch timing—renders conventional capacity assessment metrics unsuitable. To address this, we extend the classic blocking time theory and the UIC 406 methodology to support Pods platoons. A novel optimization model is proposed to minimize infrastructure occupation time. The model constructs a mapping between convoy structure, speed profile, and capacity consumption, enabling joint optimization of speed allocation. The model incorporates detailed operational rules and piecewise velocity profiles reflecting the traction–cruise–brake process. A hybrid Interior Point–Augmented Lagrangian method is employed to solve the resulting nonlinear optimization problem. Simulation results under ETCS level 2 signaling system settings show that infrastructure consumption is not linearly correlated with either platoon size or speed. The proposed coordinated structure-speed optimization can enhance capacity utilization by up to 40.8%. Optimal solutions typically exhibit a "fast-front, slow-rear" velocity pattern. Notably, operating all trains at maximum speed is neither necessary nor optimal.

Furthermore, the analysis reveals that platoon coupling time has a critical impact on capacity efficiency and optimal structure selection. When coupling time exceeds a threshold, the benefits of platoon-based optimization diminish. It will create feedback constraints on pickup and delivery windows in Pods deployment. The proposed modeling framework provides a foundation for analyzing the interactions between Pods system features and infrastructure constraints. Future work will extend the model to incorporate non-uniform mass distribution among Pods and adapt it to moving block signaling environments. This study provides a quantitative foundation for the planning and design of Pods systems.

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