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Modelling and analysis of virtual coupling for increasing service performance in the case of single-track rail lines

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Abstract
Smart and green mobility systems are key factors for the sustainability of our cities which are experiencing increasingly growing density conditions. The goal is to make public and sharing transport systems more attractive than private vehicles, thus reducing congestion levels as well as air and noise pollution in favour of the quality of life in our urban and suburban areas. In this context, the proposed paper presents a simulation-based methodology for increasing the efficiency level of railway operations, through the implementation of virtual coupling systems, intending to lead the modal split towards a more sustainable scenario. To show the feasibility of the proposed approach, it has been applied in the case of a real regional rail line. Results confirm the benefits of the adoption of such systems on the attractiveness levels by showing an increase in carrying capacity with a related reduction in user waiting times.
Keywords: Sustainable mobility; traffic engineering; rail operations; virtual coupling; carrying capacity.

1. Introduction
Nowadays, given the growing prominence assumed by the protection of the planet and the preservation of the environment, the need of identifying a sustainable framework for carrying out all human activities plays an increasingly crucial role (Amen & Nia, 2020, Aziz Amen, 2022, Amen et al., 2023) . Among such activities, we can find also journeys and mobility tasks which each one of us undertakes every day for several reasons, e.g., work, school, shopping, etc. Therefore, governments around the world are making efforts in such a direction in order to provide citizens with sustainable mobility frameworks allowing them to leave the private car in favour of public transport and other eco-friendly solutions. For example, very special attention is being given to electric options, shared solutions, MaaS services (Karmagianni et al., 2016) and autonomous driving options. The basic idea behind regards the importance of having a vehicle to use it, instead of owning it, since it is useful only during the trip. Moreover, alternative fuels and propulsion systems are being investigated (Dahal et al., 2021).
Further, it is worth noting that after the COVID-19 pandemic, mobility habits and needs are deeply changed with a tendency to prefer active modes (i.e., walking, cycling and other micro-mobility solutions). People have gained a different way of travelling and this led to different demand patterns and the rise of innovative concept as proximity and 15-minute city (Staricco, 2022). However, besides the neighbourhood scale, it is clear that, in the case of long-distance trips, public transport remains the most sustainable option (Amen, 2021). More specifically, a sustainable mobility system should be based on railway transport, representing the backbone of the framework, with electric transit solutions and active mobility options acting as feeders for the first/last mile trips. Therefore, on the one hand, it is crucial to rely on a robust and attractive public transport system and, on the other, to improve the station catchment areas and related accessibility by promoting walking and cycling modes. The latter can be achieved by enhancing the walkability of pathways and equipping them with proper services and facilities (Gholami et al., 2022). In this context, also facilities at destination points (e.g., a bike rack at the rail station) can play an important role (Pucher and Buehler, 2009). However, this work focuses on how to improve the performance and attractiveness of railway transport, thus leading the modal shift toward public transport modes in a sustainable perspective; indeed, such a transport system is green, safe, smart and presents a high suitability for intermodality.

2. Literary review and background
The main open research questions about railways regard dispatching and rescheduling problems, which consist of tasks of monitoring and controlling aimed at ensuring a smooth running of rail service, as well as re-establishing ordinary conditions, in response to any kind of system failure, by adjusting the planned service to the actual situations (Feng et al., 2021; Ghasempoura and Heydeckera, 2019; Zhu and Goverde, 2021). Clearly, it is crucial that all these tasks take into account passenger travel demand (Hartleb and Schmidt, 2022; Joubert et al., 2022).

Another crucial factor of railway service regards energy-saving strategies which can include, among others, eco-driving strategies, regenerative braking tasks and the adoption of on-board and way-side storage devices, e.g., supercapacitors (Douglas et al., 2015; González-Gil et al., 2014).
However, this work is focused on the degree of the carrying capacity offered, which depends on the capacity of single trains running the service and the number of trains which can be present on the network simultaneously. The latter represents the level of rail infrastructural utilisation and is a quite complex concept.
Indeed, as shown by Prencipe and Petrelli 2018, it is necessary to differentiate the theoretical capacity from the practical capacity and, in addition, as reported in UIC, 2013, the following elements must be considered: the average speed, the timetable stability and the level of heterogeneity concerning train motion phases. In particular, the average speed impacts the braking distance; moreover, some supplement and recovery times scheduled for addressing primary and secondary delays can reduce capacity; finally, the higher the heterogeneity level, the higher the level of consumed capacity. According to the literature, the estimation of railway capacity can be derived by adopting the following main methods: analytical approaches (RFI, 2011; Schultze et al., 2015); optimisation approaches (Gonzalez et al., 2010; UIC, 2013); simulation approaches (Lindfeldt, 2015; Prencipe and Petrelli 2018).
The degree of infrastructural use is strongly affected by the signalling and control system implemented on the network. In particular, in the European Union, it is established the adoption of the European Train Control System (ETCS) which guarantees interoperability among Member States. It can be declined through 3 different levels.
In a nutshell, ETCS-level 1 is represented by a cab signalling system which allows a discontinuous communication between the on-board and ground systems; this communication becomes continuous with level 2 thanks to the GSM-R network which ensures a continuous link between the Radio Block Centre (RBC) and each train. RBC knows in each instant train position and communicates them the movement authorities; finally, level 3 is a fully based radio system, where the physical train spacing is left in favour of the moving block principle allowing a great reduction in distance to be assured between two trains thus allowing safe braking operations. More details about this can be found in Schnieder, 2021; however, it is clear that the higher the level, the greater the network utilisation rate.
Advanced forms of signalling systems, aimed to further increase rail capacity are represented by high-density frameworks (Cuppi et al., 2021) and the Virtual Coupling (VC) technology (Quaglietta et al., 2023). The latter represents the focus of this work and, specifically, it is a concept borrowed from the automotive sectors and cooperative and autonomous driving tasks. Indeed, it is based on V2V (Vehicle-to-Vehicle) communication (Redza Khan et al., 2021) and it is largely used in the case of road transport in order to reduce congestion and emission levels (Hou et al., 2023). In the case of the railway sector, the Train-to-Train (T2T) communication is involved and, in particular, by leaving the concept of the absolute braking distance in favour of the relative braking distance, it allows trains to generate a platoon with a dramatic increase in the infrastructure utilisation rate.
Specifically, VC appeared in 1999 and then the related principles enhanced until 2006 and even more with the advent of new communication technology ensuring the exchange of dynamic information, such as position and speed, with a high rate and low latency (Felez and Vaquero-Serrano, 2023). Several European projects deal with it as, for instance, X2Rail-3; Movingrail; Scott, FRMCS and the more recent advancements in the field can be found in Aoun et al., 2020; 2021; 2023.
The paper aims to investigate the potentiality of such an innovative technology for increasing service rail performance in the case of single-track rail lines. The choice of a single-track framework is not random, but it has a specific meaning. Indeed, in this case, it could happen that the infrastructural constraints are so strict that the expected benefits are no longer worthwhile.
The remainder of the paper is so structured: Section 2 provides insights into the adopted methodology; Section 3 presents an application to a real rail network; finally, Section 4 summarises conclusions and future developments.

3. The proposed methodology

As shown by Casazza, 2020, the procedure through which two trains can make a platoon can be represented by means of the following phases: i) approaching and establishing a communication; ii) exchanging relevant mission data; iii) identification of the master and the slave vehicle; iv) sending the activation signal from the master to the slave train which acknowledges thus generating the platoon.
By way of illustration, in order to show the benefits of virtual coupling, Figure 1 presents train operations without (a) and with (b) this tool in the case of a y-shape line. As can be seen, without VC, the blue train has to wait that the green one clears the section block S2 (Phase 1) before going ahead (Phase 2). In the case of VC, instead, since the two trains make a platoon, they can cross the single-track section simultaneously (Phase 1) and then each one can follow its own itinerary (Phase 2). Clearly, a similar condition happens on the return trip.

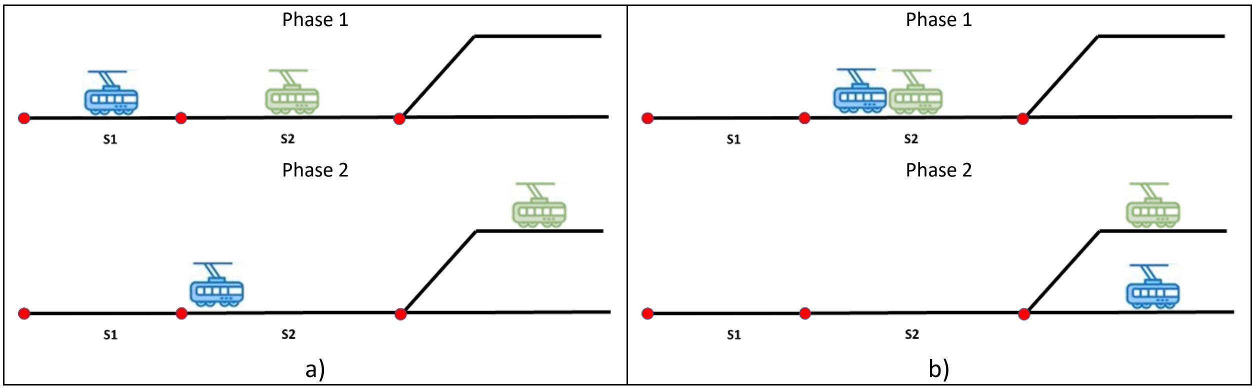

Figure 1. Train operations without VC (a) and with VC (b).

Therefore, thanks to the establishment of a platoon and the reduction of the distance between trains (i.e., the relative braking distance), the infrastructure utilisation rate increases and, hence, the carried capacity improves.
Indeed, the carrying capacity of a railway line can be computed as follows:

$$Cap_l = Cap_t \cdot f_l^p \quad (1)$$

where Cap_l is the carrying capacity of the line *l*, expressing the number of passengers who can be carried in a certain time period; Cap_t is the capacity of the single train, expressing the available seats in each vehicle; f_l^p is the planned service frequency for line *l*.
In particular, a reduced distance between trains allows lower headways and, therefore, greater frequency to be scheduled, with a consequent increase in carrying capacity and a decrease in passenger waiting times.
However, it is worth noting that, in order to ensure higher service frequencies, a greater number of trains is required. Indeed, the number of vehicles (NV) required for ensuring the planned frequency on the line *l* (i.e., f_l^p) can be computed as follows:

$$NV = int\left(CT \cdot f_l^p\right) + 1 \quad (2)$$

where CT represents the cycle time, i.e. the time required by a convoy to complete the outward trip, the following return trip and achieve the initial condition. It can be computed as follows:

$$CT = \sum_{kot} tt_{kot} + \sum_{sot} dt_{sot} + it_{ot} + \sum_{krt} tt_{krt} + \sum_{srt} dt_{srt} + it_{rt} \quad (3)$$

where tt_{kot} and tt_{krt} are the travel times associated, respectively, to link *kot* and *krt*; *kot* and *krt* are the generic links (i.e. track sections) associated, respectively, to the outward trip (*ot*) and return trip (*rt*); dt_{sot} and dt_{srt} are the dwell times associated, respectively, to platform *sot* and *srt*; *sot* and *srt* are the generic platforms of station *s* for, respectively, the outward trip (*ot*) and return trip (*rt*); and it_{ot} and it_{rt} are the inversion times (i.e. preparation times for the subsequent trip) associated, respectively, to the outward trip (*ot*) and return trip (*rt*).
Generally, also ancillary times, such as buffer or reserve times, can be added.
However, the important thing to be noticed is the necessity of accurately estimating such variables by developing a simulation model reproducing the involved components, i.e., infrastructure and signalling system features, operating rolling stock, planned timetable and passenger flows. In the following, such a simulation-based methodology has been applied to a real regional rail network, thus demonstrating its effectiveness.

4. Application to a real regional network

In order to show the feasibility of the proposed approach, it has been applied in the case of a real case study, which is the Circumvesuviana network in the South of Italy, serving the eastern and southern parts of the metropolitan area of Naples (Figure 2).

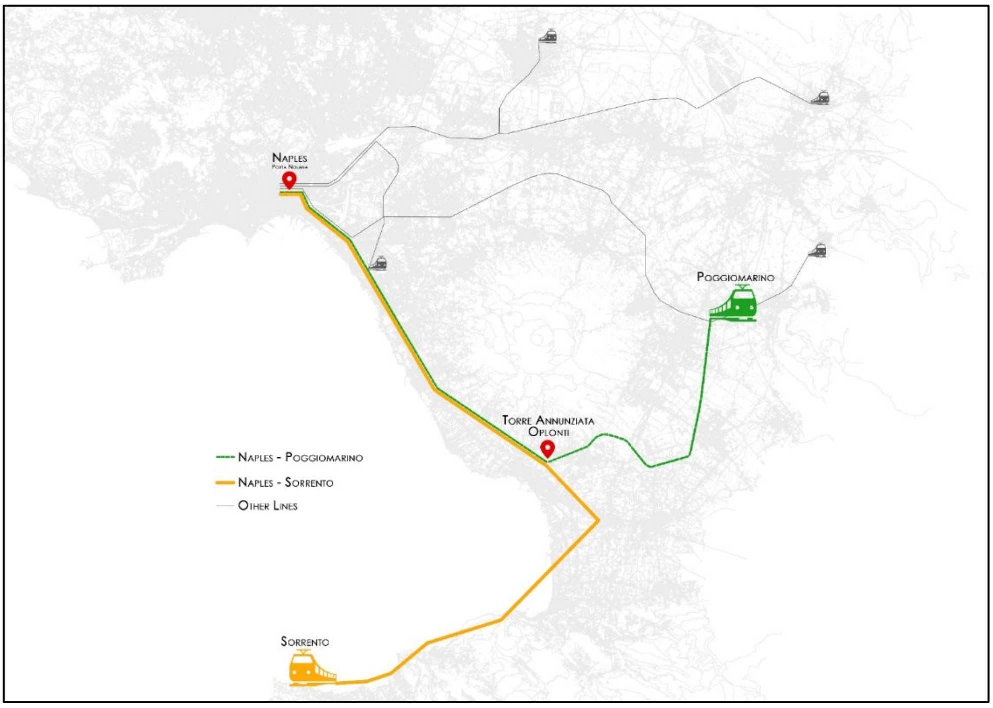

Figure 2. The analysed y-shape network

The whole network extends for 142 km, with 6 lines and 97 stations. However, more precisely, we focus on the two lines highlighted in orange and green in Figure 2, connecting the city of Naples respectively with Sorrento and Poggiomarino. As can be seen, they exactly reproduce the y-shape described above, with the station of Torre Annunziata representing the branching point where the coupling/decoupling operations can occur.

By means of the commercial software OpenTrack (Nash and Huerlimann, 2004,), we reproduced the two lines and all related features, i.e., infrastructure (e.g., slopes, radii of curvature, etc.), signalling system (e.g., braking curve transmission, wireless communication, etc.), rolling stock (e.g., speed, acceleration, number of engines, etc), planned timetable (e.g., number of runs, departure and arrival times, etc.).

In particular, three different scenarios have been simulated: i) the current condition; ii) the adoption of the standard coupling; iii) the adoption of virtual coupling and some KPIs have been computed for each one of them (Table 1).

Table 1. Numerical results.

	RAIL LINE	AVERAGE HEADWAY [min]	TRAVEL TIME [min]	INCREASE IN CAPACITY [%]
Current scenario	Naples-Sorrento	24	74	-
	Naples-Poggiomarino	24	61	-
Standard coupling	Naples-Sorrento	23	85	0
	Naples-Poggiomarino	23	70	0
Virtual coupling	Naples-Sorrento	17	78	30
	Naples-Poggiomarino	17	64	60

Numerical results show that the virtual coupling technology allows a decrease in the average headway which drops from 24 minutes to 17 minutes (-29%) for both lines and an increase in carrying capacity. Specifically, concerning capacity levels, an increase of 30% occurs on the Naples-Sorrento line which rises to 60% in the case of the Naples-Poggiomarino line.

In particular, the reduction in headways leads to lower values of waiting times for travellers which can save globally, in one year, more than 17M€. Moreover, by considering a service life of 25 years, a monetary saving per kilometre equal to 6.6M€ can be derived.

Such estimations appear crucial to support the decision-making process related to the adoption of the virtual coupling technology, in order to derive a cost-benefit analysis on the affordability of the process which properly takes into account a double perspective, i.e., rail operation and users' satisfaction.

5. Conclusions and future developments

The proposed work analysed potentialities and drawbacks of the virtual coupling technology in order to increase rail service performance. Indeed, the final goal is to lead the modal shift towards a more sustainable mobility framework with railway transport as the backbone of the systems and the other modes representing feeder options for first/last mile trips. Such a technology, based on T2T communication, and already largely used in the road transport sector, has shown great benefits also in the case of railway service with an increase in the infrastructure utilisation rate and a reduction in users' generalised cost.

In particular, the proposed simulation-based methodology focused on single-track rail lines in which, often, it could happen that the infrastructural features present so constraining limits that they could nullify the expected benefits. An application to a real rail regional line has been performed in order to show the feasibility of the proposed approach and results have shown an increase in capacity and, therefore, a decrease in passenger waiting times. Nevertheless, it is worth noting that such a result cannot be reached on an equal basis in terms of rolling stock material, but additional convoys are required with related additional costs. However, the total yearly monetary saving makes the investment in the new technology and the acquisition of additional vehicles affordable.

As research prospects, we suggest applying the proposed method in the case of other lines of the same network and on other networks with similar patterns, thus further investigating virtual coupling potentiality. Finally, besides regional contexts, also metro and high-speed lines could be analysed.

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Conflict of Interests

The authors declare no conflict of interest.

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