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Decision support for dimensioning an innovative rail-road transport system*

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Abstract

This paper proposes an optimization algorithm to support decision makers in the dimensioning of a new type of public transport service. In particular, vehicles capable of traveling on both rail and road are exploited to revitalize capillary railway lines, characterized by low demand but very high societal impact. To support decisions on infrastructure modifications and fleet size, we propose an algorithm based on the solution of a mixed-integer linear programming model. In particular, the infrastructure modifications considered consist in the construction of road-type sidings

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on the existing railway line, to allow vehicle crossing. We assess the performance of our algorithm on a real case study: the line joining the cities of Limoux and Quillan, in France. The results highlight how investing in siding construction can indeed improve the regularity of the timetable that can be planned. However, depending on the available fleet and the desired frequency, they may not be strictly necessary.

Public transport, rail-road service, timetable regularity, infrastructure modification

1 Introduction

The development of public transport plays a central role in the current movement towards sustainable mobility. While in many big cities public transport is very mature and quite efficient, this is not at all the case for most rural areas. Some of these areas were historically reached by the railway network through the so-called capillary lines. These lines are typically single-track lines, connecting a few stations with one or two platforms. The demand flow on these lines is often low, in the order of some dozens of passengers per day. Hence, the cost of infrastructure maintenance and service operation has often been considered excessive compared to the benefits brought. As a consequence, many of these lines have been abandoned in the last decades.

In recent years, new ideas have emerged to bring back to life these abandoned capillary lines. In particular, new types of vehicles and new types of service offers are being imagined to cover the mobility needs while limiting costs [1–6]. Some of these ideas are explored in the Flexmove project [7], funded by the French Government (ADEME) within the “France 2030” investment plan. In particular, the project proposes the FERROMOBILE [8], a road-to-rail vehicle meant to operate on the road and on dedicated tracks (Figure 1). Initially, the FERROMOBILE will operate only on the rail, but exploiting the flexibility of road-type *hubs* and *sidings* for crossing, stopping and recharging. The service will be either on demand or based on a fixed timetable. In the future, the road dimension is planned to be extended to allow a real door-to-door service to the users.

The level of service achievable by the envisaged system depends on several factors. Focusing on fixed timetable operations, in this paper we measure the level of service as a function of two quantities: frequency, which implies capacity, and regularity [9]. In turn, these two quantities depend on two main factors, i.e., the available fleet and the specific characteristics of the line. Indeed, single-track lines intrinsically impose constraints on frequency, mostly due to the limited crossing possibilities for vehicles traveling in opposite directions.

Depending on the desired level of service, some layout modifications will be necessary along the rail line, specifically the construction of road-type sidings to allow vehicle crossing in locations other than stations.

In this paper, we propose an optimization algorithm to support decision makers in their choices on system dimensioning. In particular, we compute the



Figure 1: The FERROMOBILE traveling on a rail track (Photo by Christophe Lepetit for ADEME 2024).

impact of changing either fleet size or siding number and position of sidings on timetable regularity. To do so, we rely on a Mixed Integer Linear Programming (MILP) model that solves a bi-objective problem. On the one hand, it determines the most efficient use of sidings. On the other hand, it schedules trains to maximize the timetable regularity. We apply this algorithm on the case study considered in the project as a demonstrator: the line between Limoux and Quillan in France. In our experimental analysis, we show how different fleet sizes impact on the quality of service when combined with the building of carefully selected sidings.

The rest of the paper is organized as follows. Section 2 describes the FERROMOBILE concept that motivates this work. Section 3 details the methodology we propose, and Section 4 reports the experimental analysis we run to showcase its applicability. Finally, Section 5 draws conclusions and highlights directions for future work.

2 The service concept

The aim of using the FERROMOBILE on capillary lines is to provide a flexible mobility service accessible to all. This is part of the French government's strategy to decarbonize the economy. Indeed, the FERROMOBILE is an electric, collective transport service, based on road vehicles adapted to rail. In

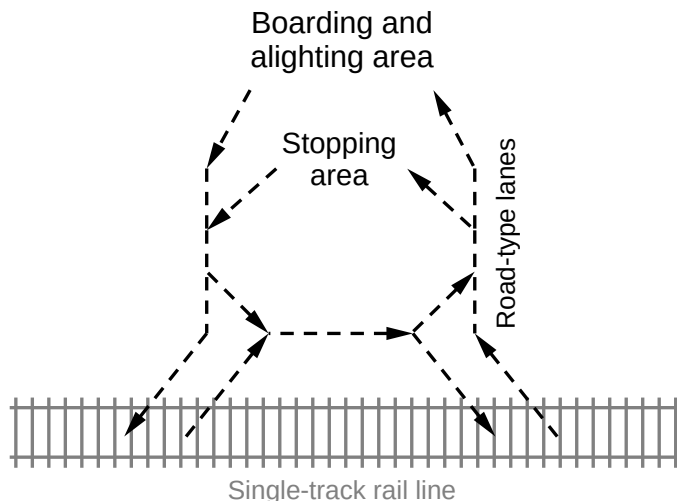


Figure 2: Example of a possible layout for a hub.

particular, these vehicles are standard road vehicles (e-traveller Peugeot from Stellantis) equipped with wheel adaptation fulfilling the technical and regulatory requirements of the rail system. This significantly reduces construction costs with respect to trains, and adds much flexibility to the vehicles capability. The FERROMOBILE vehicles have a capacity of eight passengers and run at up to 60 km/h on rail tracks and at 6 km/h on road-type areas.

In the currently studied service concept, the FERROMOBILE travels on a single track and uses road-type hubs to have passengers boarding and alighting or to cross vehicles traveling in the opposite direction. These hubs result from the conversion of the traditional rail stations. An example of the layout of a hub is represented in Figure 4.

No crossing is possible on the existing single-track lines. However, as this strongly limits the system capacity if a bi-directional timetable is to be operated, the possibility of modifying the infrastructure is envisaged. In particular, the construction of road-type sidings is possible. These are single lane road sections joined to the rail track. The length of these sidings may allow up to two vehicles to use them simultaneously. Both for accessing and leaving hubs and sidings, the vehicle needs to stop and change mode, from rail to road or vice-versa. This change requires around 10 and 30 seconds, respectively.

To maximize customer satisfaction, the system is planned to be operated both on a fixed timetable and on-demand, through a trip booking application. As the details for the functioning of the on-demand service have not been finalized yet, in this paper we focus on fixed timetable operations. Here, the whole fleet is used to perform terminal-to-terminal trips, stopping at all stations. The timetable shall be as regular as possible, in terms of headway of

successive departures at each terminal hub.

3 The proposed optimization algorithm

In this section, we propose a MILP-based optimization algorithm to support decision makers in the identification of the suitable fleet size and of the necessary sidings to be built. It is a variant of an algorithm for train routing and scheduling. This algorithm is named RECIFE-MILP [10] and it has shown its ability to find efficient working timetables in several applications [11–13].

The algorithm considers a microscopic infrastructure and vehicle movement representation, in which safety distances are ensured through space discretization. Specifically, both track and road-type sections are discretized based on the vehicle length and braking capabilities: if at most one vehicle is present in each portion at any time, safe separation is ensured. Remark that this constraint is slightly less stringent than the one typically imposed in RECIFE-MILP and in railway transport in general, as FERROMOBILE vehicles have braking distances which are much smaller than conventional trains, thanks to their rubber wheels and their limited weight.

The algorithm receives as input a microscopic infrastructure and a theoretical timetable. This timetable is perfectly regular - or periodic according to the classical rail terminology - but not necessarily feasible. In a feasible timetable, all vehicles are supposed to travel undisturbed on the line and stop at hubs. Instead, in the theoretical timetable, no guarantee exists that vehicles traveling in opposite directions do not meet on the line, which will make the timetable practically impossible to be executed.

As a first step, the algorithm re-schedules vehicles so that they only meet at hubs, use only the single-track lines among hubs, and their regularity at terminal hubs is respected as much as possible. In particular, the minimized objective function is the total *deviation* with respect to the planned regular timetable.

As a second step, the solution of the first step is used as a warm start and vehicle rerouting is considered: between hubs, vehicles can use sidings to cross. Differently from what is done in the classic RECIFE-MILP algorithm, the use of sidings is controlled by binary variables associated to the track or road-type portions belonging to sidings themselves ($z \in Z$):

$$u_z = \begin{cases} 1 & \text{if portion } z \text{ is used,} \\ 0 & \text{otherwise.} \end{cases}$$

These variables are set through the following constraints:

$$\sum_{t \in T} sU_{t,z} \leq Mu_z \quad \forall z \in Z, \tag{1}$$

with T set of vehicles, $sU_{t,z}$ continuous variable setting the time at which vehicle t starts utilizing portion z , and M large constant. Through the model detailed in [10], utilization variables are set consistently with vehicle running time in

each portion, stopping pattern, and departure times. As in the first optimization step, vehicles cannot stop on the single-track lines, but they can do so on sidings and they have to do so at hubs, where they all have planned stops.

A further constraint is added to the classic RECIFE-MILP model, to limit the number of sidings that can be used to a maximum of \bar{z} received in input by the algorithm:

$$\sum_{z \in Z} u_z \leq \bar{z}. \quad (2)$$

Finally, to avoid the use of sidings if they are not strictly necessary, we consider a weight \tilde{w} and the following objective function to minimize:

$$\min \sum_{t \in T} (D_t^+ + D_t^-) + \tilde{w} \sum_{z \in Z} u_z \quad (3)$$

with D_t^+ and D_t^- positive and negative deviation of vehicle t 's arrival time at its terminal hub with respect to the theoretical timetable.

4 Experimental analysis

In this section, we detail the experimental analysis that showcases the application of the algorithm proposed for decision support. We start with the description of the case study (Section 4.1). Then, we report our experimental set-up and results when the existing infrastructure is used (Section 4.2) and when additional sidings are built (Section 4.3).

4.1 Case study

The case study we consider is the line connecting Limoux and Quillan, in the Aude department of France (Figure 3). The Limoux-Quillan line is a 29-kilometer non-electrified single-track railway line. Its conventional train service was suspended in 2017. It serves six towns: Limoux (LMX), Alets-les-Bains (ALB), Couiza-Montazels (CMZ), Espéraza (EPZ), Campagne-sur-Aude (CPG) and Quillan (QLN). The population of these towns is between a few hundreds (Alets-les-Bains, Espéraza and Campagne-sur-Aude), and a few thousands (Couiza-Montazels and Quillan), with Limoux being slightly bigger with its 10 500 inhabitants. The intended position of the two terminal and four intermediate hubs is described in Figure 4. It corresponds to the position of the six original railway stations. The construction of a road-side siding between each pair of hubs is under study.

In this analysis, we assess the impact on the regularity of a fixed timetable of the construction of different numbers of sidings. In particular, we study the regularity achievable with different fleet sizes, which imply different service frequencies. The minimum travel time of a FERROMOBILE vehicle between the two terminal hubs is 44'45 and 43'01 in the Limoux-Quillan and the Quillan-Limoux direction, respectively. This travel time includes 45 seconds of stopping



Figure 3: Limoux-Quillan line

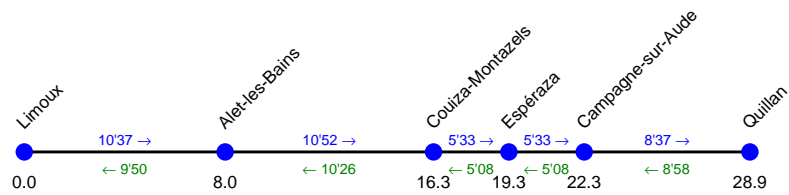


Figure 4: Hub positions and vehicles nominal travel times on the Limoux-Quillan line

time at each intermediate hub, and the specific travel time between each pair of hubs is shown in Figure 4. The minimum turn-around time at terminal hubs is of 300 seconds.

In the theoretical timetable to be optimized in connection with the available sidings, vehicles start from a terminal hub and stop at each intermediate one. The separation between a departure time and the following arrival time is set equal to the minimum travel time between the concerned hubs in the used direction. Each stop is scheduled to last 45 seconds.

Each vehicle departure time and hub depends on the fleet size. In particular, if a single vehicle is available, it starts its service in Limoux and time 00:01:00, it terminates it in Quillan at 00:45:45 and it restarts towards Limoux at 00:50:45. After the elapse of the minimum turn-around time, it performs a second back and forth trip. When two vehicles are available, one of them starts from each hub at 00:01:00 and performs two back and forth trips with the minimum travel, stop and turn-around times. With more than two vehicles (we only consider even numbers when greater than one), half of them start their first service from each terminal hub and go back and forth twice. The first departures are set to 00:01:00. The theoretical headway between departures from the same terminal hub, i.e., the headway in the theoretical timetable, is then computed according to the following function:

$$\text{theoretical headway} = \frac{\text{total duration of a back and forth trip}}{\text{fleet size}}.$$

The resulting theoretical headways with 1, 2, 4, 6, 8 and 10 vehicles are of about 98, 49, 24, 16, 12 and 10 minutes. By performing two back and forth trips with each vehicle, we ensure the central hours of the timetable are representative of a full-day one.

4.2 Use of the existing infrastructure

In the experimental analysis, we first increase the number of vehicles from one to ten, and we compute the most regular feasible timetables without the construction of any road-type siding. Figure 5 shows the distribution of headways between successive departures from the terminal hubs with the increasing numbers of vehicles. The red line shows the theoretical headway. Figure 6 reports the total travel times. Blue bullets are used for the Limoux terminal hub and for the Limoux to Quillan direction. Green bullets for Quillan and the Quillan to Limoux direction. As it emerges here, with one to four vehicles, the timetable is extremely regular even in the absence of sidings: the total deviation is of zero, 144 and 611 seconds, respectively; the headway remains virtually equal to the theoretical one, and travel times are practically always the minimal ones or only slightly higher. No crossing issues emerge.

Instead, when higher frequency is sought, and six vehicles or more are available, having them crossing only at hubs has a remarkable impact on regularity. In particular, headways are either strongly reduced or strongly increased, and

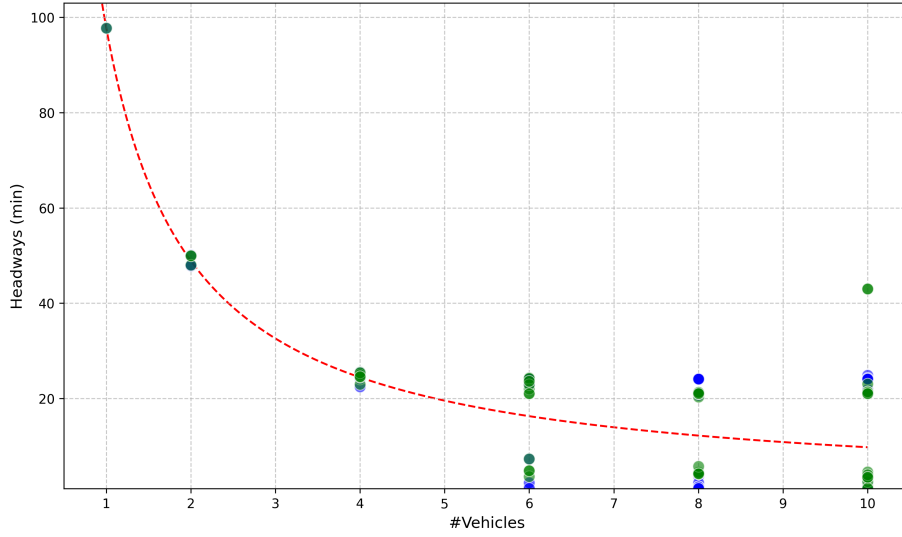


Figure 5: Headway distribution for different numbers of vehicles, with no sidings. The red line represents the theoretical value. Blue bullets are headways in Limoux, green in Quillan.

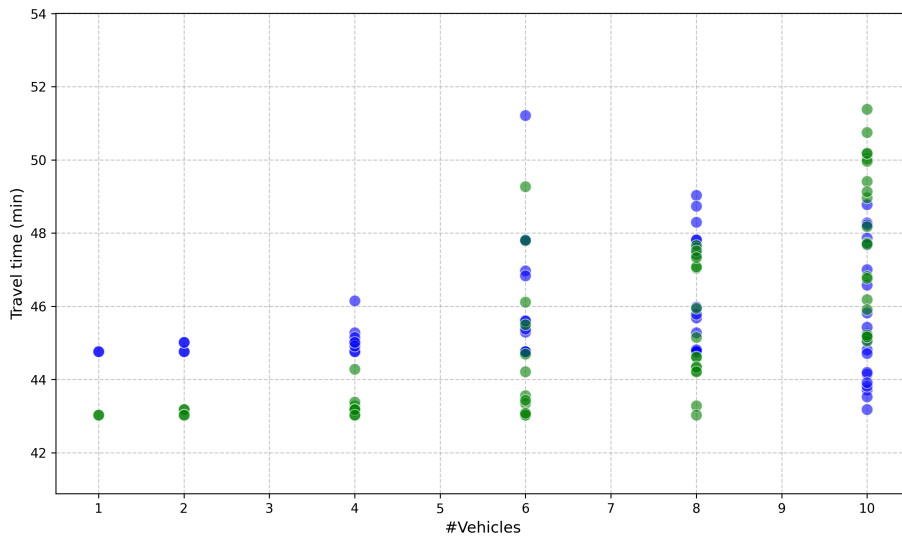


Figure 6: Travel time distribution by vehicle count, without sidings. Blue bullets represent the Limoux to Quillan direction, green ones represent the Quillan to Limoux direction.

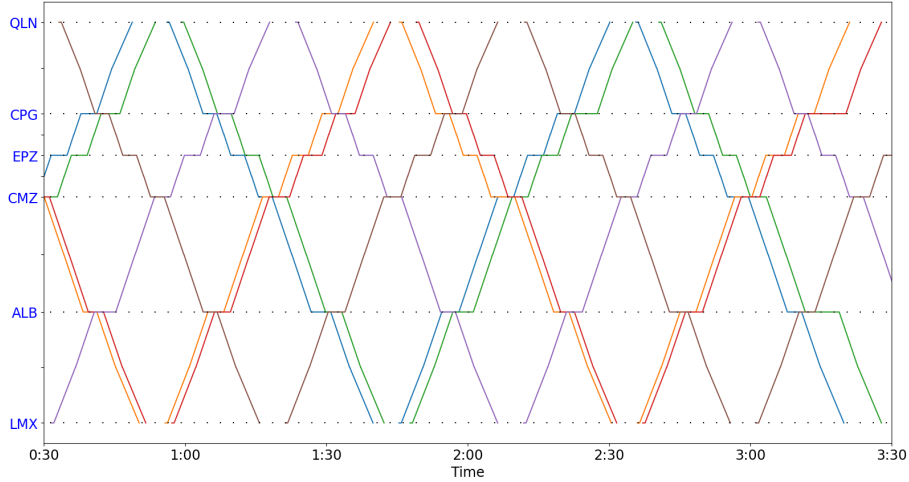


Figure 7: Space-time diagram of the best feasible timetable over three hours. Solution for six vehicles and no sidings.

travel times are sometimes significantly higher than the minimal ones. The total deviation is of 7 358, 10 649 and 15 742 seconds with six, eight and ten vehicles.

Focusing on the case of six vehicles as a representative one, Figure 7 depicts the time-space diagram showing the three intermediate hours of the best feasible timetable obtainable without building any siding. Here, time increases horizontally, while space is represented on the vertical axis with the indication of each hub. A colored line in the diagram represents a service. In this timetable, to accommodate all services deviating as little as possible from the theoretical schedules at the terminal hubs, the algorithm described in Section 3 creates seven platoons of two vehicles. We define a platoon as a group of two or more successive vehicles leaving a terminal hub and traveling in the same direction. Although this limits the deviation, such a timetable is clearly not suitable to exploit the six vehicles to supply a frequent service.

4.3 Use of sidings

For the representative case of six vehicles, we assess the impact of building different numbers of sidings. One possibly usable siding is considered between each pair of hubs, at equal distance from both. We run the algorithm of Section 3 when the number of available sidings \bar{z} goes from one to five, affecting a cost \tilde{w} equal to 10 to the use of a siding. This value is small enough not to remarkably interfere with the minimization of the total deviation from the theoretical timetable, but ensures no siding is used unless it actually improves regularity. The choice made during these experiments was to choose a very small value in comparison with the target values, solely to avoid equivalent solutions that would use one more siding and to progressively increase the number of allowed

Table 1: Impact of siding availability on timetable regularity. Non-dominated solutions are highlighted in bold.

Available sidings	0	1	2	3	4	5
Used sidings	0	0	2	3	4	4
Total deviation (min)	123	123	115	105	98	98
Gain (%)	-	0	6	15	20	20

sidings. Alternatively, this parameter could be calibrated through cost-benefit analysis to incorporate only economically justified sidings, though such an approach would require a comprehensive preliminary economic assessment.

Table 1 reports the results of this analysis. For each number of available sidings, we report the number actually used, the total deviation from the theoretical timetable, and the percentage gain in this deviation with respect to the case in which no siding is built. As a first observation, we can remark that building either one or five sidings is not pertinent if a fleet of six vehicles is envisaged, which, let us recall, allows a theoretical headway at the terminal hubs of about 16 minutes. Indeed, when up to one siding is available, the best feasible timetable is the same as when using the existing infrastructure. When five sidings are available, the best feasible timetable only needs to use four. Instead, by building two, three or four sidings, one can improve the regularity of the timetable of around ten minutes per siding. As it can be expected, the most convenient sidings, which are chosen with $\bar{z} = 2$, are the ones on the longest track stretches, between Limoux and Alet-les-Bains and between Alet-les-Bains and Couiza-Montazels. The third siding chosen is the one between Campagne-sur-Aude and Quillan, and the fourth the one between Esp  raza and Campagne-sur-Aude.

By building road-type sidings, not only can the total deviation be reduced, but the headway distribution can also be improved. This distribution is shown in Figure 8: while the extreme values are not very sensitive to the number of sidings, the split between very low and very high headways due to the platoon formation observed with the use of the original infrastructure does not emerge here. As an example, Figure 9 depicts the space-time diagram of the best feasible timetable obtainable with two sidings. Here, no platoons are created, although, in some cases, arrival and departure events can be extremely close. One such example is the schedule of the first red and brown services turning around in Limoux around 01:10.

As the total deviation, the travel time of the services decreases when adding two, three or four sidings. The distribution is shown in Figure 10. Indeed, although using a road-type siding implies more than one additional minute of travel time for slowing down, changing mode, traveling on the road, and getting back on the track, the additional crossing possibilities it supplies allow the reduction of the longest travel time of around two minutes.

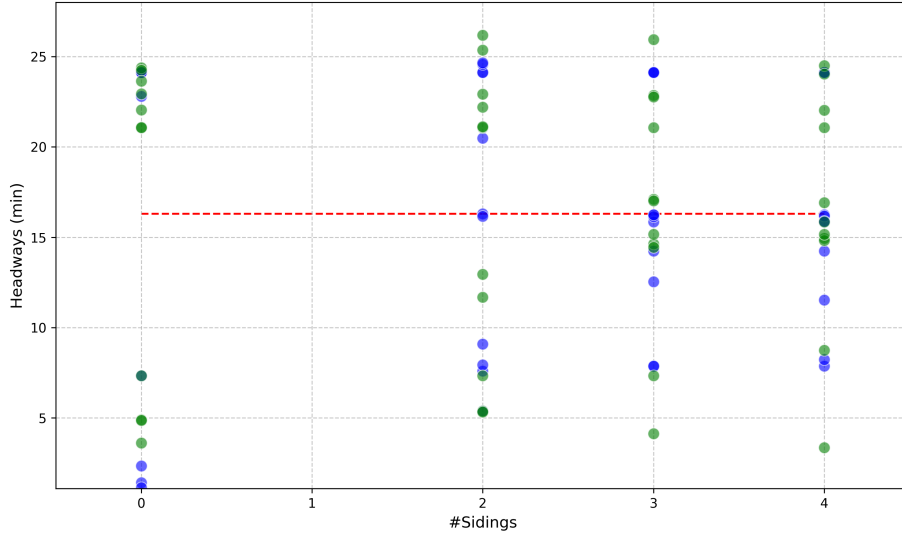


Figure 8: Headway distribution for 6 vehicles with multiple siding configurations. The red line represents the theoretical value.

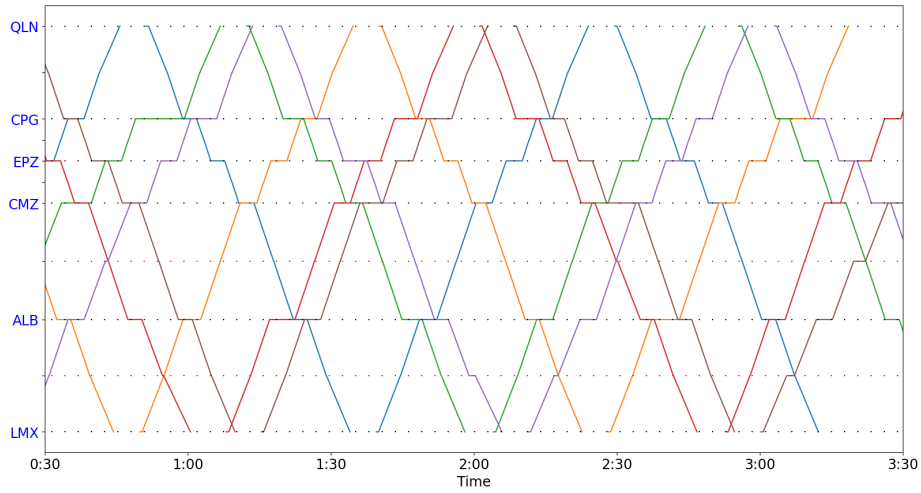


Figure 9: Space-time diagram of the best feasible timetable over three hours. Solution for six vehicles and two sidings.

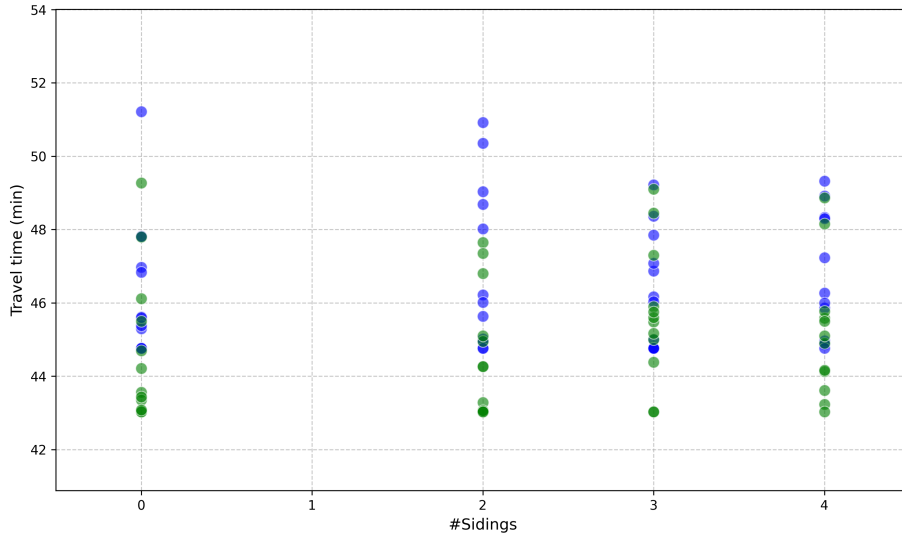


Figure 10: Travel time distribution for 6 vehicles with multiple siding configurations.

5 Conclusions and future works

Many capillary lines in large railway networks have been abandoned throughout the years due to the high operational costs, difficult to justify due to the low demand. However, these lines play a crucial role in the accessibility of territories through rail, which is today the most sustainable mode of transport. To revitalize capillary lines, projects are under study to develop new transport services, based on electric vehicles capable of traveling on both rail and road.

In this paper, we propose an optimization algorithm aiming at constituting a decision support tool in one of these projects, named Flexmove. This algorithm allows assessing the impact of the construction of road-type sidings along the existing railway line. Indeed, capillary lines are typically single tracks, which allow vehicle crossing only at stations. Through sidings, additional crossing possibilities are created. We assess this impact in terms of regularity of the timetable that can be operated with an available fleet.

In an experimental analysis based on the line connecting Limoux to Quillan, in France, we showed the applicability of our algorithm. Indeed, we quantified the achievable regularity of timetables when using the existing infrastructure, and we assessed the impact of building additional sidings with a representative fleet size. For different numbers of sidings to be built, our algorithm identified the most pertinent locations to do so, among a set of possibilities.

Future research will be devoted to the execution of an extended experimental analysis. Larger fleet sizes will be considered, as well as additional possible locations for sidings. In addition, a comprehensive model complexity analy-

sis will be performed to evaluate the scalability of the proposed approach to larger networks and to assess its computational requirements. Furthermore, future work will explore the integration of user-centric performance metrics to complement timetable regularity indicators in the context of on-demand service implementation.

Moreover, a set of interfaces will be designed to allow decision makers to understand and exploit the solutions provided by our algorithms.

Another direction for future research includes the consideration of the electric nature of the vehicles. Indeed, their charge will have to be managed while pursuing timetable regularity, probably exploiting a limited number of charging stations.

Finally, an on-demand service is also envisaged within Flexmove, although no specifications are available yet on the booking process functioning. When these specifications become available, we will propose a variant of the algorithm of this paper to satisfy demand as effectively as possible, while respecting all operational constraints.

Acknowledgment

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