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Design of Hybrid Rail Services on Conventional and High-Speed Lines

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ABSTRACT

Almost 60,000 km of high-speed lines are currently in operation worldwide, and around 90,000 km are under construction or planned. A conventional network exists in countries where the high-speed rail (HSR) network is implemented. One of the most important operating models is that which considers the use of HSR-type rolling stock also on conventional networks to produce high-quality services. The problem of designing services that operate on the two types of network is faced at a heuristic level by the different companies that manage railway services. it is therefore useful to have a design model that allows to obtain the optimal solution, with unchanged infrastructural resources. The method used is developed starting from the analysis of the services currently operating on the two networks, building a synthetic graph composed of the macro-links representative of the services existing on the two networks, optimizing the number of stops and the stop time on each macro-link. On the synthetic graph it is possible to obtain the optimal design solution by applying Bellman's theorem. The method is applied to the Italian HSR and conventional networks by studying a new service, referring to the Southern Italy. The results are interesting because compared with the services currently available, they make it possible to optimize travel times, significantly reducing. The lesson that can be drawn is that as all countries build new HSR sections, they can increase user utility by offering high-quality services that use the two networks in an integrated way.

1. INTRODUCTION

Following the updated (1st September 2022) information by UIC [1], the actual situation of high-speed rail (HSR) in the world are: in operation 58,839 km, under construction 19,710 km, planned 19,643 km, long-term planning 43,935 km, total 142,127 km.

The progress of the planning of the HSR networks, and the constant passage from lines under construction to operational lines, allows to have available routes with ever increasing percentages of lines that can be traveled at high speed.

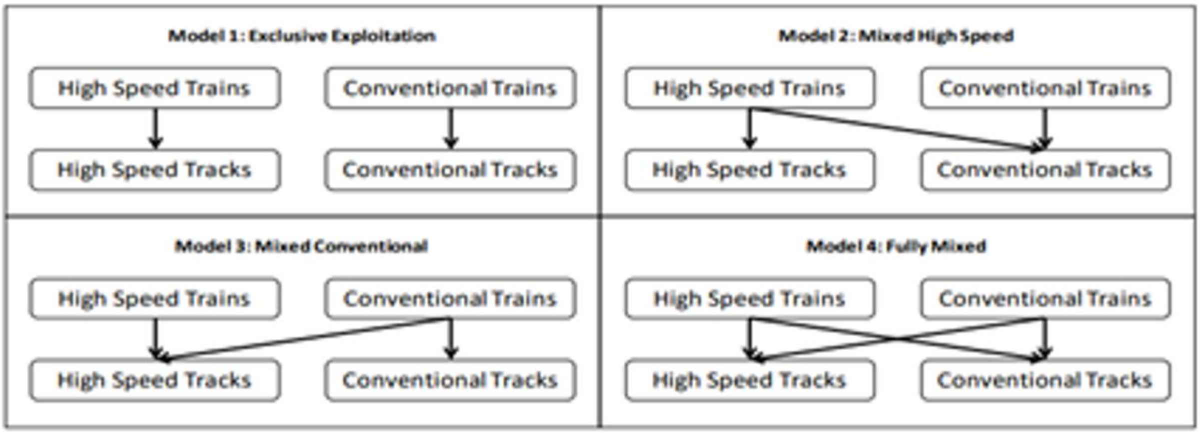
For each new configuration that the HSR network of a generic country assumes, it is possible to activate services that use the HSR network, in the latest configuration, and the existing conventional network. Similarly, in developing the planning of new lines, moving from strategic planning to the executive design phases, it is useful to know which services can be activated on the new HSR planned lines and on the conventional ones.

The need to have trains, in terms of rolling stock, capable of using both the HSR network and the conventional network is increasingly felt. Similarly, it is even more important to design hybrid services which, using adequate rolling stock, connect cities already served by the HSR and cities not yet served.

Campos et al. [2] introduced the problem of operational models in presence of HSR and conventional network, partially overlapped. They propose 4 operational models (Figure 1):

1) the *exclusive exploitation* model is characterized by a complete separation between highspeed and conventional services, each one with its own infrastructure, typical example is Japan;
2) the *mixed high-speed* model, where high speed trains run either on specifically built new lines or on upgraded segments of conventional lines, typical example is France and today also Italy;
3) the *mixed conventional* model, where some conventional trains run-on high-speed lines, typical is Spain;
4) the *fully mixed* model, is the case where both high speed and conventional services can run, typically on Germany and in the first HSR line in Italy.

On the basis of what has been seen, it emerges that for the exploitation model it is not necessary to study service design models of new type, as it involves designing different services in two different networks, both homogeneous inside. In the other cases it is of considerable interest to develop design models which allow to obtain the optimal services for the different network configurations which occur from year to year. The mixed conventional model was developed in Spain to solve the problems associated with the two different gauges of the conventional network and the HSR, determined by historical choices. It is essential for all countries with networks with the same gauge, to develop mixed high-speed models, in order to make the best use of the respective characteristics of the two different networks: therefore, trains will be able to travel at 300 km/h on the HSR network and at the maximum permitted speed on the conventional network.



Source: De Rus, G. (ed.), I. Barrón, J. Campos, P. Gagnepain, C. Nash, A. Ulied and R.Vickerman (2009): *Economic Analysis of High-Speed Rail in Europe*. BBVA Foundation, Bilbao.

Figure 1. Operational models for high-speed rail traffic

The services that operate on two different networks, both with conventional rolling stock and with HSR rolling stock, can be defined as "hybrid" by their nature. Hybrid services have not been treated in the literature [3], but are designed within the railway companies only with trial and error methods.

The countries that are making the HSR networks grow are China [4, 5] and all the European countries belonging to the EU, together with these two large groups are working on the construction of high-speed lines, other Asian countries such as Saudi Arabia [6], and the first African countries, such as Morocco. At the same time the USA, which has always been at the forefront worldwide for rail freight traffic, is developing new proposals for the construction of high-speed lines [7]. Each country has the problem of designing hybrid services using its own HSR and conventional networks.

The opening of borders in the EU to railway companies from all member countries, and the development of a shared control system is allowing the emergence of railway services using the high-speed networks of two countries and the networks of two countries [8]. Important examples are the services between Italy and France and between Spain and France.

Figure 2 [1] reports the current situation of the HSR lines in operation in European countries, of the lines that will soon be in operation, and of the planned lines.

The problem of hybrid railway services must therefore be extended to any number of HSR networks and to any number of conventional networks. In the face of the growing importance of hybrid services and therefore of design models that allow the problem to be faced and resolved, it has not been addressed organically in the literature.

Knowledge of the hybrid services that can be implemented with the available HSR and conventional networks is necessary to determine the impacts. Indeed, national level services have characteristics of high regularity and the models that simulate them place the regularity of services as a basic element [9, 10], knowing the services and the demand that uses them, it is possible to know the impacts [11-13].

Figure 2. Current situation of HSR network in EU

The work therefore answers the question: how to implement hybrid services with optimal schedules using different networks HSR and conventional.

The objective thus defined is directly shared by all users who can thus increase their utility, but it is not adequately studied by the railway companies.

Section 2 of this paper proposes the development of a theoretical model of the design which allows to obtain the best hybrid service without making any material intervention on the network. This point is particularly important, because with the separation, which took place in the EU, between the companies that manage the networks and the companies that manage the services, the hypothesis is that the timetables are prepared by the latter, which have no power to intervene on infrastructure.

After dealing with the abstract formulation of the method, in Section 3 a real case is then examined where the method can be applied. The case study in which the method is applied, is that of the Italian HSR and conventional networks. Italy is one of the first countries that built high-speed railway lines, and today it has an impressive program of new constructions [14], with particular reference to the South which is one of the European areas with the most development delays [15, 16]. The case study is particularly interesting because it presents, in addition to the HSR and conventional networks, also a maritime network that allows Sicily to be connected to mainland Italy. In the case study the proposed method is applied to the connections between the Sicilian metropolitan cities and the capital, Rome.

The proposed approach can be used for the preparation of annual railway timetables, and for the creation of services in the more complex situations of presence of "patchy", or leopard spot, HSR networks overlapped on conventional networks, such as at EU level.

The design of hybrid services that operate on different networks is therefore of interest on an operational scale for the planners of the companies that manage the railway services; on a strategic scale it is useful both for the designers of the companies that manage the railway infrastructural networks and for the technicians of the ministries. The study of hybrid services is of interest to researchers because it requires the study of general models, with the connected algorithms, which use different networks. In this sense, in addition to the exact model proposed in this note, it is also possible to develop heuristic models if the conditions of the network or the availability of adequate rolling stock should require it.

2. THE PROPOSED METHOD

The problem of producing high-quality rail services on hybrid routes is increasingly topical, as seen in the previous section, due to the increase in kilometers of high-speed networks in all states.

The problem of creating services on hybrid routes has been addressed in the implementation of railway timetables, only by trial and experience. In this section a logical method is set to optimize the construction of services as the High-Speed network increases.

The proposed method is organized into four steps that are examined in the following paragraphs:

1) Identification of the reference infrastructural graph
2) Analysis of current operative services
3) Macro-link services optimization
4) Hybrid network services design.

2.1 Reference infrastructural graph

The current situation of the countries that have built, and are building, high-speed lines is to have both the high-speed network and the conventional network, previously built. In general, on the Conventional network there are services of a national nature and services of a regional or metropolitan nature.

The supply model is assumed to consist of a network model defined by a graph and the characteristics of the links between the nodes of the graph.

A network model T is defined with the following elements:

1) a set of nodes N, with generic elements i and j;
2) a set L of pairs of nodes belonging to N, with $L \subseteq N*N$;
3) a subset of N includes origins (r) and destinations (s), where it is assumed to concentrate Origins and Destinations (O/D) of travel;
4) for each O/D pair (r,s) assumes that the user considers a K_{rs} set of attractive infrastructure paths.

In the situation considered there are two networks, one at High Speed called T_h and one conventional one called T_c, in the following the subscripts h or c are used to refer to elements of the high-speed network or of the conventional network. The presentation of the method is developed in the hypothesis of the existence of two networks. The method can be easily extended to the presence of three or more networks, and in general also to the presence of a connected conventional network and to a high-speed network present in a "leopard spot", as in the case of the European network.

With the conventions introduced, the problem to be solved is to obtain the best service for a generic O/D pair, using railway material (rolling stock) that can operate on the two conventional and high-speed networks.

After the general identification of the two networks with their link characteristics, it is necessary to identify the two reference centroids for the beginning and end of the services to be designed.

Given N_h the set of considered nodes of the high-speed network, and N_c the set of conventional nodes, the two centroids belong: $r \in N_h$; $s \in N_c$.

After identifying the start and end of service centroids, it is necessary to identify the nodes in which the two networks, with the current development of the high-speed network, allow interchange, i.e., the nodes such that: $i \in N_h$; $i \in N_c$.

In the hypotheses made, it is possible to identify the sets of infrastructural paths:

1) K_{ri} connecting node r via high-speed lines to border node i;
2) K_{is} connecting border node i to destination s via conventional lines.

It is possible to identify with:

$p_h \in K_{ri}$ the generic infrastructural path on the high-speed network belonging to K_{ri}, which for simplicity can be considered a macro-link;

$p_c \in K_{is}$ the generic infrastructural path on the conventional network belonging to K_{is}, which for simplicity can be considered a macro-link.

It is evident that the formalization is similar in the case where r is in the conventional network and s in the high-speed network.

The subset of L, K_{rs}, composed of macro-links relative to all ph and pc paths, constitutes the reference network for the realization of hybrid services.

Finally:

$$K_{rs} = K_{ri} \cup K_{is} \subseteq L \qquad (1)$$

2.2 Analysis of current services

The second step of the overall method concerns the services available on current networks. The basic assumption of the whole method proposed is that no infrastructure investment is made.

Under these conditions, the second step is resolved in the analysis of all existing services on the infrastructural macro-links belonging to the K_{rs} set.

For $\forall p_c$ and $\forall p_h$ the available railway timetables are verified and the matrices P_c relative to the macro-link p_c and P_h relative to the macro-link p_h are constructed, consisting of:

1) Name or identification number of the generic operating service on the macro-link
2) Current service time on macro-link: $g_a(p_c)$; $g_a(p_h)$
3) Technological features of the macro-link
4) Usability with specific trains (rolling stock)
5) Number of stops in the service
6) Stopping time for each stop

Each of the matrices thus defined is ordered by increasing times.

2.3 Services design on macro-links

The problem of the services design on individual macro-links belonging to the K_{rs} set, assuming not to carry out any infrastructural intervention, arises as optimization of the number of stops along the macro-link and the dwell time at each stop.

For the number of stops, considering that a high-quality service is being designed, some criteria can be defined that are those that inform the entire design of services on high-speed networks.

The basic principle is to connect the origin with the destination without intermediate stops. This principle is waived for certain services according to two criteria:

– a supply criterion, relating to distance, for which stops are introduced for distances of the order of 200 kilometers in order to allow the maximum cruising speed to be maintained and not to weigh down the times relating to the total distances of the times due to decelerations and accelerations for stops;
– a demand criterion, relating to the presence of urban areas with populations of the order of 500,000 inhabitants.

For stopping times, times of the order of 1 minute are considered for stops introduced according to the supply criterion. For stops introduced on the basis of the demand criterion, the times are longer than one minute and depend on the estimated demand for each service.

For the number of stops, according to the supply criterion introduced above, called num(p) the number of stops in the macro-link p and called l(p) the length of the macro-link p, it results: $num(p)=int\,[\,l(p)/200]\ \forall p \in K_{rs}$

On the basis of the first introduced demand criterion, called Pop(p), the total population of the territory crossed, excluding the population belonging to r and s, it results:

$num(p)=int\,[Pop(p) / 500000]\ \forall p \in K_{rs}$

The greater value between the two values of num(p) is considered.

For stopping times called u the generic stop of the set identified with the criteria defined above, called t(u) the parking time at stop u, for the stops identified with the supply criterion, it results: t(u)=1 min. For the stops identified with the demand criterion, called Pop(u) the population belonging to u, it results: t(u)=f(Pop (u))

In general, the dwell time for high-quality services is between 3 and 5 minutes.

From the application of the criteria relating to the number of stops and stopping times it is possible for each macro-link to estimate the value of the new time for each service already present in the P_h and P_c matrices. In a new column of each P_h and P_c matrix are inserted the design times, of each service operating on p, $g_n(p)$, starting from the current times $g_a(p)$.

Design times are calculated as:

$$g_n(p)=g_a(p) - \sum t_a(u) + \sum t_n(u) \qquad (2)$$

with the function valid for $p=p_c$ and $p=p_h$, where:

$\sum t_a(u)$ is the sum extended to all the current stops of the generic service carried out on the infrastructural macro-arc P, of the current stopping times;

$\sum t_n(u)$ is the sum extended to all design stops of the generic service carried out on the macro-link p, of the design dwell times.

With the values of $g_n(p)$ it is possible to reorder the P_h and P_c matrices for increasing times of $g_n(p)$.

Note that the proposed method is in absolute safety with respect to the times and would allow to further reduce the times on the macro-link if the times due to accelerations and decelerations were eliminated.

2.4 Hybrid network service design

The final part of the method concerns the composition of the times relating to the macro-arcs of the different networks. This part solves the problem. Different heuristic procedures can be put in place to compose the various times, as is currently done by the technicians of the railway companies. In the assumption of having developed the previous steps it is possible to solve the optimal problem exactly, using an algorithm of minimum paths.

In fact, available data are:

– reference infrastructural graph given by the macro-links ph and pc, defined in step 1;
– current times for each service of each macro-arc of the reference infrastructure graph defined in step 2;
– design times for each service of each macro-arc of the reference infrastructure graph in step 3.

With these elements it is possible to calculate the minimum cost paths from s to all nodes of the graph, or from all nodes of the graph to r.

Let:

g_{ij} be the cost of macro-link i, j of extremes nodes i and j

Z_{ij} be the cost of the minimum path between any pair of nodes belonging to the union of T_h and T_c

Minimum path costs always respect inequality

$$Z_{ij} + Z_{jk} \geq Z_{ik}\ \forall\ i,j,k \qquad (3)$$

Inequality implies that the costs on macro-links and those on minimum paths satisfy the condition expressed by Bellmann's principle that:

– if the macro-link i,j belongs to the minimum path between o and j, called g_{ij} the cost of the macro-link i,j is: $Z_{oi} + g_{ij}=Z_{oj}$
– if it does not belong to the minimum path: $Z_{oi} + g_{ij} \geq Z_{oj}$

Given therefore the network composed of the graph and the times associated with the macro-links, and considered a generic root tree r, called W(r), the tree W(r) is the tree of minimum cost if and only if considered a triad of nodes o, i, j belonging to W(r), the condition expressed by Bellmann's principle is satisfied.

The algorithms that solve the problem of the tree of minimum paths are based on iterative correction of the structure of an initial tree until the Bellmann principle is satisfied for all nodes of the tree.

It is therefore possible to achieve the optimal hybrid service given two networks: conventional and high-speed rail.

It is easy to see that the proposed method can be directly applied even in the presence of a third network, such as the maritime one, if there are ferries that allow trains to pass.

In an even more general way, the proposed method can be applied in the presence of any number of different networks, or in the presence of a High-Speed network distributed over the territory in a "leopard spot", i.e., with isolated areas of territory with the presence of High Speed within a larger territory served by a conventional network. Consider, for example, the case of France, Italy and Spain that have high-speed networks not connected to each other, while there is a fully interconnected conventional network.

In the next section a case study is proposed with the whole method fully applied.

3. APPLICATION

In this section an application of the proposed methodology has been implemented considering the railway network in the South of Italy with reference to the main route connecting Rome and Sicily. The railway section considered is part of the Scandinavia-Mediterranean Corridor which extends from the Russian-Finnish border and from the Finnish ports of Hamina Kotka, Helsinki and Turku-Naantali to Stockholm, passing through southern Sweden, Denmark, Germany, western Austria, Italy up to Malta [17]. The part of this corridor that affects Italy goes from North to the South. The HSR network reaches Salerno from North, further south the network is of the conventional double-track type and in Sicily some sections are single-track.

There is also a maritime link that allows trains to pass through the Messina Strait. The corridor in southern Italy with the peninsular part from Rome to Villa S. Giovanni (the extension of the HSR network in dashed) and the island parts from Messina to Catania and Palermo.

To analyze the railway routes from Sicily to Rome, the Palermo Rome routes were considered, and, for simplicity of presentation, the analysis reported concerns only even trains (south-north and east-west directions), that is, trains that go from Sicily to Rome.

3.1 Definition of the reference graph

The land route between Palermo and Rome has been subdivided in three main sections, Palermo – Messina, Villa S. Giovanni – Salerno and Salerno – Rome. In addition, the sea route concerning the crossing of the strait of Messina by railway ferry between Messina and Villa S. Giovanni has been considered.

For the Palermo – Messina route two alternatives have been considered: i) the line that runs along the northern coast of Sicily and ii) the one that crosses Sicily from Palermo to Catania and then from Catania to Messina on the eastern coast. The alternative ii) was considered by foreseeing any future developments. Two alternatives have been considered for the Salerno – Rome route, considering both conventional and high-speed infrastructural options.

Following these considerations, that derive from the set of services implemented in the considered relationship between Palermo and Rome, it is possible to define a reference graph as shown in Figure 3.

Figure 3. Representation of the considered infrastructural reference graph

Table 1. Set N of nodes of the considered graph

{N}	Description	Type
PA	Palermo	Origin
ME	Messina	service connection
CT	Catania	service connection
VG	Villa S. Giovanni	service connection
SA_c	Salerno	service connection
SA_h	Salerno	service connection
RM_h	Rome	service connection
RM_c	Rome	Destination

Table 2. Set L of pairs of nodes (arcs) of the considered graph

ID	Arc	Type
1	PA - ME	Conventional
2	PA - CT	Conventional
3	CT - ME	Conventional
4	ME - VG	Sea
5	VG - SA_c	Conventional
6	SA_c - RM_c	Conventional
7	SA_c - SA_h	Conventional
8	SA_h - RM_h	High- speed
9	RM_h - RM_c	Conventional

Referring to notation defined in 2.1, the set N of nodes are described in Table 1 where the subset of N including origin (r) and destination (s) is identified. Table 2 describes the set L of pairs of nodes belonging to N.

For the sake of simplicity, in the considered applications each arc of the graph represents a macro-link as defined in point 2.1 above. Thus, for the considered O/D pair it is possible to identify a set of attractive infrastructure paths K_{rs} shown in Table 3, where, for the sake of simplicity, paths are individuated by the succession of the ID of the pair of nodes (macro-links) described in Table 2.

Table 3. Set K_{rs} of attractive infrastructure paths

Path	Arc succession
1	1-4-5-6
2	1-4-5-7-8-9
3	2-3-4-5-6
4	2-3-4-5-7-8-9

3.2 Analysis of current services

The second step concerns the services available on current networks. it is resolved in the analysis of all existing services on the infrastructural macro-links belonging to the K_{rs} set.

To analyze the current services on the railway routes from Sicily to Rome, as said above the Palermo Rome routes were considered. For simplicity of presentation, the analysis reported concerns only even trains (south-north and east-west directions), that is, trains that go from Sicily to Rome. For the routes considered, the direct connections without service breakage (i.e., those in which there is no transshipment of travelers) have been deduced from the Trenitalia timetable [www.trenitalia.it] consulted on the 04/01/2023 with reference to trips made on 19/01/2023.

At the time being the fastest connections between Palermo and Rome are described in Table 4. The analysis of the services has been conducted by disaggregating the relationships into island and continental sections. The abbreviation HS stands for High-Speed services, IC for Intercity RV and R for Fast Regional train and for Regional train. With reference to the type of means of transport / rolling stock with which the service is provided, the abbreviations H stands for High-Speed rolling stock, C for conventional rolling stock, TF stands for train ferry, FS stands for fast speed ship (boarding of passengers after disembarking from the trains).

3.2.1 Data from timetables

The land route between Palermo and Rome has been subdivided in three main sections, Palermo- Messina, Villa S. Giovanni – Salerno and Salerno – Rome. In addition, the sea route concerning the crossing of the strait of Messina by railway ferry between Messina and Villa S. Giovanni has been considered.

The route Palermo - Messina

This route can be done considering two alternatives: i) the line that runs along the northern coast of Sicily and ii) the one that crosses Sicily from Palermo (PA) to Catania (CT) and then from Catania to Messina (ME) on the eastern coast. At the time being there is not a direct connection using the alternative ii); it was considered by foreseeing any future developments. In Table 5 the fastest services, subdivided per type, for each section of the considered routes connecting Palermo to Messina are shown.

The route Villa S. Giovanni - Salerno

This route is operated on a traditional line so, even if there are trains using the rolling stock suitable for high-speed lines, the service provided is at the level of an intercity. In Table 6 the fastest service of the considered route connecting Villa S. Giovanni to Salerno are shown.

The route Salerno – Rome

This route can be operated using both the traditional line and the high-speed one. The trains that come from Sicily, at present, are intercity trains that use the traditional line. In Table 7 the fastest service of the considered route connecting Salerno to Rome are shown.

The sea route crossing the Strait of Messina

The evaluation of the crossing time of the Strait of Messina was carried out considering the time between the arrival at the Messina Central station and the departure from the Villa S. Giovanni station for direct connections without service breakage (i.e., those in which there is no transshipment of travelers).

To extrapolate the travel time, the Milazzo – Lamezia Terme routes are examined for the pair of trains IC728 - IC730. The crossing times are summarized in Table 8.

Table 4. Fastest services between Palermo and Rome

Route	Service	Rolling stock	Dist [km]	Time [min]	Notes
Palermo Rome	IC	C + TF	860	698	Direct service
Palermo Messina	RV	C	224		
Messina Villa S.Giovanni	Sea	FS	5	553	3 service change
Villa S.Giovanni Rome	IC/HS*	HS	644		

Table 5. Fastest services between Palermo and Messina

Alt.	Route	Train	Service	Rolling stock	Dist [km]	Time [min]	No. stops	Mean stop time [sec]
i)	PA ME	5352	R	C	224	178	12	80
		5364	RV	C	224	163	9	80
		728	IC	C	224	170	7	120
ii)	PA CT	5508	RV	C	241	182	4	75
	CT ME	5378	R	C	95	81	5	60
		5386	RV	C	95	84	6	90
		722	IC	C	95	72	3	120

Table 6. Fastest services between Villa S. Giovanni and Salerno

Route	Train	Service	Rolling stock	Dist [km]	Time [min]	No. stops	Mean stop time [sec]
Villa S. Giovanni - Salerno	8332	IC	HS	380	199	3	160

Table 7. Fastest services between Salerno and Rome

Route	Train	Service	Tec	Rolling stock	Dist [km]	Time [min]	No. stops	Mean stop time [sec]
Salerno Rome	9658	HS	h	HS	264	83	1	120
	550	IC	c	C	251	171	4	300

Table 8. Characteristics of the crossing times of the Strait of Messina

Train	Rolling stock	Time [min]	Stop time at stations [min]
728	C + TF	130	60
730	C + TF	115	45

3.2.2 Characteristics of macro-links

From the analysis of timetables described above, it is possible to summarize the information by formulating, following the definitions and notations introduced in point 2.2, the matrix of macro-link shown in Table 9.

Considering the set K_{rs} of attractive infrastructure paths defined in Table 3, the resulting service for each path, obtained by means of the characteristics of each macro-link described in Table 9, is summarized in Table 10.

Table 9. Characteristics of the macro-links

ID	Macro-link	Length [Km]	Train	Time [minutes]	Line type	Rolling stock c	Rolling stock h	No stops	Mean stop time [s]
1	PA - ME	224	728	170	c	*	*	7	120
2	PA - CT	241	5508	182	c	*	*	4	75
3	CT - ME	95	722	72	c	*	*	3	120
4	ME - VG	5	730	115	tf	*	*	2	1350
5	VG - SA_c	380	8332	199	c	*	*	3	160
6	SA_c - RM_c	251	550	171	c	*	*	4	300
7	SA_c - SA_h	35	9568	15	c	*	*	-	-
8	SA_h - RM_h	224	9658	63	h		*	1	120
9	RM_h - RM_c	5	9658	5	c	*	*	-	-

Table 10. Characteristics of services for the set of attractive infrastructure paths

Path	Arc succession	Rolling stock	Time [minutes]	No stops
1	1-4-5-6	c	655	16
2	1-4-5-7-8-9	h	567	13
3	2-3-4-5-6	c	739	16
4	2-3-4-5-7-8-9	h	651	13

Table 11. Characteristics of services for the set of attractive infrastructure paths

ID	Macro-link	Length [Km]	Population	No stops	Mean stop time [s]
1	PA - ME	224	512948	1	120
2	PA - CT	241	727243	1	120
3	CT - ME	95	251531	1*	120
4	ME - VG	5	-	2**	300
5	VG - SA_c	380	297866	1	120
6	SA_c - RM_c	251	1078702	2	180
7	SA_c - SA_h	35	-	-	-
8	SA_h - RM_h	224	914406	1	120
9	RM_h - RM_c	5	-	-	-

From the application of the criteria relating to the number of stops and stopping times, the value of the new times for each service have been estimated for each macro-link. The resulting values are summarized in Table 11.

3.4 Hybrid network service design

The composition of the times relating to the macro-links of the different networks is conducted at first by subtracting the times used for stops from the current travel times, obtaining the net travel times as shown in Table 12. To these net times the stop times obtained in the previous point are added, arriving at the journey times shown in Table 13.

To obtain the optimal hybrid service, times corresponding to paths of Table 10 are updated yielding to the new situation shown in Table 14.

Table 12. Net travel time for each macro-link

ID	Macro-link	Length [Km]	Time [minutes]	No stops	Mean stop time [s]	Total stop time [min]	Net travel time [min]
1	PA - ME	224	170	7	120	14	156
2	PA - CT	241	182	4	75	5	177
3	CT - ME	95	72	3	120	6	66
4	ME - VG	5	115	2	1350	45	70
5	VG - SA_c	380	199	3	160	8	191
6	SA_c - RM_c	251	171	4	300	20	151
7	SA_c - SA_h	35	15	-	-	-	15
8	SA_h - RM_h	224	63	1	120	2	61
9	RM_h - RM_c	5	5	-	-	-	5

Table 13. Total travel time for each macro-link

ID	Macro-link	Length [Km]	Line type	Rolling stock		Net travel time [min]	No stops	Mean stop time [min]	Total travel time [min]
				c	h				
1	PA - ME	224	c	*	*	156	1	2	158
2	PA - CT	241	c	*	*	177	1	2	179
3	CT - ME	95	c	*	*	66	1	2	68
4	ME - VG	5	tf	*	*	70	2	5	80
5	VG - SA_c	380	c	*	*	191	1	2	193
6	SA_c - RM_c	251	c	*	*	151	2	3	157
7	SA_c - SA_h	35	c	*	*	15	-	-	15
8	SA_h - RM_h	224	h		*	61	1	2	63
9	RM_h - RM_c	5	c	*	*	5	-	-	5

Table 14. Characteristics of services for the set of attractive infrastructure paths

Path	Arc succession	Rolling stock	Time [minutes]	No stops
1	1-4-5-6	c	568	6
2	1-4-5-7-8-9	h	498	5
3	2-3-4-5-6	c	655	7
4	2-3-4-5-7-8-9	h	585	6

4. CONCLUSIONS

The theme explored in the note is that of the design of high-quality hybrid services operating between: the conventional railway network and the high-speed network. This theme becomes increasingly important considering on the one hand the increase in high-speed lines and on the other the time needed to complete the building of a new HSR line. In other words, it is a question of designing services that use the entire HSR network and the conventional one. To carry out the integration of services, as the HSR network grows, it is necessary to plan services with the constraint of no infrastructural intervention.

The proposed integration method is divided into four steps: identification of the infrastructural graph; analysis of existing services; macro-link optimization; hybrid services design.

The results obtained are interesting because they make it possible to significantly reduce the time required to reach destinations not yet connected by the HSR network, with time reductions exceeding 20%. On an operational level, the method can be implemented for large sub-continental areas such as the EU, or China, or the USA.

The proposed method can be further developed for each of the steps: both considering a multi-level system, where each network typology constitutes a level, and for each macro-link considering the time reductions connected to the elimination of decelerations and accelerations in the stops eliminated.

The results can be used in the analysis of the demand, allowing to estimate the variation of the users' utility for each HSR network growth scenario, explicitly considering the presence of the conventional network.

The method can be used in all countries where high-speed extension is being planned. The method is also interesting for the technicians and planners of the railway companies that manage the services because they can build new market alternatives to offer to users.

The novelty of the method is to design high quality services using the theoretical tools of the TSM, thus going beyond the heuristic procedures currently used. The present limitation concerns the need to use an existing timetable. This, which is a limitation, can be seen as an advantage, because it guarantees the absolute feasibility of the planned services. Further developments must consider multilevel networks, macro-arc time reductions and applications to a sub-continental case study.

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