360.revista de alta velocidad
número 5 - junio - 2018. Pág 167 - 189

KEYNOTE

Alternate Double–Single Track Proposals for Low and Intermediate Demand High Speed and Conventional Lines

Castillo, Enrique

Grande, Zacarías

University of Cantabria[1]

Abstract

The paper introduces the alternate double single track (ADST) as an alternative to double track lines and discusses its main advantages and shortcomings. An optimization program for the design of such lines are presented, including a detailed analysis of the selected objective function and corresponding constraints. In particular, some interesting formulas for deriving the upper bound of the capacity of these lines are derived to illustrate how the efficiency of the line can range from the single to the double track extremes. Some possible international applications of this alternative are identified in which the ADST could be advantageous. Finally, some real examples of applications, which include the cases of Spain, Chile and Ireland, are used to illustrate the proposed methods.

Keywords: Optimization, railway line design, rational investment analysis, Rail capacity, relative time

---

[1] *Castillo, Enrique. University of Cantabria. Email: castie@unican.es*
Grande, Zacarías. University of Cantabria. Email: Zgandrade@gmail.com

1. Introduction and motivation

Though when you think of high-speed lines you immediately tend to associate them with double track lines, not all high-speed lines must necessarily be built in double-track. In fact, the single track multiplies its capacity almost proportionally to the speed of the trains that circulate through it. Therefore, an increase of speed immediately produces an increase in the efficiency of the single track line. This means that single track lines today have important advantages with respect to past single track lines because train speeds have been increased substantially.

When high speed lines are used in a country for the first time, they are usually oriented to link two large populations (case 1). However, other lines may involve small and at most one large population (case 2). In this paper we point out that the above two cases 1 and 2 are completely different and require different solutions, because: (a) the number of users is necessarily much lower in the second than in the first case leading to very different train frequencies, which are determined mainly by the small size city, and (b) we must question ourselves whether or not the expensive double track is necessary in Case 2, or a new alternative should be contemplated. In addition, since decisions with optimal criteria are required, computer programs are unavoidable to design, develop preliminary projects and evaluate the proposed solutions.

It appears that the first known application of the mathematical programming methodology applied to railway optimization problems was due to (Amit & Goldfarb, 1971) Optimization and simulation were already the most commonly used methods, even before the eighties, when computers had no power enough to deal with these complex problems (see (Assad, 1980) and (Haghani, 1987)). However, nowadays problems related to railway network management and similar cannot be conceived of without computers (see (Petersen, et al., 1986), (Hellström, 1998), (Yang & Hayashi, 2002) or (Ouyang, et al., 2009)). An exhaustive review of existing optimization methods was done by (Cordeau, et al., 1998).

One of the main reasons for these railway optimization problems to be complicated is that a huge amount of continuous and binary variables and constraints are involved, leading to mixed integer (MIP) linear and non-linear related programming problems of high complexity (see, for example, (Kraay & Harker, 1995) (Carey & Lockwood, 1995) , (Higgins, et al., 1996), (DÁriano & Pranzo, 2004), (DÁriano, et al., 2007)), which require a lot of memory and CPU resources (see (Burdett & Kozan, 2010)). As indicated in (Castillo, et al., 2011), (Castillo, et al., 2015), a reduction in binary variables has an important effect on the CPU time required.

A possible alternative to single track and double track lines is the alternate double-single track (ADST) line, in which single track segments are combined with double track segments. As will be verified, the capacity of a single track line is clearly overcome by an ADST line with a very low construction and maintenance costs increase. In this paper, first, a general formula for dimensioning the lengths of single track and double track section is derived. Then, these formulas are applied to several cases that will serve us to illustrate the possibilities that the ADST lines provide from a practical point of view.

The design of a railway line must always include the predicted demand. If the demand is very high a double track is the right solution. Contrary, if the demand is very low, the right solution is the single track. However, in the most common cases of intermediate demands the optimal solution involves segments in single and segments in double track. Since in this intermediate case we must decide which segments must be in single and which in double tracks, the demand plays a relevant role in the optimal solution because the timetable must be optimized in order to reduce travel time. This implies that the costs of single and double tracks must be included in the objective function of our optimization problem. In fact, we are in front of a bi-level problem in which the first level decides about single or double tracks and the second level optimizes the timetables to reduce travel times and reduce the occupancy of the line.

KEYNOTE

The second level problem of selecting the optimal timetables, that is, to determine time departures and arrivals of trains from and at stations so that not only safety constraints but user requirements are satisfied is a very difficult one (see, for example, (Carey, 1994), (Higgins, et al., 1996), (Caprara, et al., 2002) or (Cacchiani & Toth, 2012)). There exist a wide collection of related works, such as (Jia & Zhang, 1993), (Sahin, 1999), (Carey & Crawford, 2007) and (DÁriano, et al., 2007), and a complete analysis done by (Pachl, 2014) of the timetable design principles that must rule engineering work in this area.

An alternative to the bi-level approach is to consider all into a single problem 3. For example, (Castillo, et al., 2009) combines into a single optimization problem the line and timetable designs, producing an important change in the alternate double-single track direction, as an intermediate and efficient solution between the traditional double and single track solutions.

No matter which alternative is chosen, the size of de associated problems can reach a point in which serious complexity problems appear. To solve this problem, (Lin & Ku, 2013) proposed genetic algorithms and (Castillo, et al., 2016) proposed a time partitioning technique that reduces drastically the computation time without serious losses in optimality.

2. The alternate double-single track

An alternate double-single track (ADST) line essentially consists in utilizing single track throughout expensive segments (tunnels and viaducts) and double track in cheap segments (plain areas) and only where it is necessary.

It should be clearly stated that (see (Castillo, et al., 2015)): (a) the ADST line is not a single track line, (b) the ADST line is not a double track line, (c) the ADST performance is much closer to double than to single track performance, (d) the ADST cost is much closer to single track than to double track cost, (e) it reaches practically the same performance as the double track solution for the expected demand and even slightly superior to it, (f) it reduces the construction and maintenance costs (until a 40%) and finally, (g) lines, which are nor economically viable as double track lines can become viable as ADST lines.

The design and management of an alternate double single track line is complex, because it requires:

1. Deciding which segments should be constructed in single track and which in double track.
2. Satisfy the safety and timetable constraints of the different services with the aim of obtaining small travel times when we have a single track in some segments.
3. Minimize costs and travel times and optimize the infrastructure usage.
4. Obtain all rail timetables of the whole network

Due to the complexity of the problem, the use of an optimization program is necessary in order to satisfy all the imposed safety and service conditions.

2.1 Some considerations about travel times

Since travel times of the different trains circulating along the network or line could be very different and it is not the same a delay of five minutes in a one hour trip than in a three hours trip, we use in our model relative travel times.

The relative travel time is the quotient:

$$Relative\ travel\ time = \frac{Travel\ time}{Travel\ time\ at\ maximum\ speed} \quad (1)$$

Then, a relative time *1* means that we travel at maximum speed; contrary a relative time value of *1.10* or *1.20* means that we have been used for the trip a *10%* and a *20%* more time, respectively.

This has the advantage of allowing the combination of different trains correcting the travel duration effect.

3. Elements of the optimization problem. Proposed model

This section is devoted to describe the used optimization problem (see (Castillo, et al., 2015)). In any optimization problem we must deal with four basic elements: data, variables, constraints and objective function. We analyze them in detail below.

3.1 Data

Our data will be: (a) the set of candidate segments to determine which ones should be built as single or double tracks, (b) the segment construction costs of each segment as single and double track, (c) the demand, that is, the number and priority of daily services, (d) the desired departure times and corresponding flexibilities of all services, (e) the maximum segment speeds, (f) the safe headway times between consecutive trains, and the service dwell times.

3.2 Variables

The list of variables used in our model is given in Table 1.

Table 1 List of variables used in our model.

Variable	Meaning
b_j	Binary variable which value is 0 for single tracks and 1 for double
$e_{i,j}$	Entry time of train *i* in segment *j*
$s_{i,j}$	Exit time of train *i* from segment *j*
$t_{i,j}$	Travel time of train *i* along segment *j*
ε	Maximum relative travel time of all trains (\varepsilon\ge 1)
$q_{i,j,t}$	Binary variable which value is 1 if train *i* uses track t in segment j
r_i	Departure time of train *i*
$x_{i_1,i_1,j}$	Binary variable which value is 1 if the train i_1 uses segment *j* before the train i_2
$y_{i_1,i_1,j}$	Binary variable which value is 1 if the train i_1 uses segment *j* after the train i_2.
η_{il} , η_{iu}	slacknesses in the real departure time of train *i* (before and after desired times).
t_i^0	Minimum travel time of train *i*
γ_i	Priority of train *i*
r_{0i}	Desired departure time of train *i*
r_i^l , r_i^u	Maximum allowable slacknesses in departure time of train i (before and after desired times)
t_i^0	Minimum travel time of train *i*
γ_i	Priority of train *i* $(0<\gamma i\le 1)$
r_{0i}	Desired departure time of train *i*
r_i^l , r_i^u	Maximum allowable slacknesses in departure time of train i (before and after desired times)

3.3 Constraints

In this section we provide most of the constraints used in our model.

1. Departure times equal to entry times in the first segment.

$$s_{i,1}= r_{i} \quad \forall i \in I \tag{2}$$

2. Departure times are upper and lowerly bounded.

$$r_{0i}-r^{i}_{\ell}\leq r_{i}\leq r_{0i}+r^{i}_{u} \quad \forall i \in I \tag{3}$$

3. Exit time of a segment equal to entry time plus travel time through the segment.

$$e_{i,k}= s_{i,k}+t_{i,k} \quad \forall i \in I \quad \forall k \in K_{i} \tag{4}$$

4. Bounded segments' travel times.

$$t^{i}_{k,\ell} \leq t_{i,k}\leq t^{i}_{k,u} \quad \forall i \in I \quad \forall k \in K_{i} \tag{5}$$

5. Lower bounded dwell times.

$$s_{i,k}\geq e_{i,k-1}+d^{\ell}_{i,k} \quad \forall i \in I \quad \forall k \in K_{i} \tag{6}$$

6. Null stop at no TOPP[1] nodes.

$$s_{i,k}= e_{i,k-1} \quad \forall i \in I \quad \forall k \notin PAET \tag{7}$$

7. Enforce headway times among trains circulating in opposite direction.

$$s_{i1,j}- e_{i2,j}\geq h_{j}^{0}y_{i1,i2,j}-M\,(1-y_{i1,i2,j}) \tag{8}$$

$$s_{i2,j}- ei1,j\geq h_{j}^{0}xi1,i2,j-M(1-_{xi1,i2,j})\ \forall_{i1,i2}\in I\ \forall j \tag{9}$$

8. Enforce headway times among trains circulating in same direction.

$$s_{i2,j}- s_{i1,j}\geq h_{i1,i2,j}x_{i1,i2,j}-M(1-x_{i1,i2,j});\ \ \forall i_{1},i_{2},j \tag{10}$$

$$s_{i1,j}- s_{i2,j}\geq h_{i1,i2,j}y_{i1,i2,j}-M\,(1-y_{i1,i2,j});\quad \forall i_{1},i_{2},j \tag{11}$$

$$e_{i2,j}- e_{i1,j}\geq h_{j}^{0}y_{i1,i2,j}-M(1-x_{i1,i2,j});\quad \forall i_{1},i_{2},j \tag{12}$$

$$e_{i1,j}- e_{i2,j}\geq h_{j}^{0}y_{i1,i2,j}- M\,(1-y_{i1,i2,j});\quad \forall i_{1}<i_{2}\in I\ \rho_{i1,i2,j}=1 \tag{13}$$

9. If two trains use the same track in the same segment j, at least one of them should have priority

$$b_{j}+q_{i1j2}+q_{i1j2}-2 \leq x_{i1,i2,j}+y_{i1,i2,j}\ \forall_{i1,i2}\in I\ \forall j \tag{14}$$

$$q_{i1,j,1}+ q_{i2,j,1}-1 \leq x_{i1,i2,j}+y_{i1,i2,j,}\forall i1< i_{2}\in I,\forall j,t, \tag{15}$$

10. At most a train has priority

$$x_{\{i1,i2,j\}}+ y_{\{i1,i2,j\}}\leq 1;\forall i_{1}< i_{2}\in I \qquad \forall j \tag{16}$$

---

[1] *Train Overtop and Parking Post*

4. Objective function

Though we can use many other criteria, the main one used here is to minimize the maximum relative travel time of all circulating trains.

Since there are infinitely many solutions with this minimum relative travel time, we can use other criteria to select one among them, such as minimizing the sum of all relative travel times of circulating trains.

Since we still can have infinitely many optimal solutions we can add a third criterion, such as minimum fuel consumption, which leads to strict dwell time in stations and speeds as small as possible.

Consequently, we clearly face a multiobjective hierarchical optimization problem.

The selected objective function for our model includes five hierarchized goals: (a) construction cost, (b) maximum relative travel time ε, (c) relative travel times sum, (d) fuel save and (e) sum of departure time slacknesses.

Hence, our objective function can be chosen as:

$$\underset{b,s,e,r,t,x,y,\eta}{Min} \qquad Z=c(\boldsymbol{b})+\alpha_1\varepsilon+\alpha_2 f(\boldsymbol{e},\boldsymbol{s})-\alpha_3 g(\boldsymbol{e},\boldsymbol{s})+\alpha_4 p(\boldsymbol{e},\boldsymbol{s})$$

Where

$$c(\boldsymbol{b}) = \sum_j (1-b_j)\, STC_j + b_j DTC_j \quad : \quad Construction\ Cost \qquad (18)$$

$$\varepsilon = \max_{i \in I}\left[y_i \frac{s_{i,last}-e_{i,1}}{t_i^0}\right] \quad : \quad Max\ relative\ time \qquad (19)$$

$$f(\boldsymbol{e},\boldsymbol{s}) = \sum_{i \in I} y_i \frac{e_{i,last}-s_{i,1}}{t_i^0} \quad : \quad Relative\ times\ sum \qquad (20)$$

$$g(\boldsymbol{e},\boldsymbol{s}) = \sum_{i \in I} (e_{i,k}-s_{i,k-1}) \quad : \quad Energy\ consumption \qquad (21)$$

$$p(\boldsymbol{e},\boldsymbol{s}) = \sum_{i \in I} |r_{0i}-r_i| \quad : \quad Sum\ of\ departure\ time\ slacknesses \qquad (22)$$

5. ADST Capacity

In this section we derive some interesting formulas for dimensioning the lengths of double and single track segments. They are based on the hypothetical case of assuming a maximum capacity when trains circulate in both directions at the same speed s and a headway of duration t is used to guarantee safety. Though this assumption is an ideal situation, it gives an upper bound of the capacity of the line and provides us with a good understanding of ADST lines.

KEYNOTE

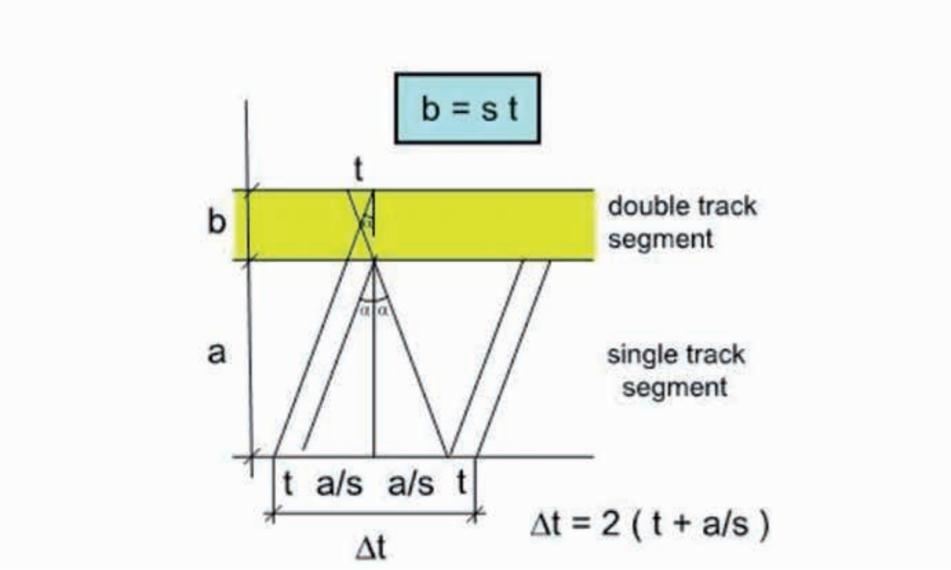


Figure 1. Circulating diagram of one single track segment (the bottom one) and one double track segment (the top one).

Figure 1 represents a diagram showing one single track segment (the one on the bottom) and one double track segment (the one on the top) and three trains circulating at speed $s=\mathrm{ctg}\alpha$, together with the headway t and lengths a and b of the segments. It represents the optimal situation in terms of efficiency of the segments, that is, the travel times of the segments is a minimum and corresponds to a minimal occupation of the line.

According to figure Figure 1, the train time lag Δt, that is, the time between two consecutive trains circulating in the same direction, satisfies the equation

$$\Delta t=2\ (t+a/s) \tag{23}$$

Similarly, from the double track segment in the top of figureFigure 1 we obtain

$$b=st \tag{24}$$

where b is the double track segment length.

This formula is very useful to design the optimal double track length in terms of s and t, which are usually selected without any problem.

From expressions (23) and (24) we have

$$\Delta t/t=2\ [1+a/st]=2\ [1+a/b], \tag{25}$$

which implies

$$\mathrm{b}/a+b=2t/\Delta t. \tag{26}$$

This equation provides the proportion of double track length with respect to the total length in terms of t and Δt.

It is relevant to note that the two equalities in (25) involve dimensionless ratios $\Delta t/t$, a/st and a/b, as suggested by the well-known $\Pi-Buckingham\ theorem$. This means that these two equations depend only on two variables (ratios) and not on four variables, $\Delta t, t$ a and s the first and $\Delta t, t$ a and b, the second, as it could appear in an initial or superficial analysis of them.

Figure 2 shows different train flow diagrams illustrating how the theoretical capacity of a line improves from 34 services per day to 264 services per day when we increase the number of double track segments from zero (single track line) to a maximum value (double track line).

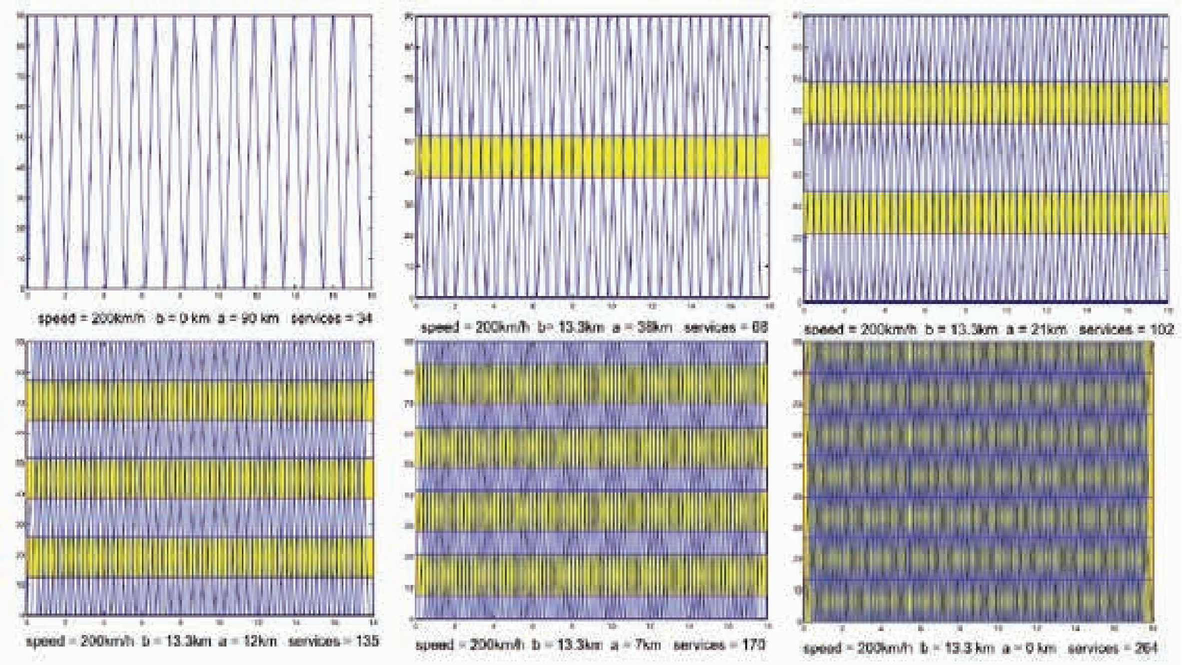


Figure 2. Train flow diagrams illustrating how the theoretical capacity of a line improves from 34 services per day to 264 services per day when we increase the number of double track segments from zero (single track line) to a maximum value (double track line).

6. Software

To solve the optimization problem (17) subject to constraints (like (2) to (16) we have written a computer program in Matlab, which provides the optimal solution. This means that the optimal sequence of single and double track segments is obtained together with the optimal timetable of the line.

In addition, the GAMS program automatically generates a Mathematica code, which after execution produces plots as those in figures \ref{f522} and \ref{f522a}, and a Latex code such that when compiled produces tables with the arrival and departure times for all stations and services (trains).

Finally, a user interface, developed in JAVA, permits a friendly data input.

7. Internationalization

There are many locations where ADST could be implemented. Some examples are given in figures Figure 3 and Figure 4, which include Thailand, Ireland, Ukraine, Morocco, Italy, Spain, Turkey, France and the United Kingdom.

Figure 3 Some possible ADST in Thailand, Ireland and Ukraine

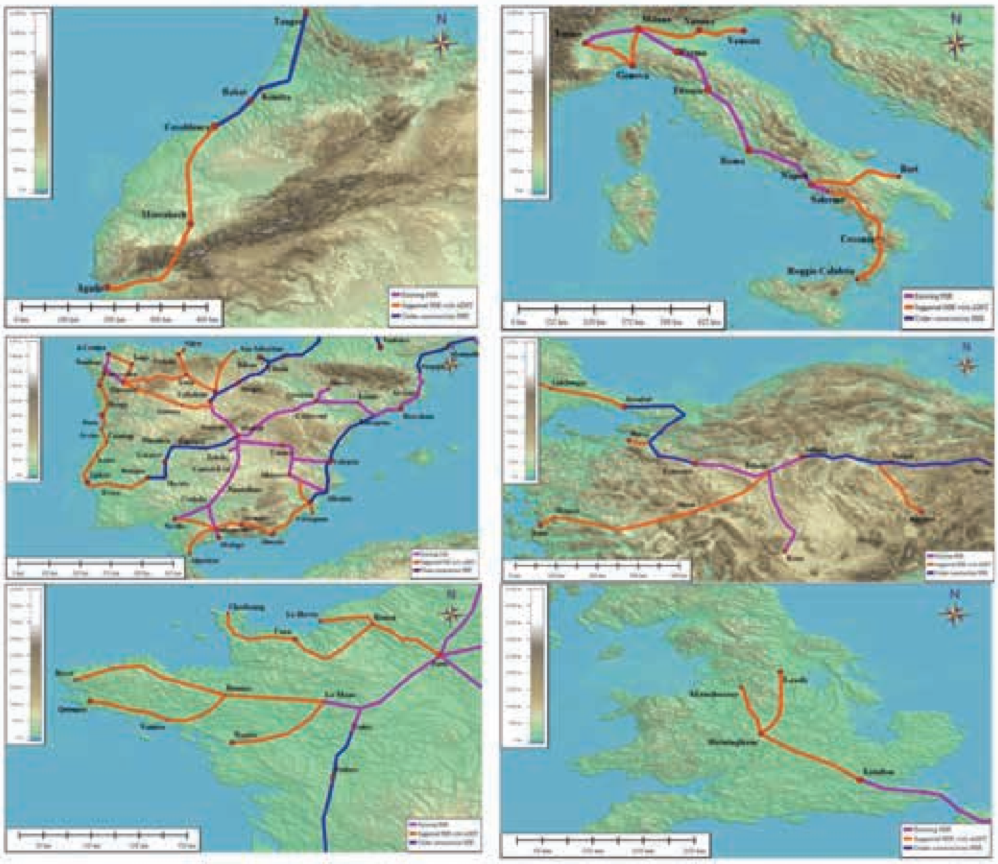


Figure 4 Some possible ADST in Morocco, Italy, Spain, Turkey, France and United Kingdom.

8. Some examples

8.1 Santiago - Valparaíso and Viña del Mar Case

We start with the simplest case, that is, when we built a new railway line. This means that we are free to choose single and double track segments.

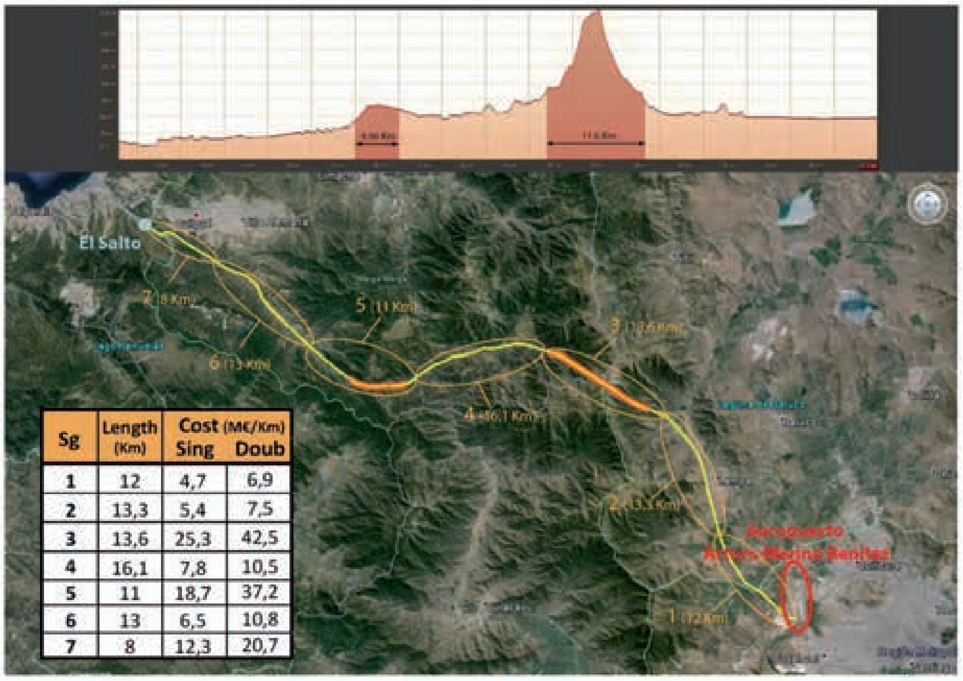
This is the case of Santiago - Valparaíso and Viña del Mar, in which among others they have the following problems:

1. 15,000 people travel for work on weekdays by bus or car from Valparaíso and Viña del Mar to Santiago and vice versa and they expend between 4 and 5 hours in transportation.
2. Valparaíso port is losing competitiveness with respect other ports in the country because it does not have transport by rail.
3. The beaches and the casino of Viña del Mar have difficult access by road from Santiago, which produces significant losses in tourist activities.
4. Citizens from Valparaíso and Viña del Mar have difficult access to the Santiago international airport.

With the idea of solving these and generating new activities, we proposed to the community to construct a new high speed railway line, based on the following ideas.

- A mixed line for passenger and freight trains was considered.
- The maximum service speeds have been 200 km/h for passenger trains and 120 km/h for freight trains.
- Two paths: Santiago-El Salto and vice versa have been studied.
- This implies a total of 100 daily services: 76 passenger trains (38 each way) and 24 freight trains (12 in each direction), 1 train every 20 minutes at peak (6:00-8:20 and 17:20-20:20), and every 30 minutes during valley hours (8:20-17:20 and 20:20-22:20).
- Five night hours have been reserved for line maintenance.

Figure 5 shows the proposed layout of the Santiago-Valparaíso line, in which only two short tunnels are required. It also shows the seven elements used for our analysis together with their lengths and construction costs as single and double track.



Sg	Length (Km)	Cost (M€/Km) Sing	Doub
1	12	4,7	6,9
2	13,3	5,4	7,5
3	13,6	25,3	42,5
4	16,1	7,8	10,5
5	11	18,7	37,2
6	13	6,5	10,8
7	8	12,3	20,7

Figure 5. Layout of the Santiago-Valparaíso line showing the seven elements considered.

Introducing these data in our computer program together with the desired departure times and their corresponding flexibilities we obtained the solution indicated in figure \ref{f502}, where the double track segments are shown in yellow color.

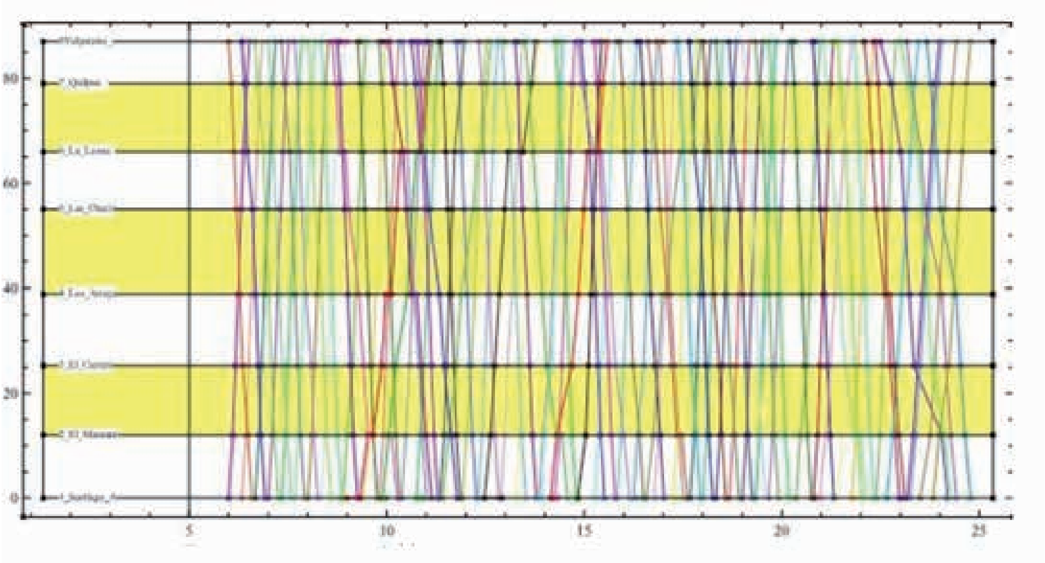


Figure 6. Proposed timetable for the Santiago - Valparaíso/Viña del Mar line

From the study above, we can conclude the following:

1. The proposed line Santiago - Valparaíso/Viña del Mar can be integrated with the metropolitan transport network (metro, buses, etc.).
2. The alternate double-single track solution (1,084 M€) allows us to achieve a saving of *36%* compared to the double track (1,700 M€) and important maintenance savings.
3. If the line were integrated with the subway of Valparaíso (same gauge), freight trains could reach Valparaíso port

This ADST project permits:

- Daily displacement of 15,000 workers from Valparaíso and Viña del Mar to Santiago, and vice versa.
- Promote tourism and leisure activities to the citizens of Santiago (beaches, casino, etc.).
- Provide Valparaíso and Viña del Mar with an international airport accessible in half an hour.
- Allow the survival of the port of Valparaíso giving it an exit by rail to Santiago.
- Generate new activities and population centers in Santiago, Valparaíso and Viña del Mar.

8.2 Palencia-Santander case

This example deals with the improvement of the Palencia-Santander line, with a length of 217.2 km. connecting Palencia (80.000 dwellers) with Santander (176.000 dwellers).

Figure 7. Layout of the Santander-Palencia line.

In this case, we have an existing conventional line, whose layout is shown in figure Figure 7 and we want to improve it to reach Madrid from Santander in 3 hours, which would allow railways to compete with air transport. This means, a target travel time of 1 hour and 45 minutes from Santander to Palencia (the actual travel time is more than 2 hours and 25 minutes).

Several years ago a high speed double track line was designed with a length of 186.6 km and a travel time of 1 hour 40 min. with a cost of 3,200 M€. Unfortunately, due to the high cost, it was neither financed nor built.

The profile of this Palencia-Santander line is shown in figure Figure 8 where we can be seen that de first 120 km are rather flat, the intermediate segments correspond to a very steep line with alternating tunnels (in red color) and viaducts (in blue color) and the final 23.7 kms are rather flat again.

It is clear that the construction of the intermediate segments is very expensive and is not justified by the actual or expected future demand, so that we expect that our optimization program will decide single track segments in this zone.

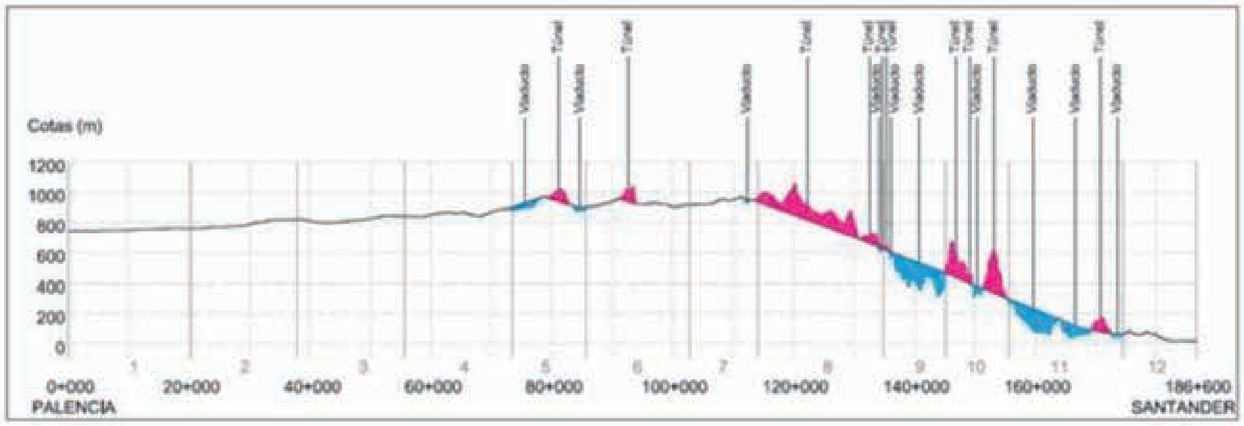


Figure 8. Profile of the Santander-Palencia line.

KEYNOTE

Figure 9 shows the Palencia-Santander trace with the 12 segments that have been considered in our analysis, from which the optimization program will select those to be built in double track.

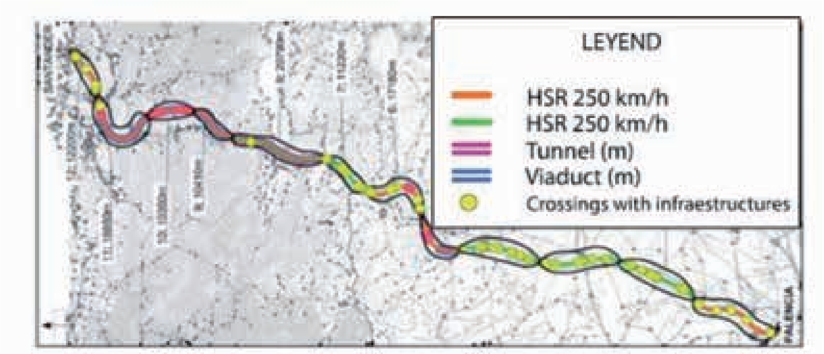
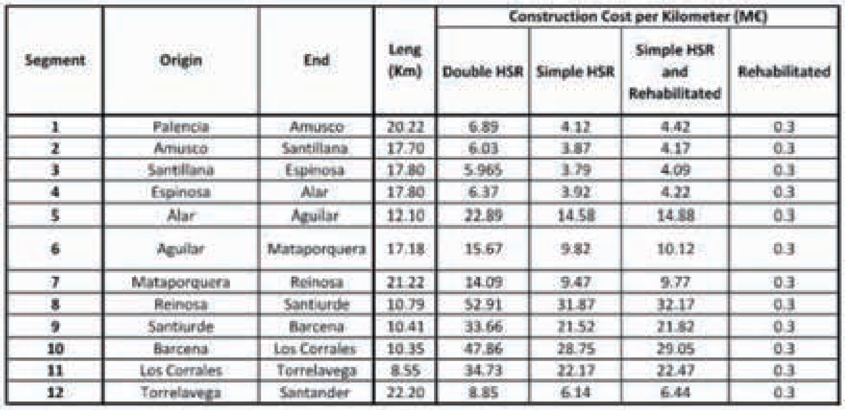


Figure 9. Description of the Palencia-Santander line, showing the 12 segments that have been considered in our analysis.

Table 2 shows the selected segments and cost per kilometer for the different alternatives (single, double track, etc.)

Table 2. Selected segments and cost per kilometer from the different alternatives.



Segment	Origin	End	Leng (Km)	Construction Cost per Kilometer (M€)			
				Double HSR	Simple HSR	Simple HSR and Rehabilitated	Rehabilitated
1	Palencia	Amusco	20.22	6.89	4.12	4.42	0.3
2	Amusco	Santillana	17.70	6.03	3.87	4.17	0.3
3	Santillana	Espinosa	17.80	5.965	3.79	4.09	0.3
4	Espinosa	Alar	17.80	6.37	3.92	4.22	0.3
5	Alar	Aguilar	12.10	22.89	14.58	14.88	0.3
6	Aguilar	Mataporquera	17.18	15.67	9.82	10.12	0.3
7	Mataporquera	Reinosa	21.22	14.09	9.47	9.77	0.3
8	Reinosa	Santiurde	10.79	52.91	31.87	32.17	0.3
9	Santiurde	Barcena	10.41	33.66	21.52	21.82	0.3
10	Barcena	Los Corrales	10.35	47.86	28.75	29.05	0.3
11	Los Corrales	Torrelavega	8.55	34.73	22.17	22.47	0.3
12	Torrelavega	Santander	22.20	8.85	6.14	6.44	0.3

The line is constructed to satisfy a certain demand. The actual demand is shown in figure Figure 10, which show the actual demand optimized circulation diagram. It consists of 70 daily trains.

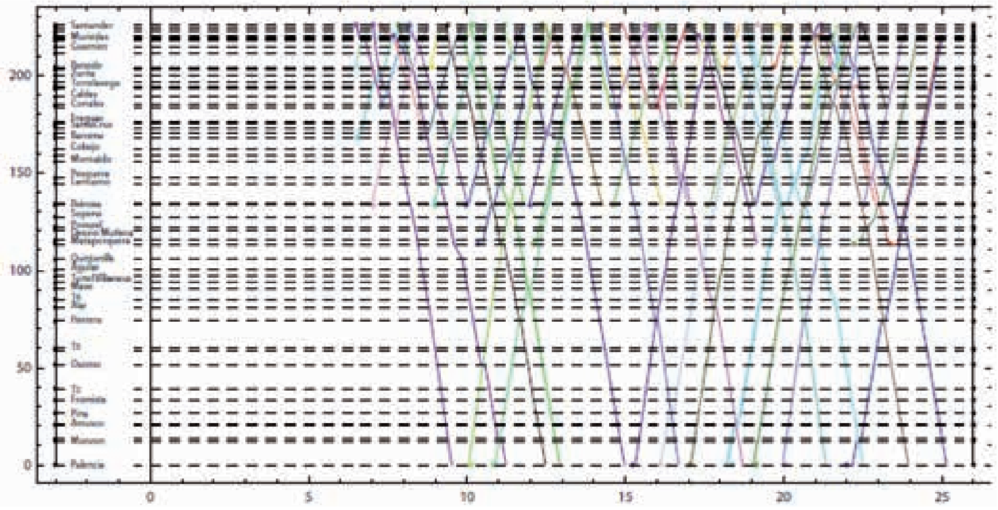
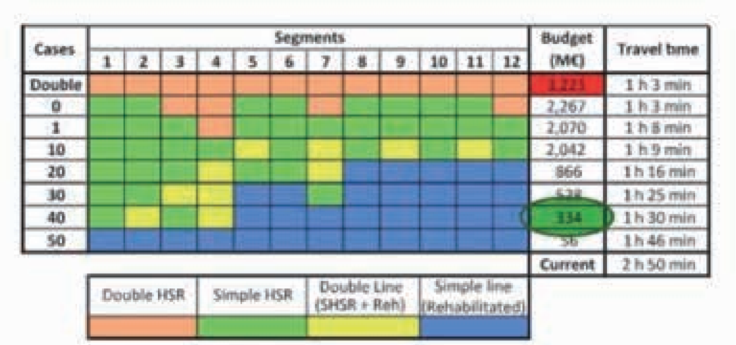


Figure 10. Current optimized circulation diagram: Santander-Palencia



Cases	Segments 1	2	3	4	5	6	7	8	9	10	11	12	Budget (M€)	Travel time
Double	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	3,221	1 h 3 min
0	🟩	🟩	🟧	🟧	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟧	2,267	1 h 3 min
1	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	2,070	1 h 8 min
10	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟨	🟩	🟨	🟩	2,042	1 h 9 min
20	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟦	🟦	🟦	🟦	🟦	866	1 h 16 min
30	🟩	🟩	🟨	🟨	🟦	🟦	🟩	🟦	🟦	🟦	🟦	🟦	528	1 h 25 min
40	🟩	🟨	🟩	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	334	1 h 30 min
50	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	56	1 h 46 min
													Current	2 h 50 min

Double HSR	Simple HSR	Double Line (SHSR + Reh)	Simple line (Rehabilitated)
🟧	🟩	🟨	🟦

Figure 11. Chart showing the different solutions an associated budget and travel times for the Santander-Palencia line

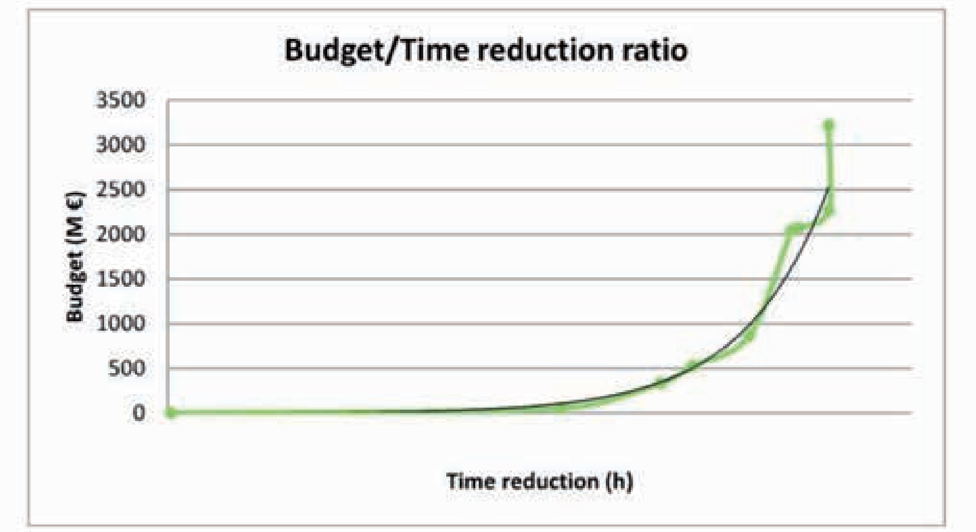
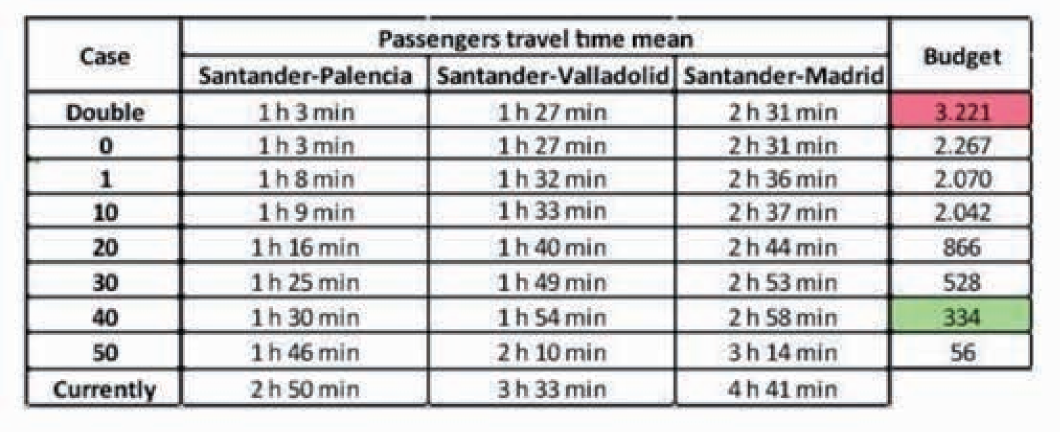


Figure 12. Cost versus reduction in travel time (in hours).

Table 3 Travel times and costs of the different analyzed solutions.



Case	Passengers travel time mean			Budget
	Santander-Palencia	Santander-Valladolid	Santander-Madrid	
Double	1 h 3 min	1 h 27 min	2 h 31 min	3.221
0	1 h 3 min	1 h 27 min	2 h 31 min	2.267
1	1 h 8 min	1 h 32 min	2 h 36 min	2.070
10	1 h 9 min	1 h 33 min	2 h 37 min	2.042
20	1 h 16 min	1 h 40 min	2 h 44 min	866
30	1 h 25 min	1 h 49 min	2 h 53 min	528
40	1 h 30 min	1 h 54 min	2 h 58 min	334
50	1 h 46 min	2 h 10 min	3 h 14 min	56
Currently	2 h 50 min	3 h 33 min	4 h 41 min	

KEYNOTE

Once the Cantabria Government had knowledge of the results of the previous study changed his mind and decides to abandon the HSR double track solution of 3221 M€ and to commission a study of the solution whose budget was 334 M€.

The optimal timetable results as in figure Figure 13 where the green segments are double track segments.

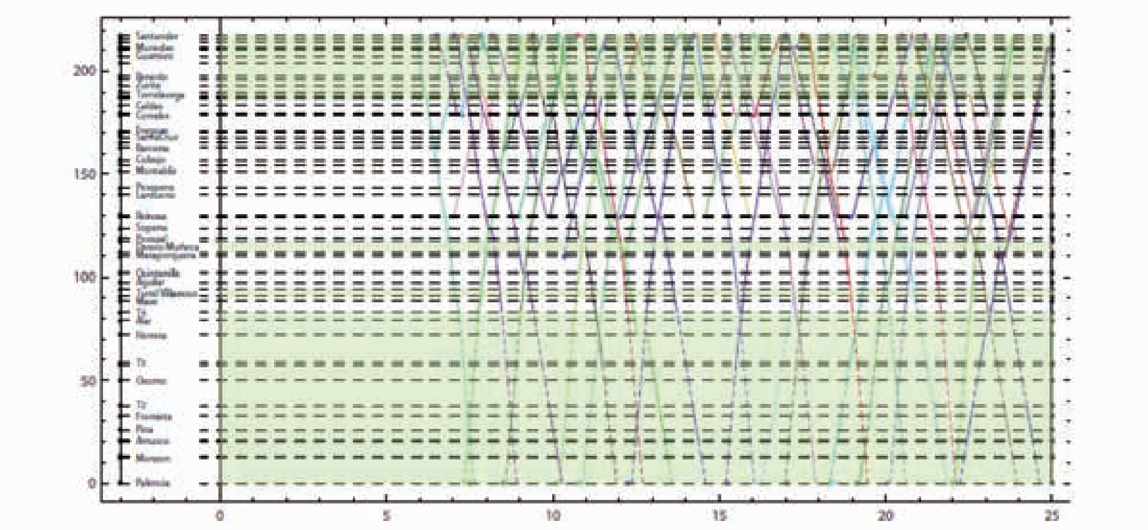


Figure 13. Example of circulation diagram with 8 additional long trip trains in the Santander-Palencia line.

Consequently, the final proposed actions to improve the Cantabrian railway service are depicted in Figure 14.

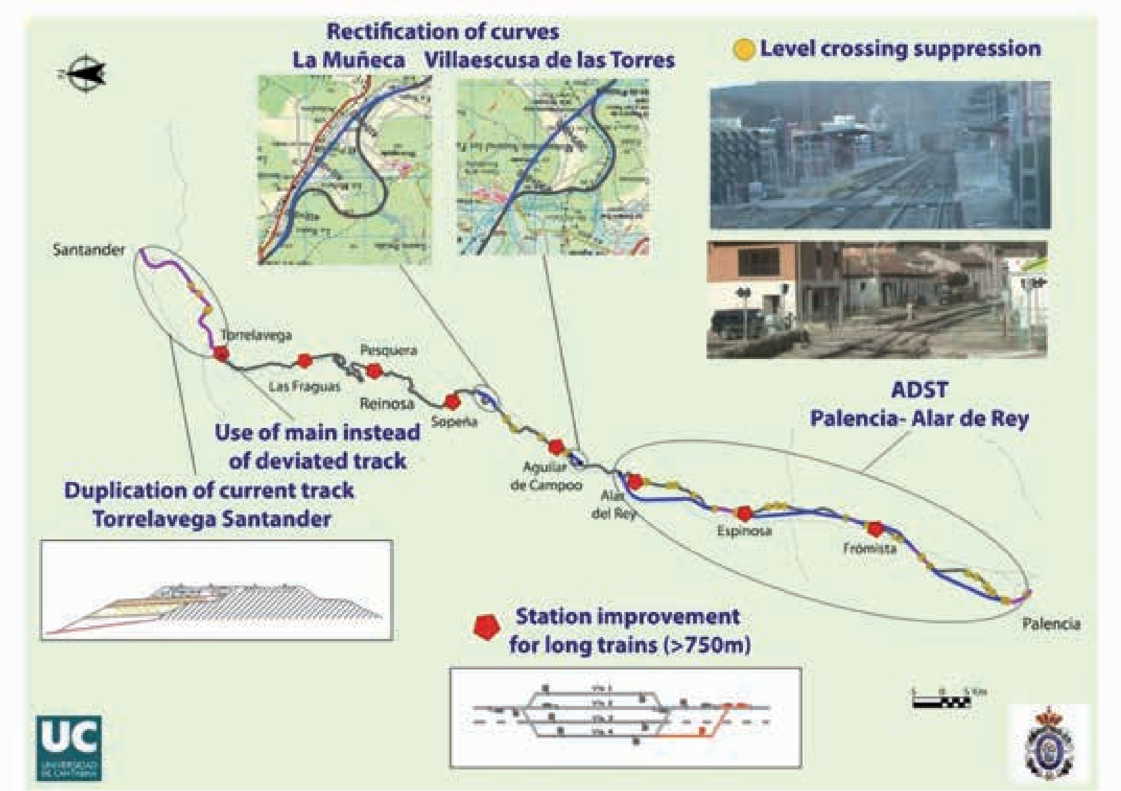


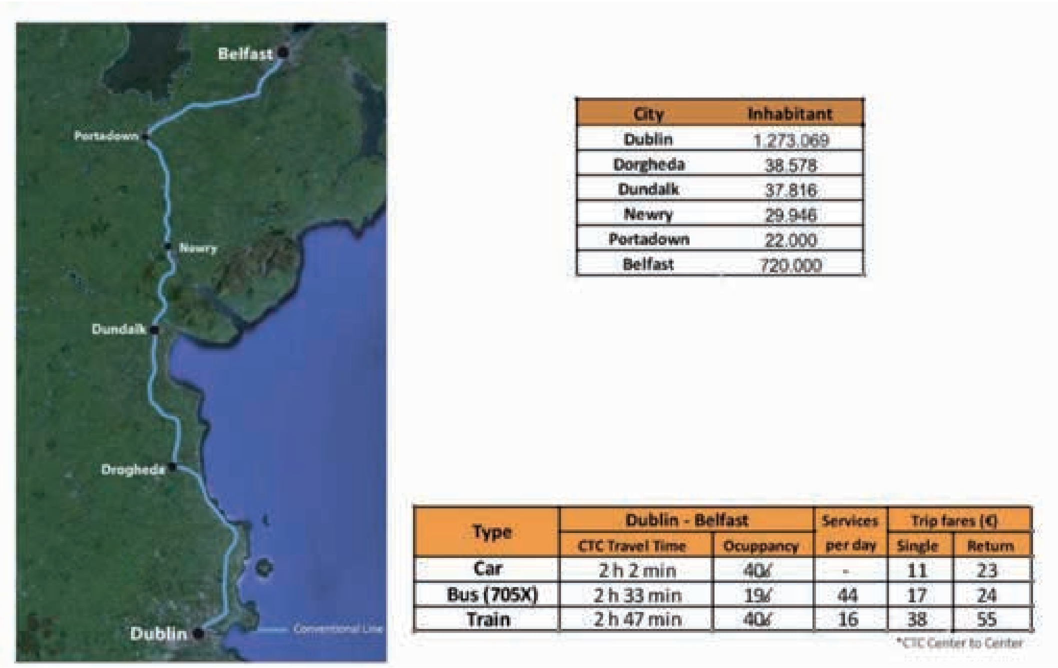
Figure 14. Set of actions.

8.3 Dublin Belfast case

In this section we analyze the existing conventional Dublin-Belfast line and analyze several alternatives for a new high speed line, showing the associated costs and travel times.

8.3.1 Current Line

Before designing a railway line it is very important to study the affected population and the possible demand. The list of the connected cities and their actual populations are shown in figure Figure 15 which shows that the Dublin-Belfast link could connect 2 million people.



City	Inhabitant
Dublin	1.273.069
Dorgheda	38.578
Dundalk	37.816
Newry	29.946
Portadown	22.000
Belfast	720.000

Type	Dublin - Belfast		Services	Trip fares (€)	
	CTC Travel Time	Ocuppancy	per day	Single	Return
Car	2 h 2 min	40%	-	11	23
Bus (705X)	2 h 33 min	19%	44	17	24
Train	2 h 47 min	40%	16	38	55

*CTC Center to Center

Figure 15. Current line description.

The trace of the current line between Dublin and Belfast together with their main stations are shown in figure Figure 15. Its length is 181 Km (113 miles) and the current travel time is 2 h and 9 min. It must be noted that, in addition to offering 16 daily services between the two cities, the network shares 312 daily services including the Dublin and Belfast commuter and freight transport services.

In addition, Figure 15 shows the travel times between both cities, occupancies and travel costs associated with the different alternatives such as, car, bus and other trains, together with their single and return trip fares. It can be seen that the railway transport is the most expensive conveyance and its daily service is significantly lower than the bus connection.

In the following sections we propose some alternatives to improve the efficiencies of the DublinBelfast services.

Figure 16. High speed line proposal showing the selected eight segments used for the analysis and the considered speeds in each segment.

8.3.2 High speed line proposal

As our first proposal we consider a new double track high speed line from Dublin to Belfast.

We propose the line shown in figure Figure 16 where the traces of the new and the existing lines are shown and the selected eight segments used for the analysis and the considered speeds in each segment. The new proposed line has a length of 160.4 Km (100.25 miles), that is, a reduction of 20 km (12.5 miles) with respect to the existing conventional line. In order to reduce travel times only one intermediate stop at Dundalk has been assumed (see Figure 16).

Table 4 Data used for our high speed proposals including the segment definition, their lengths and costs in single and double track.

Segment			Length		Cost (M€/km M£/mi)			
id	Origin	Destination	Km	Miles	Simple		Double	
1	Dublin	Donabate	16,5	10,3	7,8	9,1	14,0	16,3
2	Donabate	Pilltown	27,7	17,3	4,9	5,7	7,8	9,1
3	Pilltown	Dromiskin	28,1	17,6	5,3	6,2	8,4	9,8
4	Dromiskin	Dundalk	9,1	5,7	6,9	8,0	12,4	14,5
5	Dundalk	Newry	22,1	13,8	5,8	6,8	8,9	10,4
6	Newry	Banbridge	18,1	11,3	5,5	6,4	8,7	10,1
7	Banbridge	Mazetown	22,7	14,2	6,1	7,1	9,5	11,1
8	Mazetown	Belfast	16,1	10,1	7,4	8,6	13,9	16,2

Table 4 shows the data used for our high speed proposals including the segment definition, their lengths and costs in single and double track.

Our first high speed line proposal is a traditional double-track line, i.e., all segments are built as double-track segments. Consequently, our computer program does not need to make any decision on which segments must go in single or double-track, but it needs to optimize travel times. he resulting optimal travel time between Dublin and Belfast is 50 min., which means a reduction of 1 hour and 19 minutes with respect to the current travel time.

To summarize, the main characteristics of the proposed high speed line in the case of a doubletrack solution are: a total length of 160.4 km/100.25 Miles, a travel time of 50 min. and a construction cost of M€ 1589.54 (M£ 1158.98).

This solution is the most expensive one, but offers maximum capacity and flexibility. However, the main questions that should be asked are: whether or not to resort to a double-track solution is necessary and whether or not there are more efficient alternatives.

8.3.3 ADST proposals

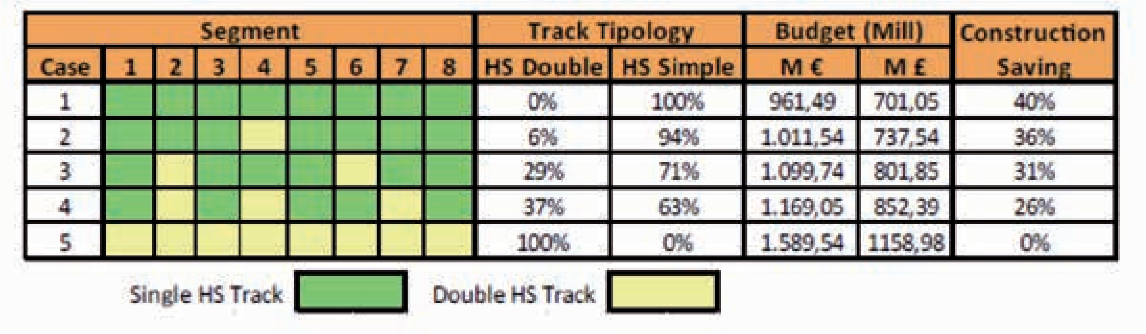
With the aim of reducing construction and maintenance costs, in this section some alternative ADST line solutions are discussed. The decision of which segments should be in double- and single-track under the assumed demand assumptions and the corresponding timetable optimization will be made with the help of the optimization program.

Only the routes of Dublin-Belfast and Dublin-Dundalk-Belfast in both directions and a demand of 16 and 32 daily services have been considered in this preliminary analysis.

The commercial speed used in the analysis was assumed 90% of the maximum speed for each segment. In addition, a headway of 4 minutes and a delay of 4 minutes per hour of travel has been assumed. This commercial speed and delay values were considered to guarantee a certain robustness of the timetables under a regular operation.

After using the proposed method, we have considered 5 different solutions that range from single track to double track with 3 intermediate cases that include one and three double track segments. They are illustrated in table Table 5, where it can be shown that the budget ranges from € 962 M/ £ 701 M, for single track to € 1590 M/ £ 1160 M, for double track.

Table 5 Cost comparison of the 5 alternatives considered.

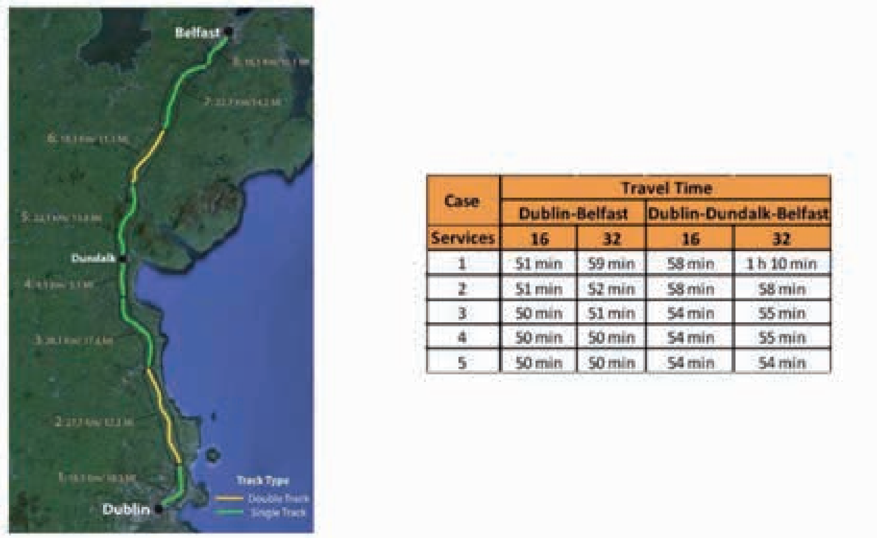


Segment									Track Tipology		Budget (Mill)		Construction Saving
Case	1	2	3	4	5	6	7	8	HS Double	HS Simple	M €	M £	
1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	0%	100%	961,49	701,05	40%
2	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	6%	94%	1.011,54	737,54	36%
3	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	29%	71%	1.099,74	801,85	31%
4	🟩	🟨	🟩	🟨	🟩	🟩	🟨	🟩	37%	63%	1.169,05	852,39	26%
5	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	100%	0%	1.589,54	1158,98	0%

Single HS Track 🟩 Double HS Track 🟨

The travel time comparison of the 5 alternatives considered in Figure 17 show that any DublinBelfast service does not take longer than one hour and in the route Dublin-Dundalk-Belfast travel time exceeds one hour only in the single track case.

KEYNOTE



Case	Travel Time			
	Dublin-Belfast		Dublin-Dundalk-Belfast	
Services	16	32	16	32
1	51 min	59 min	58 min	1 h 10 min
2	51 min	52 min	58 min	58 min
3	50 min	51 min	54 min	55 min
4	50 min	50 min	54 min	55 min
5	50 min	50 min	54 min	54 min

Figure 17. Optimal ADST railway line solution and Travel time comparison of the 5 alternatives considered.}

The optimal option is given by Case 3, a high speed line proposal composed of 2 double-track segments (in yellow color) and 6 single-track segments as shown in Figure 17.

Its main characteristics are: total length 160,4 Km , construction budget € 1.099,74 M (31 % saving w. r. t. double track), travel time 50-51 min (Dublin-Belfast) and \\ 54-55 min (DublinDundalk-Belfast), 16 and 32 daily services with a capacity of 6.200 and 12.400 daily passengers.

The resulting timetable for 32 services is shown in figure Figure 18.

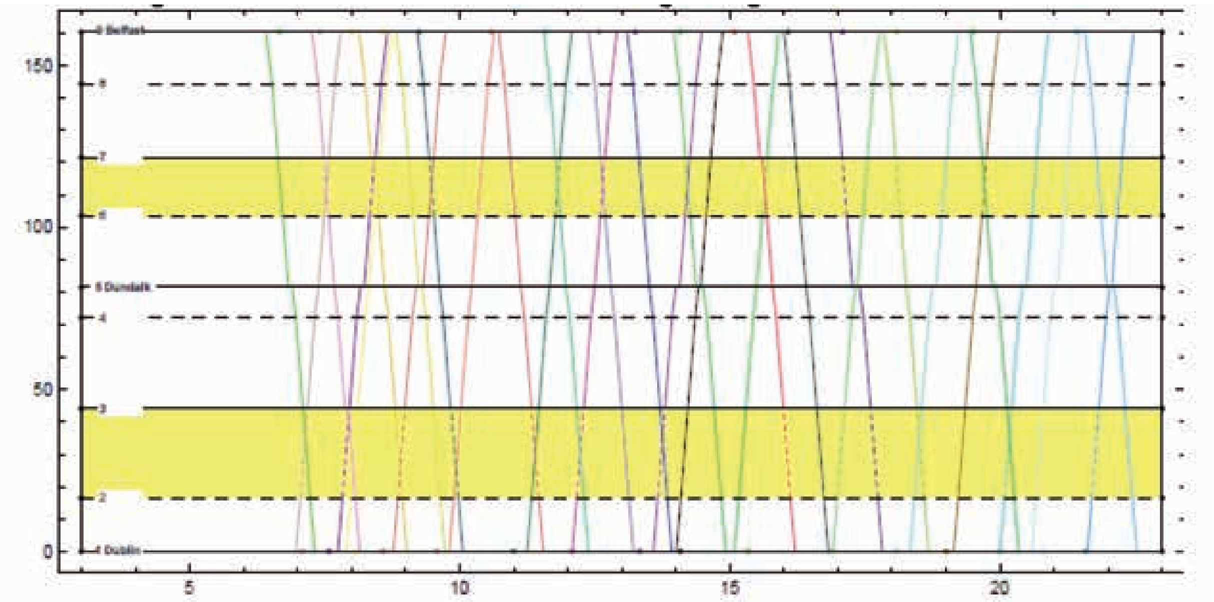
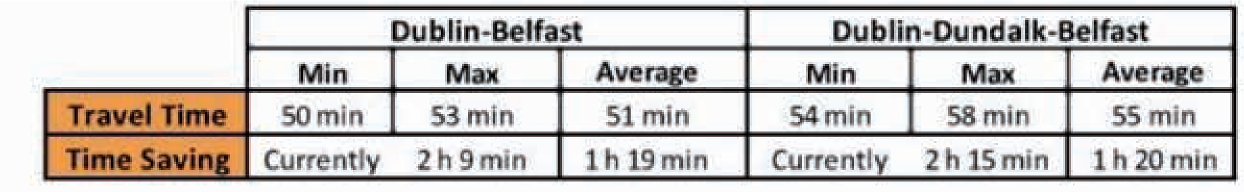


Figure 18. 32 services Timetable for the Dublin-Belfast line.

Table 6 Travel times and travel time reductions w.r.t. actual travel times.



	Dublin-Belfast			Dublin-Dundalk-Belfast		
	Min	Max	Average	Min	Max	Average
Travel Time	50 min	53 min	51 min	54 min	58 min	55 min
Time Saving	Currently	2 h 9 min	1 h 19 min	Currently	2 h 15 min	1 h 20 min

Table 6 shows the travel times and travel time reductions w.r.t. actual travel times.

8.3.4 Improvement of the existing line

In this section a final alternative that combines the existing conventional line with segments of new construction is proposed.

We propose to build 4 new segments, as shown in figure Figure 19 that is, between DonabateJulianstown-Dromiskin (segments T1-T2 and T2-T3) and Newry-Banbridge-Lisburn (segments T6T7 and T7-T8). These new segments would operate to complement the current line, so that the services (long distance link, commuter and freight traffic) could circulate using the current and new tracks, without any restriction.

The new segments should be designed to accept trains with a range of speed between 130 km/h (80 mph) and the future high speed 250 km/h (155 mph).

We study an improved line with 16+18 services between Dublin and Belfast where the new segments are assumed to be in operation with only 28 fast connection services of a total 34 links between Dublin and Belfast circulating along the new segments. With this, the total amount of services along the network is 346 trains.

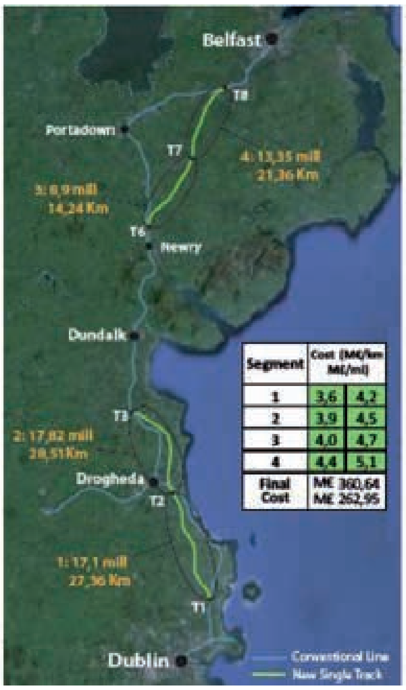
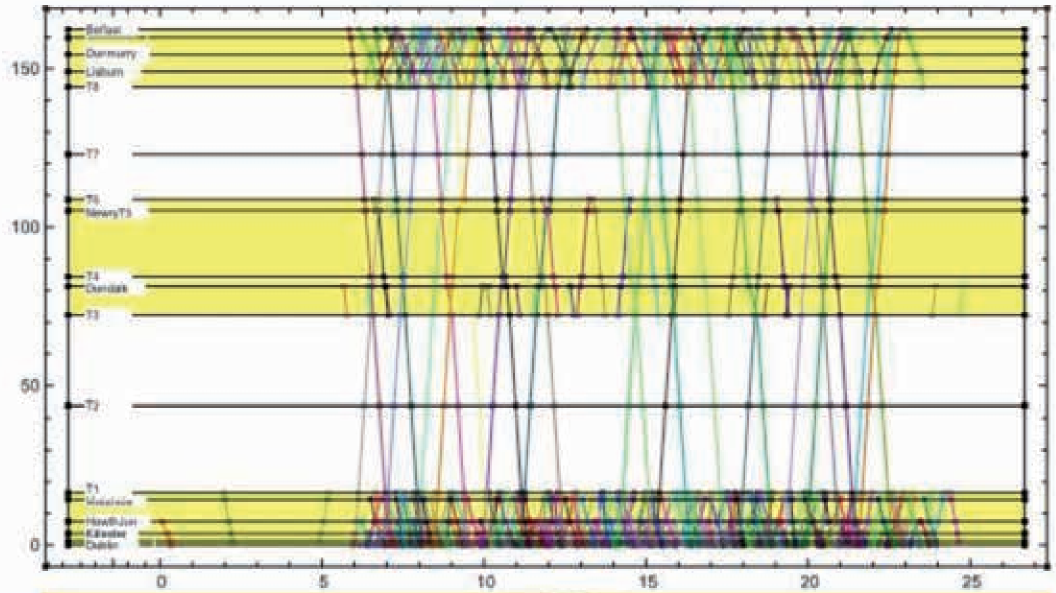


Figure 19. 4 segments to be constructed to improve the existing line.

The characteristics of the resulting optimized line are: it is a line with total length 161 km/100.6 Miles with 4 new single track segments of length (91.5 km/57.2 mile), which imply a total cost of M€ 360.64/M£ 262.95.

Finally, the result of this analysis provides the following conclusions:

1. Fast connections, less than 1 hour 25 minutes, between Dublin-Belfast are possible. They would increase Dublin-Belfast traffic rate, and generate new users.
2. New construction segments are suggested only out of the two congested metropolitan areas.
3. Four single track segments with a total length of 91.5 km (57.2 Miles) are proposed, because double-track segments are not necessary. Therefore, the resulting construction cost of the proposed line is only M€ 360.64 (M£ 264.95).
4. The new segments permit fast connection, reduce congestion in the whole network and favor cross-border freight transport.



Travel Time						
Route	11	12	101	102	111	112
Min	2 h 2 min	2 h 7 min	1 h 25 min	1 h 25 min	1 h 21 min	1 h 23 min
Max	2 h 12 min	2 h 13 min	1 h 32 min	1 h 32 min	1 h 27 min	1 h 28 min
Average	2 h 7 min	2 h 11 min	1 h 29 min	1 h 31 min	1 h 24 min	1 h 26 min

Figure 20. Improved Network (16+18 Dublin-Belfast services).

9. Conclusions

As final conclusion, Alternate Double-Single track projects, as different examples reflect, allow to:

- Minimize the construction cost with reduced travel times.
- Design railway lines under current and future demands.
- Reduce maintenance costs.
- Optimize timetables.
- Model the timetable in response to incidents on the network.

10. Bibliography

- Amit, I. & Goldfarb, D., 1971. The timetable problem for railways. *Developments in Operations Research,* Volume 2, pp. 379-387.
- Assad, A., 1980. Models for rail transportation. *Transportation Research Part A,* Volume 14, pp. 205-220.
- Burdett, R. L. & Kozan, E., 2010. A disjunctive graph model and framework for constructing new train schedules. *European Journal of Operational Research,* Volume 2010, pp. 8598.
- Cacchiani, V. & Toth, P., 2012. Nominal and Robust Train Timetabling Problems. *European Journal of Operational Research,* Volume 219, pp. 727-737.
- Caprara, A., Fischetti, M. & Toth, P., 2002. Modeling and solving the train timetabling problem. *Operations Research,* Volume 50, pp. 851-861.
- Carey, M., 1994. A model and strategy for train pathing with choice of lines, platforms and routes. *Transportation Research Part B,* Volume 28, pp. 333-353.
- Carey, M. & Crawford, I., 2007. Scheduling trains on a network of busy complex stations. *Transportation Research Part B,* Volume 41, pp. 159-178.
- Carey, M. & Lockwood, D., 1995. A model, algorithms and strategy for train pathing. *Journal of the Operational Research Society,* Volume 46, pp. 988-1005.
- Castillo, E. et al., 2015. An alternate double-single track proposal for high-speed peripheral railway lines. *Computer Aided Civil and Infrastructure Engineering,* Volume 30, pp. 181201.
- Castillo, E., Gallego, I., Ureña, J. M. & Coronado, J. M., 2009. Timetabling optimization of a single railway track line with sensitivity analysis. *TOP,* Volume 17, pp. 256-287.
- Castillo, E., Gallego, I., Ureña, J. M. & Coronado, J. M., 2011. Timetabling optimization of a mixed double- and single-tracked railway network. *Applied Mathematical Modelling,* Volume 35, pp. 859-878.
- Castillo, E., Grande, Z., Moraga, P. & Sánchez Vizcano, J., 2016. A time partitioning technique for railway line design and timetable optimization. *Computer Aided Civil And Infrastructure Engineering,* Volume 31, pp. 599-616.
- Cordeau, J. F., Toth, P. & Vigo, D., 1998. A survey of optimization models for train routing and scheduling. *Transportation Science,* Volume 32, pp. 380-404.
- DÁriano, A., Pacciarelli, D. & Pranzo, M., 2007. A branch and bound algorithm for scheduling trains in a railway network. *European Journal of Operational Research,* Volume 183, pp. 643-657.

- DÁriano, A. & Pranzo, M., 2004. *A real time train dispatching system based on blocking time theory.* Delft, DUP Science, pp. 129-152.
- DÁriano, A., Pranzo, M. & Hansen, I. A., 2007. Conflict Resolution and Train Speed Coordination for Solving Real-Time Timetable Perturbations. *IEEE Transactions on Intelligent Transportation Systems,* Volume 8.
- Haghani, A. E., 1987. Rail freight transportation: a review of recent optimization models for train routing and empty car distribution. *Journal of Advanced Transportation,* Volume 21, pp. 14-172.
- Hellström, P., 1998. *Analysis and evaluation of systems and algorithms for computer-aided train dispatching,* Sweden: s.n.
- Higgins, A., Kozan, E. & Ferreira, L., 1996. Optimal scheduling of trains on a single line track. *Transportation Research Part B,* Volume 30, pp. 147-161.
- Jia, L. M. & Zhang, X. D., 1993. Distributed intelligent railway traffic control based on fuzzy decision making. *Fuzzy Sets and Systems,* Volume 62, pp. 255-265.
- Kraay, D. R. & Harker, P. T., 1995. Real-time scheduling of freight railroads. *Transportation Research Part B,* Volume 29, pp. 213-229.
- Lin, D. Y. & Ku, Y. H., 2013. Using Genetic Algorithms to Optimize Stopping Patterns for Passenger Rail Transportation. *Computer-Aided Civil and Infrastructure Engineering,* pp. n/a--n/a.
- Ouyang, Y. et al., 2009. Optimal Locations of Railroad Wayside Defect Detection Installations. *Computer-Aided Civil and Infrastructure Engineering,* Volume 24, pp. 309-319.
- Pachl, J., 2014. Railway Timetabling and Operations. Analysis - Modelling - Optimisation - Simulation - Performance Evaluation. In: Hamburg(): Eurailpress, pp. 23-24.
- Petersen, E. R., Taylor, A. J. & Martland, C. D., 1986. An introduction to computer aided train dispatching. *Journal of Advanced Transportation,* Volume 20, pp. 63-72.
- Sahin, I., 1999. Railway traffic control and train scheduling based on inter-train conflict management. *Transportation Research Part B,* Volume 33, pp. 511-534.
- Yang, Z. & Hayashi, Y., 2002. GIS-Based Analysis of Railways Origin/Destination Path-Selecting Behavior. *Computer-Aided Civil and Infrastructure Engineering,* Volume 17, pp. 221-226.