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OPTIMAL ROUTE FINDING AND ROLLING-STOCK SELECTION FOR THE SPANISH RAILWAYS

By Antonio Hernando, Eugenio Roanes-Lozano, Alberto García-Álvarez, Luis Mesa,
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The Spanish railway network managed by the Adif company has two different track gauges, two electrification systems, and four families of signaling systems. The simulation package presented here takes these variations into account, making it easier to decide about routes, rolling-stock selection, and future infrastructure or vehicle investments.

According to the European Union's laws, the former Spanish railway company Renfe had to be split into an infrastructure company called Adif and an operating company that kept the trademark Renfe Operadora (there's a separately run narrow-gauge network in Spain that won't be addressed here). The infrastructure also had to be opened to other operating companies, following the aeronautical model. Despite these efforts, medium- and long-distance passenger services are still a monopoly of Renfe.

Yet the Spanish railways are facing exciting times for other reasons: They've just become the longest high-speed network in Europe and third in the world (only behind China and Japan).^{1,2} Nevertheless, operating the Spanish railway network is quite complex, for a variety of reasons that include two different track gauges, two electrification systems, and four families of signaling systems (we provide greater detail in the sidebar, "Overview of the Spanish Railway Network").

To help the Fundación de los Ferrocarriles Españoles (the Spanish Railways Foundation) navigate among these complexities, we review current solutions and present a software

simulation package called *Rutas-OptiRed* that makes decisions easier regarding routes, rolling-stock selection, and future infrastructure or vehicle investments.

Solutions Provided by the Rolling-Stock Manufacturers

As we mention in the sidebar, one of the complexities of this railway network is that there are two different track gauges. The problems of the coexistence of two gauges are partially surpassed by the development of rolling stock that can run on both kinds of tracks: locomotive-hauled Talgo trains formed with lightweight, single-axle (independent wheels) coaches, and multiple units developed by Talgo and the Construcciones y Auxiliarios de Ferrocarriles (Construcciones and Auxiliary of Railways, or CAF).

Appropriate devices, called *cambiadores de ancho* (gauge changeovers)³ have been installed at certain junctions, to allow these dual-gauge trains to pass from the new network to the old one (these devices are required to unlock, reposition, and relock the wheels in the new position). This way, for instance, the trains running from Madrid to Bilbao can use the new line up to Valladolid and go along the classic line the rest of the journey.

Now Renfe owns some bivoltage (3 kilovolt [KV] direct current [DC]/25 KV alternating current [AC]) locomotives (of Class 252), along with multiple units of self-propelled passenger trainsets (without an independent locomotive), and some trivoltage locomotives (1.5 KV DC/3 KV DC/25 KV AC, also of Class 252—used for hauling cargo trains into France). Some dual-gauge hybrid multiple units (diesel electric/3 KV DC/25 KV AC) have been acquired in 2011 (Class 730).⁴

To contend with the four different families of signaling systems, some trains from Renfe's rolling stock incorporate a variety of signaling equipment aboard.

Antecedents of This Work

Antonio Hernando and Eugenio Roanes-Lozano had previously collaborated with the Spanish Railways Foundation on two research projects: automatically generating maps of a railway network at any date, given a list of historical events,⁵ and simulating traffic in a double-track railway line that supports cargo trains longer than most passing loops.⁶

Mathematical studies show how the results of new approaches to classic railway problems (such as network

expansion design⁷), could be used as additional information in the decision-making process.

Goals of This Work

In mid-2010, the Spanish Railways Foundation proposed that Hernando and Roanes-Lozano collaborate on the design and development of a computer package that, given a complex network such as Adif's and a flexible park of rolling stock such as Renfe's, could find—for any given origin and destination—the detailed timings for each piece of rolling stock (that could make that journey) and the best route for it. The problem is nontrivial, as we discuss later (for instance, the standard shortest-path algorithms can't be directly applied).

The package that we came up with, RutasOptiRed, is a simulation package focused on helping the railroad company optimize the use of its rolling stock from the point of view of travel times (which the company can then use to derive costs). Ultimately, RutasOptiRed's goal is to consider all of the variables involved and streamline the use of Renfe's rolling stock, by classifying it in segments of similar railway vehicles; this will keep the company strong and competitive in future markets.

Most of Renfe's passenger trains consist of multiple units that are from different train classes (or types) and that possess different characteristics. For instance, finding alternate train classes that can be substituted with similar timings is of great interest; you can check this easily (in seconds) using RutasOptiRed.

Moreover, RutasOptiRed can also be used as an aid in making decisions regarding investments in the infrastructure or vehicles. For instance, in some cases, it would be advisable to substitute an investment in the infrastructure with a smaller investment

in vehicles with better characteristics, such as hybrid dual-gauge high-speed trains. This could be the case for some lines with intermediate traffic in Spain that perhaps could be antennas of a common high-speed line that acted as a common trunk, instead of investing in completely new lines. Another use could be to compare the effects (based on time) of constructing a new line versus implementing deep-line renewals.

Organizing the Data

We decided to organize the input data in external files, which we obtained by saving the Microsoft Excel

stations and junctions. The file consists of as many rows as necessary (one for each section). The columns are fixed and include information about

- the name or number of the line where the section is;
- for endpoint 1 and for endpoint 2, the name, category, type of gauge changeover (if this applies), and inversions;
- the section's length, gauge, double track or single track, electrification type, and signal type; and
- slope, generic maximum speed of the section (kilometers per hour); approximate average speed (at this

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data files provided by the Spanish Railways Foundation in text format (we did this to avoid difficulties with different file formats). There were four such files: the infrastructure file, trains file, stations file (optional), and cities file (optional).

The Spanish Railways Foundation obtained this information from its databases and Adif's comprehensive annual reports.⁸ It's important to point out that the information stored in these four files is completely independent from the RutasOptiRed package, and thus the package can be applied to any railway network and any rolling stock (once the data are formatted appropriately).

Organizing the Infrastructure File

The infrastructure file includes a detailed description of the characteristics of all the sections of the network. The endpoints of the sections are important

section) of train types Normal, A, B, C, and D (measured in km/h).

Additional columns are available that include intermediate stations in the section, specified by their name and a number (which represents the distance in kilometers from endpoint 1).

The amount of data that the package can handle is impressive. For example, the file used (corresponding to Adif's network) includes more than 40,000 cells of data.

Characteristics Detailed in the Trains File

The trains file stores the data of the different types of trains. The columns are fixed and include

- the gauge (Iberian/standard/dual Talgo passengers/dual Talgo cargo/dual CAF);

OVERVIEW OF THE SPANISH RAILWAY NETWORK

There are a variety of reasons why the Spanish Railway Network is so complex. First, the Iberian track gauge has traditionally been 1,668 millimeters, while the new high-speed lines are being built in the “standard gauge” (1,435 mm) used in the rest of Europe, except for Portugal (Portugal has almost the same gauge as Spain, so going forward we’ll denote both as the Iberian gauge), Finland, and the countries that once belonged to the former Soviet Union.

The first high-speed line was a completely new line built in standard gauge, although it initially started as an improvement of the existing line—the Nuevo Acceso a Andalucía, or New Access to Andalusia (NAFA). The standard gauge was also chosen for all of the high-speed lines built afterward. The chronology is as follows:¹ Madrid–Seville (SW), 1992; Madrid–Zaragoza–Lerida (NE), 2003; Madrid–Valladolid (NW), 2007; completion of the NE line to Barcelona (NE), 2008; and Madrid–Valencia (E), 2010.

Clearly, a new independent high-speed network with a radial pattern has been built in Spain (Figure A). These high-speed lines are for passenger service only, unlike the high-speed lines now under construction that are designed for mixed traffic. Only two lines have three rails with mixed-gauge tracks: the short-branch line to access Huesca from the NE high-speed line and (provisionally) one of the tracks of part of the classic line from Barcelona to the French border (until the

NE high-speed line is completed to the French border).

Moreover, two different electrification systems are implemented in the Spanish railway network: 3 kilovolt direct current (KV DC) for conventional lines and 25 KV alternating current (AC) for high-speed lines. Also, 1.5 KV DC is used in neighboring France (with some passengers and goods crossing the border using this system).

Finally, four completely different families of signaling systems are used (and within each family, multiple versions exist):

- the Spanish ASFA (Anuncio de Señales y Frenado Automático, or Signals Announcement and Automatic Breaking) in the conventional lines,
- the German LZB (Linienzugbeeinflussung, or Linear Train Control) in the high-speed line to Seville,
- Bombardier’s EBICAB in the 200 km/h Iberian gauge Mediterranean Corridor, and
- the European ERTMS (European Rail Traffic Management System), levels 1 and 2, in the newly built high-speed lines.

To avoid causing passenger transfers, different pieces of dual-gauge, multisignaling, bivoltage, trivoltage, and even hybrid rolling stock have been developed.

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- the admissible traction types and signaling systems;
- the maximum speed (km/h), speed type (Normal/A/B/C/D), acceleration type (1/2/3/4); and
- the time required to cross a gauge changeover (in seconds) and for an inversion (in seconds).

Similar to the infrastructure file, the trains file consists of as many rows as necessary.

The Stations File

This is an optional file including information about stops longer or shorter than the standard ones. It contains as many rows as necessary and has two columns: a first column with the names of the stations and a second column with the

corresponding stopping times (in seconds).

Information Stored in the Cities File

This file has two purposes. Its first purpose is to define equivalences between names of cities. For instance, A CORUÑA can also be denoted LA CORUÑA or CORUÑA. The package is informed of this by including it in the file in the following manner:

```
CORUÑA          A CORUÑA
LA CORUÑA       A CORUÑA
```

Its second purpose is to establish a generic name for all the stations of a city, without choosing a particular station. A (long) row of this file

(describing the stations at Madrid) can be

```
MADRID*  MADRID
          CHAMARTIN
          MADRID ATOCHA
          CERCANIAS
          MADRID PUERTA DE
          ATOCHA
```

As you can see in this example, the generic names are followed by an asterisk.

Our Approach

Initially, we thought that the process wasn’t very complicated and could be addressed as follows:

1. Translate the network into a graph, with a list of characteristics associated to each of its edges.



Figure A. Spanish railway network, 2010 (courtesy of the Spanish Railway Foundation). The explanation and translation of the legend is as follows: Adif = Administrador de Infraestructuras Ferroviarias (Administrator of Railway Infrastructures); Feve = Ferrocarriles de Vía Estrecha (Narrow-Gauge Railways); FGV = Ferrocarrils de la Generalitat Valenciana (Valencian Government Railways); FGC = Ferrocarrils de la Generalitat de Catalunya (Catalonian Government Railways); SFM = Serveis Ferroviaris de Mallorca (Majorca Railways); ET = Eusko Trenbideak (Basque Railways); Línea de Alta Velocidad (High-Speed Line); Vía Doble (Double Track); Vía Electrificada (Electrified Track).
Fuente: Fundación de los Ferrocarriles Españoles

2. For each piece of rolling stock, prune the graph according to the characteristics of that particular piece.
3. For each piece of rolling stock, search for the shortest path for the given itinerary in the pruned graph (we mean “shortest” from the point of view of timings).
4. Find the best piece of rolling stock for that itinerary by comparing the best timing found for each piece of rolling stock.

The compatibility of the gauge, traction system, and signaling system of the infrastructure and the trains can be assured thanks to the use of pruned graphs.

The Algorithm Used (with a Surprise)

Dijkstra’s algorithm is frequently used and even adapted to applications in transportation engineering.⁹ However, in this case, because direction and gauge changes can take place at nodes, there are sometimes delays at nodes, so Dijkstra’s algorithm can’t be directly used. Instead, we developed an algorithm inspired by Dijkstra’s that took into account these delays.

Surprisingly, all of the routes were correctly computed for all types of trains, except when calculating for dual-gauge trains. That’s because some routes, including sections with three rails (that are double-gauge sections) don’t have gauge changeovers at both endpoints. When we explored what was going on, we found that the

unexpected reason for the incorrect calculations was that the shortest path from A to B through C isn’t necessarily the concatenation of the shortest paths from A to C and from C to B!

Let’s consider, for example, the small network of Figure 1: There are two different lines (one in each gauge) between O and A, and between A and C, with gauge changeovers at O and A. There are three rail (double-gauge) lines between C and D (D is located between C and B), for fast trains to reach D from O. The line between D and B is an Iberian gauge. The best solution for a dual-gauge train is to go from A to B all the time on the Iberian gauge.

If the problem is split, however, the best solution from A to C is to use the standard gauge high-speed line.



Figure 1. Counterexample of the concatenation of shortest paths. The squares represent the gauge changeovers, the solid line represents the Iberian gauge line, the dashed line represents the standard gauge line and the double line (solid and dashed) represents the mixed gauge section.

Once the train is in C, though, it can only go on to D, not to B, because there's no gauge changeover at D. If the train is on a standard gauge track at C, it must return to the gauge changeover at A to be able to reach B, so the solution found is far from optimal! This actually happens if Dijkstra's or Floyd's algorithms are directly applied to the Madrid–Canfranc route.

Our solution was to reform the algorithm so that the gauge the train is using is taken into account before concatenating partial routes.

Calculations Performed by the Algorithm

Let's remember that the comparison between routes is based on the timings obtained by each train type, not on the length of the routes. Therefore, detailed computations must be calculated for each piece of rolling stock.

Let Γ be a certain train type. Let $S_{j,i}, j = 1, \dots, k, i = 1, \dots, m_j$ be the stations of a certain route with $k - 1$ intermediate stops, where

- $S_{1,1}$ is the origin of the route,
- $S_{j,m_j} = S_{j+1,1}, j = 1, \dots, k - 1$ are the intermediate stations where the train is planned to stop,
- $S_{j,2}, \dots, S_{j,m_j-1}, j = 1, \dots, k$ are the stations (where the train doesn't stop) between stations $S_{j,1}$ and S_{j,m_j} , and
- S_{k,m_k} is the final destination.

Let $v(S_{j,i}, S_{j,i+1}, \Gamma)$ be the average speed of trains of type Γ in the section between stations $S_{j,i}$ and $S_{j,i+1}$.

Let's denote by $tad(v, w, \Gamma)$ the time required by a type Γ train to accelerate (or decelerate) from speed v to speed w (more precisely, the delay with regards to the time required if cruising at the target speed).

For instance, the time required by a train of type Γ to complete the route from $S_{1,1}$ to S_{k,m_k} is

$$\sum_{j=1}^k \left(tad(0, v(S_{j,1}, S_{j,2}, \Gamma), \Gamma) + \sum_{i=1}^{m_j-2} \left(\frac{length(S_{j,i}, S_{j,i+1})}{v(S_{j,i}, S_{j,i+1}, \Gamma)} + tad(v(S_{j,i}, S_{j,i+1}), v(S_{j,i+1}, S_{j,i+2}, \Gamma), \Gamma) \right) + \frac{length(S_{j,m_j-1}, S_{j,m_j})}{v(S_{j,m_j-1}, S_{j,m_j}, \Gamma)} + tad(v(S_{j,m_j-1}, S_{j,m_j}, \Gamma), 0, \Gamma) + \delta(S_{j,m_j-1}, S_{j,m_j}, S_{j+1,2}) \cdot tg(\Gamma) + \delta'(S_{j,m_j-1}, S_{j,m_j}, S_{j+1,2}) \cdot tc(\Gamma) \right),$$

where

- $\delta(S_a, S_b, S_d)$ is 1 (respectively, 0) if there is (or respectively isn't) a gauge changeover required to pass from section $S_a S_b$ to section $S_b S_d$,
- $tg(\Gamma)$ is the time required by a Γ type train to change its gauge,
- $\delta'(S_a, S_b, S_d)$ is 1 (respectively, 0) if there is (or respectively isn't) a direction change to pass from section $S_a S_b$ to section $S_b S_d$, and
- $tc(\Gamma)$ is the time required by a Γ type train to perform a direction change.

Let us underline that both δ and δ' are considered equal to zero if their third input is $S_{k+1,2}$.

Implementation and Results

We implemented RutasOptiRed in Visual Basic. It was designed to execute under Windows XP or Windows 7,

where we extensively tested it.

If it's run under Windows XP, NetFramework (a free complementary software) must be installed before running the package.

We extensively tested RutasOptiRed with real data from Renfe's 2011 rolling stock (which contains 22 types of trains) and Adif's 2011 network (which has 751 sections). The package returns results for one train in tenths of a second and yields the best train for a route in 2 or 3 seconds on a standard personal computer.

Introducing data to the GUI is simple. The upper left section of the GUI (see Figure 2) is where you can select a certain train or search for the best train. Immediately after selecting a train type, its data appears in the gray window at the bottom. The same happens for the departure and arrival stations: after selecting the station, its data appears in the gray window at the bottom. Just below the train type, the departing station journey must be selected. In the lower left, the arriving station can be chosen.

You can also choose intermediate stations (with or without stops). You can select an intermediate station the same as you would the departure and arrival station (the corresponding window is the third dropdown menu in Figure 3). Including a station without a stop can be an interesting way to force a route when there are several possibilities. As soon as you introduce the data, computations begin, and the best route found is shown in the right window. Also, there's always the possibility that the selected train can't make it (for instance, an electric multiple-unit train can't reach a station if no line departing from that station is electrified).

The arrival times appear in the left column and the departure times

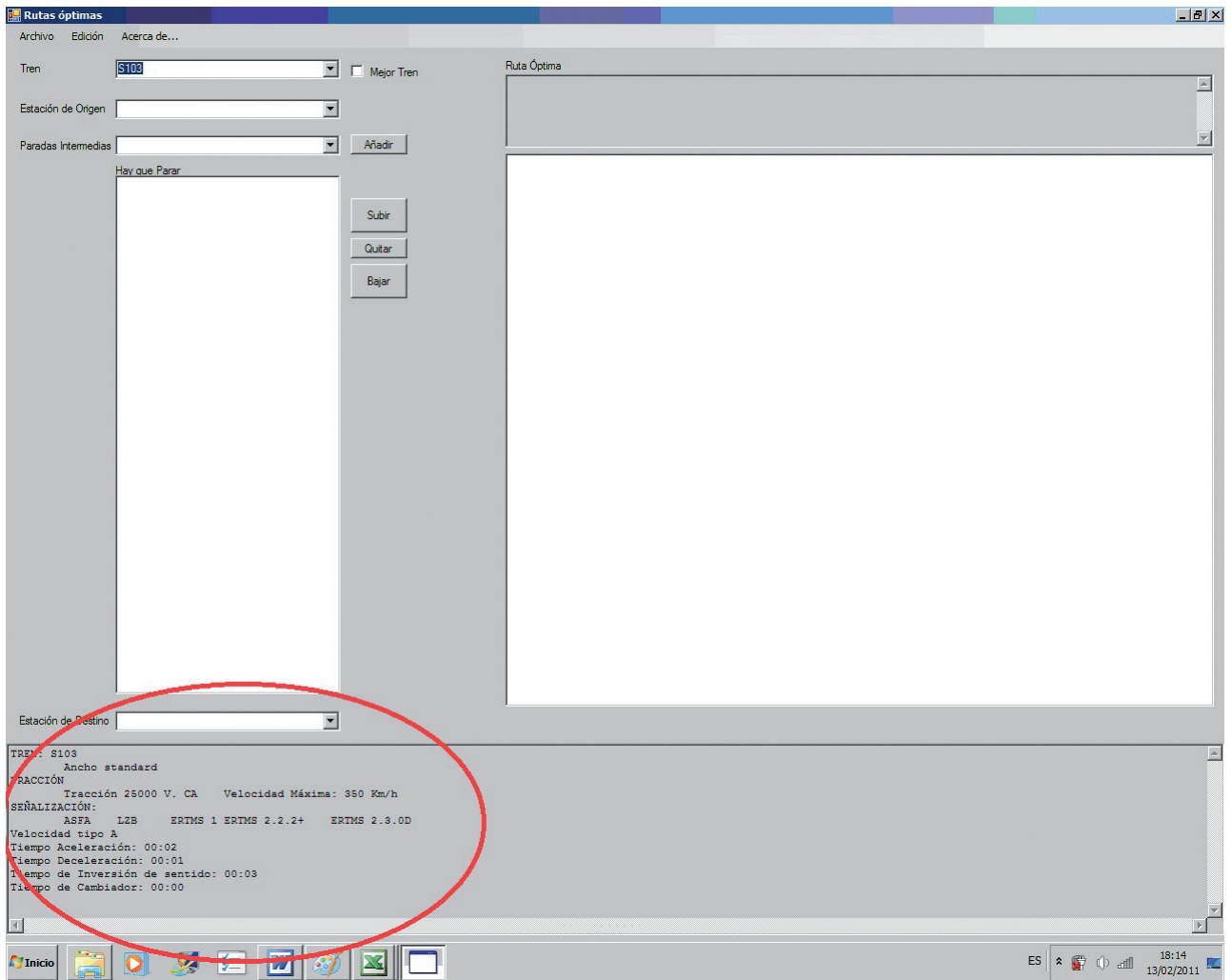


Figure 2. Interface of the RutasOptiRed package. As a first step, a Class 103 high-speed train has been selected from the upper-left dropdown menu “Tren” (train). In the lower window (circled in red), the characteristics of a Class 103 high-speed train are detailed by the package: gauge, voltage, top speed, signaling systems, speed type, deceleration time, acceleration time, time required for an inversion, and time required to cross a gauge changeover (if this applies). If a tick mark is written in the little square beside the upper-left dropdown menu (labeled “Mejor tren”), the package will look for the best train for the chosen route. The buttons on the center of the screen (Añadir, Subir, Quitar, and Bajar) let the user add, move up, eliminate, or move down a stop, respectively.

appear in the right column (see Figure 3). All intermediate stations are detailed. Stops are marked by an arrow (to the left of the station’s name), inversions by an “i,” and gauge changes by a “c.” Figure 3 shows the best route for a Class 334 hauling a Talgo from Madrid to Badajoz and passing through Plasencia and Mérida (where inversions are required).

Once an optimal route has been calculated, it can be saved as a scenario. This way, the next time you look at it, you don’t have to retype anything.

Moreover, it’s possible to compare different scenarios on the screen at the same time (opening one after another from the GUI, and moving the windows if necessary). In Figure 4, three different options from Madrid to Irún are compared. On the left, the schedule of a Talgo train hauled by a Class 334 going through the direct line (passing through Aranda de Duero) is detailed. In the center, the schedule of the same train following the classic line of Madrid—Paris (passing through Ávila and Valladolid)

can be found (this journey takes longer than the previous one). Finally, on the right, the best train and route are found: the optimal solution is to use a dual-gauge Class 130 train following the Madrid–Valladolid (NW) high-speed line, changing gauge and voltage and following the classic line afterward.

The times for coming to a complete stop and accelerating from a complete stop are detailed for each train. However, there are some simplifications in the data provided: the trains

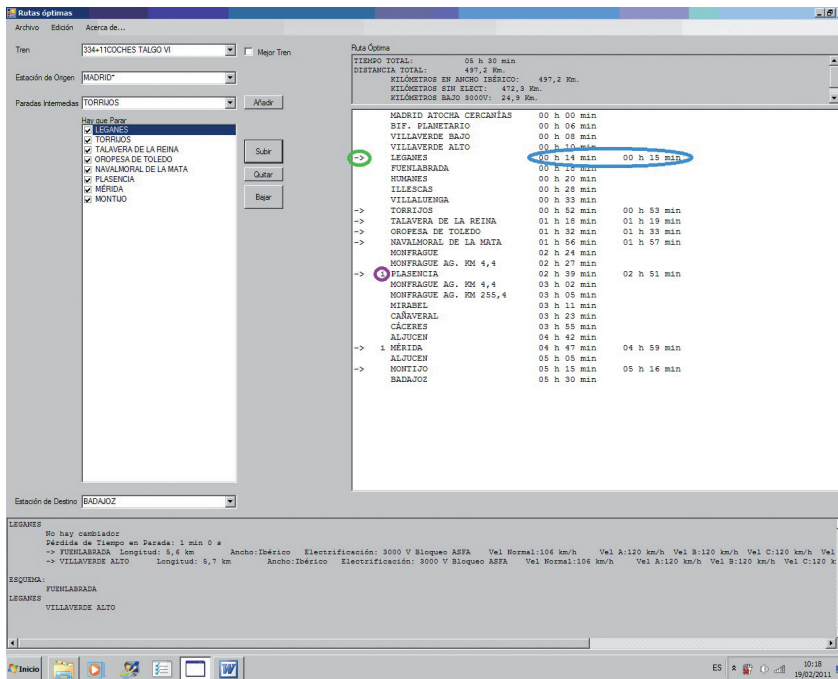


Figure 3. Example of a route computed by the package. The user selected a train consisting of a Class 334 locomotive hauling 11 Talgo VI coaches (in the upper dropdown menu), from any station in Madrid, denoted as MADRID* for the departing route (in the second dropdown menu) and Badajoz as the arrival (in the lowest dropdown menu). The third dropdown menu has been used to fix the intermediate stations where the train must stop (for example, Leganés, Torrijos, or Montijo). In the upper-right window, the results of the best route found are detailed on a gray background: estimated total time, total distance run, distance run on the Iberian gauge, distance run on non-electrified lines, and distance run on electrified lines. Below, on a white background, the timing is detailed. Stations where the train stops are marked with an arrow (an example is circled in green), and then arrival and departure times are specified (circled in blue). In case an inversion is required, there's an "i" to the left of the station name (circled in purple). If a gauge changeover is required, the system similarly indicates this with a "c" (not shown), and the corresponding time is taken into account.

have been grouped into four groups, according to their acceleration and deceleration capabilities, and these quantities are given for each of these groups (they're used when calculating the values of the *tad* function). That's why there are frequent draws among train types (in other words, why exactly the same time is returned for different train types). In such cases, the system will show one of the best ones (note that the user can ask the total times for all trains to be shown, and check for draws). This is why, when the infrastructure's maximum speed equalizes the top speed of two trains, the one with the highest centrifugal

acceleration allowed obtains the best timing. This can happen, for instance, between a diesel active-tilting body multiple-unit 598 (160D) and a passive tilting-body Talgo train (200B), or among all types of high-speed trains in a 300 km/h line, where Class 112 (330B) obtains the best timing.

There are many studies¹⁰ and computer applications (see www.quintiq.com/industries/rail.aspx) devoted to train scheduling, routing,¹¹ and rolling-stock planning.¹² There are even huge projects devoted to these topics, such as the European project called Arrival (<http://arrival.cti.gr>).

The goal in all of these cases is to provide the transport operators with theoretical or computer tools that make it possible to optimize the use of existing resources.

The RutasOptiRed application presented here focuses on a single step, but in a flexible and complex scenario: It provides a highly accurate estimation of the timetables of each type of train in a dual-gauge, multivoltage, and multisignaling system railway network. As far as we know, there's no comparable piece of software.

We believe that RutasOptiRed is a specific-purpose package that can be really useful in a complex scenario such as the Spanish railways. The lack of gauge, signaling, and electrification standardization makes the application far more complex than a railway "GPS-style" route calculator. The package is ready to be applied to any railway network, although its advantages arise when the network is complex (with different gauges, signaling systems, and so on). We plan to apply it to define a segmentation of Renfe's rolling stock and to suggest alternatives in some future railway lines now under consideration.

Acknowledgments

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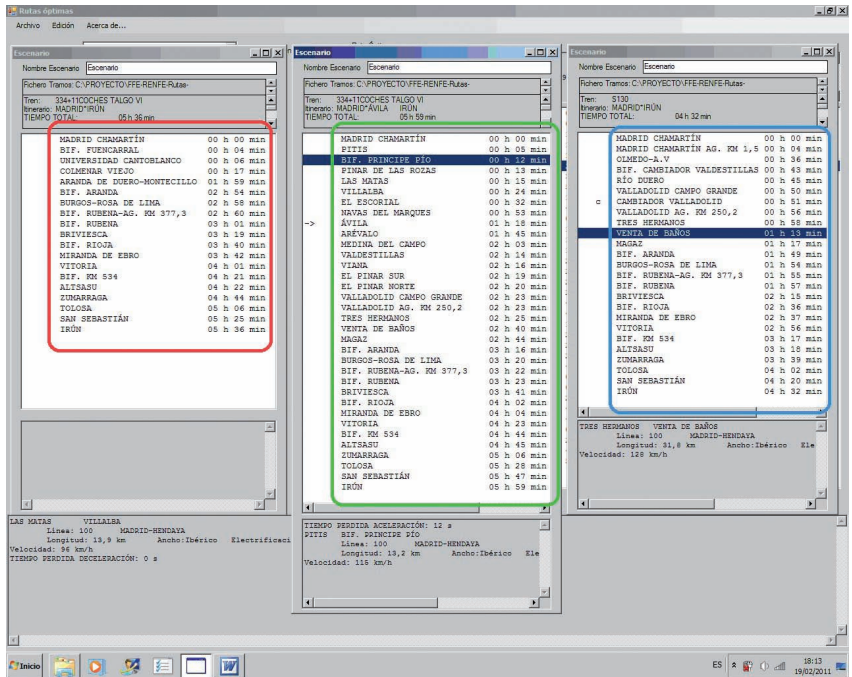


Figure 4. Comparing three scenarios for the Madrid to Irún route on the same screen. The one on the right is a dual-gauge Class 130 train, partially using the Madrid–Valladolid (NW) high-speed line.

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