Mathematical Models for Optimization of Conventional and High Speed Railway lines

Modelos Matemáticos para la Optimización de Líneas Ferroviarias Convencionales y de Alta Velocidad

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To Hernán, my parents, my brother and specially to Nicolás and Javiera, my beloved children, with all my heart for you.
My goal is not to be better than anyone else,
but to be better than I used to be.
Dr. Wayne W. Dyer
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Contents

Dedication i
Acknowledgments v
Abstract 5
Resumen 9
Objectives of this thesis 13
Original contributions of this thesis 17
List of Figures 19
List of Tables 23

I INTRODUCTION AND MOTIVATION 25

1 HIGH SPEED RAILWAYS 27
1.1 Introduction to High Speed Railways . . . . . . . . . . . . . . . . . . . . . 28
1.2 High Speed Railway Network Development . . . . . . . . . . . . . . . . . . 29
  1.2.1 Japan . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 29
  1.2.2 France . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
  1.2.3 Spain . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 32
  1.2.4 Germany . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
  1.2.5 Italy . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
  1.2.6 China . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36
1.3 The Impact of HSR . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37
  1.3.1 Transport . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37
  1.3.2 Socio-Economics . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40
  1.3.3 Environmental Impacts . . . . . . . . . . . . . . . . . . . . . . . . . . 40
1.4 Conclusions .................................................. 40

II TIMETABLE OPTIMIZATION .................................. 43
2 STATE OF THE ART IN TIMETABLE OPTIMIZATION ...... 45
  2.1 Introduction ............................................. 46
  2.2 The Sahin method ........................................ 46
  2.3 The Ghoseiri at al. model ............................. 47
  2.4 The Zhou and Zhong method ........................ 48
  2.5 The Castillo et al. single-track method ............. 49
  2.6 The Castillo et al. double-single-track method .. 50
  2.7 The Cacchiani and Toth discussion on timetabling problems ............................................ 51
  2.8 The Törnquist and Persson model for perturbations ............................................. 52
  2.9 The Acuna-Agost et al. model for dealing with perturbations ...................................... 53
  2.10 The works of Cacchiani et al. ....................... 54
  2.11 The Burdett and Kozan model ...................... 55
  2.12 The Xie and Li model .................................. 55
  2.13 The D’Ariano-Pranzo Dispatching System ........ 56
  2.14 The Carey-Crawford model for busy complex stations .............................................. 57

3 TIMETABLE OPTIMIZATION MODEL ......................... 59
  3.1 The optimization problem .............................. 60
    3.1.1 Data .............................................. 60
    3.1.2 Variables ........................................ 60
    3.1.3 Constraints ....................................... 61
    3.1.4 Objective function ............................... 64

III ALTERNATE DOUBLE-SINGLE TRACK ...................... 65
4 ALTERNATE DOUBLE SINGLE TRACK ......................... 67
  4.1 Introduction and motivation .......................... 68
  4.2 The optimization problem ............................ 71
  4.3 Proposed method to solve the problem .............. 74
    4.3.1 Proposed method based on partitioning the horizon period in small subperiods .......... 75
  4.4 Examples of applications .............................. 76
    4.4.1 The Palencia-Santander line ................... 76
    4.4.2 Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line ............................................. 84
  4.5 A detailed sensitivity analysis ...................... 87
  4.6 Conclusions ............................................ 89
## IV PROPOSALS OF ADST LINES IN CHILE AND IRELAND

5 PROPOSALS OF ADST LINES IN CHILE

5.1 Introduction ................................................. 95
5.2 Line description .............................................. 96
  5.2.1 Trace of the line .................................... 96
  5.2.2 Profile of the line .................................. 96
  5.2.3 Segmentation ....................................... 98
5.3 Hypotheses used in the calculations .............................. 98
5.4 Results of the optimization program ............................ 99
  5.4.1 Resulting circulation graphs ......................... 99
5.5 Conclusions ............................................... 100

6 PROPOSALS OF ADST LINES IN IRELAND

6.1 Introduction ................................................ 103
6.2 Description of the current line between Dublin and Belfast 104
6.3 Proposal of a High Speed Line .............................. 106
  6.3.1 Trace definition and assumptions ................... 106
  6.3.2 Double-track solution .............................. 107
  6.3.3 ADST solutions .................................... 109
  6.3.4 Selected Solution .................................. 113
6.4 Proposal based on the existing network improvement .......... 116
  6.4.1 Current framework .................................. 116
  6.4.2 Studied Cases .................................... 119
  6.4.3 Construction cost .................................. 120
  6.4.4 ADST Analysis .................................... 120
  6.4.5 Final Solution .................................... 121
  6.4.6 Conclusions .................................... 123
6.5 Other line proposals ........................................ 123
6.6 Conclusions ............................................... 126

V RE-SCHEDULING DUE TO DISTURBANCES

7 Re-scheduling due to disturbances .............................. 129
  7.1 Introduction ............................................. 130
  7.2 Dealing with disturbances ............................... 131
  7.3 Examples of application ............................... 133
7.3.1 The Palencia-Santander line ............................................. 133
7.3.2 The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line .......... 135
7.3.3 The Santiago-Valparaíso-Viña del Mar line .............................. 136

VI CONCLUSIONS AND PUBLICATIONS ......................................... 143

8 Conclusions (in English) ......................................................... 145
8.1 Conclusions on the ADST lines .............................................. 146
8.2 Conclusions on the time-partitioning technique .......................... 146
8.3 Conclusions on the re-scheduling technique ............................... 147
8.4 Future work ................................................................. 148

9 Conclusions (in Spanish) ......................................................... 151
9.1 Conclusiones sobre las líneas ADST ........................................ 152
9.2 Conclusiones sobre la técnica de particionamiento temporal ............... 152
9.3 Conclusiones sobre la técnica de reprogramación .......................... 154
9.4 Trabajo futuro ................................................................. 154

10 Publications ................................................................. 157

A Computer application ....................................................... 159
A.1 Introduction ................................................................. 160
A.2 The ADST line .............................................................. 160
A.2.1 The home screen ........................................................ 160
A.2.2 The main menus .......................................................... 166
A.2.3 The information window ................................................ 169
A.2.4 The general data window ............................................... 171
A.2.5 The nodes window ....................................................... 177
A.2.6 The segments window ................................................... 181
A.2.7 The routes window ....................................................... 184
A.2.8 The headway times window ............................................ 186
A.2.9 The speeds window ...................................................... 189
A.2.10 The trains window ...................................................... 191
A.2.11 The services window .................................................... 193
A.2.12 Generated results ....................................................... 197
A.2.13 The final result window ............................................... 200
A.2.14 Supplied results ......................................................... 200
A.2.15 Generated files .......................................................... 203
A.3 Conclusion ................................................................. 203
A.4 Shortcut summary ......................................................... 204
This thesis consists of two parts. The first one is devoted to the alternate double-single track (ADST) lines, which consist of using single tracks where the construction costs are large or very large, that is, in tunnels and viaducts, and double tracks where these costs are small (flat and open terrain) and only where they are necessary. For this to be possible, the departure times of the trains need to be modified a few minutes back or forth in order to permit the crossings of the running trains at the double track segments with the required safety margins and with no reduction or producing a very small reduction in the travel times.

ADST lines require to decide which segments must go in single-track and which ones need to go in double-track so that the required demand is satisfied and the safety constraints are satisfied. This implies the existence of the computer program that optimizes the line design. In practice, if the optimization is well done, ADST lines are not much more expensive that single-track lines.

In addition, the timetables need to be optimized in order to use the railway infrastructure in an efficient way. In fact, the resulting travel times are very similar to those of double-track solutions, so that, ADST lines are much closer in performance to double-track than to single-track lines.

A mixed integer linear programming problem is developed to decide which segments must go in single and which ones must go in double-track and to optimize timetables so that travel times are minimized subject to operation and safety constraints. Since the required CPU times are very long, a bisection technique, based on upper bounds of the maximum relative travel time constraints, is used, so that we play mainly on the unfeasible side, which is less time consuming than the feasible side. To reduce the number of train priority binary variables, a method is proposed that tries to guess their values in advance, but later, this assumptions are checked and if violated, they are corrected. This implies a very important reduction of CPU times.

To illustrate the proposed methodology, we present several real applications of this
solution to the Santiago-Valparaíso-Viña del Mar and the Dublin-Belfast lines to demonstrate that important construction and maintenance savings (up to 40%) can be achieved if the standard double-track solutions are replaced by the ADST alternative. In fact, ADST lines are closer to single-track lines than to double-track lines from the point of view of construction cost. In addition, if existing conventional lines are complemented with high speed tracks, the savings can be even more important and can reach up to 90%.

In the second part, the timetable optimization problem is addressed with the aim of reducing the computation time required and a partitioning technique is presented that allow us to reduce the computation times substantially. In fact this reduction can be of several orders of magnitude. The prize paid for this result is that the resulting timetable is not the optimal but, fortunately, it is very close to the optimal one and provides practical solutions, that is, efficient timetables and always safe.

This is important when dealing with delays or railway disturbances that force the operators to re-schedule trains under the new constraints imposed by the disturbances. In these situations the re-scheduling must be done in seconds or at most a very few minutes. Thus, computer programs requiring large computation times are not valid to solve this real operational problem.

In addition to the two above lines, the Palencia-Santander line is used to analyze the changes produced by the disturbances and several examples are given to illustrate how the proposed technique permits us to solve the re-scheduling problem in short times.

For the development of this phase of the research the related literature is investigated, analyzed and discussed.

Among the means and resources used, we mention the use of appropriate computers to run various software necessary for the development of the different studies and the different programming models used to solve problems. Among them, it is important to mention the use of different types of software such as Matlab, GAMS and MATHEMATICA.

With respect to the mathematical tools used to solve the problems, we want to mention the optimization methods that have been used for optimizing timetables and the decision about which segments must be in double-track and which should go in single-track.

Because of its importance and the social impact it has had, the research in the region of Valparaíso and Viña del Mar, should be further developed. Keep in mind that the PhD student has developed an important effort for proposing this alternative to the Chilean authorities.
In the appendix, the manual of the program that optimizes the ADST lines, which is very useful and interesting, is included.
RESUMEN

Esta tesis consta de dos partes. La primera de ellas está dedicada a la vía alternada doble-simple (ADST), que consiste en utilizar la vía única, donde los costos de construcción son elevados, es decir, en túneles y viaductos, y vía doble, donde estos costes son reducidos (en terrenos llanos y a cielo abierto) y sólo cuando sea necesario. Para que esto sea posible, los horarios de salida de los trenes deben ser modificados unos minutos con el fin de permitir que los trenes se crucen en los segmentos de vía doble y con los márgenes de seguridad requeridos y ninguna reducción o una pequeña reducción en los tiempos de viaje.

Las líneas ADST requieren decidir qué segmentos deben ir en vía única y cuáles necesitan ir en vía doble para que se pueda atender a la demanda requerida y se satisfagan todas las condiciones de seguridad. Esto implica la existencia de un programa informático que permita optimizar el diseño de la línea. En la práctica, si la optimización está bien hecha, las líneas ADST no resultan mucho más caras que las líneas en vía única.

Además, los horarios necesitan ser optimizados con el fin de utilizar la infraestructura ferroviaria de una manera eficiente. De hecho, los tiempos de viaje resultantes son muy similares a los de las soluciones en vía doble, de modo que, las líneas ADST están mucho más cerca en rendimiento a la vía doble que a la vía única.

Se desarrolla un problema de programación entera mixta para decidir qué segmentos deben ir en vía única y cuáles deben ir en vía doble y también para optimizar los horarios de manera que los tiempos de viaje sean mínimos sujetos a ciertas condiciones de operación y seguridad. Puesto que los tiempos de CPU requeridos son muy grandes, se propone una técnica de biseción, basada en limitar superiormente los tiempos de viaje relativos máximos, aproximándose del lado de la infactibilidad, ya que consume menos tiempo que el lado factible. Para reducir el número de variables binarias que definen las prioridades de los trenes se propone un método que trata de adivinar sus valores por adelantado, pero más tarde, se comprueba esta hipótesis y si es violada, se corregen éstas. Esto implica una reducción muy importante de los tiempos de CPU.
Para ilustrar la metodología propuesta, se presentan varias aplicaciones reales de esta solución a la líneas Santiago-Valparaíso-Viña del Mar y Dublín-Belfast y se demuestra que se obtiene un importante ahorro en su construcción y mantenimiento (hasta 40%) si se reemplazan las líneas en vía doble estándar por esta alternativa ADST. De hecho, las líneas ADST están más cerca de las líneas en vía única que de las líneas de vía doble desde el punto de vista de los costes de construcción y mantenimiento. Además, si las líneas convencionales existentes se complementan con algunos segmentos con vías de alta velocidad, el ahorro puede ser aún más importante (hasta 90%).

En la segunda parte, se aborda el problema de optimización de horarios con el objetivo de reducir el tiempo de cálculo requerido y se presenta una técnica basada en particionar los tiempos de estudio que nos permite reducir sustancialmente los tiempos de cálculo. De hecho, esta reducción puede ser de varios órdenes de magnitud. El premio pagado por este resultado es que el horario resultante no es el óptimo, pero, afortunadamente, es muy cercano a él y proporciona soluciones prácticas, es decir, horarios eficientes y siempre seguros.

Esto es importante cuando se producen retrasos o incidentes inesperados que obligan a los operadores a re-programar los trenes bajo las nuevas restricciones impuestas por los incidentes producidos. En estas situaciones, la re-programación debe realizarse en segundos o en el peor caso en sólo unos pocos minutos. Por lo tanto, los programas de ordenador que requieren grandes tiempos de cálculo no son válidos para resolver este problema real y de operación.

Además de las dos líneas anteriores, se utiliza la línea Palencia-Santander para analizar los cambios producidos por los incidentes y se dan varios ejemplos para ilustrar cómo la técnica propuesta nos permite resolver el problema de re-programación en unos tiempos muy cortos.

Para el desarrollo de esta fase de investigación destaca la búsqueda de bibliografía relacionada.

Entre los medios y recursos utilizados, hay que mencionar el uso de ordenadores adecuados para correr los diversos programas informáticos necesarios para el desarrollo de los distintos estudios, así como la programación de distintos modelos y software, con objeto de materializar las herramientas necesarias para resolver los problemas planteados. Entre ellos, cabe descartar la utilización de diferentes tipos de software tales como Matlab, GAMS y MATHEMATICA.

Con respecto a los instrumentos matemáticos utilizados cabe destacar los métodos de optimización, que se han utilizado para la confección de los horarios y la decisión sobre qué segmentos deben ir en vía doble y cuáles deben ir en vía única.
Por su importancia y la repercusión social que ha tenido, esta investigación en la región de Valparaíso y Viña del Mar, debe seguir desarrollándose. Hay que tener en cuenta que la doctoranda ha desarrollado un esfuerzo muy importante para proponer esta alternativa a las autoridades de Chile.

En un apéndice se incluye el manual de uso del programa que permite optimizar las líneas ADST, lo cual resulta muy útil e interesante.
OBJECTIVES OF THIS THESIS

The main objectives of this thesis are the following.

1. PART II. TIMETABLE OPTIMIZATION.

   Efficient design and use of railway networks require the optimization of the infrastructure and the timetables. Otherwise, the construction, maintenance and exploitation costs can increase substantially for a given service level. In this part of the thesis we analyze the important problem of infrastructure design and timetable optimization of railway lines that leads to a relevant increase of the practical capacity and to a cost reduction of the line being studied.

   (a) State of the art in timetable optimization.

      i. Perform a literature review. To perform a literature review of timetable optimization in order to identify the main contributions and the main pending problems to identify lines of present and future research.

      ii. Identify the most adequate approaches for timetable optimization. Since many different approaches has been used in timetable optimization, we aim at identifying the most convenient ones and those who must not be used.

   (b) Identification of existing problems deserving a research analysis.

      i. Discover the real problems caused by an excess of memory and cpu requirements. Some existing models have serious problems when the size of the problem is of medium or large size. Our aim is to find possible ways of reducing the complexity of the problem even with a loss of optimal properties but without any violation of the safety requirements.

2. PART III. ALTERNATE DOUBLE-SINGLE TRACK.

   Double-track solutions have been questioned for peripheral lines, that is, for lines where only one of the two ends are populated cities. This has led to the alternate double-single (ADST) lines, in which double-track segments alternate with single-track segments in order to obtain important reductions in the construction and maintenance costs of such a lines. In addition, the possibility of combining existing
OBJECTIVES OF THIS THESIS

conventional lines with high speed segments provides another interesting alternative that produces even more cost reductions. In this part of the thesis these possibilities are investigated.

(a) Identification of existing problems deserving a research analysis.
   i. Perform a literature review of ADST lines. The state of the art of existing alternatives to double-track lines are analyzed.
   ii. Identify the new problems that arise when other alternatives different from the double-track or the ADST solutions are used. In particular, we want to analyze how conventional lines can be combined with new high speed lines that bypass existing small size stations in order to reduce travel times.

(b) Required changes in the existing optimization problems.
   i. Analyze the required changes in the optimization programs due to the new requirements. When in addition to the use of conventional lines passing for all stations, some stations can be bypassed because of the construction of new segments, the trains have the possibility to choose between the two routes. This requires some changes in the mathematical statement of the timetable optimization problem that need to be analyzed and solved.

3. PART IV. PROPOSALS OF ADST LINES IN CHILE AND IRELAND.

In this part some international proposals are investigated. In particular, we want to analyze in detail proposals for the Santiago-Valparaíso-Viña del Mar and the Dublin-Ireland lines.

(a) Real applications of ADST lines.
   i. Look for international applications of the ADST. ADST lines have been proposed for high speed lines in Spain. In this thesis we analyze the possibilities of using this type of lines in two countries: Chile and Ireland.

(b) Proposals of ADST lines for Chile and Ireland.
   i. Proposal for the ADST Santiago-Valparaíso-Viña del Mar line. We want to propose the construction of the Santiago-Valparaíso-Viña del Mar line starting from the Arturo Merino Airport in Santiago to El Salto in Viña del Mar.
   ii. Proposal for the ADST Dublin-Belfast. We want to propose several alternatives of ADST lines to connect Dublin with Belfast.

4. PART V. TIMETABLE RE-SCHEDULING DUE TO DISTURBANCES.
In the operation of railway lines it is common that the initial time schedule of trains be subjected to delays that cause problems in the train operation. If in addition other type of disturbances, such as train or infrastructure failures occur, then timetables need to be re-scheduled. In this part we will deal with this problem.

(a) **State of the art in train re-scheduling after occurrence of disturbances.** The most important methods used for timetable re-scheduling when disturbances occur must be revised.

i. **Perform a literature review.** To perform a literature review of timetable optimization and train re-scheduling caused by disturbances in order to identify the main contributions and the main problems to identify lines of present and future research.

ii. **Identification of new ways to solve the complexity of the problem.** Since existing methods are not satisfactory, especially when we deal with the re-scheduling problem, we need to identify efficient alternatives to solve the problem.

(b) **Use of partitioning techniques.** Some researchers have recommended partitioning the time or the space dimensions in several parts. We want to investigate these possibilities and answer the questions: Is this reasonable? Is it convenient? How this can be done efficiently?

i. **Proposed partitioning technique.** A new partitioning technique based on time partitioning has to be developed.

ii. **Examples of applications.** Several examples of applications must be given to illustrate the proposed methods.
OBJECTIVES OF THIS THESIS
The main contributions of this thesis are:

1. PART II. TIMETABLE OPTIMIZATION.
   (a) **State of the art in timetable optimization.**
       i. **Literature review.** A literature review of the state of the art in timetable optimization has been done.
   (b) **Identification of existing problems deserving a research analysis.**
       i. **Insufficiency of existing methods for timetable optimization.** It is shown that: (a) existing methods collapse when the railway network has a large size, (b) the causes of this problem are identified: excess of binary variables and a time window too long, and (c) forcing the identification of the optimal solution when a sub-optimal solution, which satisfies the safety requirements is sufficient for practical purposes, has no sense.

2. PART III. ALTERNATE DOUBLE-SINGLE TRACK.
   (a) **Identification of existing problems deserving a research analysis.**
       i. **Literature review of ADST lines.** An state of the art of existing alternatives to double-track has been presented.
       ii. **Identification of new problems that arise when alternatives to double-track or the ADST solutions are used.** We have proposed to combine existing conventional lines with new segments of high speed single-tracks.
   (b) **Required changes in the existing optimization problems.**
       i. **Modified optimization problems.** We have proposed new optimization problems that allow trains to choose between two routes, one passing by small stations and another bypassing these stations. This raises some changes in the mathematical statement of the timetable optimization problem that have been analyzed and solved.

3. PART IV. PROPOSALS OF ADST LINES IN CHILE AND IRELAND.
(a) Real applications of ADST lines.
   i. **International applications of the ADST lines.** Some international locations where the ADST lines can be used have been identified. This includes: Spain, Portugal, France, United Kingdom, Morocco and Turkey (see Castillo et al. (2015)). In this thesis some new applications are investigated.

(b) Proposals of ADST lines for Chile and Ireland.
   i. **Proposal for the ADST Santiago-Valparaíso-Viña del Mar line.** We have analyzed and proposed the construction of a Santiago-Valparaíso-Viña del Mar line starting from the Arturo Merino Airport in Santiago to El Salto in Viña del Mar.
   ii. **Proposal for the ADST Dublin-Belfast.** We have analyzed and proposed several alternatives of ADST lines to connect Dublin with Belfast.

4. PART V. TIMETABLE RE-SCHEDULING DUE TO DISRUPTIONS.

(a) **State of the art in train re-scheduling after occurrence of disturbances.** The most important methods used for timetable re-scheduling when disturbances occur have been revised.
   i. **Perform a literature review.** A literature review of timetable optimization and train re-scheduling caused by disturbances have been done.
   ii. **Identification of new ways to solve the complexity of the problem.** New ways to reduce the complexity of the timetable optimization have been investigated.

(b) **Use of partitioning techniques.**
   i. **Proposed partitioning technique.** A new partitioning technique has been proposed for reducing the complexity of the timetable optimization.
   ii. **Examples of applications.** Several examples of applications have been given to illustrate the proposed methods.
List of Figures

1.1 Japan: High speed corridor (orange) compared with the conventional line (blue). .................................................. 31
1.2 France: High speed corridor (orange) compared with the conventional line (blue). ................................................. 32
1.3 Spain: High speed corridor (orange) compared with the conventional line (blue). ................................................. 33
1.4 Germany: High speed corridor (orange) compared with the conventional line (blue). ........................................... 34
1.5 Italy: High speed corridor (orange) compared with the conventional line (blue). .................................................. 35
1.6 China: High speed corridor (orange) compared with the conventional line (blue). .................................................. 36

4.1 Illustration of the proposal for the Palencia-Santander line. ......... 73
4.2 Illustration of the speed profile and of how the mean speeds were calculated considering the acceleration and deceleration of trains. .......... 80
4.3 Palencia-Santander line with existing traffic demand plus 8 more long distance trains. Cases 1, 2 and 3: Illustration of the effect of the time window duration (number of partitions p) on the resulting design corresponding to a single time window of 24 hours (Case 1 in the upper plot), a time windows of 9 hours (Case 2 in the intermediate plot) and a time windows of 2 hours (Case 3 in the lower plot). ......................... 83
4.4 The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line. Single and double-tracks are shown as thin and thick segments, respectively. 84
4.5 Case 4: The resulting optimized timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line. 86

5.1 Trace of the Santiago-Valparaíso-Viña del Mar line. .................. 96
5.2 The Santiago-Valparaíso/Viña del Mar line showing its trace, the longitudinal profile and the location of the two tunnels together with the segment costs in single and double track. ......................... 97
5.3 Proposed timetable for the Santiago-Valparaíso/Vina del Mar line, for 76 passenger and 24 freight daily trains .................................................................................................................. 99
6.1 Cost of the services between Dublin and Belfast using different alternatives (car, bus and train) ................................................................................................................... 104
6.2 Cities connected by the current line between Dublin and Belfast .................................................................................................................. 105
6.3 Cost of the services between Dublin and Belfast using different alternatives (car, bus and train) ................................................................................................................... 105
6.4 High speed corridor (orange) compared with the conventional line (blue) .................................................................................................................. 106
6.5 High speed line profile and used main design parameters (maximum speeds, maximum and exceptional slopes, curve radius, etc.) ........................................................................ 107
6.6 Left plot: High speed proposal showing the design speeds for the different segments used in the analysis. Right table: List of the eight segments in which the line has been divided showing their origins and ends, their lengths and the unit construction costs for single and double-track. ........................................................................ 108
6.7 All analyzed cases, that is, the 14 different solutions that range from single-track (case 01) to double-track for all segments (cases D1 and D2), as well as intermediate ADST alternatives. ........................................................................ 110
6.8 Five different solutions that range from single-track (case 1) to double-track (case 5) for all segments. The intermediate alternatives 2 to 4 consider one, two and three double-track segments, respectively. ........................................................................ 111
6.9 Travel times for the cases of 16 and 32 daily services and all five cases. .................................................................................................................. 111
6.10 Quality measures for the different analyzed cases and the selection of most profitable case, Case 3. .................................................................................................................. 113
6.11 Description of the proposed ADST line solution showing the location of the eight segments and the two of them (in yellow color) that resulted in double-track. .................................................................................................................. 114
6.12 Resulting timetable for 16 (upper graph) and 32 (lower graph) daily services showing in yellow color the double-track segments and minimum, maximum and average travel times together with the current travel times and the time savings. .................................................................................................................. 115
6.13 Current network improvement, consisting in 4 new segments construction along the line. .................................................................................................................. 117
6.14 Current routes including the Dublin-Belfast link, the Dublin and Belfast commuter traffic, and the freight transport currently circulating along the network. .................................................................................................................. 118
6.15 Different studied cases, in which the number of Dublin and Belfast services using the current and the new route are indicated. .................................................................................. 119
6.16 Origin and destination, length and construction costs of the new segments. .................................................................................................................. 120
6.17 Estimated percentage of the contribution of the different project components to the total cost of the project. .................................................................................................................. 120
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.18</td>
<td>Case 0 optimized timetable associated with the existing conventional line.</td>
<td>121</td>
</tr>
<tr>
<td>6.19</td>
<td>Upper plot: Case 1 optimized timetable for the new segments considering that only 10 of a total of 16 services use them. Lower plot: Case 2 optimized timetable for the new segments considering that 26 of a total of 34 services use them.</td>
<td>122</td>
</tr>
<tr>
<td>6.20</td>
<td>Final solution.</td>
<td>124</td>
</tr>
<tr>
<td>6.21</td>
<td>A comparison of the travel times between Dublin and Belfast associated with cases 0, 1 and 2.</td>
<td>125</td>
</tr>
<tr>
<td>6.22</td>
<td>1. Dublin-Limerick line (left) and 2. Dublin-Cork line (right).</td>
<td>125</td>
</tr>
<tr>
<td>6.23</td>
<td>3. Dublin-Galway/Limerick line (left) and 4. Dublin-Galway/Limerick/Cork line (right).</td>
<td>126</td>
</tr>
<tr>
<td>7.1</td>
<td>Cases 2, 5 and 6 : Timetable corresponding to the actual demand of trains of the line Palencia-Santander when no incidence occurs (Case 2 in the upper plot) and when the segment Cobejo-Bárcena is blocked for three hours, obtained with $p = 6$ (Case 5 in the intermediate plot) and $p = 10$ (Case 6 in the lower plot) partitions.</td>
<td>134</td>
</tr>
<tr>
<td>7.2</td>
<td>The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line. Single and double-tracks are shown as thin and thick segments, respectively.</td>
<td>135</td>
</tr>
<tr>
<td>7.3</td>
<td>Case 4: The resulting optimized timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line.</td>
<td>137</td>
</tr>
<tr>
<td>7.4</td>
<td>Case 11: The resulting optimized re-scheduled timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line after the segment Tarancón-Cuenca remains blocked for a period of two hours.</td>
<td>138</td>
</tr>
<tr>
<td>7.5</td>
<td>Timetable corresponding to the case of no disturbances</td>
<td>139</td>
</tr>
<tr>
<td>7.6</td>
<td>Timetable corresponding to the case of one hour disturbance at a single track segment.</td>
<td>139</td>
</tr>
<tr>
<td>7.7</td>
<td>Timetable corresponding to the case of two hours disturbance at a single track segment.</td>
<td>140</td>
</tr>
<tr>
<td>7.8</td>
<td>Timetable corresponding to the case of two hours disturbance at a double track segment.</td>
<td>140</td>
</tr>
<tr>
<td>7.9</td>
<td>Timetable corresponding to the case of two hours independent disturbances at two single track segments.</td>
<td>141</td>
</tr>
<tr>
<td>A.1</td>
<td>The home screen.</td>
<td>161</td>
</tr>
<tr>
<td>A.2</td>
<td>Create a new project.</td>
<td>162</td>
</tr>
<tr>
<td>A.3</td>
<td>Open an existing project.</td>
<td>163</td>
</tr>
<tr>
<td>A.4</td>
<td>Select a recent project.</td>
<td>164</td>
</tr>
<tr>
<td>A.5</td>
<td>Language selection.</td>
<td>165</td>
</tr>
<tr>
<td>A.6</td>
<td>Main menus.</td>
<td>166</td>
</tr>
<tr>
<td>A.7</td>
<td>The File menu.</td>
<td>167</td>
</tr>
<tr>
<td>A.8</td>
<td>The edit menu.</td>
<td>167</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

A.9 The options menu ................................................. 168
A.10 The information window ........................................ 170
A.11 The general data window ........................................ 171
A.12 The operation window .......................................... 173
A.13 The operation costs window .................................... 174
A.14 The complements window ....................................... 176
A.15 The nodes window ............................................. 178
A.16 The node edit window .......................................... 180
A.17 The segments window .......................................... 182
A.18 The segment edit window ...................................... 183
A.19 The duplication window ....................................... 184
A.20 The routes window ............................................ 185
A.21 The route edit window ......................................... 186
A.22 The headway times window .................................... 187
A.23 The headway times edit window ............................... 188
A.24 The speeds window ........................................... 189
A.25 The speed edit window ........................................ 190
A.26 The trains window ............................................ 191
A.27 The train edit window .......................................... 192
A.28 The services window .......................................... 194
A.29 The service edit window ...................................... 195
A.30 Modify flexibilities ............................................. 196
A.31 The services window showing the real departure times completed by the computer program after the optimization has finished. 198
A.32 Circulation diagrams automatically generated by the program after the optimization program has finished. 199
A.33 The Services window with the completed results in red color. 201
A.34 The information window with the added lower part indicating that an optimization is still running. 202
A.35 Timetable 0e11-11e14.pdf ...................................... 204
## List of Tables

1.1 Length of the HSR network per country under operation up to September 2014 [Albalate and Bel (2015)]. .................................................. 30

1.2 Time savings after HSR is under operation [Gourvish (2010)]. .................. 37

1.3 Air market share before and after HSR [Albalate and Bel (2015)]. ............ 38

1.4 Construction costs of HSR in different countries [Albalate and Bel (2015)]. 39

1.5 Profitable HSR Route [Albalate and Bel (2015)]. ........................................ 39

4.1 Characteristics of the different segments considered in the line. .................. 78

4.2 Characteristics of the different segments considered in the line (continuation). 79

4.3 Palencia-Santander Case vars = 78401 const= 213460 .......................... 85

4.4 RedSur Case vars = 52899 const= 151737 ........................................... 88

5.1 Description of the 7 segments considered in the Santiago-Valparaíso-Viña del Mar line showing the origins, ends, lengths, location and the construction costs associated with the single and double-track solutions. ................. 98

5.2 Priorities and resulting departures, arrivals and travel times of passenger trains. .......................................................... 100

5.3 Priorities and resulting departures, arrivals and travel times of passenger trains. .......................................................... 101

5.4 Priorities and resulting departures, arrivals and travel times of freight trains. .......................................................... 102
Part I

INTRODUCTION AND MOTIVATION
Chapter 1

HIGH SPEED RAILWAYS

Contents

1.1 Introduction to High Speed Railways ........................................ 28
1.2 High Speed Railway Network Development ............................... 29
   1.2.1 Japan ........................................................................ 29
   1.2.2 France ...................................................................... 31
   1.2.3 Spain ....................................................................... 32
   1.2.4 Germany ................................................................... 33
   1.2.5 Italy ........................................................................ 34
   1.2.6 China ....................................................................... 36
1.3 The Impact of HSR .................................................................. 37
   1.3.1 Transport ................................................................... 37
   1.3.2 Socio-Economics ......................................................... 40
   1.3.3 Environmental Impacts ................................................ 40
1.4 Conclusions ........................................................................... 40
On these days, High Speed Railways (HSR) are considered as one of the main alternatives to solve the connectivity problems between two cities. Initially its development was focused on passengers, however and due to the elevated costs of the new infrastructures for trains to achieve the high speeds, the possibility to consider a mixed line with passengers and freight has been considered as an alternative option. Despite the fact that HSR reduce travel time between two cities, we must be aware of the possible side effects that the construction of a new line can produce. In this chapter a brief introduction about the HSR is presented in order to clarify some important aspects that need to be stated. This includes first, the historical development of the HSR network, which is introduced, second, the impact of the HSR in society, and third, some conclusions on High Speed Railways.

1.1 Introduction to High Speed Railways

High Speed is a relative concept that has changed over time. In the mid 1800’s the London to Exeter express rail service was the fastest in the world with an average speed of 70 $[\text{km/h}]$; then, and due to competitive pressures, companies where induced to reduce travel times so, in late 1920’s the Great Western in Britain introduced the first scheduled train at 110 $[\text{km/h}]$ (see Allen (1992)). Between the world wars (1919-1939), several trains run into average speeds of 125 $[\text{km/h}]$ reaching top speeds of 160 $[\text{km/h}]$ on steam locomotive, however, on these days it was already clear that the path to go was on diesel or electric trains, so in mid 1930’s, both, German and American diesel powered trains ran at an average speed of 125 $[\text{km/h}]$ for the route Berlin-Hamburg and Denver-Chicago (1.633 km.), respectively. But the development of the industry continued and in 1938 on the Britain’s East Coast Main Line a speed of 203 $[\text{km/h}]$ was achieved, and in 1938-1939, the Italian ETR200 electric trains not only reached the 203 $[\text{km/h}]$ max speed in a demonstration, but also produced average speeds of 165 $[\text{km/h}]$ and 176 $[\text{km/h}]$ on the Florence-Bologna-Milan line (see Hughes (1988); Allen (1992)).

As it can be seen, previously to the world war two, the improvements of the speed were due to an improvement in the locomotive technology, however after the war, there was a combination between new lines and new train technology. Campos and de Rus (2009) identify four types of HSR:

1. Complete separation between HSR lines and traditional lines (Shinkansen in Japan).

2. Mixed high-speed systems, in which trains run on both high-speed and upgraded conventional infrastructure (TGV in France).

3. Mixed conventional systems, in which HSR trains run at high speeds on new, standard lines, while others run on both the new and older non-standard gauge (AVE
and ALVIA in Spain, in this case there is also a problem regarding the gauge between new (standard) and old (non standard), that is solved using the Talgo gauge changing technology).

4. Fully mixed systems, in which both high-speed and conventional trains can run on the infrastructure provided (ICE trains and freight trains in Germany, and Italy’s Rome-Florence line).

Despite the several different approaches, technology and types it is very well established that HSR are those that provide operational speeds above 200 \( [km/h] \) (see Nash (2009)). A classification in generations regarding the maximum operation speed is also proposed by some authors establishing that if a train has a maximum speed of 250 \( [km/h] \), it belongs to the 1st generation, if this speed is 300 \( [km/h] \) to the second, and if it is 350 \( [km/h] \) to the third generation.

Considering the definition of HSR, the first high-speed railway line was put into operation in Japan on October 1964, with a dedicated standard-gauge infrastructure from Tokyo to Osaka. However, it was not until 1977, with the opening of the London-Bristol-Swansea line and in 1978 with the London Edinburgh line, that HSR arrived to Europe. Since the 80’s several new routes were opened in Japan and in different European countries, such as the Paris-Lyon in France, Rome-Florence in Italy, Mannheim-Stuttgart in Germany, Madrid-Seville in Spain. With the arrival of the new century the first HSR route in America was opened (the Boston-New York-Washington line) while the Japan and existing networks in Europe continued to increase, as well as new HSR routes were opened in other European countries (for example, Belgium or Switzerland) and also in Asia, where besides Japan, new routes in Taiwan and China were opened (see table 1.1 for a summary of total HSR kilometres network per country).

1.2 High Speed Railway Network Development

In this section, the development of the HSR network will be presented, especially the most important cases around the world: Japan, France, Spain, Germany and China.

1.2.1 Japan

The development of the Japanese HSR network is been under a long and coherent system of planning that began in 1964 when the first route was put into operation. In Japan the first HSR, between Tokyo and Osaka with a length of 515.4 km. Actually the network in Japan has a total of 2615.7 km. and there are projects to extend the line in 547.6 km in the next years (see Figure 1.1).

The model developed by Japan consists in a complete separated line, built to the standard gauge (1435 [mm]), exclusively for the Shinkansen and only for passenger trains.
Table 1.1: Length of the HSR network per country under operation up to September 2014. (Albalate and Bel, 2015).

<table>
<thead>
<tr>
<th>Country</th>
<th>Network length [Km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>11067</td>
</tr>
<tr>
<td>Spain</td>
<td>3100</td>
</tr>
<tr>
<td>Japan</td>
<td>2087</td>
</tr>
<tr>
<td>France</td>
<td>2036</td>
</tr>
<tr>
<td>Germany</td>
<td>1013</td>
</tr>
<tr>
<td>Italy</td>
<td>923</td>
</tr>
<tr>
<td>South Korea</td>
<td>550</td>
</tr>
<tr>
<td>Taiwan</td>
<td>345</td>
</tr>
<tr>
<td>Belgium</td>
<td>209</td>
</tr>
<tr>
<td>Holland</td>
<td>120</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>113</td>
</tr>
</tbody>
</table>

One of the main important consequences of HSR is the reduction of travel times. For example, the first route opened in 1964 reduced the travel time between Tokyo and Osaka from 6.5 hours to 4 hours when the speed of operation was 210 [km/h]. Later, this route has been improved because the new technology has allowed to increase the speed up to 270 [km/h] which leads to a travel time of 2.5 hours.

As it is expected, for a narrow, mountainous and seismic country, the route has several kilometres in tunnels and viaducts what makes construction costs elevated and difficult to predict in advance. In fact the final costs of the route was twice the estimated costs (see Hood, 2006). However and despite the elevated costs, the project was justified due to a high population around the Tokyo-Kyoto-Osaka corridor that when the line was opened 60 trains per day transported 61000 passengers per day (see CJRCAR, 2011). This initial Shinkansen line was a total economic success and just in three years of operation the revenues exceeded the construction costs of the line.

After the positive experience of the first route, further Shinkansen lines were built with government financial support established via the National Development Plan of 1969 and the National Shinkansen Network Development Law of 1970 (see Jorsa, 2008). However and despite the government financing, newer Shinkansen routes were less profitable than the first ones, a situation that can be explained by different factors: (a) the first is related to less population served that traduces in less passengers per day, and (b) higher construction costs due to new regulations, environmentalists demands, and new engineering challenges among others.

Nowadays, the Shinkansen is an international example of HSR success in several aspects: (a) it is one of the most profitable HSR networks in the world, (b) since it began
its operation in 1964, there has no passengers killed or injured in train accidents and (c) the average delay is 0.6 minutes per train (see CJRCAR (2011)). These characteristics allow us to state that Shinkansen is one of the most safe and punctual transportation systems in the world.

1.2.2 France

Like Japan, in France the development of HSR was a clear path since it was accompanied by political and strategic factors (see Figure 1.2), and it was consistent with the SNDF Master Plan formulated in 1976, as well as the desire to create a transport network independent of oil supplies and economics in energy use.

The Train à Grande Vitesse (TGV) was introduced in 1981 for the route Paris-Lyon on the first dedicated line. Since 1983, when the line starts to run at max speed the travel time between both cities was just 2 hours, the line served the 40 percent of French population, and like the case of the Shinkansen in Japan, this first route was quickly paid itself after 12 years of operation, situation that has not occurred with other lines mainly due to low population densities. Nevertheless, in a political decision strategy new lines were considered from Paris to Le Mans and Tous in the 1990 with the objective of improving services to Brittany (through LeMans) and to the south west through Tous.
serving approximately 25 million of people with much lower population density, being necessary a 30 percent of central government funds (see Gerondeau (1997)). For the newer HSR projects there was a much lower rate of return, so a substantial amount of public subsidy was necessary. In spite of this, the development continued through a major reorganisation of the SNCF (Société Nationale des Chemins de Fer Français) in 1997 when the train operating and the infrastructure management functions were separated but remained both of them in the public sector and new funding regimes were incorporated for new projects including the participation of the private sector.

1.2.3 Spain

The development of HSR in Spain was late and having a big support specially after the country joined the European Union in 1986. There were some particularities in the Spanish railroad network (see Figure 1.3) that prevented the HSR development earlier as well as political internal situations.

The existing network had a broad gauge traditionally used in the country (1668 [mm]), that is, different to the standard gauges used in the rest of Europe. In addition, there
were relatively large distances among population centres.

One major step in the Spanish HSR network was the development of an interchangeable gauge equipment for rolling stock by the Spanish company Talgo, that facilitated the through traffic to France and beyond (see Allen (1992)).

A comprehensive plan was proposed in 1987 with following plans in the years 1993, 1997 and 2005. As a result of these plans, the first HSR line was opened in 1992 between the cities of Madrid and Seville with a length of 471 kilometres. Actually the Spanish HSR network is the second larger in the world with over 3000 km already in service, only behind the Chinese HSR network. On the other hand the Spanish network is the one with the lowest number of passenger per kilometre.

The whole HSR network of Spain is not profitable; however, it is expected that in next years the line Madrid Barcelona will be.

![Figure 1.3: Spain: High speed corridor (orange) compared with the conventional line (blue).](image)

### 1.2.4 Germany

The German approach to HSR (ICE) (see Figure 1.4) is a mixture between the French and Japanese models, that is, it consists of building new lines and upgrading existing lines. Also, the policy for HSR development was affected by the need to unify and reconstruct
the country after the collapse of the East German State in 1989. Also it is important to notice that a mixed line between passengers and freight is considered.

The first ICE network was opened in 1991 with a maximum speed of 280 [km/h] and on these days the total HSR network in Germany has a little more than 1000 kilometres.

Since freight is also considered, some extra considerations must be taken into account to design the line, and the German environment awareness meant that construction costs were inevitably higher than comparable solutions (3 times higher per kilometer than the French TGV). This and the fact that ICE has had a limited impact in comparison with the TGV or Shinkansen, means that the pay-off in terms of traffic generation has not been as great as in Japan and France.

![Figure 1.4: Germany: High speed corridor (orange) compared with the conventional line (blue).](image)

### 1.2.5 Italy

Italy, has a long train history. In 1913 some improvements of the infrastructure has began in the Bologna-Florence line, and the Rome-Naples line was completed by 1927. These kind of works made Italy a leader in train development by 1939 in Europe, however, after
the war the development in Italy was very slow and mainly due to limitations of the infrastructure.

Like Germany, Italy has considered the approach of upgrading basic existing infrastructures, and in 1962, the country was working on a plan to get train speeds of 250 [km/h]. In 1969 the work began in order to improve the Rome-Florence line, but the progress was very slow until the line was completed and able to handle the 250 [km/h], 23 years after the beginning of the works in 1992, from 2006 to 2009 additional lines with speeds up to 300 [km/h] were opened in the Rome-Naples, Turin-Novara, and Milan-Bologna routes.

Italy not only focused in upgrading existing infrastructures, but also has worked in the development of tilting trains, and in 1976 they put the first tilting train into operation in the line Rome-Ancona. One of the main characteristic of the HSR in Italy (see Figure 1.5), is that it has the most expensive construction cost per kilometer with an average of 61 ME per kilometer, which is almost 4 times the average cost in Spain, 4 to 10 times the average cost in China, 3 times the French and a little less than 2 times the German construction cost (see Albalate and Bell (2015)) (table 1.4 summarizes the construction costs in different countries). Actually, the Italian HSR network has a T shape with two main clear corridors; the south-north that connect Naples-Rome with Milan, Florence and Bologna, while the West-East Corridor in the North of Italy connects Turin-Milan-Venice.

![Figure 1.5: Italy: High speed corridor (orange) compared with the conventional line (blue).](image-url)
1.2.6 China

The case of HSR in China is a very especial one. It has a very short history in HSR that has began after the 2000 but its development has been very strong and their network has grown at an incredible speed reaching 11,000 [km] of HSR lines, being by far the country with the largest HSR network in the world in total.

In 2008 prior to the Olympics Games, the first 350 [km/h] route was put into operation for the Beijing-Tianjin route (120 [km] with 30 [min] of travel time).

Initially the country imported the technology, but then they started to produce local technology to their own HSR network, and also they have developed the MAGLEV technology and has put it into operation for commercial use over the Shanghai Airport to Shanghai Financial District with a maximum speed of 430 [km/h] in December 2003.

One of the main characteristics of the Chinese HSR lines, despite the fact that its construction costs per kilometre are increasing, is that they are by far the lowest in comparison with other countries, both in Europe and Asia (see Figure 1.6). Finally it is important to remark that the route that connects Jinan with Qingdao is one of the only three profitable routes in the world.

Figure 1.6: China: High speed corridor (orange) compared with the conventional line (blue).
1.3 The Impact of HSR

The construction of an HSR network has several impacts on different areas: (a) transportation, (b) socio-economics and (c) environmental.

1.3.1 Transport

It is very clear that a new transportation system will have a direct impact on existing transport alternatives. Since the main advantage of the HSR is the reduction of travel time, a considerable time saving is proposed to users of the system, and this produces changes on demand for the different alternatives.

Time Savings

It is very straightforward to appreciate the impact of the HSR regarding travel time savings. To this aim, it is important to point out that time saving is directly related to which transport mode is compared (traditional train, plane, car, etc.).

<table>
<thead>
<tr>
<th>Route</th>
<th>Travel time Before HSR [min]</th>
<th>Travel time with HSR [min]</th>
<th>Time Saving [min]</th>
<th>% gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo- Osaka</td>
<td>420</td>
<td>145</td>
<td>275</td>
<td>65</td>
</tr>
<tr>
<td>Paris- Lyon</td>
<td>227</td>
<td>115</td>
<td>112</td>
<td>49</td>
</tr>
<tr>
<td>Madrid - Seville</td>
<td>390</td>
<td>140</td>
<td>250</td>
<td>64</td>
</tr>
<tr>
<td>London - Paris</td>
<td>380-420</td>
<td>135</td>
<td>245-285</td>
<td>64-68</td>
</tr>
</tbody>
</table>

With respect to other transportation modes, in the case of road transport the time savings can be offset for the time consumed to reach the final destination (to and from the train station) especially for short trips (distances up to 80 [km]). Regarding air transportation the case is opposite as the longer the travel the more convenient the air option is, especially for trips longer than 800 [km].

Other Conveyances

Since HSR is a new transport alternative, it generates effects and impacts over existing transportation alternatives, being the most affected air transportation and regular railways.

Regarding air transportation several studies have been conducted, especially regarding the replacement or competition between both systems (see Albalate and Bel (2015)).
Generally, the studies have conducted analysis regarding passenger market share in air routes before and after the operation of HSR routes. Table 1.3 summarizes some of the results obtained from the analysis conducted.

<table>
<thead>
<tr>
<th>Route</th>
<th>Market share Before HSR</th>
<th>Market share after HSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madrid-Seville (470 km.)</td>
<td>40%</td>
<td>13%</td>
</tr>
<tr>
<td>Madrid-Málaga (513 km.)</td>
<td>72%</td>
<td>14%</td>
</tr>
<tr>
<td>Madrid-Valencia (391 km.)</td>
<td>61%</td>
<td>14%</td>
</tr>
<tr>
<td>Paris-Lyon (427 km.)</td>
<td>31%</td>
<td>7%</td>
</tr>
<tr>
<td>Paris-Brussells (312 km.)</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>Hamburg-Frankfurt (524 km.)</td>
<td>10%</td>
<td>4%</td>
</tr>
<tr>
<td>Seoul-Busan (442 km.)</td>
<td>42%</td>
<td>17%</td>
</tr>
</tbody>
</table>

The effect was not only the different market shares in air before and after HSR implementation, but also there was a change in the number of passengers, number of offered flights, and seats in each route, but in every case where the evolution after the appearance of HSR was studied the same result was obtained: a strong reduction in air market share and migration of those passenger to HSR. (the interested reader can found detailed studies in Gleave (2006), Campos and de Rus (2009) and Givoni and Dobruszkes (2013)). An important factor that affects how the market share moves between the three main alternatives (air, road or HSR) is directly related to travel time, Givoni and Dobruszkes (2013) establish that for travel time less than an hour the maximum market share obtained by HSR is no more than 30%, and between one and three hours of travel time the market share of HSR will be around 30% against road transport and up to 100% with air travel, beyond 3 hours of travel time the market share of HSR start to reduce being for travel time between 3 and 3.5 hours, at least the 50% of market share.

Finally regarding traditional Railway service, there is also a big effect on passengers of traditional railways services.

**Investment Costs and Returns**

HSR needs special infrastructure in any of the different situations considered, dedicated or upgraded lines. The need of infrastructure traduces in huge construction costs, which in many cases become in the largest investment project of each country. Since the investment needed is so high, it is usual that this be made by the central government.
CHAPTER 1. HIGH SPEED RAILWAYS

Construction costs are directly related to topography, it is not the same to build a kilometre in plain than in tunnel or in viaduct, so the line topography is very important. The design speed is also a very important factor, as it can be seen in Wu (2013) an increase of 100 [km/h] in the speed design traduces in a 100% increase in the construction cost per kilometre.

Table 1.4: Construction costs of HSR in different countries Albalate and Bel (2015).

<table>
<thead>
<tr>
<th>Country</th>
<th>Minimum M€/km</th>
<th>Maximum M€/km</th>
<th>Average M€/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>6,1</td>
<td>27,6</td>
<td>6-17</td>
</tr>
<tr>
<td>Spain</td>
<td>15,5</td>
<td>23,5</td>
<td>18</td>
</tr>
<tr>
<td>France</td>
<td>18,9</td>
<td>25,7</td>
<td>22</td>
</tr>
<tr>
<td>Taiwan</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Germany</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Korea</td>
<td>38,7</td>
<td>52,6</td>
<td>42</td>
</tr>
<tr>
<td>Japan</td>
<td>53</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Italy</td>
<td>47,3</td>
<td>96,4</td>
<td>61</td>
</tr>
</tbody>
</table>

Construction costs are not the only ones that need to be considered, it is also necessary to take into account the maintenance costs per kilometre and also the safety and signal systems.

As it can be appreciated, costs related to an HSR line in operation are very high, and not always the lines are able to cover the investment and operation costs, until today only 3 routes are classified as profitable, these lines are the Tokyo-Osaka in Japan, Paris-Lyon in France, and Jinan-Qingdao in China.

Table 1.5: Profitable HSR Route Albalate and Bel (2015).

<table>
<thead>
<tr>
<th>Route</th>
<th>Distance [Km]</th>
<th>Population [Millions of habitants]</th>
<th>Passengers per year [Millions]</th>
<th>Passengers per Km.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo -Osaka</td>
<td>515</td>
<td>40 - 20</td>
<td>140 - 150</td>
<td>281.553</td>
</tr>
<tr>
<td>Paris - Lyon</td>
<td>409</td>
<td>12.3 - 0.48</td>
<td>25</td>
<td>61.124</td>
</tr>
<tr>
<td>Jinan-Qingdao</td>
<td>362</td>
<td>4.5 - 5.7</td>
<td>28</td>
<td>77.348</td>
</tr>
</tbody>
</table>

As a conclusion of the profitability of routes, it can be concluded that the main characteristic of these lines are that they connect two great population centres with a very high density with a length of the route in the zone where HSR has a competitive advantage over air and road transport (in the range of 1 to 3 hours of travel time).
1.3.2 Socio-Economics

There are many socio-economical impacts that can be generated with the HSR line construction. The analysis of the effects has been widely studied, especially in the case of France, where as a result of the studies it can be concluded that benefits of HSR are focused by central nodes promoting the centralisation of the economical activities in large centres, and also it has promoted business travel. On the other hand, the impact on the industrial activity has been irrelevant as well in terms of decision making regarding localisation of the service industries. As a consequence, it can be concluded that HSR has promoted neither the administrative nor the economic decentralisation from Paris.

In other aspect of the social impacts, HSR have generated to railway users benefits in terms of security, since the accident levels are extremely low and also users has experienced higher comfort levels in their trips.

For non HSR users, there are also some benefits that can be considered, especially the economic growth derived from a change in the level and composition of the local economic activity.

Also some environment effects have been reported, especially related to traffic congestion and contamination. In addition, some resistance from environmentalists have been presented when these projects are presented and issues need to be solved.

1.3.3 Environmental Impacts

Every new transportation mode and infrastructure will generate and produce environment effects. Initially, it is obvious that an HSR line will generate a change in the landscape, visual intrusion, barrier effects, among others, and the operation itself of the trains will produce noise, and local air pollution.

Initially, for the first constructed lines the environmental effects were underestimated, but since then the environmental concerns have grown, and construction costs have risen in order to be able to mitigate environmental damage.

On the other hand the use of HSR is less contaminant to the air than road and air transportation. Besides if it is taken into consideration that HSR can take up to 30% of the road market share in routes up to three hours of travel time, we can conclude that the reduction of air contaminants is very important.

Finally HSR trains are more fuel efficient that their transportation alternatives.

1.4 Conclusions

HSR development in the world is strongly related to national policies and its development has only been possible due to strong political support and central government funding and permanent subsidising.
On these days, there are only three HSR routes that are profitable and economical feasible, these lines are the Tokyo-Osaka in Japan, Paris-Lyon in France, and Jinan-Qingdao in China, and the three of them have common characteristics: they connect two highly populated and density centres and a travel time under three hours. Despite this, they are not the only lines that satisfy these conditions and are not the only profitable lines that can be justified by the number of passengers per day, as well as with the increasing construction costs that new HSR lines are experienced in last years.

From the different studies analyzed, it is possible to conclude that an important parameter for HSR routes is the travel time. In order to be competitive against air transport, several authors have determined that the threshold value will be 800 [km], and the travel time range where the HSR can get the most of the market share is in routes where the travel time is between 1 and 3 hours, being up to 30% of the roads market share and up to 100% of the airplane share in some cases; for travel times between 3 and 3.5 hours it is expected that market share for HSR be at least 50%.

HSR is one of the safest transportation mode in the world and the most punctual one, being highlighted that the mean delay is near to zero.

Both, users an non users enjoy the benefits of HSR, in the first group, because they use one of the safest and punctual transportation mode, and in the second group because they take advantage of the benefits of connectivity with other population centres.

Regarding the environment, there are some pros and cons, one of the main pros of the HSR that can be stated is the reduction of congestion in roads with the consequent reduction of CO$_2$ emissions and also trains are most fuel efficient and less contaminant than planes and cars. On the other side the infrastructure for HSR is invasive with landscape.

Finally, it can be concluded that HSR is a transportation mode recommended to connect two high population centres and the best performance, in comparison to its transport alternatives, is for routes with travel time between 1 and 3 hours. The huge construction costs of the infrastructure and the high maintenance costs make it a non profitable and even non economical feasible transport system that it is only possible with government subsidies to its operation and government funding of the infrastructure. Traditional HSR as it is known in these days will not be able to connect small cities between them or small cities with large cities since the number of passengers per year will not be enough to cover operation costs, so new alternatives such as the Alternate Double Single Track (ADST) (treated in detail in chapter 4) arises as a very interesting opportunity for all these cases.
Part II

TIMETABLE OPTIMIZATION
# Chapter 2

## STATE OF THE ART IN TIMETABLE OPTIMIZATION

### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>46</td>
</tr>
<tr>
<td>2.2</td>
<td>The Sahin method</td>
<td>46</td>
</tr>
<tr>
<td>2.3</td>
<td>The Ghoseiri et al. model</td>
<td>47</td>
</tr>
<tr>
<td>2.4</td>
<td>The Zhou and Zhong method</td>
<td>48</td>
</tr>
<tr>
<td>2.5</td>
<td>The Castillo et al. single-track method</td>
<td>49</td>
</tr>
<tr>
<td>2.6</td>
<td>The Castillo et al. double-single-track method</td>
<td>50</td>
</tr>
<tr>
<td>2.7</td>
<td>The Cacchiani and Toth discussion on timetabling problems</td>
<td>51</td>
</tr>
<tr>
<td>2.8</td>
<td>The Törnquist and Persson model for perturbations</td>
<td>52</td>
</tr>
<tr>
<td>2.9</td>
<td>The Acuna-Agost et al. model for dealing with perturbations</td>
<td>53</td>
</tr>
<tr>
<td>2.10</td>
<td>The works of Cacchiani et al.</td>
<td>54</td>
</tr>
<tr>
<td>2.11</td>
<td>The Burdett and Kozan model</td>
<td>55</td>
</tr>
<tr>
<td>2.12</td>
<td>The Xie and Li model</td>
<td>55</td>
</tr>
<tr>
<td>2.13</td>
<td>The D'Ariano-Pranzo Dispatching System</td>
<td>56</td>
</tr>
<tr>
<td>2.14</td>
<td>The Carey-Crawford model for busy complex stations</td>
<td>57</td>
</tr>
</tbody>
</table>
2.1 Introduction

In this chapter we revise the most important works in timetable optimization. Since the existing literature on this topic is too extensive, we limit to the most closely related works to the models presented in this thesis. In particular we present some of the different methods used for optimizing timetables. After a brief description of each method, we list the main original contributions made by the corresponding authors.

2.2 The Sahin method

The Sahin (1999) method provides an heuristic algorithm for rescheduling trains by modifying existing meet/pass plans in conflicting situations in a single-track railway. The algorithm is based on inter-train conflict resolution using a look-ahead method to find the consequences of each alternative solution. To this end simulations based on analytical models for the computation of average interference delays are used.

To model decision behaviour of train dispatchers, it is assumed that they use a multi-attribute utility function consisting of some weighted attributes of the conflicting trains to determine dynamic priorities, which are used for conflict resolution.

The considered attributes of conflicting trains are:

1. Basic priority. A number assigned to trains according to their characteristics (speed class).
2. Critical ratio. A relative pending travel time at the meetpoint, that is the quotient between the remaining travel time from the meetpoint and the minimum possible remaining travel time (at maximum speed).
3. Delay of myopic resolution. It is the undesired stop time of the conflicting train due to conflict resolution.
4. Number of potential conflicts after current conflict resolution.

It is clear that the smaller the value of these attributes the better, that is the higher the dynamic priority.

The attribute weights are estimated using a linear programming model that minimizes deviations of the model choices with respect to those of the dispatcher.

The algorithm chooses the alternative resolution leading to a minimum total delay in the system due to conflicting trains being stopped based on a look-ahead method.

The authors indicates that his heuristic algorithm may be improved to solve control problems for double and multiple track railways with bi-directional signaling system, that is, in very general railway networks.

As important original contributions of this author we mention:
1. Introducing the idea of conflict resolution and providing methods for solving it.

2. Using simulations and look-ahead methods based on analytical models.

3. Introducing the critical ratio as a measure of quality and specially the fact that this measure is dimensionless.

4. Proposing a multi-attribute utility function.

5. Proposing a linear program to estimate the weights for the attributes.

6. A proposal for extending all these ideas to a general railway network.

2.3 The Ghoseiri at al. model

Ghoseiri et al. (2004) present a multi-objective optimization model for solving the train scheduling problem, which includes not only single and multiple tracks but multiple platforms with different train capacities.

The objective function includes two objectives: minimizing the travel times and saving fuel consumption. Thus, the Pareto frontier is obtained, from which the user can select different optimal solutions based on six different weighted measures as alternatives to the classical $L^p$-distances. It is interesting to see that the objective function terms are normalized leading to dimensionless terms.

A physical model is presented to evaluate the energy consumption in which the Davis resistance formula is used with three terms one independent of the speed and other two in terms of the speed and the square of the speed.

Among the stated constraints it is interesting to see that the train continuity constraints are forced at all nodes of the network. In addition, dwell time constraints at platforms, trip time on links, one train at a time on links (same or contrary directions) and headway at nodes constraints are used. In addition, the circulation time is restricted by upper and lower bounds.

Binary variables are used to define the priorities for pairs of trains with segment conflicts.

An interesting trick is used to convert non-linear constraints into a set of linear constraints.

The most important contributions of this work are:

1. The model is valid for multiple track networks and multiple platforms.

2. A multiple objective function is used including travel times and energy consumption.

3. The Pareto frontier is determined.

4. A physical model is given for energy consumption calculation.
5. It is a network model.

6. An original trick using sufficiently large positive constants is used to convert inactive the headway constraints when they do not apply.

7. Non-linear constraints are transformed into a set of linear constraints.

### 2.4 The Zhou and Zhong method

The Zhou and Zhong (2007) method consists of the following optimization program:

\[
\text{Minimize } \sum_{i=1}^{n} n e_{i,\sigma(i,m)},
\]

where \(e_{i,j}\) is the leaving time for train \(i\) at segment \(j\), \(\sigma(i,k)\) is the segment index of the \(k\)-th travelling segment in a route for train \(i\), \(\sigma(i,k) = k\) for outbound trains, \(\sigma(i,k) = m + 1 - k\) for inbound trains, \(m\) is the last segment in the route and \(i\) is the train number, subject to

- Departure time constraints:
  \(s_{i,\sigma(i,1)} \geq r_i, \quad \forall i \in I.\) (2.2)

where \(s_{i,j}\) is the entering time for train \(i\) at segment \(j\), \(r_i\) is the lower bound of the departure time for train \(i\) and \(I\) is the set of trains

- Free running time constraints:
  \(e_{i,\sigma(i,k)} = p_{i,\sigma(i,k)} + s_{i,\sigma(i,k)}, \quad \forall i \in I, \ k = 2, \ldots, m,\) (2.3)

where \(p_{i,j}\) is the segment \(j\) travel time of train \(i\) and \(k\) is the segment index.

- Minimum dwell time constraints:
  \(s_{i,\sigma(i,k)} \geq e_{i,\sigma(i,k-1)} + d_{i,\sigma(i,k)}, \quad \forall i \in I, \ k = 2, \ldots, m,\) (2.4)

where \(d_{i,j}\) is the lower bound of the dwell time of train \(i\) at station \(j\).

- Headway constraints at track segments:
  \(s_{i,j} \geq e_{i',j} + h_j \text{ or } s_{i',j} \geq e_{i,j} + h_j \quad \forall i, i' \in I, \ i \neq i', j \in J,\) (2.5)

where \(h_j\) is the minimum headway time between arrival and departure times of two consecutive trains at segment \(j\).

- Headway constraints on arrival times at stations:
  \(e_{i,\sigma(i,k)} \geq e_{i',\sigma(i',k')} + g_u \text{ or } e_{i',\sigma(i',k')} \geq e_{i,\sigma(i,k)} + g_u, \quad \forall i, i' \in I, \ i \neq i', \beta(i, k) = \beta(i', k') = u,\) (2.6)
where $g_u$ is the minimum headway time between arrival times of two consecutive trains at station $u$.

Maximum dwell time constraints:

$$s_{i,\sigma(i,k)} \geq e_{i,\sigma(i,k-1)} + \bar{d}_{i,\sigma(i,k)}, \quad \forall i \in I, \ k = 2, \ldots, m,$$

(2.7)

where $\bar{d}_{i,j}$ is the upper bound of the dwell time of train $i$ at station $j$.

The authors suggest to replace constraints (2.5) by

$$s_{i,j} \geq e_{i,j} + h_j - My_{i,i'}, \quad \forall i,i' \in I, \ i \neq i', j \in J,$$

(2.8)

and

$$s_{i',j} \geq e_{i',j} + h_j - M(1 - y_{i,i'}) \quad \forall i,i' \in I, \ i \neq i', j \in J,$$

(2.9)

where $y_{i,i'}$ are binary variables that take value 1 if train $i$ is scheduled before train $i'$ on segment $j$ and 0, otherwise.

Additionally, they suggest to model the headway constraints (2.5) and (2.6) as:

$$\sum_{i=1}^{n} n\delta_{i,j,t} \leq 1, \quad \forall j \in J, \ t = 1, 2, \ldots, T$$

(2.10)

where $\delta_{i,j,t} = 1$ if $s_{i,j} \leq t \leq e_{i,j} + h_j$ and $T$ is the set of times $T$ and

$$\sum_{i=1}^{r} n\epsilon_{iu,t} \leq 1, \quad \forall u \in U, \ t = 1, 2, \ldots, T,$$

(2.11)

where $\epsilon_{iu,t} = 1$ if $e_{i,\sigma(i,k)} \leq t \leq e_{i,\sigma(i,k)} + g_u$ and $T$ is the set of times $T$.

To solve this problem, the authors present an elaborated branch-and-bound procedure that permits obtaining feasible schedules with guaranteed optimality.

The most important contributions of this method are:

1. The original statement of the Problem (2.1)-(2.7).

2. The idea of replacing constraints (2.5) by (2.8) and (2.9).

3. The idea of replacing constraints (2.5) and (2.6) by (2.10) and (2.11).

4. The Branch-and-bound method and the interesting idea behind it.

### 2.5 The Castillo et al. single-track method

Castillo et al. (2009) presents a modified version of the Zhou and Zhong (2007) model for single-track lines in which the maximum relative travel time is minimized, that is, a minimax problem is suggested. The linear character of the problem is maintained thanks to some constraints that guaranteed the relative travel time variable $\epsilon$ to be above each
of the relative travel times of all trains. They also allow for several trains to circulate in the same direction along the same track if sufficient distance is allowed among them.

In addition, to reduce the computation time and since the maximum relative travel time (objective function) is easily bounded, they propose the bisection method that consists in testing by the bisection method the range of feasible and unfeasible solutions. The idea is to bound from the unfeasible side, because the computer program finds easily if the problem is unfeasible, but takes time to determine an optimal solution.

Finally, the authors perform a sensitivity analysis using an interesting result valid for linear programs (see Castillo et al. (2006b, a, 2007, 2008)) that permits obtaining these sensitivities from the primal and dual variable values.

The most important contributions of this work are:

1. Use the maximum relative travel time as the objective to be minimized.
2. Convert this program into a linear program using an auxiliary non-negative variable $\varepsilon$ and a set of constraints that force the relative travel times of all trains to be below the value of this variable.
3. Propose the bisection method to accelerate the convergence of the solution.
4. Perform a sensitivity analysis using closed formulas.

2.6 The Castillo et al. double-single-track method

Castillo et al. (2011) extend the previous method to the case of double-tracks and, more important, they suggest for the first time the use of alternate double-single track lines.

In addition, they include a constraint to bound the maximum relative travel time, that allows to control the timetable quality, and suggest a new method to reduce the number of binary variables, that cause the huge amount of cpu time required for large problems. The main idea consists in guessing the pairs of non-conflicting trains using the expected time for them to enter in conflict. After the calculations, the computer program checks if the assumed non-conflicts are so. Otherwise, a new guess is used until they correspond to the real case.

The examples of applications shown in this paper show an extremely improvement in computer time with respect to previous calculations.

The most important contributions of this work are:

1. The model is extended to double track networks.
2. For the first time the alternate double-single track (ADST) lines are proposed and some examples of applications are given.
3. A very efficient method for reducing the number of binary variables is given that performs very well and makes it possible to solve large timetable problems.
2.7 The Cacchiani and Toth discussion on timetabling problems

Cacchiani and Toth (2012) survey the main models for solving the timetabling problems. They differentiate several types of problems, as follows:

1. Cyclic (periodic), that is, timetables that repeat with time by a simple translation or non-cyclic timetables, such that they do not have a period. They describe both types of models by providing the objective functions and the constraints associated with each of them.

Since, in this thesis we deal with the most general case, that is, with non-cyclic timetables, we limit the discussion to this case. Among the different integer linear programming models that have been proposed for the non-cyclic case, Cacchiani and Toth (2012) mention two formulations. In the first (see, for example, Carey and Lockwood (1995)), the arrival and departure times at stations are represented by continuous variables and binary variables are used to express the order of the train departures from each station.

In the second one (see, for example, Caprara et al. (2002)) the time is discretized and the problem is represented on a timespace graph, where each node represents the arrival or departure time of a train to a station and the arcs represent the stop of a train at a station or the travel times of trains between consecutive stations.

2. Railway single one-way line or corridor, where a corridor is meant as a single one-way track, linking two major stations, with a number of intermediate stations in between, or more complex network lines, where several corridors are integrated with the associated interactions.

3. Freight or passenger transportation. There are passenger lines, freight lines and mixed lines. Due to the different operating conditions, the associated models must necessarily be different. In general freight trains have a lower priority and their timetables are adapted to cause no interference with passenger trains.

4. Different objective functions. We can try to adapt to the required or desired timetable and be penalized for departures from this ideal situation, we can minimize travel times, energy consumptions, etc.

They also analyze the problem of robustness of a timetable and differentiate between light and recoverable robustness. Robustness refers to schedules that avoid delay propagation as much as possible, in case of disturbances or disruptions in the railway network. A common way to obtain robust timetables is to introduce buffer times that can absorb possible delays occurring at the operational level.

The most important contributions of this work are:
1. To provide a classification of the different problems that appear in timetable optimization and to survey the most relevant methods to solve them.

2. To point out the importance of timetable robustness and how ignoring this property in the design stage of railway design can lead to timetables that are practically unfeasible.

### 2.8 The Törnquist and Persson model for perturbations

Törnquist and Persson (2007) present a mixed integer linear program to reorder and reroute trains when necessary. To this end they use continuous variables to represent start and end times of an event, that is, a segment resource request by a certain train, and continuous variables to reproduce event delays. Binary variables are used to indicate use of tracks and train priorities.

The constraints are used to:

1. Force each train event to be directly succeeded by the next one.
2. Force each event to use the assigned track at least the specified time.
3. Enforce the planned stops.
4. Ensure that events that have started but not ended prior to the occurrence of the disturbance, start as planned.
5. Record the delay magnitude of the events.
6. Enforce that every event uses exactly one track.
7. Events must be sufficiently separated.
8. Force two conflicting events must have different priority.
9. Make sure that the track used for event k is sufficiently long to accommodate the corresponding train.
10. Enforce a fixed penalty cost if a certain delay is exceeded.
11. Synchronise the connecting trains and force the trains to wait for each other.

To guarantee safe operations their model considers fixed headway times between trains and fixed running times along segments between stations. The objective function to be minimized consists of the total delay time of all trains.
Since there will be no or only a small number of changes, the idea to reduce the computational effort is to allow only for small changes. In particular they consider four strategies, based on producing some swaps.

To improve the speed of the solution, which cannot always be obtained in seconds, they present a heuristic approach that runs very fast.

The most important contributions of this work are:

1. The structure of one of the most important models for optimization of timetables is extended to the case of re-scheduling.

2. The idea of reducing the search space by analyzing only small swaps at a time. This technique reduces the CPU time, which is needed for this real time application.

2.9 The Acuna-Agost et al. model for dealing with perturbations

Acuna-Agost et al. (2011a,b) extend the model developed by Törnquist and Persson (2007) by (1) adding the delays due to decelerating, braking and accelerating, and (2) allowing two trains to circulate in the same segment if they travel in the same direction, by using a sufficiently safe headway time.

Some techniques to accelerate the computation time are presented too. The idea consists in limiting the search space to a region close to the initial timetable using a probabilistic approach.

The main original contributions of these works are:

1. Consideration of the delays associated with acceleration, deceleration and braking. In order to have realistic travel times, these issues cannot be ignored.

2. The idea of allowing two trains to circulate in the same segment if they circulate in the same direction. This solution is very efficient when we have single-tracks and there are some trains in the same direction circulating close. Consideration of this alternative can reduce the travel times substantially, especially when the single-track segment is long and there are no passing loops.

3. The introduction of probabilistic approaches to the problem of re-scheduling after disruptions.

4. The application of the proposed models to real cases, such as Chile and France railway lines.
2.10 The works of Cacchiani et al.

Cacchiani and Toth (2012); Cacchiani et al. (2014) presents a complete survey of recovery models and algorithms for real-time railway disturbance and disruption management. The authors distinguish between disruptions and disturbances. According to them:

Disturbances are relatively small perturbations of the railway system that can be handled by modifying the timetable, but without modifying the duties for rolling stock and crew. Disruptions are relatively large incidents, requiring both the timetable and the duties for rolling stock and crew to be modified.

Consequently, disruptions imply not only timetable re-schedule but rolling stock and crew changes. Thus, in this thesis we have limited our analysis to the case of disturbances.

These authors mention that most existing models consider that the routes of the different trains are given, and they limit to optimize the arrivals and departure times to stations and solving the safety conflicts among them, and that the re-routing problem is normally a separate problem. However, in the case of re-scheduling, an analysis of possible change of the train routes can lead to better solutions. In particular, when a route is blocked, the optimal re-scheduling forces changes of routes when they are possible. Consequently, models allowing for these changes are the most adequate.

The two approaches microscopic and macroscopic are distinguished. In a microscopic approach details of block sections and signals are taken into account and considered in detail. Usually blocking time graphs and the underlying data, such as maximum and minimum accelerations are used to compute detailed running and headway times. In a macroscopic approach the stations are represented by nodes, the tracks by arcs, and an operational speed is considered for each segment, that is, the small details of block sections, slopes and signals are ignored.

Since this thesis is limited to the macroscopic approach, we limit to indicate that Cacchiani et al. (2014) recommend as the most important macroscopic models among others those of Tornquist and Persson (2007), Acuna-Agost et al. (2011a) and Acuna-Agost et al. (2011b).

The main original contributions of these works are:

1. A classification of models and algorithms for real-time railway re-scheduling. This clarifies the re-scheduling problem and facilitates the understanding of the main associated concepts.

2. To distinguish between disturbances and disruptions. It is important to realize that the disruption problem is a difficult problem that implies important changes with respect to the initial timetable.

3. The distinction between microscopic and macroscopic approaches. The consideration of the railway network management problem as a whole is Today practically
impossible because of its complexity. Thus, dealing with the problem at different levels of detail is a good idea that must be acknowledged.

### 2.11 The Burdett and Kozan model

In Burdett and Kozan (2010) the authors proposed a new hybrid job shop approach to construct new train schedules. The main characteristic and contribution of this novel approach is that it incorporates unique aspects of timetable scheduling problems such as train length, blocking, alternative routing, train acceleration and deceleration, re-entrant and circular path, etc., which are necessary in order to perform a realistic scheduling, and they are incorporated by modifications conducted over the classical activity on node (AON) disjunctive graph of the job shop. It is important to note that the authors have considered in this approach to fix the train speeds and to retain the non delay scheduling. Proposed AON graph, differs from traditional versions in:

1. the disjunctive arcs are no longer the reverse of one another
2. the weights that represent time lags and overlaps between operations can take positive or negative values and incorporate the headways, dwell and processing times.

The model proposed a constructive algorithm to schedule trains, and in order to reach a feasible solution, trains are inserted iteratively, it is important to notice that in this model, authors have considered to insert trains in order from large to smallest total transit times; however any approach can be considered. Finally it is important to state that the main algorithm constructs a train-by-train schedule and operation-by-operation, using sophisticated dynamic route selection mechanisms backtracking and insertions, with these, a feasible solution is guaranteed. As a final remark, the constructive algorithm developed provides a robust (because it is suitable for any objective criterion) and substantial search capability.

The most important original contributions of this work are:

1. Crossing loop incorporation, that facilitates the circulation of trains in contrary direction when we have single-track lines.
2. Incorporation of unique aspects of timetable scheduling problems such as train length, blocking, alternative routing, train acceleration and deceleration, re-entrant and circular path for the first time in a job shop approach.

### 2.12 The Xie and Li model

In Xie and Li (2012) the authors proposed an integer linear programming model to solve the timetable rescheduling problem based on the feedback of train circulations. The model
considers a cyclic known timetable, so arrival and departure train order for stations is also 
known. The objective function minimizes the total travel times of train departures
\[
F = \text{Minimize} \sum_{i=1}^{j} (a_i^t - d_i^t) + T \sum_t p_t
\] (2.12) 
where, \(a_i^t\) corresponds to the arrival time of train \(t\) at destination station \(d\), with \(0 \leq a_i^t < T\) and \(d \in D(n)\) (being \(D(n)\) the destination train station); \(d_i^t\) is the departure time \(t\) from station \(n\), with \(0 \leq d_i^t < T\) and \(o \in O(n)\) (\(O(n)\) is the origin station of a train); \(T\) is the cycle time of timetable and \(p_t\) correspond to the binary variable of train \(t\). The model is restricted by the following constraints:

1. Fixed arrival times.
2. Fixed departures times.
3. Correct trip times.
4. Correct dwell times.
5. Trains do not meet on a track.
6. Minimum headway is respected at all times.
7. Turnaround requirements.

It is important to notice that with the proposed integer linear programming the quality 
of train set circulations has improved a lot.

The most important original contributions of this work are:

1. The literature review on cyclic timetabling, train-set circulation and timetable op-
   timization and adjustment.
2. The definition of the problem of timetable rescheduling based on train-sets circula-
   tion feedback.
3. The integer linear programming model based on the fixed departure/arrival order.

2.13 The D’Ariano-Pranzo Dispatching System

In [D’Ariano and Pranzo (2009)] the authors propose an advanced real time train dispatch-
ning system, which goal is to minimize the propagation of delays in a dispatching area under 
severe disturbances. Authors decompose a long time horizon into tractable intervals that 
are solved in cascade being the main objective to improve punctuality of trains. In this
model, authors extend the use of the real time dispatching system, ROMA (Railway traffic Optimization by Means of Alternative graphs) for short term prediction of train traffic in a dispatching area under strong disturbances.

The main contributions of the paper are:

1. Propose a decomposition of the problem into a series of smaller problems that progressively arrive to the final solution (cascade solution). The alternative graph formulation is adopted where $G = (N, F, A)$ is the graph that represent all the trains running during the entire time horizon.

2. Two resolution procedures are proposed: (1) when a single time interval is selected the approach correspond to the global resolution, otherwise (2) a temporal decomposition scheme is considered and the problem is divided into $m$ tractable alternative graphs, each one extended over a period of length $\tau$. This approach may require that some train routes need to be divided in two time intervals, a constraint coordination being necessary (i.e. the possible positions and speeds for the train route). The problem is solved enforcing some precedent relation constraints between time intervals, being the resolution process iterative; after a graph is solved a new graph is generated and the resolution process repeated until the last time interval, as a result of this decomposition, the dispatching system compute locally feasible schedules that correspond to the global feasible solution.

2.14 The Carey-Crawford model for busy complex stations

Carey and Crawford (2007) extend the model previously developed by Carey and Carville (2003) from algorithms to scheduling trains for a single busy complex station to algorithms for scheduling trains for multiple stations with single or multiple one way lines in each direction between the stations. The approach conducted by the authors correspond to an heuristic approach without mathematical programming. Since, different speed trains exists, stations are not at the same distance between them, trains can skip some stations, more trains can be scheduled at peak times, among other considerations, the system is not considered as regular. The criterion considered in the algorithms to solve the conflicts, is the least cost of the time delay and not the smallest time delay. The algorithms proposed and its main characteristics are:

1. Algorithm $M_0$: Corresponds to the extension of the Algorithm $A_1$ presented by Carey and Carville (2003) for multi-station and multi-lines. This algorithm allows us to find out the best time slot and platform for a train $t$ at a station $s$. The main change from previous algorithm ($A_1$) is the intra-and-inter-station headway times that need to be incorporated. Also it was necessary to find out and solve conflicts...
with preceding and succeeding trains. In this algorithm, when a train time conflict cannot be solved by changing platforms, the solution always came from adjustment of the current $t$ train.

2. *Algorithm $M_1$*: Provides an improved version of Algorithm $M_0$, allowing us to incorporate flexible options for solving conflicts. In this case the time conflicts can be solved by adjusting the current train $t$ or any other train in conflict, being the train to adjust the one with the least cost delay.

3. *Algorithm $M_1^*$*: Algorithm $M_1$ provides flexibility with respect to the algorithm $M_0$, nevertheless, the choice is confined to line conflicts and headway conflicts between stations. In the algorithm $M_1$ trains that use the same platforms, can also be adjusted.
Chapter 3

TIMETABLE OPTIMIZATION MODEL

Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 The optimization problem</td>
<td>60</td>
</tr>
<tr>
<td>3.1.1 Data</td>
<td>60</td>
</tr>
<tr>
<td>3.1.2 Variables</td>
<td>60</td>
</tr>
<tr>
<td>3.1.3 Constraints</td>
<td>61</td>
</tr>
<tr>
<td>3.1.4 Objective function</td>
<td>64</td>
</tr>
</tbody>
</table>
CHAPTER 3. TIMETABLE OPTIMIZATION MODEL

3.1 The optimization problem

The problem of designing an ADST railway line including the decision on single or double-track segments and the traffic demand can be stated as indicated in the following subsections, where the four elements, data, variables, constraints and objective function, of the optimization problem used in this thesis are discussed.

Due to the important role played by this model, we dedicate a whole chapter to it. In order to solve other important problems, such as the possibility of route selection and the case of disturbances, some changes will be done to this model in the following chapters.

3.1.1 Data

The data required for the design of an ADST line are:

1. List of the selected segments to be constructed as single or double-track segments.
2. Costs per km of each solution (single or double-track) for each segment.
3. The number of daily services to be attended (trains).
4. Desired departure times $r_0^i$ of all services and their corresponding lower and upper bound flexibilities $r^l_i, r^u_i$.
5. Maximum travel times associated with each segment and train.
6. Minimum headway times among consecutive trains in the same or contrary direction to guarantee the required safety level.
7. Minimum travel time $t^0_i$ per route and train $i$.
8. Priority $\gamma_i$ of train $i$ ($0 < \gamma_i \leq 1$).
9. The station dwell times of all trains.

3.1.2 Variables

Selecting the variables involved in a given optimization problem is not trivial and has relevant consequences in terms of efficiency and complexity (memory and cpu time requirements). The variables used in our model are the following:

$b_j$: binary variable which takes value 0 for single-track and 1 for double-track in segment $j$.

$e_{i,j}$: entry time of train $i$ at segment $j$.

$s_{i,j}$: exit time of train $i$ at segment $j$. 
CHAPTER 3. TIMETABLE OPTIMIZATION MODEL

\( t_{i,j} \): travel time of train \( i \) for segment \( j \).

\((\varepsilon \geq 1)\): maximum relative travel time of all trains including priority correction.

\( q_{i,j,t} \): binary variable that takes value 1 if train \( i \) uses track \( t \) at segment \( j \).

\( r_i \): departure time of train \( i \).

\( x_{i_1,i_2,j} \): binary variable that takes value 1 if train \( i_1 \) uses segment \( j \) before train \( i_2 \).

\( y_{i_1,i_2,j} \): binary variable that takes value 1 if train \( i_2 \) uses segment \( j \) before train \( i_1 \).

\( \eta_{i_1}^f, \eta_{i_1}^u \): before and after departure time flexibilities of train \( i \).

3.1.3 Constraints

1. \textit{Departure time constraints}. Departure times must coincide with the entry times to the first segment, thus, they force trains entering the first segment at departure times.

\[ s_{i,1} = r_i, \quad \forall i \in I, \] (3.1)

where \( I \) is the set of all trains.

2. \textit{Running time constraints}. The segment exit time must be the entry time plus the segment travel time. They guarantee that the speed limits are satisfied.

\[ e_{i,k} = s_{i,k} + t_{i,k}, \quad \forall i \in I; \forall k \in K_i, \] (3.2)

where \( k \) is the segment and \( K_i \) is the set of all segments in the route of train \( i \).

3. \textit{Speed constraints}. They bound the speeds from below and from above to guarantee a minimum speed and impede speeds above a given maximum.

\[ t_{i,k}^l \leq t_{i,k} \leq t_{i,k}^u, \quad \forall i \in I; \forall k \in K_i, \] (3.3)

where \( t_{i,k}^l \) and \( t_{i,k}^u \) are the lower and upper bounds of the travel time \( t_{i,k} \).

4. \textit{Dwell time constraints}. Dwell times at stations must be lower bounded to guarantee that a minimum dwell time is satisfied at each station where trains stop.

\[ s_{i,k} \geq e_{i,k-1} + d_{i,k}^l, \quad \forall i \in I; \forall k \in K_i, \] (3.4)

where \( d_{i,k}^l \) is the dwell time of train \( i \) at the station located at the end of segment \( k \).
5. **Siding constraints.** At sidings the dwell times could be non null. They eliminate dwell times at no siding nodes, that is, dwell times are allowed at nodes only if they correspond to stations or sidings.

\[
s_{i,k} = e_{i,k-1}; \forall i \in I; \forall k \notin PL,
\]

where \( PL \) is the set of passing loops.

6. **Double-track existence constraints.** Non-existing tracks must not be assigned to running trains. They impede assigning of a second track when this track does not exist.

\[
q_{ij2} \leq b_j; \forall i \in I; \forall j \in K_i
\]

7. **Departure time flexibility constraints.** Departure time flexibilities must be lower and upper bounded. They force departure times to satisfy their required margins, which are given.

\[
r_i > r_{0i} - \eta_l^i; \forall i \in I
\]

\[
r_i < r_{0i} + \eta_u^i; \forall i \in I,
\]

where \( r_{0i} \) is the desired departure time for train \( i \) and \( \eta_l^i \) and \( \eta_u^i \) are the departure time flexibilities for train \( i \).

8. **Circulation period constraints.** Line availability period must consider maintenance period. They establish that the operation period is limited, to guarantee a minimum time for maintenance operations.

\[
s_{i,1} \geq t_{\text{min}}, \forall i \in I
\]

\[
e_{i,\text{last}} \leq t_{\text{max}}, \forall i \in I,
\]

where \( t_{\text{min}} \) and \( t_{\text{max}} \) are the start and end times of the period reserved for line operations.

9. **Relative travel time min-max constraints.** They provide a common relative travel time upper bound \( \varepsilon/\gamma_i \) for all trains. They force the value of the \( \varepsilon \) variable to be the maximum relative travel time of all running trains. Normally, these relative travel times are small, that is, no more than 1.10 for high speed trains and no more than 1.25 for the rest of passenger trains.

\[
(e_{i,\text{last}} - r_i)/t_i^0 \leq \varepsilon/\gamma_i, \forall i \in I,
\]

where \( t_i^0 \) is the travel time associated with a maximum possible speed for train \( i \). Note the role of the low priorities \( \gamma_i \) in increasing the associated relative travel times.
10. **Track use constraints.** Each train uses only one track at each segment, that is, they force trains to use one and only one track per segment.

\[ \sum_t q_{i,j,t} = 1, \quad \forall i \in I, \quad j \in S, \quad (3.12) \]

where \( S \) is the set of all segments.

11. **Limited budget.** The total construction cost is guaranteed to be below the budget limit

\[ \sum_j (1 - b_j) S_j + b_j D_j \leq B, \quad (3.13) \]

where \( S_j \) and \( D_j \) are the cost associated with single or double-track of segment \( j \), respectively.

12. **Headway constraints for opposite direction trains.** They warrant safe headway times for trains circulating in contrary directions. They force a priority to be established for trains competing for common tracks and safe operations. They guarantee that trains circulate sufficiently far apart (in our examples we have used a headway of at least 4 minutes) in both the opposite and same directions. These constraints impede trains to enter a given segment immediately or before the previous train has abandoned the segment, using safe headways when this occurs.

\[ s_{i_1,j} - e_{i_2,j} \geq h_{i_1,i_2,j} y_{i_1,i_2,j} - M(1 - y_{i_1,i_2,j}) \quad (3.14) \]
\[ s_{i_2,j} - e_{i_1,j} \geq h_{i_1,i_2,j} x_{i_1,i_2,j} - M(1 - x_{i_1,i_2,j}) \quad \forall i_1, i_2 \in I; \quad \forall j, \quad (3.15) \]

where \( M \) is a high enough constant value and \( h_{i_1,i_2,j} \) are the headways associated with trains \( i_1 \) and \( i_2 \) at segment \( j \).

13. **Headway constraints for same direction.** They warrant safe headway times for trains circulating in the same direction.

\[ s_{i_2,j} - s_{i_1,j} \geq h_{i_1,i_2,j} x_{i_1,i_2,j} - M(1 - x_{i_1,i_2,j}) \quad \forall i_1, i_2, j \quad (3.16) \]
\[ s_{i_1,j} - s_{i_2,j} \geq h_{i_1,i_2,j} y_{i_1,i_2,j} - M(1 - y_{i_1,i_2,j}) \quad \forall i_1, i_2, j \quad (3.17) \]
\[ e_{i_2,j} - e_{i_1,j} \geq h_{i_1,i_2,j}^0 x_{i_1,i_2,j} - M(1 - x_{i_1,i_2,j}) \quad \forall i_1, i_2, j \quad (3.18) \]
\[ e_{i_1,j} - e_{i_2,j} \geq h_{i_1,i_2,j}^0 y_{i_1,i_2,j} - M(1 - y_{i_1,i_2,j}) \quad \forall i_1 < i_2 \in I; \quad \rho_{i_1,i_2,j} = 1, \quad (3.19) \]

where the constants \( \rho_{i_1,i_2,j} \) is equal to one if trains \( i_1 \) and \( i_2 \) compete for segment \( j \) and zero otherwise. These values can be estimated based on the desired departure times and their flexibilities, the train routes and the operating speeds. However, checking the estimates must be done after a solution is obtained. This produces important savings in the number of binary variables \( x \) and \( y \) and consequently in the CPU time required.
14. **Exclusion constraints.** If two trains use the same track at a given segment $j$, at least one of them must have priority for this segment. They avoid conflicting priority assignments when trains compete for the same segment track and avoid priorities to be given to more than one competing train.

$$b_j + q_{i_1, j} + q_{i_2, j} - 2 \leq x_{i_1, i_2, j} + y_{i_1, i_2, j}; \forall i_1, i_2 \in I; \forall j \quad (3.20)$$

$$q_{i_1, j, 1} + q_{i_2, j, 1} - 1 \leq x_{i_1, i_2, j} + y_{i_1, i_2, j}, \forall i_1 < i_2 \in I, \forall j, t. \quad (3.21)$$

15. **At most one train from each couple of trains has priority for a segment** $j$

$$x_{i_1, i_2, j} + y_{i_1, i_2, j} \leq 1; \forall i_1 < i_2 \in I, \forall j. \quad (3.22)$$

16. **Relative travel time upper bound constraints.** Bounded relative travel time $\varepsilon$. They enforce the upper bound for the optimal maximum relative travel time. We use relative travel times (quotients of the actual travel time divided by the minimum possible travel times). “Relative travel time upper bound constraints” together with “train priorities” imply fixing bounds for the arrival times of all services (trains). This means that the problem is indirectly solved in the backward-in-time direction too.

$$\varepsilon \leq \varepsilon_u. \quad (3.23)$$

### 3.1.4 Objective function

We have selected an objective function to be minimized including five objectives in hierarchy: (a) construction cost, (b) maximum relative travel time $\varepsilon$, (c) sum of relative travel times for all trains, (d) energy consumption and (e) sum of departure time flexibilities. Consequently, the objective function has been selected as:

$$\min_{b, s, e, r, t, x, y, \eta} Z = c(b) + \alpha_1 \varepsilon + \alpha_2 f(e, s) - \alpha_3 g(e, s) + \alpha_4 p(e, s) \quad (3.24)$$

where

- $c(b) = \sum_j (1 - b_j) S_j + b_j \ D_j$: Construction cost

- $\varepsilon = \max_{i \in I} \left[ \gamma_i \frac{e_{i, \text{last}} - s_{i, 1}}{t_0^i} \right]$: Maximum relative travel time

- $f(e, s) = \sum_{i \in I} \gamma_i \frac{e_{i, \text{last}} - s_{i, 1}}{t_0^i}$: Sum of relative travel times

- $g(e, s) = \sum_{i \in I, k} (e_{i, k} - s_{i, k-1})$: Sum of travel times

- $p(e, s) = \sum_{i \in I} |r_{0i} - r_i|$: Sum of departure flexibilities

The values of $\alpha_1, \alpha_2, \alpha_3$ and $\alpha_4$ must be selected with care in order to get the desired hierarchy of objectives (see Castillo et al. (2011) for a detailed description of how to select these values).
Part III

ALTERNATE DOUBLE-SINGLE TRACK
Chapter 4

ALTERNATE DOUBLE SINGLE TRACK

Contents

| 4.1 Introduction and motivation                  | 68 |
| 4.2 The optimization problem                    | 71 |
| 4.3 Proposed method to solve the problem         | 74 |
| 4.3.1 Proposed method based on partitioning the horizon period in small subperiods | 75 |
| 4.4 Examples of applications                    | 76 |
| 4.4.1 The Palencia-Santander line               | 76 |
| 4.4.2 Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line | 84 |
| 4.5 A detailed sensitivity analysis             | 87 |
| 4.6 Conclusions                                | 89 |
| 4.7 Notation                                   | 91 |
4.1 Introduction and motivation

The problem of capacity optimization of planned or existing railway lines has played an important role in the existing literature on railway management (timetabling and traffic control). Some example is the work of Caprara et al. (2007) who provide a state-of-the-art review on general railway optimization problems. In particular they discuss the train schedule problem, which can be considered as one of the most interesting problems in the planning and posterior operation of transportation systems.

The problem of timetable optimization is a very difficult (see Higgins et al. (1996)) and complex problem (NP-hard) (see Caprara et al. (2002), Carey (1994)). It consists of selecting the optimal time departures and arrivals of trains from and at stations so that safety constraints and user requirements are satisfied. This means that travel times must be minimized and all possible conflicts among running trains must be resolved. These problems have been dealt with in the literature by many authors (see, for example, Jia and Zhang (1993), Sahin (1999), D’Ariano et al. (2007a) or Carey and Crawford (2007)). For a detailed and complete analysis of the timetable design principles see Pachl (2014).

Cacchiani and Toth (2012) consider nominal and robust timetabling problems, where nominal refers to a problem satisfying the required operating and safety constraints and robust refers to problems that in case of disturbances in the railway network avoid delay propagation as much as possible. They also deal with light robustness, which consists of requiring a level of protection against the uncertainty of the coefficients in the constraint matrix and, at the same time, allowing a violation of the constraints that is minimized in the objective function. Finally, they distinguish between cyclic and non-cyclic timetables. In this chapter the robustness is taken into account with a set of generous headway times and we consider non-cyclic timetables. The model in Caimi et al. (2012) assigns precomputed blocking-stairways to trains while respecting resource-based clique constraints.

The first application of the mathematical programming methodology applied to train management optimization problems is attributed to Amit and 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 and Hayashi (2002) or Ouyang et al. (2009)). An exhaustive analysis of existing optimization methods can be seen in Cordeau et al. (1998).

One of the main reasons explaining why the formulation and solution of railway optimization problems is complicated is that many thousands of continuous and specially binary variables and constraints are involved, leading to very complex mixed integer (MIP) linear and non-linear related programming problems (see among others Kraay and Harker (1995), Carey and Lockwood (1995), D’Ariano and Pranzo (2004); D’Ariano et al. (2007b), Higgins et al. (1996)), requiring a huge amount of memory and computational
resources (see Burdett and Kozan [2010]).

As indicated, most train scheduling problems are very complex. As it is well known, binary or integer variables force branch and bound or related techniques, which require a huge amount of time and memory, and what is worse, as indicated by some authors, “it is very hard to find a generalized re-scheduling algorithm suitable for all kinds of emergency cases because of various railway infrastructure and various emergency management actions”. In fact, these cases involve solutions such as merging trains, making detours or cancelling services, which are difficult to deal with.

Unfortunately, the size of real problems can reach a point in which serious complexity problems appear. To solve this problem, Lin and Ku [2013] propose genetic algorithms.

When a review of the existing methods to optimize timetables is done, the following problems can be found:

1. When the number of services increases above a given threshold, say 70 – 100 trains, the problem complexity, measured in terms of number of variables, number of constraints, and memory or CPU time requirements, reaches a very high level. In these cases the computer models are not able to solve the stated problems because they cannot obtain the optimal solution in a reasonable time.

2. Most existing computer models for timetable optimization do not consider the case of disturbances or disruptions, that is, changes in the railway line conditions during the scheduled periods. The most common disruptions include: (a) blocking of a segment for a given period of time, and (b) speed reductions, caused by several reasons, such as weather conditions (heavy rain, snow, wind, etc.), maintenance, etc. When these events occur, timetables must be recalculated in a short period of time. If the complexity is very high, this is not possible and the models become useless. This limits considerably the practical value of the associated models.

3. Some real network topologies, for example, those containing loops do not fit the assumed topologies in some mathematical models. Then, alternate models are needed.

Since we desire a solution in a short time, we cannot expect to reach the optimal solution of the initial problem. However, we aim at obtaining a solution as close as possible to the optimum for it to become of practical value (for example, at a cost excess not larger than 1 – 5% of the optimum value or with a maximum travel time not exceeding in 20% the minimum possible, etc.). One of the methods we propose in this thesis consists of dividing the initial optimization problem in several small problems by selecting fractions (time windows) of the horizon period so that the complexity (number of variables and constraints, memory and CPU requirements) reduces considerably.

Apart from having a different objective function and constraints, D’Ariano and Pranzo [2009] introduce the partitioning idea and decompose the railway traffic into tractable time intervals to be solved in cascade by inserting the position and the speed of each train at the end of the time interval as an input constraint for the subsequent time
interval, that is, they solve independent subperiod problems and any decision made at a given subperiod is maintained. On the contrary, we divide the time horizon period in consecutive small enough partitions and solve several optimization problems in sequence, fixing some of the variables of previous partitions to fixed values. If some services have started or can be started at a given partition, the corresponding times are optimized at that stage and if the services end at that partition period, the corresponding variables (entry and exit times to segments, running times, track occupancies, etc.) are fixed, that is, they are forced to remain fixed at those values in the following steps. However, if at the end of some subperiod the end of a segment has not been reached by a train, the segment and train are incorporated to the following subproblem. Since the values of the corresponding variables are not fixed at this partition, this permits a better solution than the one resulting by optimizing these variables at the present partition. The problem of determining which variables can and must be fixed and which ones must be allowed to change in the following partition deserves a careful study.

The main original contributions of this chapter are:

1. We provide a method based on time partitioning. By time-partitioning we mean that the time horizon period is divided into small sub-periods such that the initial problem is divided into a sequence of smaller problems where only trains active in the corresponding sub-periods are optimized. In this way the problem complexity, instead of a non-polynomial increase with the number of services, exhibits a linear increase. This method does not guarantee the optimum solution, but a close solution to it (in terms of quality); however it produces a notable reduction in the time requirements and leads to safe and practical solutions.

2. Two partitioning strategies are discussed: (a) based on equal time periods and (b) based on equal number of active trains.

3. Inclusion of some new constraints and binary variables permit us to reroute trains. This case arises when existing conventional tracks are complemented with new tracks such that some unimportant stations are by-passed by the new tracks.

4. To illustrate the power of the proposed method, we apply the model to two real cases. More precisely, the cases of the Palencia-Santander and the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete lines are analyzed and discussed using the proposed models.

The chapter is organized as follows. In Section 4.2 we introduce the optimization problem to be solved. At the design stage, it includes two subproblems: (a) the sub-problem of planning the line in terms of deciding which segments must go in single-track and which must be in double-track, and (b) the subproblem of optimizing the timetable. In Section 4.3 we describe the partitioning technique to reduce the complexity of the
problem. In Section 4.4 we present two real examples of application, the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete and the Palencia-Santander line to illustrate the power of the method. In Section 4.5 we perform a sensitivity analysis. In Section 4.6 some conclusions are given. Finally, in the appendix we provide a table of notation to facilitate the understanding of the proposed mathematical model.

4.2 The optimization problem

In this section we introduce the optimization problem that allows us to obtain at the design stage: (a) the sequence of double and single-track segments that satisfies a given demand subject to the corresponding safety constraints, and (b) the optimized timetable for the given demand. When the method is used at the planning stage, it must contain some binary variables to account for the decision of which segments must go in single and which ones in double-track. However, at the implementation stage, since the decision on the single or double-track segments has already been made, the construction cost term and the associated binary variables are removed from the model.

In order to avoid repetitions, we do not give the mathematical formulation of the optimization problem, which can be seen in Chapter 3 or in Castillo et al. (2015). However, for the sake of clarity, we repeat the objective function. We minimize with respect to the variable vectors (boldfaced) $s, e, r, p, x, y, η, dt, ε$ (see table of notation at the end of the chapter), the function:

$$Q = C_1 \left[ \sum_{j \in S} (S_j(1 - dt_j) + D_j dt_j) \right] + C_2 \varepsilon + C_3 \left[ \sum_{i \in I} \frac{1}{r_i} (e_i - r_i) \right] + C_4 \sum_{i \in I} \eta_i$$

As indicated by Ghoseiri et al. (2004) our problem is multi-objective, thus we use four different objectives in our objective function (4.1) enumerated by hierarchy: (i) minimize the construction cost (only at the design stage), (ii) minimize the maximum relative travel time of all trains, where the relative travel time is the ratio between the actual travel time and the minimum possible travel time (at maximum speed), (iii) minimize the mean relative travel times, and (iv) minimize the flexibility in departure times, that is we choose departure times as close as possible (5-10 minutes at most) to the desired ones. The values of the $C_i; i = 1, 2, 3, 4$ constants are selected in decreasing order of magnitude and with adequate values to keep the hierarchy of the objectives. How this must be done has already been explained in Castillo et al. (2015). The idea consists in assigning each of the objectives one part of the significant figures in the objective function. For example, if we are able to work with a precision of 16 significant figures, we assign four of them to each of the four objectives by normalizing the values dividing by the maximum possible
CHAPTER 4. ALTERNATE DOUBLE SINGLE TRACK

ones and re-scaling them to occupy the desired place. This means that each constant \( C_i \) can be written as \( C_i = S_i/M_i \), where \( S_i \) and \( M_i \) refer to the scaling factor and to the maximum possible value of the corresponding objective functions, respectively.

A detailed description of the constraints used can be seen in Chapter 3, page 61.

Once the optimization problem has been solved, a sensitivity analysis can be and should be performed, for example, using the techniques in Castillo et al. (2004, 2006a,b, 2007, 2008). In particular the sensitivity of the final results to the model parameters is crucial.

In order to reduce the size of the problem we need a reduced number of binary variables. The \( \rho_{i_1, i_2, k, s} \) binary parameters (see Castillo et al. (2015)), which equal one if trains \( i_1 \) and \( i_2 \) share the same segment in close times, and zero, otherwise, are used to this end. Initially, we assume that two trains using the same segment compete for a track if they reach the center of the segment evaluated under maximum speeds with less than one hour difference. Otherwise, we eliminate the associated binary variables \( x \) and \( y \). A check is done after the solution is obtained and if a conflict among trains is detected, the one hour time period is increased and the problem solved again. Consequently, implementation of this technique does not change the original optimization problem. However, as indicated in Castillo et al. (2011), this reduction in binary variables has an important effect on the CPU time required.

The proposed model is a modified version of the model for alternating single and double-track segments in Castillo et al. (2015), which was already a combination of the models in Zhou and Zhong (2005, 2007) and Castillo et al. (2009), used for analyzing single–tracked railway lines, and the models of Törnquist and Persson (2007) and other used for multiple tracked lines. The changes refer to some extra constraints to account for a special type of network topologies that arise when we want to complement an already existing conventional line with some new tracks. One example where this topology arises is the case of existence of a conventional line that runs throughout several stations, when we want to build a new track, but in order to increase the speed, we do not want it to pass through some unimportant stations. Figure 4.1 shows the case of the Palencia-Santander line in which the conventional line has between Palencia and Mave, among others, the following very low demand stations: Monzón de Campos, El Carrión, Amusco, Piña de Campos, Frómista, Marcilla de Campos, Osorno, Espinosa, Herrera y Alar del Rey. The idea consists of building the new high speed track with four connections with the conventional line outside the stations, denoted by \( T_1 \) to \( T_4 \), such that stations can be by-passed. Since we want the optimization program to be able to decide whether the trains must circulate using the conventional or the new tracks, segments cannot be chosen individually but in groups (see Figure 4.1), corresponding with real segments in the conventional line but to virtual segments in the new line, and possibly returning to the conventional line but only at the connection points \( T_1 \) to \( T_4 \).

Some real network topologies, for example, those containing loops do not fit the assumed topologies in some mathematical models. Then, alternate models are needed. The
aim of the following constraint is to guarantee that this condition is satisfied, that is, segments used by a train must belong to the same group (conventional or new tracks).

Alternative route constraints. They force trains to use the same track groups associated with the established segment groups (see Figure 4.1 groups G1 to G4).

\[ q_{ikt} = q_{ik1t}; \text{ if } \sigma_{ikt} \text{ and } \sigma_{ik1t} \text{ belong to the same group } \forall i, k, t, \]  

where \( \sigma_{ikt} \) is the track \( t \) of the \( k \)-th segment number in the route of train \( i \) and the binary variable \( q_{ikt} \) equals one if train \( i \) uses track \( t \) of the \( k \)-th segment in the route of train \( i \) and zero, otherwise.

![Figure 4.1: Illustration of the proposal for the Palencia-Santander line.](image)

The relevance of considering this possibility will be illustrated in Section 4.4, but we anticipate that important savings can be obtained without loosing too much in traveling times when a combination of conventional tracks and new high speed tracks are used. In fact, new double-track lines are not necessary when the demands are low and can
be replaced by a combination of existing conventional single-tracks and new high speed tracks. Note that this constraint allows high speed trains to circulate using the new high speed tracks forcing other trains with low priority to use conventional tracks, when needed.

In this chapter we call problem $\mathcal{P}$ to the minimization of the objective function (4.1) subject to the constraints (3.1)-(3.23), pages 61 to 64 or in Castillo et al. (2015) and (4.2).

We end this section by noting that the above model depends on several parameters, in particular segment construction costs, maximum speeds, dwell times, headways, etc. Since the optimal solution obviously depends on how we fix these values, we must be careful at the parameter estimation and assignment stages.

### 4.3 Proposed method to solve the problem

In order to obtain a timetable in a short computing time, we propose two different alternatives: (a) the partitioning method based on periods of equal duration and (b) the partitioning method based on periods of equal active trains. As already indicated, the basic idea of the proposed method consists of dividing the initial time horizon of the optimization Problem $\mathcal{P}$ in several ones of small size such that either they have the same duration or they have the same number of active trains. To this end, we partition the total time period in small subperiods (time windows) taking into account the desired departure times and the corresponding flexibilities. Though these methods do not guarantee the optimal solution, and normally they provide different ones, they have the virtue of providing a good enough solution from a practical point of view in a very reduced time (say a few seconds). While the previous problem is non-linear in the number of services, the proposed partitioning method is linear in the number of services (trains) and partitions, which is very important.

With respect to the schedule problems it is important to realize that the optimization problem has an objective function and a set of constraints and that solving the problem provides a feasible solution which is optimized, where feasibility means that it satisfies the constraints, including safety constraints. We note that safety is the first aim of engineering design and optimality is only a desirable but secondary objective. Safe and efficient schedules are sufficient for engineering purposes, but optimal ones are the only valid from a mathematical point of view. In practice, safety must be satisfied but optimality is not always attainable or not attainable in a limited time. The solutions provided by the proposed method are always safe (feasible). We note that in this thesis we face our problem as engineers.
4.3.1 Proposed method based on partitioning the horizon period in small subperiods

In this subsection we explain how the method can be applied based on Problem $\mathcal{P}$. To solve the optimization problem in a reasonable time we propose the following algorithm.

**INPUT:** The main data of the problem consists of a horizon period $(\tau_{\text{min}}, \tau_{\text{max}})$, the number $n_{\text{services}}$ of railway services demanded in this period together with the desired departure times and associated flexibilities, the line characteristics (segments, segment lengths, allowable speeds, train characteristics, etc.), the number of parts $p$ used for the partition of the horizon period and the option selected (time windows of (a) equal duration or (b) with the same number of active trains).

**OUTPUT:** A train timetable as close as possible to the optimum of the Problem $\mathcal{P}$.

1. **Initiation. Set the partitions.** The partition counter $p$ is initiated to 1. The time horizon $(\tau_{\text{min}}, \tau_{\text{max}})$ is divided into small time windows $(\tau_1, \tau_2, \ldots, \tau_{p+1})$. With the intention of having small and similar complexities for all subproblems, the criterion used for selecting the value of the subperiod durations is to have the same durations or the same number of active trains. To this end, the desired departure times and their flexibilities are used. Let $\tau_1 = \tau_{\text{min}}$.

2. **Step 1. Update the time period for the current partition $p$.** Update the initial time $\tau^p_{\text{begin}} = \tau_p$ and the end time $\tau^p_{\text{end}}$ for the current time window of partition $p$ as follows. If the equal duration option is selected, $\tau^p_{\text{end}} = \tau^p_{\text{begin}} + (\tau_{\text{max}} - \tau_{\text{min}})/p$. Otherwise, $\tau^p_{\text{end}}$ is selected such that $n_{\text{services}}/p$ trains could have departed in the current partition, based on the desired departure times and the associated departure flexibilities.

3. **Step 2. Optimize the traffic in the current partition.** The set of services (trains) that can be running in this partition are activated and the optimization problem $\mathcal{P}$ is solved only for this set of services.

4. **Step 3. Check for segments already traveled.** Determine the segment time entries and exits (values of the variables $s_{i,\sigma_{i,k}}$ and $e_{i,\sigma_{i,k}}$, respectively) of trains occurred before $\tau^p_{\text{end}}$ and fix them at their actual partition optimized values. Similarly, determine origin train departures (variables $r_i$) occurred at this subperiod and fix them to their optimal values. Do the same with the running time variables $p_{i,\sigma_{i,k}}$ and tracks used by these trains (binary variables $q_{i,t}$).

5. **Step 4. Check for concluded services and remove them.** If services $i$ and $i_1$ have concluded at this stage, fix the corresponding $x_{i,i_1,k,k_1}$ and $y_{i,i_1,k,k_1}$ priority variables, that is, fix them to their constant values (zero or one).
6. **Step 5. Test for end of horizon period.** If the actual partition is the last partition, exit the cycle and provide results. Otherwise, move to the following partition, that is, let $p = p + 1$ and go to Step 1.

We finally note that since re-scheduling must be done in a limited time, this algorithm becomes especially useful for the case of disturbances that imply a modification of the time schedule, that is, when a re-scheduling is needed. In these cases, we need only to fix the disturbance occurrence time to coincide with $\tau_{min} = \tau_1$, that is, the boundary of the first partition.

Some illustrations of how this algorithm works are given in the following section.

### 4.4 Examples of applications

In this section we illustrate the proposed methods by their application to two real cases: The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete and the Palencia-Santander lines.

#### 4.4.1 The Palencia-Santander line

Here we present the case of the Palencia-Santander line, a single-track line that belongs to the Spanish conventional railway network. For many years Cantabrian politicians have petitioned to the central government for a high speed line to replace this line without success. However, things have changed recently, because the Madrid-Palencia high speed double-track line is already in service facilitating the connection between Santander and Madrid in a reasonable travel time. A project approved several years ago permits the connection with a high speed line of Palencia and Santander at a cost of 3,329 M€, which implies a travel time between Santander and Madrid of two and a half hours, but lacks financial support.

**Planning application**

In a previous paper (see Castillo et al. (2015)) it has been shown how the use of the alternate double-single-track (ADST) approach, which combines single and double-track segments, permits reducing the construction costs from 3,329 M€ to 2,493 M€ with very similar travel times, showing clearly that the ADST solution is an efficient alternative that should not be ignored. However, its cost was still too high to be a reasonable solution, due to the low associated traffic demands, because neither Santander nor Palencia are highly populated areas. This was the main reason why the central government did not provide financial support for the project during several years.

Apart from the ADST, in this example we present another alternative that allows reducing the cost to one tenth with an increase of half hour in travel time between Santander and Madrid.
In order to decide about the most convenient solution, we will use the proposed method to decide which segments must go in single and which segments must go in double-track.

However, before using our model, we must take into account the proper characteristics of the existing Santander-Palencia single-track line (see Figure 4.1). The platform of the last segment of 27 km between Torrelavega and Santander is already prepared to include a second track, so that the costs of duplicating the track in this section are not high. In addition, the number of circulating trains in this segment is the largest one. Consequently, it is clear, from the very beginning, that this segment is a good candidate for double-track.

In addition to the possibility of adding the second track between Torrelavega and Santander, at a low cost, we consider the possibility of rectifying, at a reasonable cost, the curves at two locations, and the possibility of building a high speed single-track to complement the existing conventional track, but only where this second track is necessary and cheap (see Figure 4.1).

With respect to the costs for single and double-track segments to be used as data in our optimization problem in this case, we consider the existing infrastructure at no construction cost, because it already exists, but we include the cost of removing level-crossings at the conventional line segments. This permits an important speed increase at the corresponding segments.

Tables 4.1 and 4.2 show some of the characteristics relevant to the optimization problem of the different segments considered in the Palencia-Santander line. Its columns give the segment number, the names of the segment end stations, the segment lengths for the two possible tracks, the maximum and minimum associated track speeds and an estimate of the construction costs. The maximum speeds in this table have been calculated taking into account the slopes, curve radii, train power, the times required for acceleration and deceleration of trains (see Figure 4.2). As an illustrative example, this figure shows the distance-speed diagram, given in km-km/hour, from Santander to Bárceña, considering the acceleration and deceleration curves and stops only at Torrelavega and Bárceña. This detailed diagram is needed to estimate the mean speeds (given in km/hour in the figure) and segment travel times to be used in the calculations. In addition to generous headways of 4 minutes, extra reductions of 5% of the segment travel times and a margin of 3 minutes per 100 km have been considered in order to guarantee robust solutions. The construction costs have been estimated taking into account the topography and the type of terrain and mainly whether or not tunnels or viaducts are needed for the new line (second track). Repair costs are estimated for the conventional line (first track). It must be indicated that the optimal solution (objective function value) obviously depends on these values, but the sequence of single and double-track segments could be not especially sensitive to them.

The segments between Torrelavega and Alar del Rey (see Figure 4.1) contain curves of small radio, tunnels and, in some parts (from Torrelavega to Reinosa), a maximum slope. Consequently, it is an area where tunnels and viaducts are practically the only possible solution for building a high speed track. This implies a very high construction cost. Thus,
Table 4.1: Characteristics of the different segments considered in the line.

<table>
<thead>
<tr>
<th>Segment number</th>
<th>Segment end stations</th>
<th>Length(km)</th>
<th>Mx (km/h)</th>
<th>Mi (km/h)</th>
<th>Cost(M€/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Palencia Monzon</td>
<td>12.1</td>
<td>11.3</td>
<td>109</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>Monzon ElCarrion</td>
<td>1.2</td>
<td>1.2</td>
<td>114</td>
<td>190</td>
</tr>
<tr>
<td>3</td>
<td>ElCarrion T1</td>
<td>7.2</td>
<td>7.2</td>
<td>114</td>
<td>190</td>
</tr>
<tr>
<td>4</td>
<td>T1 Amusco</td>
<td>0.1</td>
<td>0.1</td>
<td>114</td>
<td>190</td>
</tr>
<tr>
<td>5</td>
<td>Amusco Pina</td>
<td>5.3</td>
<td>5.3</td>
<td>114</td>
<td>190</td>
</tr>
<tr>
<td>6</td>
<td>Pina Fromista</td>
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<td>7.0</td>
<td>113</td>
<td>190</td>
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<tr>
<td>7</td>
<td>Fromista T2</td>
<td>5.1</td>
<td>5.1</td>
<td>114</td>
<td>190</td>
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<tr>
<td>8</td>
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<td>11.7</td>
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Table 4.2: Characteristics of the different segments considered in the line (continuation).

<table>
<thead>
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<th>Segment number</th>
<th>Segment end stations</th>
<th>Length(km)</th>
<th>Mx</th>
<th>S.</th>
<th>Mi</th>
<th>S.</th>
<th>Cost(M€/km)</th>
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<td>28</td>
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Figure 4.2: Illustration of the speed profile and of how the mean speeds were calculated considering the acceleration and deceleration of trains.

the segments in this area are clear candidates to single-track, that is, no change in the line can be done at a reasonable cost. Nevertheless, we note that an improvement of the track, ballast and catenary has already been done and this permits a small speed increase in these segments.

The first part, including approximately 90 km from Palencia to Alar del Rey, are flat and with good soil conditions, implying that construction of a new track allowing high speed is cheap. We also note that the existing conventional segments in this area have very many protected and unprotected level crossings, that cause a high reduction in speed.

Another possibility to improve the travel time consists of rectifying some curves. This is reasonably cheap in only two places, where a short viaduct and a short tunnel in a good terrain allow the rectification. If this new track is constructed, we convert these two segments into double-track segments, though one of then, the existing one, will be of low speed. The proposed method will decide about this possibility.

With all these considerations, we have introduced the data, corresponding to the existing services (demand) after increasing the number of long distance trains between Santander-Madrid and vice versa in 8 units, into our computer model and we have obtained the solution of problem $P$ obtained without partitions, that is, with $p = 1$ and denoted as Case 1. The results are in the upper plot of Figure 4.3 where we can see that the expected optimal double-track segments (shown in yellow color) appear between Santander and Torrelavega, at the two places where curves can be easily rectified, between
CHAPTER 4. ALTERNATE DOUBLE SINGLE TRACK

Alar del Rey and Palencia, where the cost of the new line is low, and a few more segments.

We have used the following constant values for the objective function:

\[
C_1 = 753116.85; C_2 = 89285.71; C_3 = 12.75;
\]

\[
C_4 = 0.07742; C_5 = 0.0000093985.
\]

Figure 4.1 shows the solution proposed to the Cantabrian government, which includes a detailed description of the suggested changes. It is based on the results in Figure 4.3 and consists of double-track in segments 1 to 13 (from Palencia to Alar del Rey), segment 16 (in Villaescusa de las Torres), segment 21 (in La Muñeca) and segments 42 to 54 (from Torrelavega to Santander). The rest of segments, due to the high cost of double-track, are planned to be single-track segments.

We note that, in addition to constructing the double-track segments, we have proposed to remove the level crossings in order to permit an important speed increase at the conventional segments. Finally, we have also increased the track length at 8 stations in order to allow freight trains 750 m. long to cross. This will permit an important development of the Santander port.

The resulting solution deserves some comments, such as the following:

1. The optimal solution includes several double-track segments. The first is from Torrelavega to Santander, where the traffic is very high and the cost of implementing the second track, as already commented, is low due to the fact that the platform is already built.

2. The longest double-track section appears between Alar del Rey and Palencia, where the traffic is low and the terrain flat. The reason explaining this result is not a high traffic demand nor a low cost but the need to attain the low travel times (high speeds) imposed. Note that the existing conventional line permits smaller speeds than the new ones, even though we have removed the level crossings in this part of the line.

3. The other two parts of the line where double-track appears in the optimized solution corresponds to the removed curves in Villaescusa de las Torres (with an easy to construct tunnel because of a favourable terrain) and La Muñeca (with a viaduct). These double-track segments are also motivated because of the high speed required.

4. Finally, the surprising result is that the cost of the new solution is 334 M€, that is, only one tenth of the initially projected double-track line. This confirms that solutions combining conventional lines with new high speed tracks appear to be very reasonable and raise serious doubts about indiscriminately using double-track high speed lines independently of the traffic demand, as it is usually done.
To see the influence of the number $p$ of time partitions or, more precisely, of the time window duration used on the resulting design and on the CPU time required, we present in Figure 4.3 the resulting time-distance diagrams for the Cases 1, 2 and 3, for a unique partition (upper plot), $p = 4$ partitions (intermediate plot) and $p = 16$ partitions (lower plot), respectively, assuming equal time partitions. Note that the timetables are very similar showing that partitioning does not produce an important change in the timetable quality. The resulting CPU times were 9664, 97.77 and 25.00 seconds\(^1\) respectively, showing an important improvement and consequently, the efficiency of the proposed method. If instead of equal duration partitions we use the same number of active trains per partition, the results are very similar with CPU times of 9664, 101.82 and 31.17 seconds. Though the CPU times are a little larger than the previous ones, we can see in Table 4.3 that the construction cost (boldfaced in the table) are smaller than those obtained with the same duration partitions. This proves that the equal number of active trains strategy is better than the equal time partitioning strategy. Though these CPU times are not relevant at the design stage, we note that using 4 partitions implies a reduction of the CPU time by a factor of 100 and using 16 partitions leads to a reduction factor of 400. Finally, we indicate that the three diagrams suggest double-track (see the yellow shadowed regions) at the two extremes and some intermediate short segments.

Table 4.3 shows the results of a sensitivity analysis in which the effect of the number of partitions or time window durations on the CPU or the quality of the solutions are analyzed. The table includes in its columns the number of services, the number of partitions, the time window duration or the number of active trains per partition, the optimal total construction cost of the line, the total CPU time required for the optimization and the CPU associated with the first partition, the value of the relative duality gap of the last partition, the maximum and mean relative travel times corresponding to the maximum priority trains (long distance trains), the same values for all trains, the maximum relative travel time for all trains, the mean relative travel time, the mean flexibilities for departure times. At the end of the table we show the number of variables and constraints required in the initial problem, respectively. They give an idea of how the CPU times and the qualities of the solutions, measured in relative travel times or maximum relative travel time $\epsilon$, are affected by the time window duration.

The upper half of the table, which corresponds to the design stage, reveals that the CPU times increase with the time window duration, illustrating the important savings that can be obtained with the proposed method. A comparison of the quality of the solutions, measured by the different construction costs or relative travel times, shown in the table, indicates that they are very similar, indicating that the effect of the time window duration is small. Consequently, the proposed method has shown to be computationally efficient.

The lower part of Table 4.3 shows the same results for the case of exploitation, that is,

\[^1\]These values can be reduced if we fix a larger duality gap without affecting safety. In the experiments a value of 0.001 was used.
Figure 4.3: Palencia-Santander line with existing traffic demand plus 8 more long distance trains. Cases 1, 2 and 3: Illustration of the effect of the time window duration (number of partitions $p$) on the resulting design corresponding to a single time window of 24 hours (Case 1 in the upper plot), a time window of 9 hours (Case 2 in the intermediate plot) and a time window of 2 hours (Case 3 in the lower plot).
Figure 4.4: The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line. Single and double-tracks are shown as thin and thick segments, respectively.

when the line has already been designed and only the timetable is optimized. We can also see that important CPU time reductions are obtained and that again the equal number of active trains appears to be better than the equal time partitions in terms of the objective function, which in this case is $\epsilon$ (boldfaced in the table), that is, the maximum relative travel time for the slowest train.

4.4.2 Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line

In this subsection we analyze the case of the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line, that was discussed in Example 2 of [Castillo et al. (2011)]. The network is shown in Figure 4.4.

The demand includes a total of 170 trains per day, with 36 Madrid-Málaga, 32 Madrid-Valencia, 42 Madrid-Sevilla, 18 Madrid-Toledo, 30 Madrid-Puertollano and 12 Madrid-Albacete trains and vice versa.

In [Castillo et al. (2011)], the difficulties associated with the complexity of this example were discussed and several methods and strategies were presented and discussed. Several methods were shown to be unable to provide a solution, but the bisection method was given as the best in terms of a CPU of 2658.53 seconds time required.

In this thesis, we limit to apply the proposed method to solve this problem and to show
### Line Design

**Time partition**

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### Train partition

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### Timetable optimization

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*Table 4.3: Palencia-Santander Case vars = 78401 const = 213460*
Figure 4.5: Case 4: The resulting optimized timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line.
the effect on the CPU and the quality of the resulting solutions. We report the CPU times and qualities associated with different values of the number of partitions $p = 1, 2, 4, 8, 16$.

The resulting timetable, which is very similar for the different number of partitions, is shown in Figure 4.5 (Case 4), where the different routes are shown with indication of the double-tracks in yellow color.

In the upper part of Table 4.4 which corresponds to the case of a design stage where the single and double track segments must be identified, we can see that the CPU times required at the design stage are very low (a few seconds) and that the time window duration has practically no effect on the total required CPU. This is due to the fact that trains circulate at very similar speed and this produces simple timetables. An important result is that the sequences of single or double track and consequently the construction costs are identical for any number of partitions and that no significant differences are observed for the cases of equal time or equal active trains partitioning.

In the lower part of the Table 4.4 we have considered a line with a more strict design (note that the construction cost is 11467 M€ instead of 12193 M€). This means that the timetable optimization is more complex because the number of double track segments is smaller. In this case, the CPU time reduction produce by the partitioning technique is very important and produces a reduction factor close to $70\% - 100\%$ when moving from one partition to 16 partitions, depending on the strategy used. However, the lost paid in terms of the objective function (maximum relative travel time $\epsilon$ value) is very small.

We have used the following constant values for the objective function:

\[
C_1 = 79778.21; C_2 = 83333.33; C_3 = 0.4902; \\
C_4 = 0.07059; C_5 = 0.000025907.
\]

### 4.5 A detailed sensitivity analysis

In order to test the efficiency and behavior of the two alternative partitioning techniques, i.e. those based on equal times and those based on equal number of active trains, a set of experiments have been designed. The following cases have been considered:

1. **Lines with equal and unequal train speeds.** We analyze two different types of lines: (a) the Palencia-Santander line, which combines long distance, commuter and freight trains, that is, trains with fairly different speeds circulate along the line, and (b) the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete high speed line, that is, a line in which only long distance trains with very similar operating speeds are circulating.

2. **Different partitioning strategies.** We have considered time windows based on: (a) equal time durations or (b) equal number of active trains.
### Line Design

#### Time partition

| trains | \( \Delta t \) | Cost | cpu | cpu\(_1\) | optcr | mxrt \(_1\) | mnrt \(_1\) | mxrt \(_a\) | mnrt \(_a\) | \( \epsilon \) | mean\(_\epsilon\) | flex | (sec) | (M) | (sec) | (sec) | \( \epsilon \) | mean\(_\epsilon\) | flex | min |
|--------|----------------|------|-----|----------|-------|-----------|-----------|-----------|-----------|--------|---------|------|-------|------|-------|--------|---------|------|-----|
| 170 1  | 16.25          | **12193** | 4.43 | 4.43    | 0.000000 | 1.016  | 1.000  | 1.016  | 1.000  | 1.016  | 1.000  | 1.016  | 1.000 | 0.68  | 1.230 | 1.008 | 1.230 | 1.008 | 3.53  |
| 170 2  | 8.13           | **12193** | 3.50 | 1.78    | 0.000003 | 1.090  | 1.003  | 1.090  | 1.003  | 1.090  | 1.003  | 1.090  | 1.003 | 0.98  | 1.230 | 1.015 | 1.230 | 1.015 | 3.94  |
| 170 4  | 4.06           | **12193** | 2.70 | 0.39    | 0.000003 | 1.093  | 1.005  | 1.093  | 1.005  | 1.093  | 1.005  | 1.093  | 1.005 | 1.52  | 1.230 | 1.020 | 1.230 | 1.020 | 5.18  |
| 170 8  | 2.03           | **12193** | 3.68 | 0.08    | 0.000000 | 1.100  | 1.034  | 1.100  | 1.034  | 1.100  | 1.034  | 1.100  | 1.034 | 3.12  | 1.230 | 1.023 | 1.230 | 1.023 | 4.12  |
| 170 16 | 1.02           | **12193** | 7.96 | 0.13    | 0.000000 | 1.100  | 1.029  | 1.100  | 1.029  | 1.100  | 1.029  | 1.100  | 1.029 | 2.75  | 1.230 | 1.025 | 1.230 | 1.025 | 4.61  |

### Train partition

| trains | \( \Delta t \) | Cost | cpu | cpu\(_1\) | optcr | mxrt \(_1\) | mnrt \(_1\) | mxrt \(_a\) | mnrt \(_a\) | \( \epsilon \) | mean\(_\epsilon\) | flex | (sec) | (M) | (sec) | (sec) | \( \epsilon \) | mean\(_\epsilon\) | flex | min |
|--------|----------------|------|-----|----------|-------|-----------|-----------|-----------|-----------|--------|---------|------|-------|------|-------|--------|---------|------|-----|
| 170 1  | 170.00         | 11467| 2218| 2218     | 0.000000| 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008 | 3.53  | 1.230 | 1.008 | 1.230 | 1.008 | 3.53  |
| 170 2  | 85.00          | 11467| 401 | 58       | 0.000000| 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008 | 3.77  | 1.230 | 1.008 | 1.230 | 1.008 | 3.77  |
| 170 4  | 43.00          | 11467| 81  | 5        | 0.000000| 1.237  | 1.008  | 1.237  | 1.008  | 1.237  | 1.008  | 1.237  | 1.008 | 4.12  | 1.237 | 1.008 | 1.237 | 1.008 | 4.12  |
| 170 8  | 21.00          | 11467| 44  | 0.7      | 0.000000| 1.237  | 1.010  | 1.237  | 1.010  | 1.237  | 1.010  | 1.237  | 1.010 | 4.28  | 1.237 | 1.010 | 1.237 | 1.010 | 4.28  |

### Timetable optimization

#### Time partition

| trains | \( \Delta t \) | Cost | cpu | cpu\(_1\) | optcr | mxrt \(_1\) | mnrt \(_1\) | mxrt \(_a\) | mnrt \(_a\) | \( \epsilon \) | mean\(_\epsilon\) | flex | (sec) | (M) | (sec) | (sec) | \( \epsilon \) | mean\(_\epsilon\) | flex | min |
|--------|----------------|------|-----|----------|-------|-----------|-----------|-----------|-----------|--------|---------|------|-------|------|-------|--------|---------|------|-----|
| 170 1  | 170.00         | 11467| 2218| 2218     | 0.000000| 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008 | 3.53  | 1.230 | 1.008 | 1.230 | 1.008 | 3.53  |
| 170 2  | 85.00          | 11467| 401 | 58       | 0.000000| 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008  | 1.230  | 1.008 | 3.77  | 1.230 | 1.008 | 1.230 | 1.008 | 3.77  |
| 170 4  | 43.00          | 11467| 81  | 5        | 0.000000| 1.237  | 1.008  | 1.237  | 1.008  | 1.237  | 1.008  | 1.237  | 1.008 | 4.12  | 1.237 | 1.008 | 1.237 | 1.008 | 4.12  |
| 170 8  | 21.00          | 11467| 44  | 0.7      | 0.000000| 1.237  | 1.010  | 1.237  | 1.010  | 1.237  | 1.010  | 1.237  | 1.010 | 4.28  | 1.237 | 1.010 | 1.237 | 1.010 | 4.28  |

*Table 4.4: RedSur Case vars = 52899 const= 151737*
3. **The design and the exploitation stages:** (a) at the design stage a decision must be made on which segments must go in single or double track in order to optimize the design, but taking into account the present and future demands, and (b) at the timetable optimization stage, that is, when the program is used only to optimize the timetables once the single and double track segments have been selected.

This makes a total of eight possible combinations. Tables 4.3 and 4.4 show the corresponding results. The gap between the optimal solution and those produced by the proposed model can be seen by comparing the case of a unique partition with those corresponding to several partitions (different values of $p$).

A comparison of these results leads to the following conclusions:

1. The CPU time required to optimize the timetables in the case of a line with trains circulating at the same speed is much smaller than the CPU required to optimize timetables with trains circulating at different speeds. Consequently, the proposed partitioning technique is especially useful for the second case, where the reduction of the associated CPU times can be very important (several orders of magnitude).

2. Though the time window based on active trains strategy does not appear to provide important savings in CPU, it provides better solutions, in terms of the objective function values, than the time window based on identical time durations strategy. This implies lower construction cost when used at the design stage, and smaller travel times, when used at the timetable optimization stage. In fact, consideration of active trains leads to more complex (better) solutions than those with equal time durations, which would require more CPU time if they were calculated with equal time duration windows and the same value of the objective function.

3. The design and the timetable optimization stages can show different results with respect to the partitioning strategy. If the line is saturated, the improvements in the CPU times due to partitioning is very important at both stages, but more important at the design stage, because of the complexity of the problem (it includes single and double track decisions). If the line is not saturated, the solutions are simple and then the differences are small.

### 4.6 Conclusions

The following conclusions can be drawn from the previous discussion:

1. The proposed method, based on time-partitioning of the horizon period in small subperiods (time windows), permits obtaining in a period of time much shorter (it can be one or several orders of magnitude) than the one associated with a unique partition, a feasible solution of the timetable optimization problem, which is close
enough (practically acceptable) to the optimal one and satisfactory for daily practice.

2. In complex timetables (including a large number of trains and having different speeds) the reduction due to partitioning appears to be very relevant. On the contrary, in timetables where the train speeds are similar, there are no many train crosses and no train overlappings, the reduction appears to be small.

3. Time windows based on equal number of active trains (similar complexity) seem to be better than time windows based on equal duration. Though the CPU time in our experiments were similar, the resulting solutions were better in terms of the objective function, for the same number of active trains strategy. This means that for the same quality the CPU times would have been better too.

4. Though in some cases quick solutions are looked for, it must be taken into account that the main aim of scheduling or re-scheduling of train operations is to provide safe operations and optimality is only a secondary but desirable objective. In practice, safety must be satisfied but optimality is not always attainable in a short time. The solutions provided by the proposed methods are always safe (feasible) and satisfactory from a practical point of view.

5. The solution provided by the first partition is obtained in an even more reduced time. Thus in re-scheduling cases, this allows us to re-start the train operations in a safe way without waiting for the computer to finish the calculations for the whole period. This implies a further time reduction with practical relevance.

6. The proposed methods can be used for planning new lines, for optimizing timetables and for re-scheduling operations due to disturbances in existing lines.

7. The modified optimization problem, including constraints of the type (4.2) allows different trains to choose between alternative subpaths joining the same points. This permits dealing with important design alternatives or complementing the existing conventional lines with new high speed segments that by-pass some stations in order to reduce the travel times. This has been illustrated by means of the Palencia-Santander line for which these solutions appear to be very satisfactory. In other words, the combination of conventional lines with new high speed single-tracks seems to be a very reasonable solution and raises serious doubts about indiscriminately using double-track high speed lines independently of the traffic demand, as it is usually done. The proposed methods contribute to the design of such lines and to the corresponding timetable optimizations in a reasonable time.

8. Further work is needed to improve the existing methods. Alternative strategies can be analyzed for the case of very large and complex railway networks, where the time
CHAPTER 4. ALTERNATE DOUBLE SINGLE TRACK

partitioning technique appears to be one of the main components. However, some techniques, such as those used in numerical integration to manage the step size and to allow it to vary depending on the complexity of the problem must be analyzed in order to reduce the computational time required.

4.7 Notation

\(dt_j\) binary variable that takes value 0 or 1 if segment \(j\) is a single or double-track, respectively

\(C_j\) cost coefficient of the objective function term \(j\)

\(D_j\) construction costs of segment \(j\) as a double-track

\(e_{ij}\) leaving time from segment \(j\) of train \(i\)

\(i\) dummy train index

\(n_p\) number of partitions

\(p\) partition

\(p_{ij}\) the actual running time of segment \(j\) for train \(i\)

\(p^l_{i,\sigma_i,k,t}\) lower bound of the running time for the \(k\) segment in the route of train \(i\) using track \(t\)

\(p^u_{i,\sigma_i,k}\) upper bound of the running time for the \(k\) segment in the route of train \(i\)

\(Q\) the objective function value

\(q_{i,k,t}\) binary variable that takes value one if train \(i\) uses track \(t\) of the \(k\)-th segment in the route of train \(i\) and zero, otherwise

\(r_i\) actual departure time of train \(i\)

\(s_{ij}\) the entering time for train \(i\) at segment \(j\)

\(S\) set of all segments

\(S_j\) construction costs of segment \(j\) as a single-track

\(x_{i_1,i_2,\sigma_{i_1,k_1}}\) a binary variable that takes value 1 if train \(i_1\) is scheduled to enter before train \(i_2\) in the common \(\sigma_{i_1,k_1}\) segment and 0 otherwise

\(y_{i_1,i_2,\sigma_{i_1,k_1}}\) a binary variable that takes value 1
if train $i_2$ is scheduled to enter before
train $i_1$ in the common $\sigma_{i_1,k_1}$ segment
and 0 otherwise

$\varepsilon$ actual maximum relative travel time
$\eta^f_i$ before departure time flexibility
$\eta^\mu_i$ after departure time flexibility
$\rho_{i_1,i_2,k_1,k_2}$ are one if trains $i_1$ and $i_2$ share the same
segment in close times
$\sigma_{ik}$ the $k$-th segment in the route of train $i$
$\tau$ time
$\tau_p$ starting time of partition $p$
$\tau_{\text{min}}$ earliest time when circulation of trains is
allowed
$\tau_{\text{max}}$ latest time when circulation of trains
is allowed
$\tau^0_i$ minimum travel time for train $i$
$\tau^p_{\text{begin}}$ starting time of time partition $p$
$\tau^p_{\text{end}}$ ending time of time partition $p$
Part IV

PROPOSALS OF ADST LINES IN CHILE AND IRELAND
Chapter 5

PROPOSALS OF ADST LINES IN CHILE

Contents

5.1 Introduction ......................................................... 95
5.2 Line description ...................................................... 96
  5.2.1 Trace of the line ............................................. 96
  5.2.2 Profile of the line ........................................... 96
  5.2.3 Segmentation .................................................. 98
5.3 Hypotheses used in the calculations ................................. 98
5.4 Results of the optimization program .............................. 99
  5.4.1 Resulting circulation graphs ................................. 99
5.5 Conclusions ......................................................... 100

5.1 Introduction

This proposal is purely indicative, as it does not have sufficient information to make a more complete study, which moreover is not the goal of this work. Therefore it must be understood in this sense.

The basic idea behind this preliminary study is to achieve the objectives at minimal cost, without losing the character of a high speed line.

As indicated in Chapter 2, to do this it uses the Alternate Double-Single Track (ADST) solution, which is based on building single track on sections where the constructive cost is high (tunnels and viaducts) and double track where the cost is low (sections with favorable terrain) and adjust departure times of trains, so that railroad crossings occur in the areas of two-way (low cost), while optimal travel times are kept.
5.2 Line description

5.2.1 Trace of the line

To this end we used the computer optimization railway line tool developed by the group, which not only decides which sections should be in single track and double, but also optimizes timetables.

In order to demonstrate the actual capacity of the ADST solution we have assumed 100 daily services, including 76 passenger trains and 24 freight trains.

The line starts from the Arturo Merino Benítez Airport and reaches El Salto, near the metro station for easy access to the metropolitan environment (see Figure 5.1). The aim of these point locations is to offer a feasible, intermodal and fast access to the two main metropolitan areas Santiago and Valparaíso-Viña del Mar.

Its length is 87.4 km.

5.2.2 Profile of the line

The line runs as closely as possible to the terrain profile. However, it is necessary to drill two tunnels of 13.6 and 5 km, respectively, shown in the profile of Figure 5.2. The remaining slopes are solved by cuttings, embankments and some viaducts.
Figure 5.2: The Santiago-Valparaíso/Viña del Mar line showing its trace, the longitudinal profile and the location of the two tunnels together with the segment costs in single and double track.
5.2.3 Segmentation

For the study of the line we have considered the 7 segments shown in Figure 5.2 and Table 5.1, which contains their origins and destinations, lengths, location and construction costs for both single and double track.

Table 5.1: Description of the 7 segments considered in the Santiago-Valparaíso-Viña del Mar line showing the origins, ends, lengths, location and the construction costs associated with the single and double-track solutions.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Origin</th>
<th>Destination</th>
<th>Length Km</th>
<th>PK Initial</th>
<th>Final</th>
<th>Cost (M euros/km)</th>
<th>Single</th>
<th>Double</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Santiago (AMB)</td>
<td>El Manzano</td>
<td>12</td>
<td>0</td>
<td>12</td>
<td>4.7</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>El Manzano</td>
<td>El Carrizo</td>
<td>13.3</td>
<td>12</td>
<td>25.3</td>
<td>5.4</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>El Carrizo</td>
<td>Los Arrayanes</td>
<td>13.6</td>
<td>25.3</td>
<td>38.9</td>
<td>23.1</td>
<td>42.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Los Arrayanes</td>
<td>Las Chacalllas</td>
<td>16.1</td>
<td>38.9</td>
<td>55</td>
<td>7.8</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Las Chacalllas</td>
<td>La Leona</td>
<td>11</td>
<td>55</td>
<td>66</td>
<td>18.7</td>
<td>37.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>La Leona</td>
<td>Quilpué</td>
<td>13</td>
<td>66</td>
<td>79</td>
<td>6.5</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Quilpué</td>
<td>El Salto</td>
<td>8</td>
<td>79</td>
<td>87</td>
<td>12.3</td>
<td>20.7</td>
<td></td>
</tr>
</tbody>
</table>

The segments have been chosen of very similar length to facilitate the optimization program to select which ones should be in single and double track to reduce construction costs and maintenance.

5.3 Hypotheses used in the calculations

For the study of the line the 7 segments in Figure 5.2 have been considered, where their lengths and construction costs in both single and double track are shown.

The result of the optimization program leads to 4 single track segments, corresponding to the two tunnel sections and the two ends, and 3 double track segments. The resulting approximate cost is M€1084, while the cost in double-track would have been M€1700, representing a saving constructive 36.2%. The resulting travel time was 30 minutes.

The main assumptions are:

- 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.
- To ensure safe headway times of trains in different segments. Times of 3 to 4 minutes for passengers and goods, respectively, have been considered.
- Only two paths: Santiago-El Salto and vice versa have been studied.
• We have assumed a demand of 1 train every 20 minutes at peak (6:00-8:20 and 17:20-20:20) hours, and every 30 minutes during valley hours (8:20-17:20 and 20:20-22:20).

• This implies a total of 38 passenger trains each way and 24 freight trains (12 in each direction) circulating during valley hours and at the end of the day.

• Finally, five night hours have been reserved for line maintenance.

• We have worked with relative travel times, that is, the ratio between the actual travel time and the minimum possible travel time (at maximum speed). For example, a relative time of 1.10 implies that the train takes 10% more than it would take at maximum speed.

• The resulting travel time for passengers was 30 minutes.

5.4 Results of the optimization program

5.4.1 Resulting circulation graphs

The result of the optimization program leads to 4 segments in single track, corresponding to the two tunnel sections and the two end segments, and 3 segments of double track, as
shown in Figure 5.3. The resulting approximate cost, excluding the stations, is 1,084 million euros, while the cost in double track would have been 1,700 million euros, representing a constructive saving of 36.2%.

As indicated in Tables 5.2 and 5.3, the travel times of passenger trains oscillate between 30 and 36 minutes (0.5-0.6 hours), and the relative times are 1,000 and 1,199, respectively.

Table 5.2: Priorities and resulting departures, arrivals and travel times of passenger trains.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1.029</td>
<td>6.000</td>
<td>6.516</td>
<td>0.516</td>
<td>1.000</td>
</tr>
<tr>
<td>2 1.031</td>
<td>6.333</td>
<td>6.850</td>
<td>0.517</td>
<td>1.000</td>
</tr>
<tr>
<td>3 1.029</td>
<td>6.667</td>
<td>7.183</td>
<td>0.516</td>
<td>1.000</td>
</tr>
<tr>
<td>4 1.029</td>
<td>7.000</td>
<td>7.516</td>
<td>0.516</td>
<td>1.000</td>
</tr>
<tr>
<td>5 1.031</td>
<td>7.333</td>
<td>7.850</td>
<td>0.517</td>
<td>1.000</td>
</tr>
<tr>
<td>6 1.029</td>
<td>7.667</td>
<td>8.183</td>
<td>0.516</td>
<td>1.000</td>
</tr>
<tr>
<td>7 1.029</td>
<td>8.000</td>
<td>8.516</td>
<td>0.516</td>
<td>1.000</td>
</tr>
<tr>
<td>8 1.199</td>
<td>8.333</td>
<td>8.935</td>
<td>0.602</td>
<td>1.000</td>
</tr>
<tr>
<td>9 1.136</td>
<td>8.902</td>
<td>9.472</td>
<td>0.570</td>
<td>1.000</td>
</tr>
<tr>
<td>10 1.199</td>
<td>9.386</td>
<td>9.988</td>
<td>0.602</td>
<td>1.000</td>
</tr>
<tr>
<td>11 1.000</td>
<td>9.811</td>
<td>10.313</td>
<td>0.502</td>
<td>1.000</td>
</tr>
<tr>
<td>12 1.145</td>
<td>10.380</td>
<td>10.955</td>
<td>0.574</td>
<td>1.000</td>
</tr>
<tr>
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<td>11.315</td>
<td>0.565</td>
<td>1.000</td>
</tr>
<tr>
<td>14 1.199</td>
<td>11.347</td>
<td>11.948</td>
<td>0.602</td>
<td>1.000</td>
</tr>
<tr>
<td>15 1.196</td>
<td>11.916</td>
<td>12.516</td>
<td>0.600</td>
<td>1.000</td>
</tr>
<tr>
<td>16 1.000</td>
<td>12.317</td>
<td>12.818</td>
<td>0.502</td>
<td>1.000</td>
</tr>
<tr>
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<td>12.886</td>
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</tr>
<tr>
<td>18 1.127</td>
<td>13.268</td>
<td>13.833</td>
<td>0.565</td>
<td>1.000</td>
</tr>
<tr>
<td>19 1.199</td>
<td>13.848</td>
<td>14.449</td>
<td>0.602</td>
<td>1.000</td>
</tr>
<tr>
<td>20 1.000</td>
<td>14.265</td>
<td>14.766</td>
<td>0.502</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Similarly, as indicated in Table 5.4, the travel times of freight trains range from 48 to 1 hour 46 minutes (0.81 to 1.765 hours) and the relative travel times range from 1.0 to 2.184, respectively.

5.5 Conclusions

The most important conclusions derived from this work are:

1. The proposed line Santiago-Valparaíso-Viña del Mar is limited to facilitate the transport of passengers and goods between intermodal nodes, so that it can be integrated
CHAPTER 5. PROPOSALS OF ADST LINES IN CHILE

Table 5.3: Priorities and resulting departures, arrivals and travel times of passenger trains.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>1.162</td>
<td>6.667</td>
<td>7.250</td>
<td>0.583</td>
</tr>
<tr>
<td>42</td>
<td>1.162</td>
<td>7.000</td>
<td>7.583</td>
<td>0.583</td>
</tr>
<tr>
<td>43</td>
<td>1.164</td>
<td>7.333</td>
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<td>0.584</td>
</tr>
<tr>
<td>44</td>
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<td>8.250</td>
<td>0.583</td>
</tr>
<tr>
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<td>8.583</td>
<td>0.583</td>
</tr>
<tr>
<td>46</td>
<td>1.035</td>
<td>8.333</td>
<td>8.852</td>
<td>0.519</td>
</tr>
<tr>
<td>47</td>
<td>1.000</td>
<td>8.751</td>
<td>9.253</td>
<td>0.502</td>
</tr>
<tr>
<td>48</td>
<td>1.000</td>
<td>9.260</td>
<td>9.761</td>
<td>0.502</td>
</tr>
<tr>
<td>49</td>
<td>1.048</td>
<td>9.805</td>
<td>10.330</td>
<td>0.526</td>
</tr>
<tr>
<td>50</td>
<td>1.199</td>
<td>10.398</td>
<td>11.000</td>
<td>0.602</td>
</tr>
<tr>
<td>51</td>
<td>1.047</td>
<td>10.771</td>
<td>11.297</td>
<td>0.525</td>
</tr>
<tr>
<td>52</td>
<td>1.000</td>
<td>11.365</td>
<td>11.866</td>
<td>0.502</td>
</tr>
<tr>
<td>53</td>
<td>1.000</td>
<td>11.765</td>
<td>12.267</td>
<td>0.502</td>
</tr>
<tr>
<td>54</td>
<td>1.002</td>
<td>12.333</td>
<td>12.836</td>
<td>0.503</td>
</tr>
<tr>
<td>55</td>
<td>1.199</td>
<td>12.916</td>
<td>13.518</td>
<td>0.602</td>
</tr>
<tr>
<td>56</td>
<td>1.070</td>
<td>13.250</td>
<td>13.787</td>
<td>0.537</td>
</tr>
<tr>
<td>57</td>
<td>1.199</td>
<td>13.898</td>
<td>14.499</td>
<td>0.602</td>
</tr>
<tr>
<td>58</td>
<td>1.040</td>
<td>14.266</td>
<td>14.788</td>
<td>0.522</td>
</tr>
</tbody>
</table>

2. The alternate double-single track solution (1,084 M euros) allows us to achieve a saving of 36% compared to the double track (1,700 M euros) and important maintenance savings too. Furthermore, according to the results of the simulation carried out, it allows at least a circulation of 100 trains a day (76 passenger trains and 24 freight trains).

3. Being a new line of construction and have the services of Metro Santiago and Valparaíso-Viña del Mar gauge (1.435 and 1.676 mm, respectively), the line can be built in either gauge. In this election the possible integration with subway systems of these cities and how it is made play a major role.

4. If the line were integrated with the subway of Valparaíso choosing the same gauge, freight trains could, without building a new track, continue their journey to other possible destinations in particularly to the Valparaíso port.

5. The rationale for choosing El Salto, as the terminal station is to provide a de-
Table 5.4: Priorities and resulting departures, arrivals and travel times of freight trains.

<table>
<thead>
<tr>
<th>Relat. time</th>
<th>Depart.</th>
<th>Arriv. travel</th>
<th>Prior.</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>2.184</td>
<td>9.320</td>
<td>11.085</td>
</tr>
<tr>
<td>78</td>
<td>2.048</td>
<td>8.608</td>
<td>10.264</td>
</tr>
<tr>
<td>79</td>
<td>1.770</td>
<td>14.148</td>
<td>15.579</td>
</tr>
<tr>
<td>80</td>
<td>1.629</td>
<td>14.833</td>
<td>16.150</td>
</tr>
<tr>
<td>81</td>
<td>1.000</td>
<td>20.960</td>
<td>21.768</td>
</tr>
<tr>
<td>82</td>
<td>1.358</td>
<td>21.037</td>
<td>22.135</td>
</tr>
<tr>
<td>83</td>
<td>1.697</td>
<td>16.566</td>
<td>17.938</td>
</tr>
<tr>
<td>84</td>
<td>1.239</td>
<td>16.615</td>
<td>17.616</td>
</tr>
<tr>
<td>85</td>
<td>1.504</td>
<td>11.413</td>
<td>12.629</td>
</tr>
<tr>
<td>86</td>
<td>1.425</td>
<td>10.628</td>
<td>11.780</td>
</tr>
<tr>
<td>87</td>
<td>1.598</td>
<td>12.475</td>
<td>13.767</td>
</tr>
<tr>
<td>88</td>
<td>1.338</td>
<td>13.500</td>
<td>14.581</td>
</tr>
<tr>
<td>89</td>
<td>1.000</td>
<td>22.657</td>
<td>23.465</td>
</tr>
<tr>
<td>90</td>
<td>1.271</td>
<td>22.085</td>
<td>23.112</td>
</tr>
<tr>
<td>91</td>
<td>1.000</td>
<td>23.178</td>
<td>23.987</td>
</tr>
<tr>
<td>92</td>
<td>2.103</td>
<td>22.500</td>
<td>24.200</td>
</tr>
<tr>
<td>93</td>
<td>1.000</td>
<td>23.250</td>
<td>24.058</td>
</tr>
<tr>
<td>94</td>
<td>1.556</td>
<td>23.167</td>
<td>24.425</td>
</tr>
<tr>
<td>95</td>
<td>1.136</td>
<td>23.500</td>
<td>24.418</td>
</tr>
<tr>
<td>96</td>
<td>1.567</td>
<td>23.000</td>
<td>24.266</td>
</tr>
<tr>
<td>97</td>
<td>1.552</td>
<td>9.897</td>
<td>11.151</td>
</tr>
<tr>
<td>98</td>
<td>1.341</td>
<td>10.055</td>
<td>11.138</td>
</tr>
<tr>
<td>99</td>
<td>1.169</td>
<td>23.833</td>
<td>24.778</td>
</tr>
<tr>
<td>100</td>
<td>1.383</td>
<td>23.667</td>
<td>24.785</td>
</tr>
</tbody>
</table>

Congested area usable space and the existing transport infrastructures in order to facilitate the access and exit of users to the new line. Leave users in an area of difficult entry and exit, would defeat the time saved with the high-speed line.

6. This proposal was made with a minimum of available data. Therefore, for a more detailed and complete cost and performance of the line estimate much more information would be needed.

7. The methodology of the ADST lines is applicable not only to the high speed, but to all kinds of lines, achieving savings of the same order of magnitude.
Chapter 6

PROPOSALS OF ADST LINES IN IRELAND

Contents

6.1 Introduction ............................................. 103
6.2 Description of the current line between Dublin and Belfast ...... 104
6.3 Proposal of a High Speed Line ..................................... 106
   6.3.1 Trace definition and assumptions ................................ 106
   6.3.2 Double-track solution ........................................... 107
   6.3.3 ADST solutions .................................................. 109
   6.3.4 Selected Solution ............................................... 113
6.4 Proposal based on the existing network improvement ............... 116
   6.4.1 Current framework .............................................. 116
   6.4.2 Studied Cases .................................................. 119
   6.4.3 Construction cost ............................................... 120
   6.4.4 ADST Analysis .................................................. 120
   6.4.5 Final Solution .................................................. 121
   6.4.6 Conclusions .................................................... 123
6.5 Other line proposals ............................................ 123
6.6 Conclusions .................................................... 126

6.1 Introduction

This chapter presents the application of the ADST methodology to the case of the Dublin-Belfast line.
CHAPTER 6. PROPOSALS OF ADST LINES IN IRELAND

<table>
<thead>
<tr>
<th>Type</th>
<th>Dublin - Belfast</th>
<th>Services per day</th>
<th>Trip fares (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTC Travel Time</td>
<td>Ocuppancy</td>
<td>Single</td>
</tr>
<tr>
<td>Car</td>
<td>2 h 2 min</td>
<td>40%</td>
<td>-</td>
</tr>
<tr>
<td>Bus (705X)</td>
<td>2 h 33 min</td>
<td>19%</td>
<td>44</td>
</tr>
<tr>
<td>Train</td>
<td>2 h 47 min</td>
<td>40%</td>
<td>16</td>
</tr>
</tbody>
</table>

*CTC Center to Center

This chapter has been organized as follows, In section 6.2 the existing railway line between Dublin and Belfast is described. In section 6.3 an ADST high speed line between Dublin and Belfast is presented. In section 6.4 an ADST line using the existing conventional line is proposed. Finally in section 6.6 some conclusions are drawn.

6.2 Description of the current line between Dublin and Belfast

We start with a short description of the current Dublin-Belfast line.

In Figure 6.4 the trace of the current line between Dublin and Belfast together with their main stations are shown. 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, which are shown in Figure 6.13, the network shares 312 daily services including the Dublin and Belfast commuter and freight transport services.

The main characteristics of the Dublin-Belfast service are:

- **Total length** 181 km / 113 Miles.
- **Stop Stations** 5.
- **Daily services** 16.

The list of the connected cities and their actual populations are shown in Figure 6.4 which shows that the Dublin-Belfast link could connect 2 million people.

In addition, Figures 6.2 and 6.3 show the city populations and 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.
### Chapter 6. Proposals of ADST Lines in Ireland

#### Figure 6.2: Cities connected by the current line between Dublin and Belfast

<table>
<thead>
<tr>
<th>City</th>
<th>Inhabitant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dublin</td>
<td>1,273,069</td>
</tr>
<tr>
<td>Drogheda</td>
<td>38,578</td>
</tr>
<tr>
<td>Dundalk</td>
<td>37,816</td>
</tr>
<tr>
<td>Newry</td>
<td>29,946</td>
</tr>
<tr>
<td>Portadown</td>
<td>22,000</td>
</tr>
<tr>
<td>Belfast</td>
<td>720,000</td>
</tr>
</tbody>
</table>

#### Figure 6.3: Cost of the services between Dublin and Belfast using different alternatives (car, bus and train).

<table>
<thead>
<tr>
<th>Type</th>
<th>Dublin - Belfast</th>
<th>Services per day</th>
<th>Trip fares (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTC Travel Time</td>
<td>Ocuppancy</td>
<td>Single</td>
</tr>
<tr>
<td>Car</td>
<td>2 h 2 min</td>
<td>40%</td>
<td>-</td>
</tr>
<tr>
<td>Bus (705X)</td>
<td>2 h 33 min</td>
<td>19%</td>
<td>44</td>
</tr>
<tr>
<td>Train</td>
<td>2 h 47 min</td>
<td>40%</td>
<td>16</td>
</tr>
</tbody>
</table>

*CTC Center to Center*
In the following sections we propose some alternatives to improve the quality of the Dublin-Belfast services.

6.3 Proposal of a High Speed Line

This first proposal refers to a new and independent high speed line between Dublin and Belfast.

6.3.1 Trace definition and assumptions

We propose the line shown in Figure 6.4, where the traces of the new and the existing lines are shown. 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.

![Figure 6.4: High speed corridor (orange) compared with the conventional line (blue).](image)

In order to reduce travel times only one intermediate stop at Dundalk has been assumed (see Figure 6.4). This decision was based on the facts that: (a) Drogheda and
Newry are saturated areas, (b) Dundalk has more potential for city development than other city areas, and (c) difficulties of connection with the Drogheda train station.

**Figure 6.5: High speed line profile and used main design parameters (maximum speeds, maximum and exceptional slopes, curve radius, etc.).**

Figure 6.5 shows the trace and its longitudinal profile together with the main design parameters.

In order to optimize an ADST solution, the line has been partitioned into the eight segments shown in Figure 6.6 where the design speeds for the different segments used in the analysis are shown in the left graph. Note that the proposed high speeds are higher than those of the current line.

### 6.3.2 Double-track solution

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, though in a very simple case, because only a few services compete for segments.
Thus, if a double-track line is assumed, the travel time between Dublin and Belfast can be reduced to 50 minutes, which means a reduction of 1 hour and 19 minutes with respect to the current travel time. This important time reduction would induce an increase in the number of the railway line users, some coming from other conveyances and other new users, and will cause the appearance of new travel types.

To summarize, the main characteristics of the proposed high speed line in the case of a double-track solution are:

- **Total length**: 160.4 km / 100.25 Miles.
- **Intermediate stop stations**: 1.
- **Travel time**: 50 min.
- **Construction cost**: M€1589.54 (M£1158.98).

Figure 6.6: Left plot: High speed proposal showing the design speeds for the different segments used in the analysis. Right table: List of the eight segments in which the line has been divided showing their origins and ends, their lengths and the unit construction costs for single and double-track.
It is important to conclude indicating that 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.

### 6.3.3 ADST solutions

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.

#### Assumptions

Figure 6.6 in its right table shows the origins and ends of each of the 8 segments in which the line has been partitioned, together with their lengths (in km and miles) and the corresponding unit construction cost estimates for single- and double-track segments.

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 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.

#### Case studies

In the analysis, instead of using travel time, we have used relative travel time (RT), which is defined as:

\[
RT = \frac{\text{Travel time}}{\text{Minimum required travel time}}.
\]

Relative travel times were used because they permit a simple interpretation of the results when trains with different travel times are analyzed. This is the case of commuters and long distance trains. For example, a relative travel time value of 1.10 means that the train completes the trip in a time that is 10% higher than the minimum required time for that train.

In order to have a wide range of ADST solutions in our analysis, six different allowable relative travel time values (1.000, 1.025, 1.050, 1.075, 1.100 and 1.125) and the cases of 16 and 32 daily services were considered. If the double-track solution is included, they make a total of 14 different cases, which when optimized lead to 14 track schemes.

Figure 6.7 shows the 14 different solutions with the corresponding relative travel times and number of daily services, the percentages of double-track length and the associated
construction costs. They range from a single track line solution with associated cost of €961.49M (£701.05M) to a double track line solution with associated cost of €1589.54M (£1158.98M), with intermediate solutions of ADST schemes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Max Relative Time</th>
<th>Services</th>
<th>Segment</th>
<th>Track Tipology</th>
<th>Construction Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Double HS</td>
<td>Simple HS</td>
</tr>
<tr>
<td>01</td>
<td>1,125</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>02</td>
<td>1,100</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>31%</td>
<td>69%</td>
</tr>
<tr>
<td>11</td>
<td>1,075</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>6%</td>
<td>94%</td>
</tr>
<tr>
<td>12</td>
<td>1,050</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>37%</td>
<td>63%</td>
</tr>
<tr>
<td>21</td>
<td>1,025</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>17%</td>
<td>83%</td>
</tr>
<tr>
<td>22</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>37%</td>
<td>63%</td>
</tr>
<tr>
<td>31</td>
<td>1,025</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>17%</td>
<td>83%</td>
</tr>
<tr>
<td>32</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>37%</td>
<td>63%</td>
</tr>
<tr>
<td>41</td>
<td>1,025</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>29%</td>
<td>71%</td>
</tr>
<tr>
<td>42</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>29%</td>
<td>71%</td>
</tr>
<tr>
<td>51</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>48%</td>
<td>52%</td>
</tr>
<tr>
<td>52</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>48%</td>
<td>52%</td>
</tr>
<tr>
<td>81</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>82</td>
<td>1,000</td>
<td>16</td>
<td>1 2 3 4 5 6 7 8</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Figure 6.7: All analyzed cases, that is, the 14 different solutions that range from single-track (case 01) to double-track for all segments (cases D1 and D2), as well as intermediate ADST alternatives.

From this set of 14 different ADST schemes, 5 were chosen to develop a more exhaustive comparison. To this end the calculations were repeated for 16 and 32 daily services.

Figure 6.8 shows the results of the optimization program for the selected five solutions that range from single-track (case 1) to double-track (case 5) for all segments. The intermediate alternatives 2 to 4 consider one, two and three double-track segments, respectively. The percentages of single-track length with respect to the total length, the construction costs (in euros and pounds) and the percent savings with respect to the double-track solution construction cost complete the columns of the table. It is interesting to see that important cost reductions can be obtained if some segments are built as single-track segments.

Figure 6.9 gives information about the resulting travel times for the different case combinations and the two routes, Dublin-Belfast and Dublin-Dundalk-Belfast after optimizing the timetables, and how they change when 32 daily services are considered instead of 16.

Based on this information, the travel times for the different cases should be analyzed to determine the best solution.

After an analysis of the resulting travel times it can be observed that for 16 daily services, cases 3, 4 and 5 circulate in the minimum possible time, in 50 and 54 minutes,
CHAPTER 6. PROPOSALS OF ADST LINES IN IRELAND

Figure 6.8: Five different solutions that range from single-track (case 1) to double-track (case 5) for all segments. The intermediate alternatives 2 to 4 consider one, two and three double-track segments, respectively.

for the Dublin-Belfast and Dublin-Dundalk-Belfast routes, respectively. For 32 daily services the travel times are not equal, but they differ in one minute (50-51 and 54-55 minutes).

In the cases 1 (single-track) and 2 (one double track segment) travel times coincide for 16 daily services and are slightly higher (1 and 4 minutes) than the travel times for cases 1, 2 and 3. However, for 32 daily services the increase is more important.

It is worth while mentioning that only in case 1 with 32 daily services for the route with stop at Dundalk (Dublin-Dundalk-Belfast) the travel time exceeds 1 hour, and this occurs because of the usage of intermediate TOPP

Figure 6.9: Travel times for the cases of 16 and 32 daily services and all five cases.

---

1 Train Overtaking and Parking Post
CHAPTER 6. PROPOSALS OF ADST LINES IN IRELAND

Quality measures

In order to select the optimal scheme, a comparison of the quality of the different alternative solutions is needed. To this aim, three quality measures have been considered:

- **$QM_1$ : Percent of fast services.** This rate defines the basic quality of the cases considering only the services which circulate throughout the network with a relative travel time $RT$, defined in (6.1), smaller than 1.2.

\[
QM_1 = 100 \times \frac{\sum \text{Services}(RT < 1,2)}{\sum \text{Services}}. \tag{6.2}
\]

- **$QM_2$ : Weighted percent of fast services.** This rate emerges as a more exhaustive estimation, because it weights the services according to their RT.

\[
QM_2 = 100 \times \frac{\sum Service_i \times weight_i}{\sum Service_i}. \tag{6.3}
\]

<table>
<thead>
<tr>
<th>Relative Time</th>
<th>1-1.05</th>
<th>1.05-1.1</th>
<th>1.1-1.15</th>
<th>1.15-1.2</th>
<th>&gt;1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- **$QM_3$ : Saved time/budget ratio.** This quality measure is the best profitable rate, which compares the saved time with the corresponding budget of each case:

\[
QM_3 = \frac{(Current \ Travel \ time - New \ Travel \ Time_i)}{Budget_i}. \tag{6.4}
\]

The resulting quality measures for the 5 cases are shown in Figure 6.10.

Since Cases 1 and 2 do not reach 100% for quality measures $QM_1$ and $QM_2$, they were considered as not satisfactory and discarded. On the contrary, Cases 3, 4 and 5 show very good quality under these two criteria.

Finally, using the $QM_3$ quality measure, the resulting most profitable, and consequently the best scheme, was Case 3.

An illustration of the inverse of the $QM_3$ quality ratio is given in the bottom part of Figure 6.10. This ratio illustrates how the construction costs increase with the travel time reduction (in hours). It can be seen that large reductions in travel time can be achieved with small cost increments. However, after a given value, the costs increase exponentially. Consequently, there is a point above which a reasonable solution should not go further. Consequently, under this criterion, Case 3 results as the most profitable solution.
Figure 6.10: Quality measures for the different analyzed cases and the selection of most profitable case, Case 3.

6.3.4 Selected Solution

As it has been indicated and as a result of the ADST analysis, the selected scheme is Case 3. This high speed line proposal is composed of 2 double-track segments (in yellow color) and 6 single-track segments, as shown in Figure 6.11. The double track segments are located at the second and sixth segments starting from Dublin, and they will allow the services to cross at double-track segments, so the trains would not stop at a station or use TOPP in normal situations.

The main characteristics of this solution are:

- Total Length: 160.4 Km/100.25 Miles.
- Construction Budget: M€1,099.74/M£801.85.
- Travel Times: 50-51 min (Dublin-Belfast) and 54-55 min (Dublin-Dundalk-Belfast).
• Daily services: 16 and 32 trains.
• Offered capacity: 6,200 and 12,400 daily passengers.

The resulting timetables are given in Figure 6.12 where the shadowed segments correspond to double-track segments.

This solution was designed as a high speed passenger line to be shared with freight transport between Dublin and Belfast, however, it should be studied in more detail because:

• The trace was considered as a platform independent of the current line.
• The current commuter traffic of both metropolitan areas were ignored.
• The cost of high speed rolling stock should have added to the budget.
Figure 6.12: Resulting timetable for 16 (upper graph) and 32 (lower graph) daily services showing in yellow color the double-track segments and minimum, maximum and average travel times together with the current travel times and the time savings.
• Important construction budget and rolling stock investment should have been assumed.

However, a new analysis considering the current traffic and the combination of new tracks with the network currently in service will be detailed in section 6.2.

6.4 Proposal based on the existing network improvement

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

This proposal aims to:

• Provide a connection between Dublin-Belfast in less than 1 h 30 min.
• Increase the capacity of the network.
• Optimize the intermediate long distance link.
• Promote the Dublin-Belfast commuter and business connections.
• Facilitate the cross border freight connection.

Considering the above aims and taking into account the suggested high speed line previously explained in section 6.3, we propose to build 4 new segments, as shown in Figure 6.13, that is, between Donabate-Julianstown-Dromiskin (segments T1-T2 and T2-T3) and Newry-Banbridge-Lisburn (segments T6-T7 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).

6.4.1 Current framework

In this section the current traffic is described and analyzed, including the Dublin-Belfast link, the Dublin and Belfast commuter traffic, and the freight transport currently circulating along the network. To this end, all the operating routes along the network are detailed in Figure 6.14. This means that the overall daily services consists of 328 trains.
Figure 6.13: Current network improvement, consisting in 4 new segments construction along the line.
Table: Dublin commuter traffic

<table>
<thead>
<tr>
<th>Route</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>31</td>
<td>16</td>
</tr>
<tr>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td>42</td>
<td>1</td>
</tr>
<tr>
<td>51</td>
<td>32</td>
</tr>
<tr>
<td>52</td>
<td>32</td>
</tr>
<tr>
<td>61</td>
<td>40</td>
</tr>
<tr>
<td>62</td>
<td>40</td>
</tr>
<tr>
<td>71</td>
<td>82A</td>
</tr>
<tr>
<td>82A</td>
<td>82B</td>
</tr>
<tr>
<td>131</td>
<td>5</td>
</tr>
<tr>
<td>132</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>328</td>
</tr>
</tbody>
</table>

Table: Dublin Belfast connection

<table>
<thead>
<tr>
<th>Route</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>101</td>
</tr>
<tr>
<td>12</td>
<td>102</td>
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<tr>
<td>21</td>
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<td>12</td>
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<tr>
<td>41</td>
<td>11A</td>
</tr>
<tr>
<td>42</td>
<td>11B</td>
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<tr>
<td>51</td>
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<td>52</td>
<td>32</td>
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<td>62</td>
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<td>131</td>
<td>131</td>
</tr>
<tr>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Total</td>
<td>328</td>
</tr>
</tbody>
</table>

**Figure 6.14:** Current routes including the Dublin-Belfast link, the Dublin and Belfast commuter traffic, and the freight transport currently circulating along the network.
### 6.4.2 Studied Cases

This proposal is analyzed considering three different situations, which vary depending on the amount and proportion of the Dublin-Belfast connections using different routes (the current and new routes), as shown in Figure 6.15.

0. **Current network and traffic.** This case refers to the current situation of traffic and routes, assuming that trains use the actual network, without any new segment. It is the reference case for the analysis of the possible improvements to be considered in the other two cases.

1. **Improved Network with 16 services between Dublin and Belfast.** In this case the new segments are assumed to be in operation with only 10 fast connection services of a total 16 links between Dublin and Belfast circulating along the new segments. However, the total amount of services along the network is still 328 trains.

2. **Improved Network with 16+18 services between Dublin and Belfast.** Our last case consists of the previous case plus 18 new services between Dublin-Belfast, where 16 of them use the new proposed infrastructure (fast connections) and the other 2 are planned to circulate along the current network.

Figure 6.15 provides a detailed description of the services that have been considered in each of the cases.
### Chapter 6. Proposals of ADST Lines in Ireland

#### 6.4.3 Construction Cost

First of all, it should be recalled that the proposed segments are designed both for future high speed traffic (250 km/h 155 mph), as well as for the current services. Consequently, the renewal of specific rolling stock and the electrification of the corridor for this first stage with only 16 services is avoided.

The unit costs per kilometer of the segments in both single- and double-track, are shown in Figure 6.16. They have been calculated taking into account the costs of the Irish Rail 2030 Rail Network Strategy Review and some projects of similar characteristics. The percentage of the contribution of the different project components to the total cost of the project are shown in Figure 6.17.

It should be emphasized that these costs are only a rough appraisal; thereby the final value of construction requires a more detailed and accurate evaluation.

#### 6.4.4 ADST Analysis

Once demand and unit costs are defined, the different cases can be analyzed:

<table>
<thead>
<tr>
<th>Segment</th>
<th>Origin</th>
<th>Destination</th>
<th>Length</th>
<th>Cost (M£/Mile M€/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mile</td>
<td>Km</td>
</tr>
<tr>
<td>1</td>
<td>T1 (Donabate)</td>
<td>T2 (Julianstown)</td>
<td>17,10</td>
<td>27,36</td>
</tr>
<tr>
<td>2</td>
<td>T2 (Julianstown)</td>
<td>T3 (Dromiskin)</td>
<td>17,82</td>
<td>28,51</td>
</tr>
<tr>
<td>3</td>
<td>T6 (Newry)</td>
<td>T7 (Banbridge)</td>
<td>8,90</td>
<td>14,24</td>
</tr>
<tr>
<td>4</td>
<td>T7 (Banbridge)</td>
<td>T8 (Lisburn)</td>
<td>13,35</td>
<td>21,36</td>
</tr>
</tbody>
</table>

**Figure 6.16:** Origin and destination, length and construction costs of the new segments.

<table>
<thead>
<tr>
<th>Cost Reporting</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Earthworks and demolition</td>
<td>15</td>
</tr>
<tr>
<td>2 Drainage</td>
<td>2,5</td>
</tr>
<tr>
<td>3 Structure</td>
<td>32</td>
</tr>
<tr>
<td>4 Tunnel</td>
<td>0</td>
</tr>
<tr>
<td>5 Expropriations and restoration service</td>
<td>7,5</td>
</tr>
<tr>
<td>6 Track construction</td>
<td>26</td>
</tr>
<tr>
<td>7 Track safety and communication</td>
<td>9,5</td>
</tr>
<tr>
<td>8 Unexpected</td>
<td>5,5</td>
</tr>
<tr>
<td>9 Security and health</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
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</table>

**Figure 6.17:** Estimated percentage of the contribution of the different project components to the total cost of the project.
CHAPTER 6. PROPOSALS OF ADST LINES IN IRELAND

Figure 6.18: Case 0 optimized timetable associated with the existing conventional line.

- To assess the travel times of the Dublin-Belfast links.
- To determine the track typology (single or double) of the new segments.
- To optimize the timetable for the new traffic demand.

With this goals in mind, the three studied cases have been analyzed and the resulting optimized timetables and travel times have been obtained and shown in Figures 6.18 and 6.19, where the shadowed segments refer to double track segments, and the corresponding travel times for all routes are given.

The first conclusion that can be drawn from the optimization is that all segments should be constructed as single track segments.

6.4.5 Final Solution

As a consequence of the previous analysis, our final proposal consists of constructing the new four segments as single track segments, as shown in Figure 6.20. With this, the main characteristics of the finally proposed line, depicted in Figure 6.20 are the following:
Figure 6.19: Upper plot: Case 1 optimized timetable for the new segments considering that only 10 of a total of 16 services use them. Lower plot: Case 2 optimized timetable for the new segments considering that 26 of a total of 34 services use them.
• **New line length:** 161 km / 100.6 Mile.

• **Single track segments:** 4 (91.5 km / 57.2 Mile).

• **Final estimated budget:** M €360.64 / M £262.95.

A comparison of the travel times of the different cases, shown in Figure 6.21, shows that the travel time reduction, derived from the construction of the new segments, is significant with respect to the travel times in the current situation. In fact, the travel time of most Dublin-Belfast links are below 1 hour 30 minutes, which implies a reduction that exceeds 40 minutes.

### 6.4.6 Conclusions

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.

### 6.5 Other line proposals

In this section we identify other Irish lines where the present ADST solutions could be used.

A rough analysis of the complete network in Ireland, invites to develop a similar analysis, in both high speed and mixed lines with the current traffic and future predictions, in the following lines:

1. **Dublin-Limerick line.** The possible travel time in this line could be around 1 h 15 min. See the scheme in Figure 6.22.

2. **Dublin-Cork line.** The possible travel time in this line could be around 1 h 55 min. See the scheme in Figure 6.22.
Figure 6.20: Final solution.
### 0.- Current Track 16 Services D-B

<table>
<thead>
<tr>
<th>Route</th>
<th>11</th>
<th>12</th>
<th>101</th>
<th>102</th>
<th>111</th>
<th>112</th>
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</thead>
<tbody>
<tr>
<td>Min Time</td>
<td>2:09</td>
<td>2:08</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max Time</td>
<td>2:13</td>
<td>2:13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>2:11</td>
<td>2:12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 1.- Improved Network 16 Services D-B

<table>
<thead>
<tr>
<th>Route</th>
<th>11</th>
<th>12</th>
<th>101</th>
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<th>111</th>
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<tbody>
<tr>
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<td>2:03</td>
<td>1:20</td>
<td>1:24</td>
<td>1:16</td>
<td>1:17</td>
</tr>
<tr>
<td>Max Time</td>
<td>2:13</td>
<td>2:13</td>
<td>1:29</td>
<td>1:32</td>
<td>1:27</td>
<td>1:27</td>
</tr>
<tr>
<td>Average</td>
<td>2:09</td>
<td>2:07</td>
<td>1:25</td>
<td>1:28</td>
<td>1:20</td>
<td>1:21</td>
</tr>
</tbody>
</table>

### 2.- Improved Network 16+18 Services D-B

<table>
<thead>
<tr>
<th>Route</th>
<th>11</th>
<th>12</th>
<th>101</th>
<th>102</th>
<th>111</th>
<th>112</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Time</td>
<td>2:02</td>
<td>2:07</td>
<td>1:25</td>
<td>1:25</td>
<td>1:21</td>
<td>1:23</td>
</tr>
<tr>
<td>Max Time</td>
<td>2:12</td>
<td>2:13</td>
<td>1:32</td>
<td>1:32</td>
<td>1:27</td>
<td>1:28</td>
</tr>
<tr>
<td>Average</td>
<td>2:07</td>
<td>2:11</td>
<td>1:29</td>
<td>1:31</td>
<td>1:24</td>
<td>1:26</td>
</tr>
</tbody>
</table>

**Figure 6.21:** A comparison of the travel times between Dublin and Belfast associated with cases 0, 1 and 2.

**Figure 6.22:** 1. Dublin-Limerick line (left) and 2. Dublin-Cork line (right).
3. **Dublin-Galway/Limerick line.** The possible Dublin-Galway travel time in this line could be around 1 h 20 min. See the scheme in Figure 6.23.

4. **Dublin-Galway/Limerick/Cork line.** See the scheme in Figure 6.23.

### 6.6 Conclusions

The following conclusions can be drawn from this chapter:

1. Though the classical double-track solution solves the problem of railway link connections between Dublin-Belfast in 50 minutes, it is very expensive. The estimated budget is M€1,589.54 (M£1,158.98).

2. One interesting alternative to reduce costs is the ADST line that leads to a travel time of 50-54 minutes with a cost of M€1,099.74 (M£801.85).

3. Finally, improvement and complement of the current conventional line with high speed new segments can lead to travel times of 1 hour and 25 minutes, with a budget of €360.64M (£262.95M).

4. Since the above estimates have been done with the required information, a more detailed analysis is needed in order to have more reliable estimates.

5. These solutions can be extended to other Irish lines, such as Dublin-Cork, Dublin-Limerick and Dublin-Cork, in which the travel times could be substantially reduced.
Part V

RE-SCHEDULING DUE TO DISTURBANCES
Chapter 7

Re-scheduling due to disturbances

Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>130</td>
</tr>
<tr>
<td>7.2</td>
<td>Dealing with disturbances</td>
<td>131</td>
</tr>
<tr>
<td>7.3</td>
<td>Examples of application</td>
<td>133</td>
</tr>
<tr>
<td>7.3.1</td>
<td>The Palencia-Santander line</td>
<td>133</td>
</tr>
<tr>
<td>7.3.2</td>
<td>The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line</td>
<td>135</td>
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<tr>
<td>7.3.3</td>
<td>The Santiago-Valparaíso-Viña del Mar line</td>
<td>136</td>
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</table>
7.1 Introduction

In this chapter we deal with the problem of disturbances, that is, small delays produced in one or several services that cause timetable re-scheduling.

Though in this thesis we have no room to deal with disruptions and because the proposed methods are of especial interest to re-schedule trains after the occurrence of these events, we include some references of works dealing with these problems.

Unfortunately, some disturbances can occur in practice and then a timetable re-scheduling becomes necessary. Following Cacchiani et al. (2014) a distinction between disturbances and disruptions must be made, where disturbances refer to relatively small disturbances influencing the railway system, and disruptions is used for relatively large external incidents leading to the cancelation of a number of trips in the timetable and rerouting trains.

There are specific publications dealing with re-scheduling problems, such as Corman et al. (2009), who evaluates the green wave policy, in which trains are allowed to stop only at their scheduled stops, in real-time railway traffic management and show that this policy has some advantages for reducing train delay and energy consumptions, avoiding the need of complex speed optimization methods; Törnquist and Persson (2007), who analyzes how disturbances propagate in n-tracked networks and which actions to take in order to minimise the consequences. Meng and Zhou (2011), who formulate a stochastic programming with recourse model framework and solve a robust single-track train dispatching problem under stochastic segment running times and capacity duration; Boccia et al. (2013), Lusby et al. (2013) and Mannino and Mascis (2009) use microscopic approaches to analyze small disturbances. Schöbel (2009), Acuna-Agost et al. (2011a) and Kecman et al. (2013) use macroscopic analysis of the railway network to handle disturbances; Wang et al. (2014) suggest an optimization based high-speed railway train re-scheduling method for the case of speed restriction using the reduction factor method (see Yang (1999)); Caimi et al. (2012), who presents a discrete-time model for re-scheduling in complex central railway station areas using the blocking-stairways technique in which the model assigns precomputed blocking-stairways to trains while respecting the operating constraints.

Corman et al. (2011) deal with the problem of serious disruptions and propose centralized and distributed approaches that permit delegating scheduling decisions to local schedulers by using adequate constraints; Louwerse and Huisman (2014) discuss the problem of adjusting the timetable of a passenger railway operator in case of major disruptions (partial or complete blockades) using an integer programming formulation and maximizing the service level offered to passengers; Wang et al. (2012) presents a fuzzy optimization model for high-speed railway timetable re-scheduling applied to a one direction line; Other interesting contributions are those of D’Ariano and Pranzo (2009) or Albrecht et al. (2013) and that of Veeleuturf et al. (2014) who deal with the problem of re-scheduling assuming a known large disruption time (for example, blocking a track for two hours or more) and based on an event-activity network.
In this thesis we consider disturbances, that is, small timetable changes, but no disruptions: In other words, neither short-turnings nor cancelling trains (see Cacchiani et al. (2014)) are considered.

Most existing computer models for timetable optimization do not consider the case of disturbances or disruptions, that is, changes in the railway line conditions during the scheduled periods. The most common disruptions include: (a) blocking of a segment for a given period of time, and (b) speed reductions, caused by several reasons, such as weather conditions (heavy rain, snow, wind, etc.), maintenance, etc. When these events occur, timetables must be recalculated in a short period of time. If the complexity is very high, this is not possible and the models become useless. Since this limits the practical value of the associated models, we include next an algoprithm to deal with disruptions.

7.2 Dealing with disturbances

In this section we explain how the partitioning algorithm must be modified to allow for disturbances.

The algorithm solves Problem $P$ including disturbances considering the partitions indicated in chapter 4 with the corresponding modifications. We remind the reader that in the case of complex problems, solving the optimization problem in a reasonable time requires this algorithm or a similar one. Otherwise, decisions could not be taken in real time. The algorithm is as follows.

**INPUT:** The main data of the problem consists of a horizon interval $(\tau_{\text{min}}, \tau_{\text{max}})$, the number $n_{\text{services}}$ of railway services demanded in this period together with the desired departure times and associated flexibilities, the line characteristics (segments, segment lengths, allowable speeds, train characteristics, etc.), the number of parts $p$ used for the partition of the horizon period and the option selected (time windows of (a) equal duration (opt=1) or (b) with the same number of active trains) (opt=2). Finally, we need to provide the list of disturbances by supplying the segments and services implied and the associated durations.

**OUTPUT:** A train timetable as close as possible to the optimum of the Problem $P$ that satisfies the constraints due to the given disturbances.

1. **Initiation. Set the partitions.** The partition counter $p$ is initiated to 1. The time horizon $(\tau_{\text{min}}, \tau_{\text{max}})$ is divided into small time windows $(\tau_1, \tau_2, \ldots, \tau_{p+1})$. With the intention of having small and similar complexities for all subproblems, the criterion used for selecting the value of the subperiod durations is to have the same durations
(opt=1) or the same number of active trains (opt=2). To this end, the lower bounds of the desired departure times are used. Let $\tau_1 = \tau_{\text{min}}$.

2. **Step 1. Update the time period for the current partition $p$.** Update the initial time $\tau_{\text{begin}}^p = \tau_p$ and the end time $\tau_{\text{end}}^p$ for the current time window of partition $p$ as follows. If the equal duration option is selected, $\tau_{\text{end}}^p = \tau_{\text{begin}}^p + (\tau_{\text{max}} - \tau_{\text{min}})/p$. Otherwise, $\tau_{\text{end}}^p$ is selected such that $n_{\text{services}}/p$ trains could have departed in the current partition, based on the lower bounds of the desired departure times.

3. **Step 2. Optimize the traffic in the current partition.** The set of services (trains) that can be running in this partition are activated (their lower bounds of the desired departure times are in the interval $[\tau_{\text{begin}}^p, \tau_{\text{end}}^p]$) and the optimization problem $\mathcal{P}$ is solved only for this restricted set of services.

4. **Step 3. Check for disturbances starting at this partition.** For any disturbance starting at this partition at time $\tau_{\text{entry}}$, activate the disturbance and change the current partition end time to $\tau_{\text{end}}^p = \min(\tau_{\text{end}}^p, \tau_{\text{entry}})$.

5. **Step 4. Force delays to be satisfied.** Let $p = \text{opt} - 1$. Fix the travel time for the service causing the disturbance to the corresponding value at the associated segment, that is, the values of $p_{i,s}$ to the disturbance travel time for the service $i$ causing the disturbance and the corresponding segment $s$. Fix the $\epsilon$ bound to a large value, say 4 times the actual value, that is $\epsilon_u = 4\epsilon_u$.

6. **Step 5. Check for segments already traveled.** Determine the segment time entries and exits (values of the variables $s_{i,\sigma_i,k}$ and $e_{i,\sigma_i,k}$, respectively) of trains occurred before $\tau_{\text{end}}^p$ and fix them at their actual partition optimized values. Similarly, determine origin train departures (variables $r_i$) occurred at this subperiod and fix them to their optimal values. Do the same with the running time variables $p_{i,\sigma_i,k}$ and tracks used by these trains (binary variables $q_{i,k,t}$).

7. **Step 6. Check for concluded services and remove them.** If services $i$ and $i_1$ have concluded at this stage, fix the corresponding $x_{i,i_1,k,k_1}$ and $y_{i,i_1,k,k_1}$ priority variables, that is, fix them to their constant values (zero or one).

8. **Step 7. Test for end of horizon period.** If the actual partition is the last partition, exit the cycle and provide results. Otherwise, move to the following partition, that is, let $p = p + 1$ and go to Step 1.

Since re-scheduling must be done in a limited time, this algorithm becomes especially useful for the case of disturbances that imply a modification of the time schedule, that is, when a re-scheduling is needed in real time. In these cases, we need only to fix the disturbance occurrence time to coincide with $\tau_{\text{min}} = \tau_1$, that is, the boundary of the first partition.

Some illustrations of how this algorithm works are given in the following section.
7.3 Examples of application

In this section we give several examples of application to illustrate how the proposed algorithm works in real cases. We have selected the Palencia-Santander, the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete and the Santiago-Valparaíso-Viña del Mar lines, that were introduced in previous chapters. The idea is to produce a disturbance and to re-schedule the timetable using the algorithm. We start with a single disturbance and in our third example we consider two disturbances.

7.3.1 The Palencia-Santander line

The Palencia-Santander line was described in Subsection 4.4.1 in page 76. It is a single-track line in which some segments have been completed with a second track. From Torrelavega to Santander a conventional track is constructed and from Palencia to Alar del Rey a new high speed track is considered.

In this subsection we present a re-scheduling application. As indicated, we use the alternate double-single track line finally proposed to the Cantabria government an described in detail in chapter 4 page 76.

In Figure 7.1, where the double track segments are shown in yellow, we show:

1. The timetable corresponding to the actual demand of trains of the line Palencia-Santander with 8 more long distance trains, when no incidences exist (obtained with \( p = 6 \) partitions). This timetable shows a homogeneous and optimized diagram, which corresponds to the regular operation of the line. It is clear that the upper segments between Torrelavega and Santander correspond to a more dense traffic because of the commuter trains. Contrary, the lower segments, that is, between Palencia and Reinosa have a few long distance circulation trains.

2. The timetable after an incident of service 47 at segment 31 (Cobejo-Bárcena), shadowed in the figure. The incident consists of a blocking time of the single track segment for a period of three hours.

The re-scheduled timetable shows that this long duration disturbance produces serious problems to the circulation of trains, not only to service 47, but to several more that need re-schedules of different sizes depending on how close or far they circulate from the train causing the disturbance. The shadowed region permits and facilitates the visualization of the affected zone and times. The plot also shows how the last services in the day are practically not affected by the peturbation.

3. The timetable after an incident of service 47 at segment 31, indicated by a shadowed area in the figure. The solutions were obtained with 6 and 10 partitions in 115.2 and 86 seconds, respectively.
CHAPTER 7. RE-SCHEDULING DUE TO DISTURBANCES

Figure 7.1: Cases 2, 5 and 6: Timetable corresponding to the actual demand of trains of the line Palencia-Santander when no incidence occurs (Case 2 in the upper plot) and when the segment Cobejo-Bárdena is blocked for three hours, obtained with $p = 6$ (Case 5 in the intermediate plot) and $p = 10$ (Case 6 in the lower plot) partitions.
CHAPTER 7. RE-SCHEDULING DUE TO DISTURBANCES

Figure 7.2: The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line. Single and double-tracks are shown as thin and thick segments, respectively.

Note that the differences between the two solutions, resulting for 6 and 10 partitions are not extremely important.

The service affected by the incidence and the corresponding segment is indicated using a shadowed area.

It can be seen that the re-scheduled timetable is very good and difficult to improve. Note how the incidence produces a delay in several services, but this effect disappears in a relatively short period of time, so that the train circulating during the last hours of the day suffer no change.

7.3.2 The Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line

In this section we analize a disturbance in the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line, that was introduced in Chapter 4 and page 84.

Figure 7.2 is repeated here for the sake of clarity. Note that this line has some single-track segments, shown by a thin line and some double-track segments, shown as a thick in Figure 4.4.

Figure 7.3 shows the optimized timetable corresponding to this line without disturbances, where the yellow areas correspond to double-track segments and the white areas to single-track segments. Note that the Madrid-La Sagra and La Sagra-Córdoba segments
have a dense traffic, especially the first one, while La Sagra-Valencia, Córdoba-Málaga and Córdoba-Sevilla have an intermediate traffic. Finally, the segment Motilla-Albacete has a very low traffic density.

Figure 7.4 shows the re-scheduled timetable after an incidence consisting in an obstruction of the single track segment 3 (Tarancón-Cuenca) for two hours, where the most affected services and their corresponding segments have been shadowed.

We note that, as should be expected, the main timetable changes correspond to the line La Sagra-Valencia where the disturbance takes place.

However, the La Sagra-Córdoba and the Madrid-La Sagra suffer some timetable reschedules too and also the Córdoba-Sevilla line but in a smaller amount.

### 7.3.3 The Santiago-Valparaíso-Viña del Mar line

In this section we present two examples of one and two hours disturbances in the saturated Santiago-Valparaíso-Viña del Mar line.

We consider the case already described in Chapter 4 with 100 services, 76 passenger trains and 24 freight trains. The timetable with no disturbances is given in Figure 7.5, where we can see that the line is saturated and that we have 4 single track segments and 3 double track segments.

Figure 7.6 shows the resulting optimized timetable for the case of occupation of the single track segment 3 during one hour by train 29.

It is interesting to see how some services are re-scheduled in the double track segments 2 and 4 and how the corresponding trains need to wait suffering the corresponding delay.

Figure 7.7 shows the resulting optimized timetable for the case of occupation of the single track segment 3 during two hours by train 29.

In this case more services must be delayed and re-scheduled in the double track segments 2 and 4, so that the corresponding trains need to wait until the problem is solved.

Finally, Figure 7.8 shows the resulting optimized timetable for the case of occupation of one of the tracks of the double track segment 4 during two hours by train 29.

In this case the affected services are forced to circulate by the other track in order to avoid important delays. Note that in the case of disturbances, the double-track segment has clear advantages with respect to the single-track segment.

Finally, in this example we consider two disturbances of two hours duration at two single-track segments.

The resulting optimized timetable is shown in Figure 7.9 where it can be seen how the trains close to the affected space-time areas suffer important delays, but other trains are not affected. The resilient properties of the proposed algorithm seem to be good because a rapid restoration of the initial timetable is obtained.
CHAPTER 7. RE-SCHEDULING DUE TO DISTURBANCES

Figure 7.3: Case 4: The resulting optimized timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line.
Figure 7.4: Case 11: The resulting optimized re-scheduled timetable for the Madrid-Sevilla-Toledo-Málaga-Valencia-Albacete line after the segment Tarancón-Cuenca remains blocked for a period of two hours.
CHAPTER 7. RE-SCHEDULING DUE TO DISTURBANCES

Figure 7.5: Timetable corresponding to the case of no disturbances

Figure 7.6: Timetable corresponding to the case of one hour disturbance at a single track segment.
Figure 7.7: Timetable corresponding to the case of two hours disturbance at a single track segment.

Figure 7.8: Timetable corresponding to the case of two hours disturbance at a double track segment.
Figure 7.9: Timetable corresponding to the case of two hours independent disturbances at two single track segments.
Part VI

CONCLUSIONS AND PUBLICATIONS
Chapter 8

Conclusions (in English)

Contents

8.1 Conclusions on the ADST lines . . . . . . . . . . . . . . . . . . 146
8.2 Conclusions on the time-partitioning technique . . . . . . . . 146
8.3 Conclusions on the re-scheduling technique . . . . . . . . . . 147
8.4 Future work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 148
CHAPTER 8. CONCLUSIONS (IN ENGLISH)

8.1 Conclusions on the ADST lines

1. The alternate double-single track (ADST) lines provide a very useful alternative to double track lines. The theoretical and practical results in this thesis confirm that the commonly used double track solution is not the most reasonable alternative in peripheral lines, in which only one highly populated city is connected with other small cities because the number of trips is mainly regulated by the small city size and the size of the large city plays a secondary role.

2. The alternate ADST and mixed conventional-high speed solutions are also very efficient solutions to reduce travel times significantly when conventional lines need to be improved and renovated. The examples in this thesis prove that they provide important savings with respect to double-track lines and with a very efficient traffic operation in terms of cost and travel times.

3. The construction and maintenance costs of double-track lines of new construction can be up-to 60% more than ADST lines and this can even much higher when conventional lines are complemented with segments of new construction. Consequently, double-track lines need a serious justification before being constructed. In this thesis some real examples of cases where ADST is the best solution are given.

4. Though the capacity of ADST lines is significantly smaller than the one of double-track lines, this capacity is seldom needed in peripheral lines. Thus, the efficiency of ADST lines in terms of number of trains and travel times is similar to that of double track lines.

8.2 Conclusions on the time-partitioning technique

5. The proposed time-partitioning method in which the time horizon period is divided into small subperiods (time windows), permits to re-schedule timetables in real time. This means that the calculation time is much shorter (it can be several orders of magnitude) than that of a unique partition. This solution, though not optimal is a feasible solution and close enough (practically acceptable) to the optimal, that is, of practical use.

6. The CPU time reduction due to the partitioning technique is very relevant in the case of complex networks with intense and heterogeneous traffic (a large number of trains with different speeds).

7. When trains circulate at similar speeds this reduction in the CPU time is much smaller.
8. Two different alternatives have been studied to define the partitions (time windows). The first is based on equal number of active trains, looking for similar complexity, and the second uses identical duration subperiods. The cases analyzed so far demonstrate that the first option is better than time windows based on identical duration.

9. When comparing these two types of time windows not only the CPU but the quality of the solutions must be considered, that is, how close are the resulting solutions to the optimal one.

10. Though for real time applications quick solutions are looked for, it should not be forgotten that the most important is to provide safe timetables, i.e. safe operations. Thus, optimality is only a secondary but desirable objective.

11. Since to re-start operation after a disturbance we need only the re-scheduled timetable portion of the first partition, if needed we can re-start the train operations in a safe way without waiting for the computer to finish the calculations for the whole period. This implies a further time reduction with a practical relevance.

12. Though the main application of the time partitioning method is the re-scheduling operation due to disturbances in existing lines, the proposed methods can also be used for planning new lines and for optimizing timetables.

13. The constraints of the type (4.2), which have been added to the initial optimization problem, allow different trains to choose between alternative subpaths between given nodes in the railway network. This is an important contribution because it allows train to choose between different routes, when in the previous models trains were forced to follow a given route.

This permits complementing the existing conventional lines with new high speed segments that by-pass some stations in order to avoid decelerations, stops and posterior accelerations, i.e. travel times reductions. This possibility has been analyzed and discussed in the Palencia-Santander line leading to a very efficient solution. We have proved that the combination of conventional lines with new high speed single-tracks is a very reasonable solution and raises serious doubts about the indiscriminate use of double-track high speed lines for any traffic demand level, as it is usually done. The proposed methods are also applicable to these lines.

8.3 Conclusions on the re-scheduling technique

14. The time partitioning technique is the only possibility for solving the timetable re-scheduling problem when some disturbances occur in large and complex networks. The main reason for this is that the CPU time required for the re-scheduling is too
high in order to provide solution of the problem in real time (seconds or at most a very few minutes).

15. Though in this thesis we have analyzed only the case of disturbances, i.e. the case of small delays, and we have omitted the case of disruptions, in which some cancellation of trains and other important changes must be considered, we can say that for this purpose the time partitioning technique is useful. The illustrative examples developed in Chapter 7 illustrate how these disturbances produce important changes in the affected trains, but the timetable is satisfactorily adjusted so that after some reasonable time after the disturbance, the timetable recovers becoming close to the initial timetable.

16. Though the re-scheduled timetable is not optimal but close to it, the safety and operational constraints in the optimization problem guarantee that the resulting solution after re-scheduling satisfies all the necessary requirements for a safe operation of trains. It is important to realize that optimality is convenient but difficult to attain, but safety is necessary and computationally easy to attain.

8.4 Future work

1. The optimization problem presented in this thesis solves many of the real problems of railway operation, but not all. In this sense in future work it must be extended to contemplate the real capacity of stations and their associated platforms.

2. It would be of interest to improve the capacity of trains to choose different routes. The model described in this thesis provides the uncommon possibility of this route selection, but need to be improved.

3. Further work is also needed to improve the existing methods for solving our optimization problems and reduce the CPU time even more. Alternative strategies and time partitioning techniques need to be given for very large and complex railway networks.

4. Sensitivity analysis is one important and appealing area where future work can be of interest. In particular, it is closely related to timetable robustness, which is very important for practical application of the methodologies proposed in this thesis.

5. The optimization models in this thesis and many other provided by other authors need to be used systematically to solve daily railway operations. An effort must be done in this direction for all operators to be aware of the important tools available nowadays.
6. Several groups of people in different countries are developing railway operation tools based on the computer. The cost of these studies is high and requires a lot of time, knowledge and dedication. It would be convenient to make an effort to bring these people together in order to attain a higher synergy and efficiency.
Chapter 9

Conclusions (in Spanish)

Contents

9.1 Conclusiones sobre las líneas ADST .......................... 152
9.2 Conclusiones sobre la técnica de particionamiento temporal 152
9.3 Conclusiones sobre la técnica de reprogramación ............. 154
9.4 Trabajo futuro ......................................................... 154
9.1 Conclusiones sobre las líneas ADST

1. Las líneas de vía alternada doble-simple (ADST) proporcionan una alternativa muy útil a las líneas de vía doble. Los resultados teóricos y prácticos de esta tesis confirman que la solución de vía doble, de uso común, no es la alternativa más razonable en líneas periféricas, en las que sólo una ciudad densamente poblada está conectada con otras ciudades más pequeñas debido a que la demanda se rige principalmente por el tamaño de la ciudad pequeña, jugando el tamaño de la ciudad grande un papel secundario.

2. La combinación de las líneas ADST de alta velocidad con las líneas convencionales conduce a soluciones muy eficientes para reducir significativamente los tiempos de viaje cuando las líneas convencionales necesitan una mejora de los tiempos de viaje. Los ejemplos de esta tesis demuestran que proporcionan ahorros muy importantes con respecto a las líneas de vía doble y con una operación de tráfico muy eficiente en términos de coste y tiempos de viaje.

3. Los costes de construcción y mantenimiento de líneas de vía doble de nueva construcción puede ser de hasta un 60 % más que el de las líneas ADST e incluso mucho mayor cuando las líneas convencionales existentes se complementan con segmentos de nueva construcción. En consecuencia, las líneas de vía doble necesitan una seria justificación antes de ser construidas. En esta tesis se dan algunos ejemplos reales en los que las líneas ADST son la mejor solución.

4. Aunque la capacidad de las líneas ADST es significativamente menor que las líneas de vía doble, esta capacidad es raramente necesaria en líneas periféricas. Por lo tanto, la eficiencia de las líneas ADST en términos de número de trenes y tiempos de viaje es similar a la de las líneas de vía doble.

9.2 Conclusiones sobre la técnica de particionamiento temporal

5. El método propuesto para particionar el período de análisis en pequeños subperíodos (ventanas temporales), permite reprogramar los horarios en tiempo real. Esto significa que el tiempo de cálculo es mucho más corto (puede ser varios órdenes de magnitud) que el correspondiente a una partición única. Esta solución, aunque no es óptima es una solución factible y lo suficientemente cercana (prácticamente aceptable) a la óptima, es decir, de uso práctico.

6. La reducción del tiempo de CPU debida a la técnica de partición es muy relevante en el caso de las redes complejas con tráfico intenso y heterógénea (cuando circulan un gran número de trenes con diferentes velocidades).
CHAPTER 9. CONCLUSIONS (IN SPANISH) 153

7. Cuando los trenes circulan a velocidades similares esta reducción del tiempo de CPU es mucho más pequeña.

8. Se han estudiado dos alternativas diferentes para definir las particiones (ventanas temporales). La primera se basa en la igualdad de número de trenes activos, en busca de complejidad similar, y la segunda utiliza subperíodos de idéntica duración. Los casos analizados hasta el momento demuestran que la primera opción es mejor que las ventanas temporales que se basan en idéntica duración.

9. Al comparar estos dos tipos de ventanas temporales no sólo debe considerarse el tiempo de CPU, sino la calidad de las soluciones, es decir, cuánto las soluciones resultantes se acercan a la óptima.

10. Aunque para aplicaciones en tiempo real se buscan soluciones rápidas, no hay que olvidar que lo más importante es proporcionar horarios seguros, es decir, aquellos que conducen a operaciones seguras. Por lo tanto, el óptimo, aunque deseable, sólo es un objetivo secundario.

11. Para poder continuar con la operación de la línea tras la ocurrencia de perturbaciones, se necesita sólo la parte del horario correspondiente a la primera partición, por lo que, si es necesario, se puede continuar con la operación de los trenes de una manera segura sin esperar a que el ordenador finalice los cálculos para todo el período. Esto implica una reducción de tiempo adicional, que tiene una relevancia práctica.

12. Aunque la principal aplicación del método de las particiones es la reprogramación debido a perturbaciones en las líneas existentes, los métodos propuestos también pueden utilizarse para la planificación de nuevas líneas y para la optimización de los horarios.

13. Las restricciones del tipo \([4.2]\), que se han añadido al problema de optimización inicial, permiten a los diferentes trenes elegir entre rutas alternativas entre dos nodos dados en la red ferroviaria. Esta es una contribución importante porque permite a los trenes elegir entre diferentes rutas, cuando en los modelos anteriores los trenes están obligados a seguir una ruta determinada. Esto permite complementar las líneas convencionales existentes con nuevos segmentos de alta velocidad que no pasan por algunas estaciones con el fin de evitar las deceleraciones, las paradas y las aceleraciones posteriores, es decir, importantes reducciones en los tiempos de viaje. Esta posibilidad ha sido analizada y discutida en la línea Palencia-Santander que conduce a una solución muy eficiente. Se ha demostrado que la combinación de líneas convencionales con vías nuevas de alta velocidad es una solución muy razonable y plantea serias dudas sobre el uso indiscriminado de las líneas de vía doble de alta velocidad para cualquier nivel de demanda de tráfico, lo que se suele hacer. Los métodos propuestos son aplicables también a estas líneas.
9.3 Conclusiones sobre la técnica de reprogramación

14. La técnica de partición en ventanas temporales propuesta es la única posibilidad de resolver el problema de reprogramación de horarios cuando se producen interrupciones en las redes ferroviarias grandes y complejas. La razón principal es que el tiempo de CPU requerido para la reprogramación es demasiado alto con el fin de proporcionar una solución al problema en tiempo real (unos segundos en la mayoría de los casos).

15. Aunque en esta tesis hemos analizado sólo el caso de interrupciones, es decir, el caso de pequeños retrasos, y hemos omitido el caso de grandes perturbaciones, en los que se debe considerar la posible cancelación de trenes y otros cambios importantes, se puede decir que para este fin la técnica de partición propuesta es muy útil. Los ejemplos ilustrativos desarrollados en el capítulo 7 ilustran cómo estas alteraciones producen cambios importantes en los trenes afectados, pero el horario se ajusta de manera satisfactoria por lo que después de un tiempo razonable tras la interrupción, el horario se recupera siendo muy semejante al inicial.

16. Aunque el horario reprogramado no es óptimo, es cercano al óptimo y cumple con todas las restricciones operativas y de seguridad, por lo que la solución resultante tras la reprogramación satisface todos los requisitos necesarios para una operación segura de los trenes. Es importante darse cuenta de que la optimalidad es conveniente pero difícil de alcanzar, pero la seguridad es necesaria y computacionalmente fácil de satisfacer.

9.4 Trabajo futuro

1. El problema de optimización presentado en esta tesis resuelve muchos de los problemas reales de la operación ferroviaria, pero no todos. En este sentido el trabajo futuro debería contemplar la capacidad real de las estaciones y sus respectivas plataformas.

2. Sería de gran interés mejorar la capacidad de los programas de optimización para que los trenes pudieran elegir diferentes rutas. El modelo descrito en esta tesis ofrece la posibilidad poco común de esta selección de ruta, pero tiene algunas limitaciones.

3. Es necesario mejorar aún más los métodos existentes para la resolución de los problemas de optimización y reducir los tiempos de CPU aún más. Debe también trabajarse en estrategias y técnicas de partición alternativas especialmente en el caso de redes ferroviarias muy grandes y complejas.

4. El análisis de sensibilidad es un área importante y muy atractiva en la que el trabajo futuro puede ser de gran interés. En particular, está estrechamente relacionada con
el problema de la robustez de los horarios, que es una propiedad muy importante para la aplicación práctica de los métodos propuestos en esta tesis.

5. Los modelos de optimización en esta tesis y muchos otros proporcionados por otros autores deberían ser utilizados de forma sistemática para resolver los problemas de operación de redes ferroviarias. Debe hacerse un gran esfuerzo en esta dirección para que las compañías responsables de la operación estén al tanto de las nuevas e importantes herramientas disponibles en la actualidad.

6. Varios grupos de personas en diferentes países están desarrollando herramientas de explotación de ferrocarril basadas en el ordenador. El coste de estos estudios es alto y requiere mucho tiempo, conocimiento y dedicación. Sería conveniente hacer un esfuerzo para agrupar a estas personas y grupos con el fin de lograr una mayor sinergia y eficiencia.
Chapter 10

Publications

In this chapter we include the main publications in journals or congresses resulting from this thesis.


Appendix A

Computer application for timetable and ADST optimization

Contents

A.1 Introduction ........................................... 160
A.2 The ADST line ......................................... 160
   A.2.1 The home screen .................................. 160
   A.2.2 The main menus .................................. 166
   A.2.3 The information window ......................... 169
   A.2.4 The general data window ......................... 171
   A.2.5 The nodes window ................................ 177
   A.2.6 The segments window ............................ 181
   A.2.7 The routes window ................................ 184
   A.2.8 The headway times window ....................... 186
   A.2.9 The speeds window ................................ 189
   A.2.10 The trains window ................................ 191
   A.2.11 The services window ............................. 193
   A.2.12 Generated results ................................. 197
   A.2.13 The final result window ......................... 200
   A.2.14 Supplied results ................................. 200
   A.2.15 Generated files .................................. 203
A.3 Conclusion ............................................ 203
A.4 Shortcut summary .................................... 204
A.1 Introduction

This software is the result of the research being conducted by the Applied Mathematics and Transportation groups from the Universities of Cantabria and Castilla-La Mancha, respectively, on the rationalization of the conventional and high speed railway infrastructures. This program uses the GAMS modeling system software for mathematical optimization, to decide which segments should be built in single or in double track, based on a known specific demand of services and a series of homogenous segments of the routes, whose construction costs in single and double track are known. This program adjusts the time schedules of the services that travel along the railway line by slightly modifying the departure times of the trains so that they cross at the double track segments without having to slow down or stop at passing loops or stations more than necessary. In this way an infrastructure solution that greatly reduces construction and maintenance costs without the need for substantial increase of travel times and using a minimum of double track segments is obtained.

In addition to optimizing the design by choosing the segments of double and single track, the program optimizes the train schedules, so that it is also a program for design of alternate double-single track lines and for optimization of timetables, given the line infrastructure and associated demand.

The optimized timetable aims to adjust the service travel times to achieve a maximum of single track, but without generating a delay exceeding a given threshold.

This manual explains how data must be given to the optimization program, how they are sent, via Dropbox, to the calculation center and finally how you receive the results, as well as a description of what you receive as a solution to the problem. This will give the necessary instruments for the correct definition of a railway line in order to be able to perform the corresponding analysis for its design as an alternate double-single track line.

In the following paragraphs, the procedures necessary to complete the information required by the program and to find an optimal solution are explained.

The working environment is very intuitive and easy to follow, thanks to the graphical part of each element and the control that is exercised to prevent undesired deleted items if there are other items that are dependent on them. Its similarity with other professional applications of Windows is obvious.

A.2 The ADST line

A.2.1 The home screen

The home screen, shown in Figure A.1 includes some buttons to:

- Create a new project
- Open an existing project
Next, we proceed to explain the basic functions of each one of the existing buttons in this home screen.

In the central part of the home window, see Figure A.1, there are a series of buttons that permit create or open projects in different forms. The buttons are:

- **CREATE A NEW PROJECT...**: This option opens a window where the new project can be defined with its name. The extension of this file name is *.viacomp.

- **OPEN EXISTING PROJECT...**: With this option an existing project can be opened. The user is allowed to navigate in order to find the desired project file.
Figure A.2: Create a new project.
Figure A.3: Open an existing project.
• **RECENT PROJECTS:** In the intermediate part of the window a deployable menu appears in which a list of previous projects are displayed from which the desired project can be selected.

• **OPEN:** Opens the selected project and the information window to be described later.

• **LANGUAGE:** At the bottom right corner of the home screen appears a menu, which displays the list of available languages, to select the language you want to work with. Once selected, a pop-up window appears in the selected language, warning: "The program will exit automatically. To complete the change of language, reopen it".

• **QUIT:** This button closes the program.
Figure A.5: Language selection.
A.2.2 The main menus

At the top left of the main window, shown in Figure A.6, there are a series of tabs corresponding to the different menus.

When clicking on them the corresponding menu items are shown in order to select the desired options. It is advisable to warn that these tabs remain always visible, regardless of the section of the program in which you are working. These menus are:

The file menu.

It contains the following menu items, see Figure A.7:

- CLOSE PROJECT: Closes the current project and returns to the home screen.
- QUIT: Exits the computer program.

The edit menu.

This menu item defines the basic operations of data management (see Figure A.8), such as:

- UNDO [CTRL + Z]: Undo the previous change and recover the previous state.
- CUT [CTRL + X]: Copy and delete the selected element.
- COPY [CTRL + C]: Copy the selected elements keeping them inside the clipboard.
- PASTE [CTRL + V]: Paste the clipboard content at the selected location.
Figure A.7: The File menu.

Figure A.8: The edit menu.
• DELETE: Eliminate the selected elements.

• SELECT ALL [CTRL + A]: Selects all elements at once.

The options menu.

This menu allows us the access to the different elements that permit the definition of the railway line, as well as to the general features of the line (see Figure A.9). These are:

• INFO WINDOW [CTRL + 0]: Redirects to the information window.

• NODES [CTRL + 1]: Opens the node window.
• SEGMENTS [CTRL + 2]: Opens the segment window.
• ROUTES [CTRL + 3]: Opens the route window.
• SAFETY TIMES [CTRL + 4]: Opens the headway times window.
• SPEEDS [CTRL + 5]: Opens the speed window.
• TRAIN TYPES [CTRL + 6]: Opens the train types window.
• SERVICES [CTRL + 7]: Opens the services window.
• MODIFY FLEXIBILITIES: Opens the modify flexibilities window.
• AUXILIAR WINDOW: Opens the auxiliar window.
• GENERAL AND OPERATING DATA: Opens a window in which the general and operating data are defined.
• GENERATE FILES: Sends the required data to the calculation center via Dropbox and waits until the optimization problem is solved and the associated results sent to the database via Dropbox.
• IMPORT RESULTS: Loads in the database the results stored in the Dropbox in order to generate the circulation graphs and the tables with the problem solution.
• DELETE RESULTS: Deletes the results of the problem to allow for data change edition. The program does not allow any data change if some results are active. Consequently, a data change requires a previous data elimination.

A.2.3 The information window

This window, Figure A.10, has a double function:

• To show the elements (nodes, segments, routes, times, speeds, trains and services) that define the line of study. The numbers of items of each type are explicitly shown. This is of great utility to quickly identify the different cases studied by their existing services, or by their routes, nodes or segments.

• To allows access from this screen with a single keystroke to each of the elements, in order to view their actual content and create new or modify existing elements.

At the top of the window the name of the project is displayed, with which it is identified in the program, as well as in the results folder. In this case the name is "project-ADST". This name can be a name different from the one used in the file *.viacomp in the computer.
Figure A.10: The information window.
folder, although it is recommended to define the same name to avoid errors when operating with several cases.

In the middle of the window, all the elements which define the project are shown with accessible hyperlinks, and the number of items of each class that already exist. At the bottom, the path of the file in which they are saved is reported in gray letters.

### A.2.4 The general data window

This auxiliary window, shown in Figure A.11, which is accessed from the “general and operating” item of the “Options” menu, allows us to introduce the general and global exploitation characteristics of the project.

This window is divided into four tabs, which are explained below.

The window, Figure A.11, includes the general and default data of the line that you are simulating. This is divided into three sections that correspond to the three different parts of definition of the project.

1. Identification

   **NAME OF THE PROJECT:** As indicated, this is the name with which the project
is defined in the program and in the results folder, but not in the computer, whose name is the one defined above that is chosen by the user.

2. Default data

NETWORK SHUTDOWN TIME: Defines the time limit, from which the railway line does not support more services. It is a time when the maintenance of the line starts.

DEPARTURE TIME FLEXIBILITY: Defines the default admissible flexibility for the train departure times in order to allow them to cross at double-track segments, they are defined in minutes with decimal.

DEFAULT SAFETY TIMES: Default minimum time difference that must exist between two services, both in the same or opposite direction in order to be able to move safely. Defined in minutes with decimal.

DEFAULT MAX SPEED: default maximum speed, in km/h, for designing the railway line.

3. Result destination

EXPORT AND RESULTS FOLDER: In it, using the menu ”Select Folder...”, the final folder where you will spill the data and recover the results of the optimization is defined. In this case you use the Dropbox. If the folder has already been defined (selected) its name appears in the corresponding field, which in this example is:

C:\Users\grandez\Dropbox\AVEOptimum’’.

The operation window.

In this tab, Figure A.12, the railway charges and fees associated with the line are defined. These data are given with the aim of estimating expenditure of exploitation that the line should settle with the infrastructure manager in the exploitation phase, assuming the characteristics of the line and an average passenger occupancy of the trains.

In the case of the Spanish network, ADIF as administrator of infrastructures annually determines and updates the quantities corresponding to these rates and canons, in its Network Declaration. In the program the following rates and canons are considered:

- SAFETY TAX: safety tax rate for travellers in the monitoring and control of access, in euros by person and travel.
- ACCESS CANNON: quantity by access to the railway network, in Euros per year.
- RESERVE CAPACITY CANNON: Train reserve tax of kilometers by train, following the period in rush hour or zone time, euros by train and reserved kilometre.
Figure A.12: The operation window.
Figure A.13: The operation costs window.

- CIRCULATION CANNON: Tax for use of the reserved capacity, in euros by train and circulated kilometre.

- RUSH HOUR TRAFFIC CANNON: tax for capacity of supplied places, following the period in rush hour or zone time, euros per 100 places and reserved kilometre.

- USE OF STATIONS CANNON: Station cannon for travellers use of stations, in euros by traveller.

- STATION TRAIN PARKING CANNON: Cost of stations train parking, euros by train.

- TRAIN OCCUPATION: estimation of average occupation of trains.

The operation costs window.

This tab, which appears in A.13, groups the power and operation costs of the services that will circulate later along the designed infrastructure in the exploitation phase.

The considered operation costs are:
• ENERGY COST: Estimation of the cost of energy consumed by each service, in euros by supplied passenger and kilometer.

• STAFF COST: Cost of personnel of the railway operator, in euros by supplied passenger and kilometer.

• CUSTOMER SERVICES COST: Cost of the services on board, euros by passenger on board supplied and kilometer.

• HIGH SPEED TRAIN COST: Cost of the own train, in million euros.

• TRAIN MAINTENANCE COST: Cost of maintenance of the rolling stock, in euros by supplied passenger and kilometer.

• TICKET COST: In euros by traveller and kilometer, considers the average occupation of the services.

NOTE: Since the data introduced in the operation and operation costs tabs, do not interfere in the track morphology, but they depend directly on the supplied services, in this edition of the program their calculation has not been developed. However, it is worthwhile noticing that these tax and cannon calculations will be helpful for obtaining the final costs due to operation, that can turn out helpful to realise a correct cost-benefit analysis of the analyzed lines.

The complements window.

In this window, see Figure A.14 some GAMS commands can be introduced that impose quality constraints to the optimized design. This is important because the very demanding designs can be untractable due to calculation time. Nevertheless, a reduction of the exigency can lead to obtention of very fast feasible solutions.

This window allows us for implementing in GAMS other options not contemplated initially in the computer program.

Some of the allowed options are explained next:

• OPTCR: The program ends when the differences between the primal and dual results are below this optcr value. A typical value for the optcr parameter is 0.05, and one very demanding one is 0.01 or less.

• OPTCRVAL: Is identical to the previous one.

• EPSILONBOUND: It determines the maximum allowable relative travel time of the services. Typical values are 1.1 and 1.2, that imply a 10% and a 20% more than the minimum travel time (at maximum speed).
Figure A.14: The complements window.
• SEGMENTTRACKSVAR.fx(SEGMENT)=SEGMENTTRACKS(SEGMENT)-1;: This command limits the maximum possible number of tracks of each segment.

• PARAMETER CC(GROUP,SEGMENT)=yes;: This command allows us to group different segments in several groups, so that they act like a supersegment, that is to say, in that group no track change is allowed. This command can be used when some segments allow for bypassing some stations.

### A.2.5 The nodes window.

This section can be accessed by pressing the “Nodes” hyperlink in the information window, see Figure A.10 or executing the command [CTRL + 1]. In it the points or nodes in which stations or segment changes are located can be defined. The nodes window is shown in Figure A.15.

In the upper part of the window, three buttons appear, which are common to all windows. Thus, they will only be explained for this window:

• NEW: When pressing this button, a new window appears, different for any element being considered. This permits to create new elements (node, segment, route, etc.).

• MODIFY: This button can be selected only when previously at least one of the elements of the window has been marked (node, segment, etc.). When pressing the button a window appears that shows the data of the element previously selected, with the purpose of modifying it.

• DELETE: This button can be selected only when previously at least one of the elements of the window has been marked (node, segment, etc.). When pressing the button the selected element is deleted. It is important to inform that a node cannot be erased if another existing element depends on it. Thus, the system exerts an exhaustive control of existing elements and their dependencies so that that necessary elements cannot be deleted erroneously.

*IMPORTANT* Segments, cannot be created, previously if its nodes have not been generated, routes cannot be created, if their segments have not been created, and so on. In this program, with the purpose of assuring a correct definition of the elements necessary to define the railway line, data must be defined in order, without being able to define an element if the necessary elements that compose it have not been defined previously. For this reason they need to be defined in the following order:

General data : Nodes : Segments : Routes : Headway times : Speeds : Train types : Services
Figure A.15: The nodes window.
In the same way, an element cannot be suppressed if previously, the subordinated elements have not been eliminated, for that reason the suppressing order is the reverse of the previous one.

Returning again to the definition of the Node window, see Figure A.15, it is divided in two parts:

- The data window. It is the upper window of white color, in which the properties of each element are determined, like its name, the x and y coordinates, the node type and the number of available tracks. They can be sorted in ascending or descending order according to anyone of the identifiers previously described, see Figure A.15.

- The graphic window. It is the gray picture that is in the lower part of the window, in which the created nodes are shown. It is advisable to inform that if an element in the data part is selected, to favor the recognition of the node, it will appear in red, as shown in Figure A.15.

The node edit window.

After selecting the New button, a new window emerges, as shown in Figure A.16, where a new node can be defined; similarly, after selecting the Modify button, a window appears with the node data to allow for its modification.

The following information appears in the node window:

- **NAME**: It is the node name (it can be a number or a chain of characters).

- **X and Y COORDINATES**: They define the position of each node. The coordinates can be defined with X and Y coordinates to reproduce railway networks, and not only simple lines. It is recommended to refer all nodes with respect to an origin (Node 0), for a better understanding of the network.

- **TYPE**: In this column the type of node is defined by selecting from a drop-down menu, the kind of node. They are:
  - **GENERIC**: Single bond between two different segments. It defines the transition from one segment to another.
  - **PAET**: It is a passing loop for overtaking and train parking.
  - **STATION**: It is a node that allows the descent and ascent of passengers during a given time. In addition it also assumes the same function of a passing loop.

- **NUMBER OF TRACKS**: In the PAET and STATION node types, you must define the number of tracks, according to the node type and its possible functions. In the case of generic, it is not allowed to modify it, because they will have the same number as the corresponding segment.
Figure A.16: The node edit window.
With these conditions nodes can be defined in the desired number and with a configuration independent among them, resulting in a set of points with their names and certain features and located at coordinates X and Y as desired.

A.2.6 The segments window.

This section defines the segments on which services circulate. They permit to define the railway line. To access the window, as in the case of the nodes, you can select the hyperlink “Segment” in the information window, see Figure A.10, or use the shortcut [CTRL + 2].

The segments window is similar to the nodes window, see Figure A.17, and has two parts. Thus, we describe only the main differences.

- **Data window.** The segments are described by means of the start and end nodes, the number of tracks, the segment length and the costs for single and double track. Several peculiarities must be noted:
  
  - Number of tracks: The maximum number of available tracks must be given (one or two). If we do not want the program to decide between single or double track, we must add the following line to the “Complements” file: segmenttracksvar(segment)= segmenttracks(segment)-1;.
  
  - Length: If the computer program has computed the length it will be shown in red, see Figure A.17.

- **Graphic window.** As in the case of the nodes window, the selected items are highlighted in red in the graph.

The segment edit window.

After selecting the “new” button in the segments window, a window pops up, see Figure A.18, to define a new segment; similarly, when you select the modify button, a window appears with the data of the selected segment to allow for its modification.

The data in this window are:

- **ORIGIN NODE:** Node previously defined, from which the segment starts. It is selected from a dropdown list.

- **DESTINATION NODE:** Node previously defined, where the segment ends. It is selected from a dropdown list.

- **NUMBER OF TRACKS:** It is the number of tracks of the selected segment. It supports only 1 or 2 tracks.
**Figure A.17: The segments window.**

<table>
<thead>
<tr>
<th>Origin node</th>
<th>Destination no...</th>
<th>Tracks</th>
<th>Length km</th>
<th>Single Cost</th>
<th>Double Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>13</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>29</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>27</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2</td>
<td>22</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>2</td>
<td>10</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>2</td>
<td>8</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>2</td>
<td>11</td>
<td>24</td>
<td>39</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>2</td>
<td>12</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>2</td>
<td>6</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
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<td>6</td>
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<td>13</td>
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<td>2</td>
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</tr>
<tr>
<td>31</td>
<td>32</td>
<td>2</td>
<td>92</td>
<td>21</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure A.18: The segment edit window.
• LENGTH: It is the length of the segment, in km. If the CALCULATE option is selected this length is calculated from the corresponding node coordinates. If the desired length is not the straight line distance between the end nodes, you must provide this length in the blank field, in which case this length will be used.

• SINGLE TRACK COST: Cost per kilometer of the single-track segment.

• DOUBLE TRACK COST: Cost per kilometer of the double-track segment.

After defining the segments with their single or double track and the associated costs, the program can identify the segments where services can cross and the cost of the corresponding infrastructure automatically.

A.2.7 The routes window.

This window defines the routes as sequences of segments. To access this window you must select the hyperlink “Routes” in the information window, see Figure [A.10] or use the shortcut [Ctrl + 3].

In this case, in addition to the buttons defined in the case of the nodes window a new button appears:
• DUPLICATE. When pressing this button, that can be selected only for already existing routes, a new window, as the one in Figure A.19 appears with a duplicate of the previous element.

This window, as shown in Figure A.20, is different from the previous data windows and has only the data window in which existing routes are shown.

The route edit window

After pressing the “New” button, a window pops up, see Figure A.21, to define a new route. Similarly, when you press the “Modify” button, the same window appears with the data of the selected route. Once routes have been defined, they can be associated with the different services.

The items to be defined in the route edit window are:

• ROUTE NAME: It is the route name.

• SEGMENT SEQUENCE: This allows to define the different routes. The different segments are displayed in order to select the sequence of segments that define the route.
STOP TIME: this defines the dwell times, in minutes, associated with each service and station.

In the lower part there are three windows with the following functions:

- **DELETE**: Permanently deletes the selected route. We must warn that once deleted, it cannot be recovered.

- **CANCEL**: Changes will not be stored and the window will be closed with no changes in data.

- **OK**: The window is closed and the changes done are stored in the database.

All these comments are also valid for the cases of headway times, speeds, trains and services.

### A.2.8 The headway times window.

We show in this section how to provide the headway times of the different segments with a differentiation of the two directions. To access the window we can click the “Times” hyperlink, see Figure A.10 or use the shortcut [CTRL + 4].
It is convenient to define as many headway times as needed, in order to model the correct management of services across segments. Once defined, these times will be the minimum headway time margins between services for each segment and direction (same or contrary direction trains).

This window is identical to the one explained for the case of Nodes, as shown in Figure A.22. As the routes window, it has only the data window, where the existing headway times are shown, with their corresponding names.

**The headway times edit window**

After clicking the “Times” hyperlink, a window pops up, see Figure A.23, to define a new set of headway times. Similarly, when you select Modify, the same window appears with the existing headway times.

Headway times are initially defined by default in the General Information tab. To fully define them the following data must be given:

- **NAME**: It is the associated name to the group of headway times.
- **SEGMENTS**: It is the segment to which the headway times are applied, distinguishing the travel direction.
- **TIME**: It is the headway time, in minutes, that must exist between two trains in a row in the same direction or in the opposite direction of the corresponding segment. They can be changed one by one into the center square, but also selecting using the following option.
- **MODIFY ALL...**: It permits assigning a common unique value to all headway times.

At the bottom of the window three buttons exist, whose functions have already been described for routes.
Figure A.23: The headway times edit window.
A.2.9 The speeds window.

This section defines the speeds with which the different types of trains circulate along the different segments taking into account of the travel direction. The window can be accessed by selecting the hyperlink “Speed”, see Figure [A.10] or using the shortcut [CTRL + 5].

It must be remembered that both the working and maximum speeds must be defined for every type of train and segment. In this example, see Figure [A.24] the maximum possible speed, which is unique, and the working speeds of each type of train circulating along the line are defined.

This window, as shown in Figure [A.24] is identical to those described for the case of nodes and as the routes window has only the data window in which existing speeds with their names are shown.

The speed edit window

After pressing the “New” button, a window pops ups, see [A.25] to define a new set of speeds. Similarly, when you press the “Modify” button, the same window appears with the existing selected speed data set.

Similarly to the definition of headway times, the default speed value provided in the general data window is used for all trains.

- **NAME:** It is the name of the speed group.

- **SEGMENT:** It is the segment at which the speed is applied.

- **SPEED TRACK 1/TRACK 2:** It is the speed in km/h, to be used in each segment with consideration of its direction and track. They can be modified one by one in
Figure A.25: The speed edit window.
Figure A.26: The trains window.

the central field but also all together by pressing the “Modify all speed 1 or speed 2” buttons, in which case a common value is used for all of them.

In the lower part of the window three windows appear, that have been described for the case of routes.

A.2.10 The trains window.

This section defines the train types corresponding to the different services that circulate along the line. We can access this option clicking the “Trains” hyperlink in the home window, see Figure A.10 or the shortcut [CTRL + 6].

The uniqueness of this section and the next (Services) is that because previous elements have been already defined both, the train type and the services, can be defined very quickly.

These windows, as shown in Figure A.26 are identical of those for nodes and as the routes window has only the data window in which existing trains with their names are shown.

The train edit window

After pressing the “NEW” button, a new window appears, see Figure A.27 which allows us to define a new train type. Similarly, when pressing the “Modify” button, the same window appears with the data of the selected train type.

To define the train type, see Figure A.27 you need to define:

• NAME: It is the name of the train type.

• LENGTH: It is the length of the train in meters.

• NUMBER OF PASSENGERS: It is the train capacity in number of passengers.
Figure A.27: The train edit window.
• HEADWAY TIME SAME DIRECTION: The headway time group for this train and the same direction is selected.

• HEADWAY TIME OPPOSITE DIRECTION: The headway time group for this train and the opposite direction is selected.

• MAXIMUM SPEED: The speed group for this train maximum speed is selected.

• NORMAL SPEED: The speed group for this train working speed is selected.

In the lower part of the window three windows appear, that have already been described for the case of routes.

A.2.11 The services window.

Finally, this section is devoted to the last element to be defined. As all previous windows, they are accessible via the Home screen, clicking the “Services” hyperlink, see Figure A.10 or using the shorcut [ CTRL + 7 ].

This section is responsible for defining services that eventually will circulate along the rail network, see Figure A.28. In addition, after the optimization, the final timetable information of each service can be obtained, as it will be shown below in Figure A.28.

Again it is worth noting that the definition of these services is very fast, because it is based on the selection of already existing elements, which permits creating services quickly and efficiently.

In this section, in addition to the windows defined for nodes, we have a new window:

• CIRCULATION GRAPH: It can only be selected if the optimization program has finished the calculations and the results have been received in the database, see Figure A.31.

In the middle box, the dwell time at each station are shown. The remaining data will be completed automatically after the optimization program sends the results to the database.

This window, as shown in Figure A.28, similarly to the case of routes, has only the data window, but now each service is characterized by its name, route, train and desired departure time.

The service edit window

After pressing the button “New”, a window pop-ups, see Figure A.29, to define a new service. Similarly, the same window appears when you press the “Modify” button but then it shows the data associated with the selected service.

To define the services, see Figure A.29 we need to define the following fields:
Figure A.28: The services window.
Figure A.29: The service edit window.
APPENDIX A. COMPUTER APPLICATION

Figure A.30: Modify flexibilities.

- NAME: It is the name of the service.
- ROUTE: It is the route associated with the service.
- TRAIN: It is the associated train type.
- DEPARTURE TIME: It is the desired departure time.
- DEPARTURE TIME FLEXIBILITY: It is the allowable flexibility, in minutes, to advance or delay the departure time.

In the lower part of the window three windows appear, that have been described for the case of routes.

With respect to the departure time flexibility it must be remembered that it is defined by default in the general data window, see Figure A.11. However, there is another window, see Figure A.30, that can be accessed with the menu item “Modify flexibilities” of the “Options” menu, which permits modifying flexibilities (in minutes) one by one.

It should be noted that the flexibility changes overwrites data manually entered into the services individually, so this modification must be done before possible individual changes.
A.2.12 Generated results

When the program has generated the final optimal timetable and the sequence of optimal single and double tracks, if you select the menu item “Import results” from the “Options” menu and the result is dumped into the database, as follows.

1. In the services window, see Figure A.31, the field real departure time is filled automatically (in red) showing the real departure times of each service. This permits a comparison of the desired and real departure times.

2. Circulation diagrams: As shown in Figure A.32, after the calculations have been done and the results sent to the database, the circulation graphs can be seen, see Figure A.32 by selecting any route in the menu.

The circulation graphs represent the location in space and time of all the services running along the line. Each one is represented with lines of different color, if they are continuous they use track 1, and if they are dashed they correspond to services using track 2.

These graphs are demarcated by two axes:

- The vertical axis of the graph represents the route of the line, from the initial station to the end station.
- The horizontal axis represents the hours in which the different services circulate starting at their departure times and ending with their arrival times.

The horizontal dotted lines shown in the graph determine the origin and end of the various segments in which the line is divided.

Finally, the slopes of the trajectories are associated with the corresponding speeds. The more vertical they are the faster they are.

In addition, we can press the “Print” button, see Figure A.32 to print the circulation graphs.

3. Service window: If a service is selected, see Figure A.30 another window pops-up, in which the service data are completed, in red color.

As you can see it is no longer possible to modify any data. Furthermore, information of each service flow can be printed, namely:

- REAL DEPARTURE TIME: from the service origin.
- ENTRY END EXIT SEGMENT HOURS: They are the entry and exit times of the different trains for all the segments.
- DWELL TIME: It is the dwell time between segments. It is the station or the passing loop dwell time.
Figure A.31: The services window showing the real departure times completed by the computer program after the optimization has finished.
Figure A.32: Circulation diagrams automatically generated by the program after the optimization program has finished.
• TRACK: It is the track used by the service at each segment.

With this information, we can know all details of the timetable and service interactions.

Up to this point we have described the commands necessary to model an alternate double-single track project and we have seen the results generated. In the next section, we proceed to explain the files that the software produces to generate the results.

A.2.13 The final result window.

For the program to issue the result, the first thing to do is to dump all the data in a Dropbox folder. For it to be possible we need to indicate in the “general data” window, the direction of the destination folder and select GENERATE RESULTS (see Shortcuts), after confirming that you want to generate the result, see Figure A.33.

In the main window we have the following buttons:

• CHECK NOW: checks whether or not the calculations have finished. It they are, it brings the results to the database via Dropbox.

• CANCEL CALCULATIONS: This cancels the optimization program and the corresponding results and unblocks the database so that data can be modified.

The program checks every minute if the optimization program has finished the calculations. If this is true, the program sends the results to the database via Dropbox.

A.2.14 Supplied results

Once the results are available in the database, the main window is modified and they can be accessed.

The window with the results contains the following information:

• DATE WHEN THE RESULTS WERE CALCULATED: the date on which the results were created is shown.

• DISCARD RESULTS. When selecting this option the result information is eliminated after confirming this in an emergent window. Once the results are discarded, data can be modified, but not before.

• SERVICE SCHEDULE. Displays the relative travel times of each service.

• CIRCULATION GRAPH. It allows to visualize the circulation graphs.

• OPEN DOCUMENT. The deployable window permits opening the pdf files of the different circulation graphs of each route.
Figure A.33: The Services window with the completed results in red color.
Figure A.34: The information window with the added lower part indicating that an optimization is still running.
A.2.15 Generated files

A folder with the results of the project will appear in the Dropbox at the end of the calculations, with the name “RESULTS/projectname.done”. It contains the following files:

- **DATA FILES**: It contains the generated data files: (PARAMETERS, SCALARS, SETS, TABLES AND COMPLEMENTS).

- **PLOTS FOLDER**: It contains a series of plots in pdf format with all the timetables associated with the routes. See, for example, Figure A.35.

- **SALIDAREALBASIC.TXT**: This file can contain the following:
  - There is no solution: It indicates that the optimization problem has no feasible solution and shows the possible collisions of the different services.
  - If a solution exists, it supplies:
    - Desired and real departure times of the different services.
    - Entry times of all services at the different segments.
    - Exit times of all services from the different segments.
    - Relative travel times of all services. They are very useful to obtain quality of the different services.
    - Summary of the ADST project. It provides:
      - Construction cost of the optimal solution encountered.
      - Maximum relative travel time.
      - Mean relative travel time.
      - Limit relative travel time.
      - Double track segments.
      - Summary of the double track solution, with its cost, and the mean and maximum relative travel times.

These results allow us to analyze the different alternatives and find the optimal result.

A.3 Conclusion

This program gives us the optimum use of the infrastructure, with an adjustment of the generated services and the sequence of single and double track segments.

The program aims to adjust and optimize services with a solution in which the number of segments in single track is maximized as long as the associated relative travel times of services does not exceed a given limit, defined by the variable epsilonbound in the file “Complements”.
The generated result is an alternate double-single track line which shows significant savings in construction and maintenance costs when compared with the double track solution and adjust the timetable for all trains circulating along the line.

### A.4 Shortcut summary

In this section we include a summary of the main shortcuts.

- [CTRL + Z] UNDO
- [CTRL + X] CUT
- [CTRL + C] COPY
- [CTRL + V] PARTE
- [CTRL + A] SELECT ALL
- [CTRL + 0] INFORMATION WINDOW
- [CTRL + 1] NODES
- [CTRL + 2] SEGMENTS
- [CTRL + 3] ROUTES
- [CTRL + 4] HEADWAY TIMES
- [CTRL + 5] SPEEDS
- [CTRL + 6] TRAINS
- [CTRL + 7] SERVICES
Bibliography


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