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Optimal Location of Access Points in Controlled Entry Transportation Networks

Doctoral thesis

Thesis submitted to the Faculty of Sciences and Technology of the University of Coimbra in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the field of Civil Engineering, with specialization in Spatial Planning and Transportation.

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In memory of the ones who named me,

Celestino Varela

António Repolho

'Só as folhas das árvores voam depois de mortas…'

'Only Autmun leaves fly after death…'

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When asked about my motivation for starting such a challenging project I genuinely didn't know what to answer. However, there are two reasons for sure that had a major impact: the non-appealing sight of a daily work journey performing traditional civil engineering tasks and the thought of having someone who I admire believing in my capacities for undertaking such a demanding and alluring objective. Also, and given the fact that the initial proposal was made while I was doing a student interchange program at Rio de Janeiro, the opportunity of going abroad to the United States to continue my academic formation was also very tempting. The one who made that original proposal is Professor Pais Antunes and for his efforts in enlightening me with this alternative path I truly thank him. His confidence, optimism and guidance during these four years were decisive for the conclusion of this thesis.

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Abstract

Decisions regarding the location of access points in national transportation networks need to be made very carefully because of their economic and social implications. The success of any investment made in transportation networks is highly dependent on the amount of users/passengers captured by the networks, which in turn depends on the location of their access points. This thesis presents a set of strategic decision-making tools (optimization models) addressing the problem of locating access points in controlled entry transportation networks. Two particular types of networks are studied, motorways and railway lines.

The location of controlled access points along with possible tolls dictates the level of service provided for individual trips. The corresponding investment along with the level of service provided by existing competitive modes is central to the work developed in this thesis. The models proposed choose the optimal subset of access points, from a set of possible locations defined a priori, according to a certain objective defined in each case (e.g. minimize travel costs, maximize profits, maximize travel cost savings, and maximize social welfare benefits). In general the models are based on hub location theory.

Road users and potential rail passengers select their itineraries and transportation modes according to the routes' attractiveness, which is measured by travel costs. With respect to motorways, the choice is between using the existing road network or a combination of existing road segments with new motorway segments, while for railway lines the choice is between using the new rail service and the existing transportation network.

Regarding the motorways, the interchange location planning problem is analyzed from the two major perspectives, government (and users) and private investors. Each perspective is analyzed, first, alone and then simultaneously. The risks and uncertainties involved in motorway investment decisions are also considered through the formulation of stochastic models.

In rail services, special attention is given to the sensitivity of rail ridership to time losses due to stops at intermediate stations. Given the complexity of railway transportation planning, the analysis goes beyond strategic issues. Indeed, we have formulated a mixed-integer optimization model that integrates all strategic issues related to infrastructure with tactical issues (rolling stock management, line planning and train scheduling) that may influence optimal investment decisions.

The thesis is also concerned with the applicability of the models developed. More than academic modeling, the study aims for the characterization of real-world problems and the development of formulations capable of providing optimal solutions. With this in mind, the models are tested on two academic examples based on real-world networks: an important Portuguese motorway, the A25; and a high speed railway line expected to be built in Portugal in the future (Lisbon-Porto high line). The solutions provided by the models are compared with the ones already implemented in reality (the case of the A25 motorway) or the ones planned to be implemented (the case of the Lisbon-Porto line).

Resumo

A localização dos pontos de acesso a redes de transportes tem implicações enormes no desenvolvimento económico e social das regiões. Tal torna-se mais evidente quando se trata de redes de transporte cujo acesso é restringido a um conjunto diminuto de pontos. Sendo que o sucesso dos investimentos depende em grande parte do volume de utilizadores captados, e este por sua vez depende da localização dos pontos de acesso, o planeamento destas redes e em particular a escolha das localizações dos pontos de acesso deve ser reflectida e baseada em métodos decisórios precisos. Esta tese apresenta um conjunto de instrumentos estratégicos de apoio à decisão (modelos de optimização) com respeito a problemas de localização de pontos de acesso em redes de transportes de acesso limitado. Dois tipos de redes são estudados: auto-estradas e linhas ferroviárias. Nas primeiras o acesso é feito pelos nós de auto-estrada, nas segundas através das estações.

Os modelos propostos determinam a localização óptima dos pontos de acesso às redes, de entre um conjunto de localizações previamente definido, de acordo com um determinado objectivo definido para cada caso (e.g. minimização de custos de viagem, maximização de lucro, maximização da diminuição dos custos de viagem, maximização dos benefícios sociais). Em geral os modelos apresentados são do tipo *hub location*.

Os utilizadores das redes de transportes seleccionam os seus itinerários de acordo com a atractividade de cada percurso, a qual é medida pelos custos que a viagem representa.

No caso das auto-estradas a escolha é feita entre a rede rodoviária existente e uma combinação de segmentos da rede rodoviária e existente e segmentos da nova auto-estrada. No caso das linhas ferroviárias a escolha é feita entre os novos serviços ferroviários e a rede de transportes existente.

O problema de localização de nós de auto-estradas numa primeira fase é analisado na perspectiva de cada um dos intervenientes principais (utilizadores e concessionários) separadamente, e numa fase posterior considerando as duas perspectivas simultaneamente. Alguns riscos e incertezas inerentes a decisões de investimento em redes de auto-estradas são também abordados através da formulação de modelos estocásticos.

Nos modelos ferroviários tem-se em conta a elasticidade da procura de viagens em função do número de paragens em estações intermédias numa dada rota. A complexidade dos processos de planeamento de linhas ferroviárias é também tida em conta, já que o estudo apresentado extravasa o domínio meramente estratégico. Com efeito, é formulado um modelo de optimização inteiro-misto que integra as questões estratégicas relativas às infra-estruturas com as questões tácticas subsequentes (constituição da frota, planeamento de linhas e horários de comboios) que de alguma forma podem influenciar a decisão óptima de investimento.

A tese preocupa-se ainda com a aplicabilidade dos modelos desenvolvidos em situações reais, tendo sido estudados problemas reais na perspectiva da identificação de soluções óptimas. Neste contexto foram considerados dois casos práticos, a auto-estrada A25 e a nova linha de alta velocidade Lisboa-Porto, ambas localizadas em Portugal. As soluções obtidas pelos modelos desenvolvidos nesta tese são comparadas com a solução

efectivamente adoptada no caso da A25 e com a solução apresentada para a futura linha Lisboa-Porto pela empresa responsável.

OPTIMAL LOCATION OF ACCESS POINTS IN CONTROLLED ENTRY TRANSPORTATION NETWORKS

Chapter 1

Introduction

1.1 Problem statement

For the last few decades the world has evolved towards a global integration of economies and societies. The tendency to bring the world closer through the exchange of goods, services, information, knowledge and culture is seen as inevitable. Such phenomenon has created new travelling dynamics and accessibility needs that have led national governments to make huge investments in transportation networks in the last few decades. Furthermore, the investment effort is planned to continue in the following decades. According to the OECD (2006), until 2030 the investments all over the world are estimated at USD 220-290 billion per year for road transportation infrastructures and at USD 48-58 billion per year for rail-track infrastructures. Regarding the European Union (EU), the costs to develop a transportation infrastructure to match the demand for transport is estimated at over a total of 1.5 trillion Euros for 2010-2030. The EU members have agreed and planned (EUROPEAN UNION, 1996; EUROPEAN COMMISSION, 2001; EUROPEAN COMMISSION, 2005) a Trans-European

Transport Network, TEN-T, in order to create a unique and multimodal network that integrates land, sea and air transportation networks within the EU. The completion of the entire TEN-T network is estimated to cost 600 billion Euros, 252 billion of which correspond to a set of thirty priority projects and axes. Among those, there are eighteen rail projects (five of which are High Speed Rail – HSR – projects), three road projects (two of which are motorways), and three multimodal projects that also include road and rail investments. Because transportation network investments are usually bulky, difficult to reverse and have a long term character, the challenge is then to develop planning tools aimed at assisting transportation systems administrations or other decision-makers upon the definition of development strategies.

For its economic and social relevance, the concept of accessibility is fundamental in transportation network planning (MORRIS et al., 1979). Though widely used, accessibility is hard to fully define. GOULD (1969) used a curious but sagacious expression while referring to accessibility that fully captures the complexity of the concept. He stated 'accessibility is a slippery notion … one of those common terms that everyone uses until faced with the problem of defining and measuring it'. The first significant study on this topic dates back to HANSEN (1959). Since then, the research on the topic has flourished (surveys can be found in BARADARAN and RAMJERDI, 2001, CURTIS and SCHEURER, 2010, and LEI and CHURCH, 2010a). While GEURS and VAN ECK (2001) define 'accessibility as the extent to which the land use-transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)', BHAT et al. (2000) state that 'accessibility is a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time. These two definitions clearly show the multiplicity of components (e.g. transportation infrastructure, budget, multimodal possibilities, modal competition, time availability, etc.) inherent in the concept. Despite all of the controversy in defining accessibility, its role for the characterization of how well modern societies work is undeniable. Improving accessibility to jobs, services, amenities, etc. is essential to promote a better quality of life for the population.

Transportation planning processes can be divided in three major stages according to the planning horizon and the objectives: strategic, tactical and operational stages (ANTHONY, 1965). Each stage can be further divided into sub-stages. Traditionally transportation planning decisions, particularly those regarding the infrastructure (the scope of this thesis), are made at a strategic level regardless of the "daily" tactical or operational problems. Each stage and sub-stage is usually addressed separately in a hierarchical and sequential order. However, in order to evaluate possible strategic alternatives it is imperative to consider the subsequent tactical stages (BUSSIECK et al., 1997). The lack of integration of such stages compromises the search for the global optimum. The search for an integrated planning process that captures the entire spectrum of a transportation network planning problem is therefore a goal worth pursuing. Actually, the search for integrated planning processes is now present in most fields of modern science.

Among the wide panoply of subjects related to transportation infrastructure planning, this thesis is concerned with the location of access points in controlled entry transportation networks, particularly in motorways and railway lines. A controlled entry transportation network can be defined as a complete system of interconnected roads, streets, railway lines or any other structure that permits vehicular movement of some modality, and that can only be accessed (or exited) in special places. The access points are respectively the interchanges and the stations. The effectiveness with which a region is served by a controlled entry transportation network is highly dependent on the location of their access points. Discarding the network design component (a survey on road network design can be found in YANG and BELL, 1998) the access points' problem can essentially be posed as a strategic facility location problem.

Facility planning (or location) models are integer optimization models aimed at helping decision-makers in selecting the best location and size of any kind and number of facilities – including motorway interchanges and railway stations. Several objectives can be considered, e.g., minimizing cost, maximizing accessibility, maximizing coverage, etc. The models are classified as continuous or discrete, depending on whether the facilities can be located anywhere on the plane (or at set of points on the plane specified in advance. The controlled access points location problem, as most practical oriented applications do, involve a discrete model. Research on facility location problems was initiated by WEBER (1909) with a study on how to locate a single warehouse such that the total distance between it and several customers was minimized. It continued with the development of central place theory involving the location of retail centers (CHRISTALLER, 1933). However, facility location research only began to flourish in the late 1950s with the ground-breaking work of authors such as KOOPMANS and BECKMANN (1957), COOPER (1963), HAKIMI (1964 and 1965), REVELLE and SWAIN (1970), TOREGAS et al. (1971) and CHURCH and

REVELLE (1974). These authors are responsible for establishing the basic set of facility planning models. Since that period, two main directions of research have been pursued. One of them led to new, exact solution methods to the basic models, as well as to faster heuristic solution methods (e.g. FISHER, 1981; NARULA, et al. 1977; ERLENKOTTER, 1978 and BEASLEY, 1988). The other led to the development of models aimed at representing real-world problems of different degrees of complexity, including coverage models (CHURCH et al., 1996), multi-period models (ANTUNES and PEETERS, 2000), hierarchic models (ANTUNES, 1999), undesirable facility models (MURRAY et al., 1998), and many others. A detailed presentation of the subject is given in a textbook by DASKIN (1995). OWEN and DASKIN (1998), CURRENT et al. (2002) and REVELLE and EISELT (2005) contain (relatively) recent reviews on facility planning. Two areas of research related with the facility location topic are of special interest within the scope of this thesis. The first is hub location, the second concerns uncertainty issues.

Hub location models allocate demand centers to hubs such that traffic is routed at minimum cost, taking advantage of lower travel costs on inter-hub connections. This class of models was introduced in O'KELLY (1986) and have since their appearance been applied to a large number of transportation and telecommunication problems (CAMPBELL et al., 2002). CAMPBELL (1994) presents the integer model formulation for the *p*-hub median problem, the uncapacitated hub location problem, the *p*-hub center problem and the hub covering problem, and evinces their relationship with the basic facility planning models. A recent review on hub location literature can be found in ALUMUR and KARA (2008). The two types of controlled entry transportation networks studied in this thesis, motorways and railway lines, may be properly handled through hub location models because travelling through these networks' segments benefits the users by allowing higher travel speeds.

When making decisions about the location of facilities there are various sources of risk and uncertainty (a planning environment is said to involve risk when it is possible to assign probabilities to possible states of the world, and is said to involve uncertainty when it is not possible). Parameters like demand or specific costs are quite difficult to forecast when, as often is the case with infrastructure, the planning horizon is long. Planning problems involving risk can be dealt with through stochastic models (e.g., WEAVER and CHURCH, 1983; LOUVEAUX and PEETERS, 1992; RAVI and SINHA, 2006). Robust models apply to planning problems involving uncertainty. Several robustness measures may be used: minimax regret (AVERBAKH and BERMAN, 2000), alpha-reliable minimax regret (DASKIN et al. 1997) and *p*-robustness (SNYDER and DASKIN, 2006) are some examples. For a review of the many stochastic and robust models that have been applied to facility location in the past, the reader is referred to SNYDER (2006).

The two types of controlled entry transportation networks addressed in this thesis are usually of critical interest for several sectors of the society. Ultimately, decisions are taken by governments based on economic, social, and political reasons. Given the existence of numerous alternative development strategies, the full exploration of possible planning decisions can only be achieved if optimization-based approaches are used. The goal of this thesis is then to develop strategic planning tools that take into account the issues mentioned in this chapter, and that may be used to assist transportation administrations in planning processes. To the best of the author's knowledge the formulation of such planning tools for the examples studied here or the relevant features captured by the models have not been reported previously in the literature.

1.2 Research objectives

This thesis addresses strategic decision-making tools about facility location in the context of controlled entry transportation networks. Particularly, the thesis focuses on motorways and railway lines. As mentioned before, to the best of the author's knowledge there is no report in the literature of optimization models applied to the study of the optimal location of motorway interchanges. As for the optimal location of railway stations there are a number of optimization models currently available. However, none of them captures all relevant features involved in a railway station location problem – in particular, the implications of the number of intermediate stops encountered on a trip upon travel demand has been neglected in prior work. Also, it appears that no model has yet been proposed that simultaneously optimizes infrastructure location decisions and the subsequent sub-problems that define the future level of service provided by a railway line.

The primary objective is to model the access points' location problem in motorways and railway lines through optimization models that can be used by decision makers and transportation administrations when they set up the location of the accesses to those kinds of controlled entry transportation networks.

The second objective is the application of the models to real case studies. They should be chosen within projects that are already concluded or projects for which there are available studies and proposals. The objective is to compare the solutions obtained through the models formulated in this thesis with the solutions obtained through the existing planning processes.

Additionally, a set of objectives specific of each type of controlled entry transportation network considered in this thesis was defined.

With regard to motorways, the specific objectives are as follows:

1. Analyze the problem from the perspective of users (public), concessionaires (private), separately and simultaneously.
2. Model users travel behavior with respect to traffic flows and route choices.
3. Analyze and compare the possible approaches and models that can be used to determine robust solutions for (discrete) facility planning problems.

With regard to railway lines, the specific objectives are as follows:

1. Incorporate the effect of rail ridership sensitivity to time losses due to stops at intermediate stations.
2. Incorporate (static) competition between alternative travelling modes in the model.
3. Develop an integrated model that optimizes simultaneously all strategic issues related to infrastructure and the subsequent sub-problems (line planning and train scheduling) that may influence optimal investment decisions.

1.3 Outline

The thesis is organized into six chapters. Besides, Chapters 1 and 7, respectively the thesis introduction and conclusion, all chapters are based on a scientific paper. Each chapter (between 2 and 6) is dedicated to the study of an independent optimization model (or set of models) used to solve the problem of locating access points in a controlled entry transportation network. Hence, they all contain an introduction section, sections addressing literature overview, problem statement, model formulation, a case study application, and finally a conclusion section. The reader can therefore read all chapters sequentially or separately with no constraints. The drawback of such independency is the undesirable but inevitable repetition of a few ideas throughout the thesis.

In spite of the independency between chapters, this thesis is more than a collection of papers. All papers (chapters) are interrelated and do form a consistent Ph.D. formal document. All chapters address the subject of access point location, but applied to different transportation networks or analyzed from different perspectives. Moreover, the solutions found in each chapter are consecutively used to improve the ones that follow.

Chapters 2, 3 and 4 are dedicated to the study of access points in road networks, more specifically the optimal location of motorway interchanges. The chapters present several optimization models aimed at assisting road administrations when they set up the location of interchanges for a new motorway. The new motorway is assumed to be built within the framework of a private funding financial arrangement, more specifically a build-operate-transfer concession contract (BOT), where two main parties are involved, public entities and private investors. Chapters 2 and 3 optimize interchange locations taking into account only one party. Chapter 4 integrates both perspectives in the same model.

In Chapter 2 the decisions are assumed to be made from the users' perspective (public), with the objective of minimizing travel costs. The number of interchanges being located is used as a proxy for the budget used in the construction of interchanges. Within the system two types of trips are considered: trips which are made through the existing road network only and trips made through a combination of existing road segments with new motorway segments. Three optimization models are presented, two of which are based on existing hub location models, whereas the third one is a new model based on the concept of a prescreened list of viable route alternatives. A comparison of the efficiency of the three models is performed throughout the application of the models to a real-world application involving one of the most important Portuguese motorways, A25. For that case study, the analysis shows how to select a proper subset of interchanges without sacrificing many of the benefits generated by the upgraded motorway.

In Chapter 3 the decisions are assumed to be made from the concessionaires' perspective (private investor), with the objective of maximizing profit. Profit is given as the difference between total toll fee revenues and the fixed charges for installing and operating the interchanges and for building and maintaining the roadway. Thus, the number of interchanges being located is endogenously determined. The location of motorway interchanges affects the traffic that the motorway captures and consequently the revenues. Road users are assumed to select their itineraries according to the routes' attractiveness, which is measured by travel costs (vehicle operating costs, accident costs, user time costs, and tolling costs). Users may choose between the existing road network only or a combination of existing road segments with new motorway segments. A specific model is formulated to represent travel behavior with respect to both traffic flows and route choices. The problem is modeled firstly using a deterministic model and then by two stochastic models. The latter take into account the risks involved in motorway investment decisions. The fluctuation of parameters is represented with a finite set of scenarios. Once again the models usefulness is illustrated using the A25 case study (though with a dataset slightly different from the one used in Chapter 2).

In Chapter 4 the motorway interchange location problem is analyzed simultaneously from a public and private perspective. The model looks for a win-win solution for both parties, maximizing social welfare benefits such that a given level of concessionaire's profit is ensured. The social welfare benefits measure used is consumers' surplus gains. The model is applied to the A25 case study (using Chapter 3 dataset). Results are compared with the ones obtained in Chapter 3.

Chapters 5 and 6 are dedicated to the study of access points in rail transportation networks, more specifically the optimal location of intermediate stations on high speed railway lines.

Chapter 5 presents a mixed-integer optimization model that determines the optimal location (and number) of stations along a railway line that will be introduced over an existing transportation network. The stations are chosen within a set of possible locations defined a priori according to the objective of maximizing travel cost savings. The model takes into account the sensitivity of rail ridership to time losses due to stops at intermediate stations, the access speed to trains, the dynamic characteristics of trains, the standing time of trains in stations and the intermodal transfer time at stations as well as the competition from other modes. The practical usefulness of the model is illustrated with a case study involving a high speed railway line expected to be built in Portugal in the near future: the Lisbon-Porto line.

Chapter 6 extends the analysis initiated in Chapter 5. Among the several sub-stages of the hierarchical planning process that characterizes a railway transportation planning problem, in Chapter 5 only the station locations problem is dealt with. Although sub-stages are usually addressed separately, most of them are interrelated. Chapter 6 integrates and optimizes simultaneously all strategic issues related to infrastructure and the subsequent sub-problems (line planning and train scheduling) that may influence optimal investment decisions. In detail, four main aspects are dealt with: travel demand, infrastructure, service provided and rolling stock. The mixed-integer optimization model presented determines the optimal number and location of intermediate stations and the fleet characteristics, designs the line system and a master timetable, and quantifies the volume of ridership such that social net benefits are maximized. Most assumptions made in Chapter 5 are also valid in Chapter 6. The usefulness of the model is once again illustrated with the new Lisbon-Porto high speed railway line.

Finally, the research work described in the thesis and its conclusions are summarized in Chapter 7 along with the discussion of future areas of research.

1.4 Publications

As mentioned in the previous section, this thesis is organized on the basis of several scientific papers. Thus, as a conclusion to this introductory chapter, it is worth listing the publications that resulted (or are expected to result in the near future) from the research accomplished during the doctoral program. Some of the papers have been published (or have been accepted for publication) in international journals, while others are currently under review.

The first two papers regarding motorway interchanges (Chapters 2 and 3) were accepted in one of the best engineering journals dedicated to transportation, the *Journal of Transportation Engineering* (a publication of the American Society of Civil Engineers). The paper underlying the users' perspective (Chapter 2), "Optimum location of motorway interchanges: Users' perspective", has already been published in *Journal of Transportation Engineering* (REPOLHO et al. 2010). The research work on the concessionaires' perspective (Chapter 3), "Optimization models for the location of the motorway interchanges: Concessionaires' perspective", will be published in a forthcoming *Journal of Transportation Engineering* issue (REPOLHO et al. 2011a). The third paper on motorway interchanges (Chapter 4) has not yet been submitted.

The research regarding high speed rail planning (Chapters 5 and 6) have not been published yet. Nevertheless, the work on the "Optimal location of railway stations" and respective application to "the Lisbon-Porto high speed railway line" described in Chapter 5 was submitted to *Transportation Science* and has been conditionally accepted (REPOLHO et al. 2011b). Finally, the research work on station location and train scheduling applied to the high speed rail reported in Chapter 6 has not yet been submitted. The submission of this last paper to the *Transportation Research Part E: Logistics and Transportation Review* is currently being considered.

Besides publications in international journals it is also important to highlight conferences where the papers described in this thesis have been presented. As a matter of fact, all papers have been presented and discussed in at least one of the following conferences:

- *11th International Symposium on Locational Decisions* (ISOLDE XI), June 26 - July 1, 2008, Santa Barbara, California, USA;
- *23º Congresso da Associação Nacional de Pesquisa e Ensino em Transportes* (XXIII ANPET), November 9-13, 2009, Vitória, Brazil;
- *12th World Conference on Transportation Research* (XII WCTR), July 11-15, 2010, Lisbon, Portugal;
- *16th Pan-American Conference of Traffic and Transportation Engineering and Logistics* (XVI PANAM), July 15-18, 2010, Lisbon, Portugal;
- *15º Congresso da Associação Portuguesa de Investigação Operacional* (IO 2011 APDIO), April 18-20, 2011, Coimbra, Portugal;
- *1st Education, Employment and Entrepreneurship Conference* (E3), June 30, 2011, Lisbon, Portugal.

Chapter 2

Optimum Location of Motorway Interchanges: Users' Perspective

2.1 Introduction

"Good transport connections" is usually amongst the most important factors considered by industrial and commercial firms when they make their location or relocation decisions. A recent report based on interviews with senior executives of 500 top European companies ranks "easy access to markets, customers or clients" and "transport links with other cities and internationally" in the 2^{nd} and 4^{th} positions (out of 12) as "absolutely essential" location factors (CUSHMAN and WAKEFIELD, 2007). The vast majority of firms are primarily concerned with road transport (RIETVELD and BRUINSMA, 1998). In particular, the study described in BUTTON et al. (1995) makes this very clear. For a large sample of Scottish firms, "road links" was the No. 1 location factor among 18, whereas "bus links", "air links", and "rail links" were rated as No. 13, 14, and 15.

The fastest road trips often take place on controlled access motorways. Controlled access motorways can only be accessed (or exited) in special places: the interchanges. This means that the number and location of interchanges determine, in large part, the effectiveness with which a motorway serves a region. As shown for example in KAWAMURA (2001) for the region of Chicago (USA) or in DE BOK and SANDERS (2005) for the province of South Holland (The Netherlands), interchange locations can have significant implications upon the geographic pattern of economic development. Recognizing this, local authorities often engage in harsh disputes with their neighboring authorities and with the government because they want an interchange (or more) in the territory under their jurisdiction. Therefore, for economic and political reasons, decisions regarding the location of motorway interchanges need to be made very carefully.

In this chapter, we present a set of optimization models for assisting road administrations in the analysis of possible solutions for motorway interchange location problems, or MILP for brevity. The models apply to a region comprising several trip generation centers. These centers can represent municipalities, cities, etc. The region will be crossed by a motorway whose corridor has been previously defined. The objective is to determine the locations for a given number of interchanges such that the total cost incurred by the road users travelling between the trip generation centers of the region is minimized. The number of interchanges being located can be viewed as a proxy for the budget used in the construction of interchanges. In principle, the intersections between the motorway corridor and the existing road network are possible sites for the location of interchanges. However, some of these sites may be inadequate to place an interchange, particularly because of physical and/or environmental constraints (for a detailed presentation of interchange location and design criteria, see AASHTO, 2004 and LEISCH, 2006). The inadequate sites need to be identified at the outset and eliminated from the set of possible interchange locations. The determination of this set certainly is an important issue, but was not defined as an objective for the work described in this thesis. It is assumed that there is and will be no traffic congestion both in the existing road network and in the motorway, because the region crossed by the motorway is rural and the motorway is designed to ensure level of service A. The models are generically designated as motorway interchange location models (MILM).

The MILP has all the ingredients of a p-hub median problem. CAMPBELL (1994) defines a hub as a facility that serves as transshipment and switching points for transportation and telecommunication systems with many origins and destinations. As pointed out in CAMPBELL et al. (2002), hub location problems are quite frequently found in areas such as air transportation planning, rapid transit design, postal distribution systems, large regional trucking operations, and telecommunication systems. The corresponding optimization models often involve the location of one or more hub facilities as well as the allocation of demand centers to hubs in order to route traffic at minimum cost, taking advantage of an exogenously determined, flow-independent discount across the inter-hub links. O'KELLY and BRYAN (1998) state that "the assumption of flow-independent costs not only miscalculates total network cost, but may also erroneously select specific hub locations (and associated flow allocations) as being optimal". When deciding the location of motorway interchanges in uncongested road networks, the cost function has mainly to do with travel distances and design speeds, being essentially independent from traffic flows. For a recent state-of-the-art review on hub location models, the reader is referred to ALUMUR and KARA (2008).

The MILP is also related to the location of stations on rapid transit lines and longer rail routes. LAPORTE et al. (2002) presented a model to locate a prefixed number of stations so that the weighted coverage was maximized for an urban region, when the alignment of a new line of rapid transit system had already been designed. More recently, the determination of alignments and locations of stations was studied altogether (LAPORTE et al., 2007; MARÍN, 2007). BRUNO et al. (1998) and HAMACHER et al. (2001) have also modeled rapid transit using a covering objective. Although a covering objective captures the major design element in a rapid transit setting, it is not a key design issue in interchange location problems. In fact, prospective users quite far from a motorway may use it as it improves their service even when they are not close to (covered by) a given interchange.

More specifically, the MILP can be classified as a non-strict multiple-allocation p-hub median problem (AYKIN, 1995). It is non-strict because, after the introduction of the motorway, there are two types of trips to consider: trips which are made through the existing road network and trips which use some motorway segments (inter-hub links). The motorway segments are chosen only if drivers find them cost efficient. It is a multiple-allocation problem because trips that begin at a given origin can be made through different motorway interchanges according to their final destination. Detailed information on multiple-allocation p-hub median problems is available in EBERY et al. (2000).

The usefulness of the model is illustrated with a case study involving the A25, one of the most important Portuguese motorways. The A25 is the result of the recent conversion of a national road, the IP5, to a controlled access motorway. Specifically, the many intersections of IP5 with other roads were converted into motorway interchanges. It would have been possible to save a significant amount of money if only a subset of the interchanges were kept (an interchange can easily cost more than 2 million EUR). In this chapter, we shed light on how to select a proper subset of interchanges without sacrificing many of the benefits generated by the upgraded motorway.

The remainder of the chapter is organized as follows. In the next section we describe the A25 case study in detail. Then, we present two *p*-hub median models applicable to the case study and introduce a new model (based on the concept of a prescreened list of viable route alternatives). The computation effort required for solving the three models is thoroughly analyzed. Afterwards, we describe the results obtained for the case study. Finally, we provide some concluding remarks and identify directions for future research.

2.2 Case study presentation

The A25, formerly the IP5, is a motorway that crosses the middle portion of the northern half of Portugal. It is perpendicular to the Atlantic coastline (Figure 2.1), crosses 14 municipalities, including three district capitals (Aveiro, Viseu and Guarda), and involves 33 interchanges. The IP5 was opened in 1991 as the first "fast" two-way road connecting the Portuguese coastal area with inland regions and with Spain (through the Vilar Formoso/Fuentes de Oñoro border). The conversion of the IP5 into the A25 was made by the same private company that currently operates the motorway (ASCENDI, until recently named AENOR). Despite being built and operated by a private company, the A25 is toll-free – it has "virtual" tolls paid by the government as a development incentive to the region. In 2007, the average annual daily traffic (AADT) in the 32 A25 segments ranged between 5,000 and 23,000 passenger-car units (pcu). This is clearly below the capacity of a motorway designed to accommodate 2,400 pcu/lane/h at level of service A. The truck volume expressed as a fraction of the total traffic is quite significant, as many Portuguese exports and imports are made through the A25.

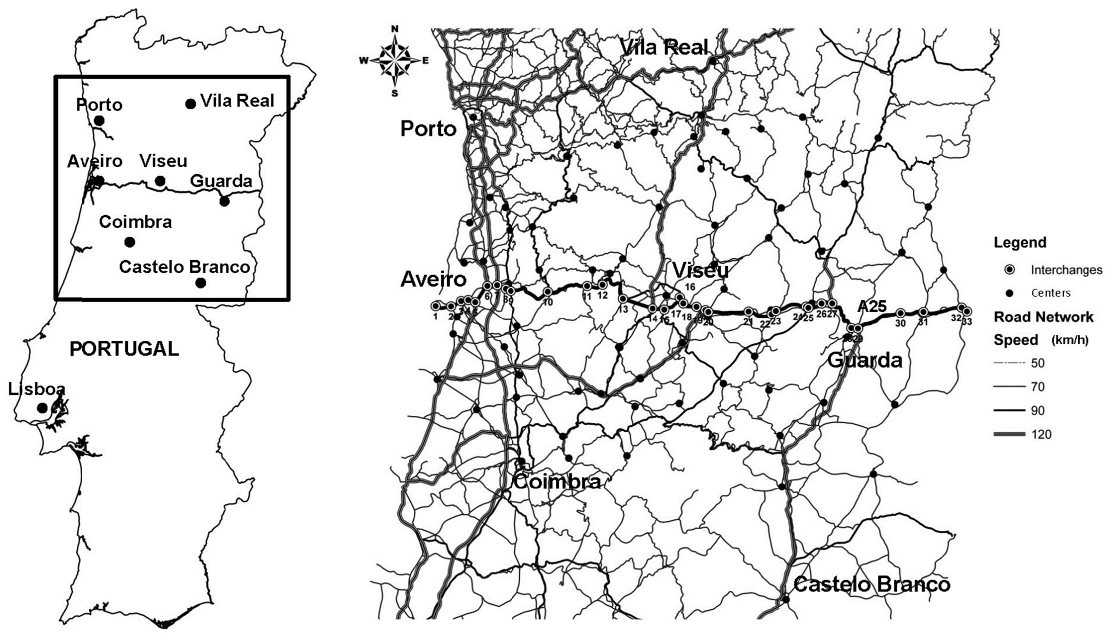

Figure 2.1 - Location and corridor of the A25 motorway

The area crossed by the A25 is predominantly mountainous. The slopes of its predecessor, the IP5, were extremely steep. The IP5 experienced a high rate of accidents, which had been attributed to the combination of steep slopes and high levels of truck traffic. The strategic importance of this road along with the safety problems led the government to promote its upgrading to a controlled access motorway.

The purpose of our case study was to analyze the decision of converting all the 33 intersections of the IP5 with other roads into motorway interchanges. More specifically, we wanted to assess whether it made sense to convert all 33 intersections to interchanges and determine if most of the travel time savings could be achieved by converting only a selective subset of the intersections to interchanges. To answer this, we wanted to establish the relationship between the number (and, indirectly, the cost) of interchanges and the travel time spent in the A25 area (travel time was used as an indicator of travel cost).

For the analysis, all 71 municipalities that were located within the range of 30 km north and south from the motorway were considered as trip generation centers. We added two centers that are located farther than the 30 km distance to represent the metropolitan areas of Lisbon and Porto. The decision to add these two areas was made because they represent approximately 35 percent of the population and 50 percent of the gross domestic product of Portugal, as well as serve as the origin or destination for a large share of traffic using the A25.

The traffic between the centers (O/D matrix) considered in the analysis was assumed to be given. The assignment of traffic to the road network was made assuming that drivers will always choose the fastest route for their trips. The travel time for each route was calculated considering the following design speeds: 120 kph for motorways, 90 kph for other national roads, and 70 kph for other roads. Figure 2.2 illustrates two basic route alternatives. Finally, we assumed that international traffic could be eliminated as a majority of such traffic uses the full extent of the A25 motorway as a route to the Portuguese coast. We recognize that these assumptions are somewhat simplistic. However, the intent was to concentrate on the traffic that is likely lost due to selectively adding or reducing the number of interchanges. Even though the results should be viewed with some caution, they do capture the essence of the underlying problem.

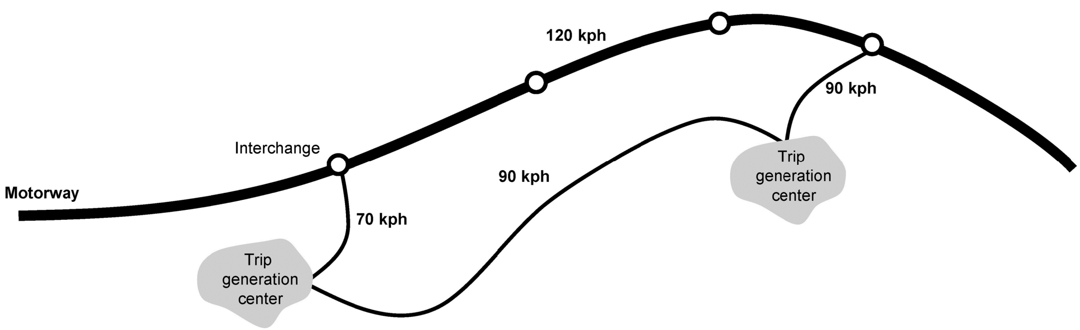

Figure 2.2 – Example of route alternatives

2.3 Motorway interchange location models

This section presents three models for the MILP. The first is an adaptation of the multiple-allocation *p*-hub median model proposed in CAMPBELL (1994). We designate it as the motorway interchange location model based on CAMPBELL (MILM-C). The second is based on a model for the same problem proposed in ERNST and KRISHNAMOORTHY (1998), and is designated as MILM-EK. The third is a new model that is based on the concept of a prescreened list of viable route alternatives and is designated as MILM-L. The three models were tested on the case study and also on a large sample of random instances designed to mimic real-world problems. Below we provide detailed information on model formulation and model solving. The information on model solving is given primarily for the case study because the conclusions we obtained from the application of the models to the random instances were essentially the same.

2.3.1 MILM-C

Consider the set of trip generation centers of a region, J, an existing road network, a new motorway, and a set of candidate motorway interchanges, M. The traffic flow between each pair of centers, q_{ij}, is known. Motorway interchanges are seen as uncapacitated facilities and access points to motorway segments. Trips may use the new motorway when beneficial, but otherwise will remain using existing roads. It is assumed that all trips will be made according to the most efficient route. The cost for travelling between two centers, i and j, through the existing road network is c_{ij}. If the motorway is used between interchanges m and n, then the cost is c_{im} + c'_{mn} + c_{nj}, (where c'_{mn} designates the cost for travelling in the motorway between two interchanges m and n). Traffic flows and travel costs are symmetric (a typical assumption of interurban road network planning). We wish to establish the location of a given number of motorway interchanges, p, and a network of traffic assignments so that the total travel cost in the region is minimized.

The mathematical formulation of MILM-C is as follows:

$$Min \quad C = C^0 - \sum_{i \in J} \sum_{j \in J : i < j} \sum_{m \in M} \sum_{n \in M : m \neq n} \left[c_{ij} - (c_{im} + c'_{mn} + c_{jn}) \right] q_{ij} x_{ijmn} \qquad (2.1)$$

s.t.

$$\sum_{m \in M} \sum_{n \in M: m \neq n} x_{ijmn} \leq 1 \quad \forall i, j \in J : j > i \tag{2.2}$$

$$\sum_{m \in M} y_m \leq p \tag{2.3}$$

$$\sum_{n \in M: n \neq m} \sum_{i \in J} \sum_{j \in J: j > i} x_{ijmn} \leq g_m^a y_m \quad \forall m \in M \tag{2.4a}$$

$$\sum_{m \in M: m \neq n} \sum_{i \in J} \sum_{j \in J: j > i} x_{ijmn} \leq g_n^e y_n \quad \forall n \in M \tag{2.4b}$$

$$y_1 = 1 \tag{2.5a}$$

$$y_M = 1 \tag{2.5b}$$

$$x_{ijmn} \geq 0 \quad \forall i, j \in J, m, n \in M \tag{2.6}$$

$$y_m \in \{0,1\} \quad \forall m \in M \tag{2.7}$$

where C^0 is the total travel cost without the motorway, which is given by $\sum_{i \in J} \sum_{j \in J} q_{ij} c_{ij}$; x_{ijmn} is the fraction of traffic from origin i to destination j routed via the motorway interchanges m and n in this order; y_m is a binary variable which takes the value 1 if a motorway interchange is located at the candidate interchange m, and zero otherwise; and $g^a{}_m$ ($g^e{}_n$) is the maximum number of trips that may use interchange m (n) as a motorway access (exit).

The objective function (2.1) of this optimization model expresses aggregate travel cost, given as the difference between the initial aggregate travel cost (without the motorway) and the travel cost savings promoted by the introduction of the motorway and selected interchanges. We use this objective function instead of just the maximization of travel cost savings because we verified that it makes the model easier to solve when commercial software is used. The assignment constraints (2.2) ensure that each trip is assigned to no more than one route. If the route is composed by some motorway segment then $x_{ijmn} = 1$, where *mn* is the motorway segment. Otherwise, $x_{ijmn} = 0$, meaning that the trip is made through the existing road network. Being a multiple-allocation *p*-hub median model the x_{ijmn} variables may be fractional as proved by Lemma 1 in ERNST and KRISHNAMOORTHY (1998). For the same *ij* pair there may coexist multiple routes with the same travel cost. Either way, the sum must be at most one. The facility constraints (2.3) ensure that only *p* or less facilities are located, where $p \geq 2$ is defined by the decision maker. The bounding constraints (2.4a) and (2.4b) prevent a trip to enter at interchange *m*, use segment *mn*, and exit at interchange *n* unless both interchanges *m* and *n* have been selected. With respect to interchange locations, the linear relaxation provided by these Efroymson-and-Ray-type, aggregate bounding constraints is tighter than the one provided by the numerous Balinski-type, disaggregate bounding constraints used in CAMPBELL (1994). Indeed, in the absence of fixed costs for opening interchanges, Balinski-type constraints would create lots of "partial" interchanges when integrality is relaxed (see SKORIN-KAPOV et al., 1996). Moreover, the model efficiency relies more on the number of constraints than any other parameter (CHURCH, 2003). The use of Efroymson-and-Ray-type constraints instead of Balinski-type constraints means reducing bounding constraints from $2\times|J|^2\times|M|^2$ to $2\times|M|$. Detailed information on the original Balinski and Efroymson-and-Ray constraints is available, respectively, in BALINSKI (1965) and EFROYMSON and

RAY (1966). Constraints (2.5a) and (2.5b) locate interchanges by default at the extremities of the motorway. Finally, constraints (2.6) state that the assignment decision variables are nonnegative and constraints (2.7) state that the interchange location decision variables are binary. Some pre-processing steps must be taken. The total number of potentially improving routes and, particularly, the ones that use interchanges m and n are identified in advance, allowing us to define a valid upper limit on $g^a{}_m$ and $g^e{}_n$, instead of being set at some arbitrarily predefined large number (improving the models' efficiency).

Despite having a simple formulation, MILM-C is difficult to solve due to the number of decision variables involved. Assignment variables must have four subscripts so that itineraries can be properly described. This means millions of variables for mid-size problems. In order to reduce the size of the model it is important to eliminate superfluous variables and constraints. Since all traffic (q) and travel cost (c) matrices are symmetric the assignment (x) matrices are also symmetric, and we only use their upper triangle ($i < j$) without losing generality. Additionally, since the access interchange for one trip cannot be simultaneously the exit, we eliminate all assignment variables where $m = n$. Most of the assignment variables represent routes that do not improve travel cost. It is useless to consider variables with costs which are not competitive (HAMACHER et al., 2004). Thus, following the size reduction ideas referred to in MARÍN et al. (2006), we pre-analyze the data to identify which routes can actually be improved by using a motorway segment. The variables associated with non-competitive routes are then removed entirely from the model according to the following rule:

$$\text{eliminate } x_{ijmn} \text{ when } c_{im} + c'_{mn} + c_{nj} \geq c_{ij} \quad \forall i, j \in J, j > i, m, n \in M, m \neq n \quad (2.8)$$

In solving the above model for the A25 problem, we used two commercial optimizers: LINGO (LINDO SYSTEMS, 2003) and Xpress-MP (DASH OPTIMIZATION, 2008). Though we have performed a large reduction in the number of variables and constraints we could not generate solutions for the case study using an Intel Core 2 Duo Processor T7500 2.2 GHz computer with 2 GB of RAM. With LINGO we reached the optimum solution after four days of computing but were unable to see the solution report. When generating the solution report LINGO considered all possible variables (based upon the specification of sets), even the ones we discarded in the data pre-analysis phase, and ran out of memory. When using Xpress-MP the computer ran out of memory even before reaching a solution. The calculations were made using Efroymson-and-Ray-type constraints (in smaller problem instances we confirmed that they were indeed more efficient than Balinski-type constraints). Following the ideas in ROSING et al. (1979), we also tried a hybrid formulation that started with the Efroymson-and-Ray-type constraints and added a small subset of Balinski-type constraints for each ij pair (one subset for each of the three least cost routes connecting i and j) so that the resulting model would be integer-friendly (see MORRIS, 1978, and REVELLE, 1993). However, this effort was fruitless. Instead of contributing to speed up calculations, these constraints slowed the search for the optimum solution.

In order to overcome the difficulties stated above, we applied the model separately between interchanges that we suspected might be included in the final solution. Thus, we divided the A25 in two stretches, the east and the west. The breaking point was candidate interchange 14, located near Viseu, an important city located halfway between the Atlantic Coast and the Spanish border. Accordingly, the area crossed by the A25 was divided into two sub-areas. Our problem was then converted into two smaller sub-problems, one for each sub-area. The size of the east and the west sub-problems was respectively 38 and 35 centers, and 20 and 14 candidate interchanges. Besides the two extremities, the breaking point was also selected to accommodate an interchange (that is, we augmented the model with constraint $y_{14} = 1$). For both sub-problems we were able to reach the optimum solution in less than 10 seconds, regardless of the number of interchanges (p) considered. But it is worth noting that, by dividing the motorway problem in two separate stretches, we added conditions which are not part of the original problem. Specifically, we implicitly assumed that the trip generation centers located in the east can only access the motorway through interchanges located in the eastern stretch of the motorway, which, particularly for the centers near the breaking point, may not be optimum. The same happens respectively for the west. Also, we did not analyze all trips, but only trips made within each sub-area. Moreover, the number of interchanges to locate in each stretch had to be pre-defined, whereas this number should be endogenously determined through the application of the entire model. It is easy to conclude that the MILM-C model can be used to solve only small instances of motorway interchange location problem.

2.3.2 MILM-EK

The second model, MILM-EK, is based on the *p*-hub median model proposed in ERNST and KRISHNAMOORTHY (1998), which is generally considered to be more efficient than the Campbell model (see CAMPBELL et al., 2002). It involves a much smaller number of variables because it is based on two- and three-subscripted (instead of four-subscripted) assignment variables: z_{im} is the traffic going from trip generation center i to access interchange m; h_{imn} is the traffic going from centers i to access interchange m and then to exit interchange n; x_{ijn} is the traffic going from exit interchange n to center j originated in center i; and w_{ij} is the traffic going through the existing road network from trip generation center i to trip generation center j. The latter set of variables is required because the MILP is non-strict, *i.e.* using the motorway is not mandatory.

The mathematical formulation of MILM-EK is as follows:

$$Min\ C = \sum_{i \in J} \left(\sum_{m \in M} c_{im} z_{im} + \sum_{m \in M} \sum_{n \in M : m \neq n} c'_{mn} h_{imn} + \sum_{n \in M} \sum_{j \in J : i < j} c_{jn} x_{ijn} + \sum_{j \in J : i < j} c_{ij} w_{ij} \right) \tag{2.9}$$

s.t. (2.3), (2.5), (2.7) and

$$\sum_{j \in J} w_{ij} + \sum_{m \in M} z_{im} = O_i \quad \forall i \in J \tag{2.10}$$

$$w_{ij} + \sum_{n \in M} x_{ijn} = q_{ij} \quad \forall i, j \in J : i < j \tag{2.11}$$

$$z_{im} + \sum_{n \in M : m \neq n} h_{inm} - \sum_{n \in M : m \neq n} h_{imn} - \sum_{j \in J : i < j} x_{ijm} = 0 \quad \forall i \in J, \forall m \in M \tag{2.12}$$

$$z_{im} \leq O_i y_m \quad \forall i \in J, \forall m \in M \tag{2.13}$$

$$x_{ijn} \leq q_{ij} y_n \quad \forall i, j \in J, \forall n \in M : i < j \tag{2.14}$$

$$\sum_{n} y_{imn} \leq O_i y_m \quad \forall i \in J, \forall m \in M \tag{2.15}$$

$$\sum_{m} y_{imn} \leq O_i y_n \quad \forall i \in J, \forall n \in M \tag{2.16}$$

$$\sum_{n} y_{imn} = z_{im} \quad \forall i \in J, \forall m \in M \tag{2.17}$$

$$x_{ijn} \geq 0 \quad \forall i, j \in J, n \in M \tag{2.18}$$

$$z_{im} \geq 0 \quad \forall i \in J, m \in M \tag{2.19}$$

$$h_{imn} \geq 0 \quad \forall i \in J, m, n \in M \tag{2.20}$$

where $O_i = \sum_{j \in J: i < j} q_{ij}, \forall i \in J$ (*i.e.*, O_i is the total traffic originating at center *i*).

The objective function (2.9) and constraints (2.10) and (2.11) are the non-strict formulation of the corresponding strict expressions in the Ernst and Krishnamoorthy model. Constraints (2.15)-(2.17) are not included in the Ernst and Krishnamoorthy model, because they are not necessary when travel costs satisfy the triangle inequality property (MARÍN et al., 2006). However, when they do not satisfy triangle inequality, the optimum solution may include routes connecting more than two hubs and traffic flows may be assigned to non-hub nodes. In our case study (and, in general, in motorway interchange location problems), the triangle inequality property does not necessarily hold. To overcome this situation, we adopted the formulation suggested in MARÍN et al. (2006), but kept the Balinski-type constraints (2.13 and 2.14) of the Ernst and Krishnamoorthy model instead of the Efroymson-and-Ray-type constraints used by Marín et al. and used equality instead of inequality in constraints (2.17). Moreover, we eliminated some non-competitive (parts of) routes by adding the following constraints to the model:

$$x_{ijn} = 0 \quad \forall i, j \in J, n \in M : c_{jn} \geq c_{ij} \tag{2.21}$$

With our model we could successfully solve the case study with Xpress-MP for any number of motorway interchanges. The maximum CPU time we had to spend for getting the optimum solution was 4,228 seconds (approximately 1 h and 10 min), for p=8. Instances involving 4 to 11 interchanges always required more than 10 min. But, this was often much less (up to 80 percent) than the time spent for solving the model proposed by Marín and co-authors using the same computer, with the same software.

After getting results for MILM-EK, we were able to examine the implications of dividing the case study problem into two sub-problems, east and west, when solving the MILM-C model. The optimum solution to the problem (*i.e.* the solution to MILM-EK) never included the candidate interchange 14 until p = 14. The solutions obtained for the "sub-problems" approach using MILM-C are inferior to that of the global problem solved using MILM-EK. Indeed, using this approach, the travel time savings (recall that we are using travel time as a proxy for travel cost) vary between 54.66 percent (p = 3) and 93.58 percent (p = 10) of the savings generated by the MILM-EK for the entire problem. Even the optimal solution obtained using MILM-EK for p > 13, which included interchange 14, produced travel time savings over that generated by the MILM-C model (up to 5.98 percent). If interchange 14 was forced into the solution of MILM-EK (for p < 14), the travel time savings would naturally be smaller, but would be larger than those obtained with the MILM-C model through the sub-problems approach. In Table 2.1, we specify the differences between the travel time savings obtained for p = 8. In this case, the travel time savings obtained through the application of MILM-EK are 88.72 percent of those obtained through MILM-C.

Table 2.1 - Comparison of results for MILM-C east/west and MILM-EK when the number of interchanges is equal to 8

Model	Optimal interchange locations	Travel time savings	
		h/day	%
MILM-C east/west	1-3-7-9-14-27-28-33	3,170	88.72
MILM-EK with interchange 14	1-3-7-9-14-15-28-33	3,318	92.86
MILM-EK	1-3-7-9-11-15-28-33	3,573	100.00

2.3.3 MILM-L

In addition to the MILM-C and MILM-EK models presented above, we developed a new model based on the concept of a prescreened list of viable route alternatives, referred to as MILM-L. In the new model, all decision variables have only one subscript and the optimum routes for traveling between trip generation centers are clearly identified (something that does not happen with the MILM-EK).

For formulating the MILM-L, we define K as the set of routes potentially using the motorway (*i.e.* routes that lead to a decrease in travel costs). Then, we define R (dimensioned as $\#K\times4$) as the matrix containing the definition of the routes. Each column of R identifies, in this order, a traffic origin center (i), a traffic destination center (j), an access interchange (m), and an exit interchange (n) – if, for instance, it contains a row [1, 2, 9, 19], this means that a trip from center 1 to center 2 is less costly using motorway segment 9-19 than using only the existing road network. Therefore, we can replace the x_{ijmn} decision variables of MILM-C by x_k, $k \in K$, which take the value 1 if route k is part of the optimum solution or 0 if not. As before, there may be multiple routes with the same travel cost. If this is the case, the x_k will be fractional, and their sum is at most 1. Then, for each route we define $s_k = q_{ij}\ [c_{ij} - (c_{im}+c'_{mn}+c_{jn})]$ as being the total travel cost savings for route k (from i to j using the motorway segment mn). The set K, the matrix R, and the variables s_k are identified and calculated as a pre-process step.

Given the definitions above, the mathematical formulation of MILM-L is as follows:

$$Min \quad C = C^0 - \sum_{k \in K} s_k x_k \tag{2.22}$$

s.t. (2.3), (2.5), (2.7) and

$$\sum_{k \in K: R(k,1)=i \text{ and } R(k,2)=j} x_k \leq 1 \qquad \forall i, j \in J : i < j \tag{2.23}$$

$$\sum_{k \in K: R(k,3)=m} x_k \leq g_m^a y_m \quad \forall m \in M \tag{2.24a}$$

$$\sum_{k \in K: R(k,4)=n} x_k \leq g_n^e y_n \quad \forall n \in M \tag{2.24b}$$

$$x_k \geq 0 \quad \forall k \in K \tag{2.25}$$

The meaning of the objective function and each set of constraints is the same referred to before but adapted to the new formulation. The assignment constraints (2.23) assure that traffic between each pair of centers will follow at most one route using a motorway segment (except if there are several such routes with the same travel cost). The Efroymson-and-Ray-type constraints (2.24a and 1.24b) prevent any route in R which involves candidate interchanges m and n, respectively as access or exit, to be used unless both interchanges m and n have been selected as motorway interchanges.

Table 2.2 - Comparison of solution times for solving MILM-EK and MILM-L as the number of interchanges increases

Number of interchanges	Solution time (seconds)	
	MILM-EK	MILM-L
3	23	2
4	901	135
5	2,930	364
6	2,538	788
7	1,938	959
8	4,228	1,140
9	1,299	1,257
10	867	1,004
11	662	891
12	239	530
13	799	486
14	575	556
15	296	371
16	106	347
17	189	221
18	164	126
19	170	128
20	138	101
21	147	43
22	141	35
23	99	19
24	32	13
25	32	12
26	27	2
27	23	1
28	15	1

We solved the case study problem again using this new model MILM-L. The data screening identified 61,183 routes which could potentially improve travel time depending upon which interchanges are selected. Using Xpress-MP we were able to find optimum solutions to the case study within a maximum of 21 min (for $p = 9$). Table 2.2 shows the CPU times needed to solve the case study to optimality with MILM-L and compare them with the CPU times required by MILM-EK. MILM-L was always faster than MILM-EK for $p < 10$ and also for $p = 13$, $p = 14$, and $p > 17$. Thus, the MILM-L model was faster than MILM-EK in 19 cases out of 25 and the total time in solving all problems was substantially smaller than what was needed in solving all problems by MILM-EK.

2.4 Case study results

The results obtained for the A25 case study are summarized on Table 2.3. The Xs marked on the rows of the table specify the interchanges included in the optimum solution as the number of intersections of IP5 to be converted to A25 interchanges increases from 2 to 27. In general, as the number of interchanges increases, a new location is added and the previous ones remain. As one could expect, the first interchanges are located close to large cities like Aveiro (interchange 3), Viseu (interchange 15) or Guarda (interchanges 27 and 28), at the intersection of the A25 with motorways A29 (interchange 6), A1 (interchange 7) and A23 (interchanges 27 and 28), and next to a concentration of smaller cities (interchange 11). It was also expected that travel time savings would become progressively smaller as new interchanges are added (see Figure 2.3). With just 11 interchanges (of the 33 considered), the travel time savings already amount to 84.95 percent of the maximum possible savings (Table 2.3). After adding 17 interchanges, the reduction in travel time for each additional interchange is less than one percent of the total that can be achieved. Six of the candidate interchange locations, 2, 18, 21, 23, 30 and 32, do not contribute at all to the travel time savings given by the model. Of course, this does not mean they are never used, because travel demand is more dispersed across the A25 region than we assumed, and also because some trips are not made using the fastest routes. But this indicates that the contribution of the interchanges located there is really very minor.

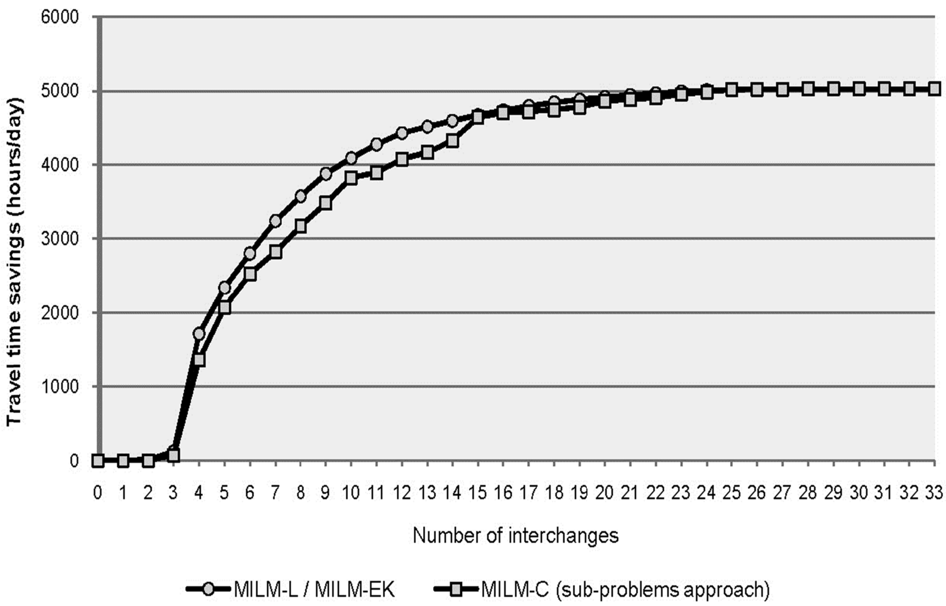

Figure 2.3 - Increase in travel time savings as the number of interchanges increases

We stated earlier in this chapter that the results of the case study must be taken with caution because some of its assumptions are a bit restrictive. Despite this, this analysis clearly suggests that too many intersections of the IP5 were converted into A25 interchanges. If, say, only 17 intersections were converted, it would have been possible to save an amount in the order of 32 million EUR with only minor negative implications with regard to travel times. Such an amount could have been put to more productive use in improving roads in the less developed or deprived areas crossed by the A25 motorway.

Table 2.3 - Characterization of model solutions for the A25 case study

Number of interchanges	Location of interchanges																																	Travel time savings	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	h/day	%
2	x																																x	7	0.13
3	x																											x					x	124	2.46
4	x						x								x																		x	1,710	34.02
5	x						x								x													x					x	2,337	46.48
6	x		x				x								x													x					x	2,802	55.73
7	x		x				x				x				x													x					x	3,241	64.47
8	x		x				x		x		x				x													x					x	3,573	71.07
9	x		x				x		x		x				x												x	x					x	3,875	77.09
10	x		x				x		x		x				x					x							x	x					x	4,086	81.27
11	x		x			x	x		x		x				x					x							x	x					x	4,270	84.95
12	x		x		x	x	x		x		x				x					x							x	x					x	4,428	88.08
13	x		x		x	x	x		x	x	x				x					x							x	x					x	4,516	89.84
14	x		x		x	x	x		x	x	x			x	x					x							x	x					x	4,596	91.43
15	x		x		x	x	x		x	x	x			x	x					x		x					x	x					x	4,673	92.96
16	x		x		x	x	x		x	x	x			x	x					x		x					x	x	x				x	4,736	94.20
17	x		x		x	x	x	x	x	x	x			x	x					x		x					x	x	x				x	4,795	95.39
18	x		x		x	x	x	x	x	x	x			x	x				x	x		x					x	x	x				x	4,844	96.36
19	x		x		x	x	x	x	x	x	x	x		x	x				x	x		x					x	x	x				x	4,881	97.09
20	x		x		x	x	x	x	x	x	x	x		x	x				x	x		x					x	x	x		x		x	4,916	97.79
21	x		x		x	x	x	x	x	x	x	x		x	x				x	x		x		x			x	x	x		x		x	4,943	98.32
22	x		x		x	x	x	x	x	x	x	x		x	x	x			x	x		x		x			x	x	x		x		x	4,968	98.83
23	x		x	x	x	x	x	x	x	x	x	x		x	x	x			x	x		x		x			x	x	x		x		x	4,990	99.26
24	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x		x		x			x	x	x		x		x	5,006	99.58
25	x		x	x	x	x	x	x	x	x	x	x		x	x	x	x		x	x		x		x	x		x	x	x		x		x	5,009	99.64
26	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x		x	x		x	x	x		x		x	5,024	99.95
27	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x		x		x	x	x	x	x	x		x		x	5,027	100.00

2.5 Conclusions

In this chapter, we have presented three optimization models applicable to motorway interchange location problems. The objective is to determine the locations for a given number of interchanges such that the total cost incurred by road users is minimized. Two of the models are based upon existing hub location models. The third one is a new model which, in most cases, tended to perform better than the other two in the case study application. Hub location models have been applied to a wide variety of transportation engineering problems since they were first introduced in the 1980s. However, to the best of our knowledge, this is the first work to propose the use of a hub location model in the design of a controlled access motorway.

Despite the fact that we believe the three models – and in particular the new model – can be very useful in real-world applications as they are, we recognize that they have a number of drawbacks. Indeed, the models are based on the assumption that the road system is uncongested and that travel demand is inelastic (*i.e.* the O/D matrix does not change in response to different decisions regarding the location of motorway interchanges). Also, they are based upon an objective to minimize travel costs, when it would be more relevant from an economic standpoint if the objective was to maximize users' benefits (consumers' surplus). The consideration of these more sophisticated assumptions would however make the models much more complex, since the MILM would have to be integrated with a road network design model (YANG and BELL, 1998). The integrated model would be highly nonlinear and extremely difficult, if not impossible, to solve to exact optimality. The development of models which integrate motorway interchange location decision making with road network design, however, cannot be dismissed because of the computational complexity alone and remains a potentially valuable research direction for future work (the authors have previously worked with road network design models in several occasions – see e.g. ANTUNES et al., 2003; SCAPARRA and CHURCH, 2005, MURAWSKI and CHURCH, 2009; SANTOS et al., 2009). Other interesting research directions can be pursued within the current MILM framework. In particular, we plan to address motorway interchange location problems from the perspective of a concessionaire who builds and operates a toll-based motorway (instead of the perspective of users). This problem is more complex than the ones addressed in this chapter because interchange location, toll fee, and route choice decisions are all interrelated. Also, we want to focus on interchange location approaches capable of dealing successfully with the uncertainty that characterizes the long-term evolution of travel demand. These are the research directions in which we plan to concentrate our efforts in the near term.

Chapter 3

Optimization Models for the Location of Motorway Interchanges: Concessionaires' Perspective

3.1 Introduction

In many cases the construction of a motorway takes place within the framework of build-operate-transfer (BOT) concession contracts. The government (through the Department of Transportation) sets the corridor of the motorway and the company who wins the contract sets the detailed design for the motorway that it will operate for the number of years specified in the contract. For a motorway concessionaire the design decisions regarding the location of interchanges – that is, the sections where drivers can enter or exit the motorway – are extremely important, because they strongly impact the amount of traffic that the motorway can capture from the existing road network.

In this chapter, we present a set of optimization models for assisting toll-motorway concessionaires in the analysis of the most profitable locations for interchanges. The models apply to a region comprising several trip generation centers (which can represent municipalities, cities, etc.) where a new motorway will be built. It is assumed that the corridor of the motorway has been previously defined. The intersections of the corridor with the existing road network are the potential locations for the interchanges. The motorway is designed to ensure level of service A and crosses a rural region. Thus, no traffic congestion is expected both in the motorway and in the existing road network. The models are generically designated as motorway interchange location models. We consider a deterministic model (all parameters are known with certainty) and two stochastic models (some parameters are uncertain but their probability distribution is known). The latter models identify solutions that perform well under all possible realizations of the uncertain parameters, but are not necessarily optimal in any of them (SNYDER et al., 2007). They are included in this study to exemplify two of the many possible ways of coping with the risks inherent to motorway investments decisions. For a recent state-of-the-art on facility location under uncertainty, the reader is referred to SNYDER (2006).

Motorway interchange location models belong to a class of models widely represented in the optimization literature: hub location models. These models allocate demand centers to hubs such that traffic is routed at minimum cost, taking advantage of lower travel costs on inter-hub connections. They were introduced in O'KELLY (1986) and have since their appearance been applied to a large number of transportation and telecommunication problems (CAMPBELL et al., 2002). The vast hub location literature was recently reviewed by ALUMUR and KARA (2008). To our best knowledge, hub location models were first applied to motorway interchanges in

REPOLHO et al. (2010)/Chapter 2. There, the location of interchanges was analyzed from the perspective of users. Herein, we focus on the viewpoint of concessionaires.

The classic hub location models force each demand center to assign to one and only one hub. This is not applicable to interchange location problems because, once a new motorway becomes available, drivers do not necessarily use the motorway for their trips. It may be better for them to continue traveling through the existing network. Also, drivers do not necessarily gain from making all their trips through the same interchange, as the interchange they choose depends on the origin and destination of the trip. Hub location models that match these features of interchange location problems are classified in the literature as non-strict multiple-allocation (AYKIN, 1995; EBERY et al., 2000).

A distinctive feature of the models we propose relates with the way travel behavior is dealt with. In general, this behavior is assumed to depend on travel costs. These costs typically include three components: vehicle operating costs, accident costs, and user time costs (DFT, 2006; WORLD BANK, 2010). A fourth component associated with tolling costs may be important when applicable. However, there are factors other than costs that may significantly affect travel behavior – in particular, route choice. Empirical evidence clearly suggests that habit is one such factor (RAMMING, 2002; HANDY et al., 2005). Our travel behavior model takes travel costs and travel habits simultaneously into account.

The remainder of the chapter is organized as follows. In the next section, we present the travel behavior model. Then, we introduce the deterministic and the two stochastic motorway interchange location models. Afterwards, we describe a case study involving an important Portuguese motorway, to exemplify the type of data required to run the models and the type of results that can be obtained through their application. In the final section, we provide some concluding remarks and identify directions for future research.

3.2 Travel behavior modeling

An essential ingredient of the motorway interchange location models described in this chapter is the model used to represent travel behavior with respect to both traffic flows and route choices.

As regards traffic flows, we have assumed that the traffic between trip generation centers is assumed to be given by an unconstrained gravity model (ORTÚZAR and WILLUMSEN, 2001). Hence, before the construction of the motorway, the flow between centers i and j, q_{0ij}, can be calculated as follows:

$$q_{0_{ij}} = \alpha \frac{m_i m_j}{f(c_{0_{ij}})} \tag{3.1}$$

where α is a calibration parameter; m_i is the "mass" (measured e.g. by population) of center i; $f > 0$ is an impedance function (expresses the decrease in traffic flow associated with the increase of travel cost); and c_{0ij} is the travel cost between centers i and j before the construction of the motorway.

The introduction of a new motorway in the road network creates new routes with new travel costs, thus changing the average travel costs between trip generation centers i and

j from c_{0ij} to c_{Fij}. Therefore, using the same unconstrained gravity model, the flow between these centers after the construction of the motorway, q_{Fij}, is given by:

$$q_{F_{ij}} = \alpha \frac{m_i m_j}{f(c_{F_{ij}})} \tag{3.2}$$

Comparing expressions (3.1) and (3.2), it is visible that new routes may generate additional traffic flows: if the travel cost between centers i and j decreases with the construction of the motorway ($c_{Fij} < c_{0ij}$), the traffic flow between the two centers will increase ($q_{Fij} > q_{0ij}$).

As regards route choice, we have assumed that drivers opt between traveling through the best (least-cost) route which uses only the existing road network (route 1) and traveling through the best route which uses one or more segments of the new motorway (route 2). The traffic flows corresponding to routes 1 and 2 are designated as q_{1ij} and q_{2ij}, respectively, and the corresponding travel costs as c_{0ij} (the initial cost) and c_{2ij}. Thus, traffic flows and average travel costs after the construction of the motorway can be expressed as follows:

$$q_{F_{ij}} = q_{1_{ij}} + q_{2_{ij}} \tag{3.3}$$

$$c_{F_{ij}} = \frac{c_{0_{ij}} q_{1_{ij}} + c_{2_{ij}} q_{2ij}}{q_{F_{ij}}} \tag{3.4}$$

Furthermore, we have assumed that if it is less costly to use only the existing network for a given trip, drivers will not use the motorway. But the opposite is not true: because of habit, a fraction of the drivers will continue to travel through the existing road network even when this is more costly than using the motorway.

The fraction of traffic that will use the motorway after it becomes available (i.e., the fraction of drivers that will make route choice 2) is assumed to be proportional to the impedance of the route that uses the motorway over the sum of the impedance of the two routes (1 and 2); that is:

$$\frac{q_{2_{ij}}}{q_{F_{ij}}} = \frac{f(c_{2_{ij}})}{f(c_{0_{ij}}) + f(c_{2_{ij}})} \tag{3.5}$$

Combining equations (3.1)-(3.5) it is possible to determine expressions for the total traffic flow after the construction of the motorway and for the distribution of this traffic across the two routes. Naturally, these expressions depend on the form taken by the impedance function.

We consider here two of the most common forms for the impedance function: the exponential form, $f(c_{ij})=\exp(\delta c_{ij})$; and the power form $f(c_{ij})=c_{ij}^{\beta}$ (δ and β are calibration parameters).

If the exponential form is used (note that, in this case, expression (3.5) becomes a logit model):

$$q_{F_{ij}} = \exp\left(-\delta \frac{c_{2_{ij}} - c_{0_{ij}}}{1 + \exp\left(\delta(c_{2_{ij}} - c_{0_{ij}})\right)} \right) q_{0_{ij}} \tag{3.6}$$

$$\frac{q_{2_{ij}}}{q_{1_{ij}}} = \exp\left[\delta \left(c_{0_{ij}} - c_{2_{ij}} \right) \right] \tag{3.7}$$

If the power form is used:

$$q_{F_{ij}} = \left(1 + \frac{c_{2_{ij}}^{\beta}}{c_{0_{ij}}^{\beta}}\right) \frac{c_{0_{ij}}^{2\beta-\beta^2}}{(c_{0_{ij}}^{1-\beta} c_{2_{ij}}^{\beta} + c_{2_{ij}})^{\beta} (c_{0_{ij}}^{\beta} + c_{2_{ij}}^{\beta})^{1-\beta}} q_{0_{ij}} \quad (3.8)$$

$$\frac{q_{2_{ij}}}{q_{1_{ij}}} = \left(\frac{c_{0_{ij}}}{c_{2_{ij}}}\right)^{\beta} \quad (3.9)$$

Both forms are used in practice, but it is worth noting here that, for interurban trips, power-form impedance functions typically fit real-world observations better than exponential-form impedance functions (FOTHERINGHAM and O'KELLY, 1989; DE VRIES et al., 2009).

3.3 Deterministic motorway interchange location model

Decision-making environments are traditionally categorized into three classes: certainty, risk, and uncertainty (ROSENHEAD et al., 1972). The model presented in this section for the problem faced by motorway concessionaires when choosing the best location for interchanges assumes a certainty environment – all parameters are known – being designated as Deterministic Motorway Interchange Location Model (DMILM).

Consider an existing road network, a new motorway, a set of trip generation centers of a region, *J*, and a set of candidate motorway interchanges, *M*. Trips are made through the least cost route according to the travel behavior model presented in the previous section. The cost of traveling between two centers, *i* and *j*, through the existing road network is c_{ij}, c_{im} is the cost of traveling between center *i* and interchange *m* through the existing road network, and c'_{mn} is the cost of traveling in the motorway between two interchanges m and n. If the motorway is used between interchanges m and n when traveling between centers i and j, then, the total route cost is $c_{ijmn} = c_{im} + c'_{mn} + c_{nj}$. Figure 3.1 illustrates the travel costs applicable to the two route alternatives.

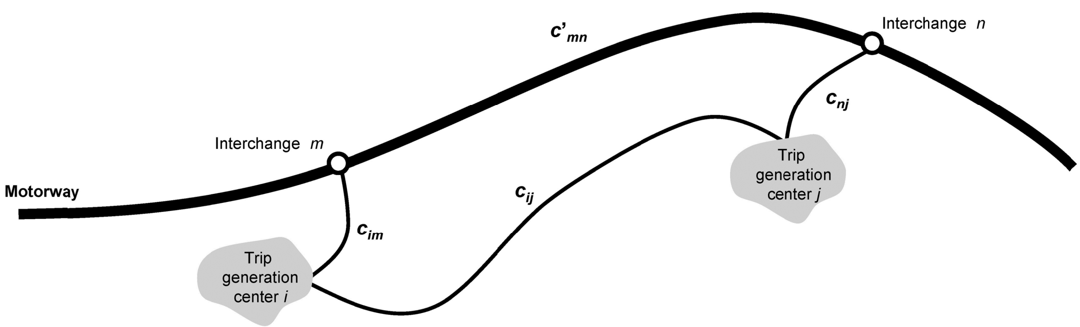

Figure 3.1 – Travel costs applicable for the two route alternatives

The distance between interchanges m and n is d_{mn}. The term a_{ijmn} represents the proportion of the original flow between i and j that will switch to using the motorway when interchanges m and n are built and when the route $i \rightarrow m \rightarrow n \rightarrow j$ is less costly than the route through the existing road network. The a_{ijmn} values are determined by one of the two forms of the travel behavior model. The product $a_{ijmn}q_{0ij}$ then represents the traffic flow between ij using motorway segment mn. Knowing that c_{0ij} is equal to c_{ij} and c_{2ij} is equal to c_{ijmn}, a_{ijmn} is given by q_{2ij}/q_{0ij} if $c_{ijmn} < c_{ij}$ and is equal to zero otherwise. Given a certain toll fee per kilometer, t, a fixed daily cost for installing and operating an interchange, f, and a fixed daily cost for building and maintaining the motorway, w, we wish to determine the number and location of motorway interchanges, as well as the traffic flow using the motorway, so that profit is maximized. The mathematical formulation of DMILM is as follows:

$$Max \quad \pi = 2\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} t\, d_{mn} a_{ijmn} q_{0_{ij}} x_{ijmn} - \sum_{m\in M} f y_m - w \tag{3.10}$$

s.t.

$$\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} x_{ijmn} \leq 1 \quad \forall i,j\in J: i<j \tag{3.11}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{n\in M:a_{ijmn}\neq 0} x_{ijmn} \leq g^a_m y_m \quad \forall m\in M \tag{3.12a}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M:a_{ijmn}\neq 0} x_{ijmn} \leq g^e_n y_n \quad \forall n\in M \tag{3.12b}$$

$$\sum_{u\in R_{ijmn}}\sum_{v\in R_{ijmn}} x_{ijuv} + y_m + y_n \leq 2 \quad \forall i,j\in J: i<j, \forall m,n\in M: a_{ijmn}\neq 0 \tag{3.13}$$

$$y_1 = 1 \tag{3.14a}$$

$$y_M = 1 \tag{3.14b}$$

$$x_{ijmn} \geq 0 \quad \forall i,j\in J, m,n\in M \tag{3.15}$$

$$y_m \in \{0,1\} \quad \forall m\in M \tag{3.16}$$

where y_m is a binary location decision variable that takes the value of 1 if a motorway interchange is located at the candidate interchange m, and zero otherwise; x_{ijmn} is an assignment decision variable representing the fraction of traffic from origin i to destination j routed via the motorway interchanges m and n in this order; $g^a{}_m$ ($g^e{}_n$) is an upper limit on the number of trips that may use interchange m (n) as a motorway access (exit); and $R_{ijmn}=\{v,b|c_{ijuv}>c_{ijmn}\}$ is the set of potential routes ($i\rightarrow u\rightarrow v\rightarrow j$) between trip generation centers i and j that cost more than the route using motorway segment mn ($i \rightarrow m \rightarrow n \rightarrow j$).

The objective function (3.10) expresses the profit, π, for the concessionaire, given as the difference between total toll fee revenues (multiplied by two to consider both traffic directions) and fixed charges for installing and operating the interchanges and for building and maintaining the roadway. Constraints (3.11) guarantee that each trip is assigned to no more than one route. If the route is composed of some motorway segment, mn, then x_{ijmn}=1. If the trip is made only through the existing road network then x_{ijmn}=0. Since we are dealing with a multiple-allocation hub location model, x may be fractional if for the same ij pair there exist more than one route with the same travel cost (see Lemma 1 in ERNST and KRISHNAMOORTHY, 1998). Constraints (3.12a) and (3.12b) work in tandem to prevent a trip to be assigned to a motorway segment unless two interchanges have been installed in both extremities. Constraints (3.13) were adapted from WAGNER and FALKSON (1975) where they ensure that demand is assigned to the closest facility in a "public-fiat" location model. They work together with binary constraints (3.16) to ensure that each trip is assigned to the least-cost route available (for route choice 2). If candidate motorway interchanges m and n are chosen (y_m=1 and y_n=1), then no trips from i to j can be assigned to routes belonging to R_{ijmn} (that is, the constraint eliminates routes from being selected that cost more than c_{ijmn}, when interchanges are located at m and n). Omitting constraints (3.13) would allow the model to assign trips to routes with longer motorway segments (leading to higher profit for the concessionaire), but which were not necessarily the least-cost routes available (within route choice 2). Further information on closest assignment constraints is available in GERRARD and CHURCH (1996) and LEI and CHURCH (2010b). Constraints (3.14a) and (3.14b) locate interchanges by default at the extremities of the motorway. Constraints (3.15) ensure that the assignment decision variables are nonnegative. Constraints (3.16) guarantee that the location decision variables are binary.

The model takes advantage of the symmetric characteristic of all traffic (*q*) and travel cost (*c*) matrices by only using their upper triangle ($i<j$). In order to eliminate unnecessary constraints and variables, the objective function (3.10) and the constraints (3.11), (3.12) and (3.13) only consider an assignment variable x_{ijmn} if $a_{ijmn}>0$.

3.4 Stochastic motorway interchange location models

Deterministic models like the one presented on the previous section are based on the assumption that all parameters are known with certainty. However, during the lifespan of a motorway, several parameters (e.g., traffic flows and fuel price) may fluctuate widely. These fluctuations can be dealt with through two types of model: stochastic and robust. The former apply when the probability distribution of the parameters is known, that is, when the decision environment is risky (according to the classification of ROSENHEAD et al., 1972) whereas the latter apply when the probability distribution of the parameters is unknown, that is, when the decision environment is uncertain (the typical objective of robust models is the maximization of worst-case performance). For a review of the many stochastic and robust models that have been applied to facility location in the past, the reader is referred to SNYDER (2006).

In this section, we present two stochastic models for the motorway interchange location problem, with the main purpose of exemplifying how one can evolve from a deterministic model to models that can cope with the risk inherent to motorway investments. Both models apply when the fluctuations of parameters can be represented with a finite set of scenarios (scenario planning). The first model deals with traffic flow risks and considers a classic mean-outcome approach, being based on the models proposed in WEAVER and CHURCH (1983) and MIRCHANDANI et al. (1985). We designate it as Stochastic Motorway Interchange Location Model (SMILM). The second model addresses fuel cost risks and derives from a much more recent approach, based on the concept of *r*-robustness introduced in SNYDER and DASKIN (2006), which adds a robustness feature to a stochastic model. We designate it as *r*-Robust Stochastic Motorway Interchange Location Model (*r*-SMILM).

Though the two stochastic models involve scenarios defined in terms of a single parameter, they can be easily extended to cope with scenarios defined in terms of various parameters. We decided to consider simple, one-parameter scenarios to facilitate the presentation of the models and the assessment of results (in particular, the assessment of the influence of parameters on solutions). However, we recognize that, in real-world applications, the various sources of risk must be dealt with simultaneously. The implications of this in terms of model formulation are minor, but the number of scenarios to analyze can increase substantially, making model instances so large that, even with the computing capabilities available today, they become impossible to solve to exact optimality.

3.4.1 SMILM

For the SMILM, traffic flows are assumed to be discrete random variables, corresponding to a finite number of scenarios, while fuel costs are assumed to be known. Travel costs are the same across all scenarios and therefore the traffic assignment network (drivers' route choices) is common to all of them. Thus, the SMILM is a one-stage model, in that strategic (interchange locations) and tactical (assignment network) decisions are made at the same time.

We define S as the set of scenarios. The initial traffic flow for each scenario s is q_{0ijs} and p_s is the probability of occurrence of that scenario. Given these definitions, the mathematical formulation of SMILM is as follows:

$$Max \quad \pi = 2\sum_{s\in S}\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} p_s\, t\, d_{mn} a_{ijmn} q_{0_{ijs}} x_{ijmn} - \sum_{m\in M} f y_m \quad (3.17)$$

s.t. (3.11), (3.12), (3.13), (3.14), (3.15) and (3.16)

The objective function (3.17) expresses the expected profit for the toll-motorway concessionaire over all scenarios, considering the corresponding probabilities.

3.4.2 *r*-SMILM

In *r*-SMILM fuel costs are assumed to be discrete random variables, corresponding to a finite number of scenarios, while traffic flows are assumed to be known. Travel costs are not the same across all scenarios and the assignment solution may be different between each scenario. Therefore, and contrary to the SMILM, the *r*-SMILM is a two-stage model, in that strategic (interchange locations) decisions are made first, before knowing which scenario will prevail, while tactical (assignment network) decisions are made later, after the uncertainty regarding fuel cost has been resolved.

Like the *r*-Robust Stochastic Uncapacitated Facility Location Model proposed in SNYDER and DASKIN (2006), the *r*-SMILM takes advantage of both the stochastic and the robust optimization approaches. The model searches for the solution that maximizes expected profit while bounding the relative regret in each scenario to be no more than r (r can thus be seen as the robustness measure). The relative regret associated with scenario s is the percentage of profit loss, i.e., the difference in percentage between the objective function value that results from selecting some compromise locations for the interchanges and the highest objective function value that could be obtained for scenario s, V_s. The value of r ($0 \leq r \leq 1$), which expresses the desired robustness level, is defined by the decision-maker. By mixing the stochastic and the robust optimization approaches, the *r*-SMILM, on the one hand, minimizes the risk of generating solutions that are far from the best that could be attained for the prevailing scenario if considered alone (a recurring issue in stochastic models) and, on the other hand, leads to a solution that is less pessimistic than the one that would be obtained with a classic robust model (which tends to be overly pessimistic since it plans against a worst scenario which may be extremely unlikely to occur).

The notation previously introduced must be redefined within the context of scenario planning for a two-stage model. The cost of traveling between two centers, i and j, through the existing road network under scenario s is c_{ijs} and c'_{mns} is the cost of traveling in the motorway between two interchanges m and n under scenario s. If the motorway is used between interchanges m and n under scenario s, then, the total route cost is $c_{ijmns}=c_{ims}+c'_{mns}+c_{njs}$. R_{ijmns} is the set of potential routes between trip generation centers i and j that cost more than the route through the motorway segment mn under scenario s and a_{ijmns} is the constant by which initial traffic flow, q_{0ijs}, must be multiplied to obtain the traffic flow traveling through routes containing a motorway segment (choice 2) under scenario s. Here, a_{ijmns} is given by q_{2ijs}/q_{0ijs} if $c_{ijmns}< c_{ijs}$ and is equal to zero otherwise. The r-SMILM seeks the number and location of motorway interchanges that maximizes the expected profit, as well as the traffic flow using the motorway in each scenario. Given this notation, the mathematical formulation of r-SMILM is as follows:

$$Max \quad \pi = 2\sum_{s\in S}\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmns}\neq 0\end{cases}} p_s\, t\, d_{mn} a_{ijmns} q_{0_{ijs}} x_{ijmns} - \sum_{m\in M} fy_m - w \tag{3.18}$$

s.t. (3.14), (3.16) and

$$\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmns}\neq 0\end{cases}} x_{ijmns} \le 1 \quad \forall i,j\in J, \forall s\in S: i<j \tag{3.19}$$

$$\sum_{u\in R_{ijmns}}\sum_{v\in R_{ijmns}} x_{ijuvs} + y_m + y_n \le 2 \quad \forall i,j\in J: i<j, \forall m,n\in M, \forall s\in S: a_{ijmns}\neq 0 \tag{3.20}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{n\in M:a_{ijmns}\neq 0} x_{ijmns} \le g^{a}_{ms} y_m \quad \forall m\in M, \forall s\in S \tag{3.21a}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M:a_{ijmns}\neq 0} x_{ijmns} \le g^{e}_{ns} y_n \quad \forall n\in M, \forall s\in S \tag{3.21b}$$

$$2\sum_{s\in S}\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:n\neq m \text{ and } a_{ijmns}\neq 0} q_{ij}a_{ijmns}x_{ijmns}d_{mn}t-\sum_{m\in M}y_m f\geq(1-r)V_s \quad \forall s\in S$$

(3.22)

$$x_{ijmns}\geq 0 \quad \forall i,j\in J,m,n\in M,s\in S \tag{3.23}$$

where x_{ijmns} is the fraction of traffic from origin i to destination j routed via the motorway interchanges m and n, in this order, under scenario s; and g^a_{ms} (g^e_{ns}) is the maximum number of trips that may use interchange m (n) as a motorway access (exit) under scenario s. The set $R_{ijmns}=\{v,b|c_{ijuvs}>c_{ijmns}\}$ is the set of potential routes ($i\rightarrow u\rightarrow v\rightarrow j$) between trip generation centers i and j that cost more than the route using motorway segment mn ($i\rightarrow m\rightarrow n\rightarrow j$), under scenario s.

The meaning of the objective function and constraints is the same as presented in the previous models but adapted to the context of scenario planning. Constraint (3.22) ensures that the objective function value for each scenario under the compromise locations is not more than r percent worse than the best objective function values that could be obtained for each scenario alone, V_s; that is, it enforces the r-robustness condition. For r=1 we get (1-r) V_s=0, i.e. constraint (3.22) only assures that each scenario is not non-profitable. On the other hand, when the value of r is small the above model may not have a feasible solution. That is, it may not be possible to derive a robust solution which performs close enough to optimum across all scenarios.

3.5 Case study

The models presented in the previous sections were applied to a case study involving the A25 motorway, in Portugal. This road is one of the most important in Portugal since it provides the fastest connection between the coastal and inland areas of northern Portugal and between northern Portugal and the other European Countries (particularly Spain). More information on the A25 motorway is available in REPOLHO et al. (2010)/Chapter 2.

For the case study we considered 33 candidate motorway interchange locations and 55 trip generation centers, which represent the municipalities located in the region crossed by the motorway. The road network, the motorway, and the set of centers are represented in Figure 3.2.

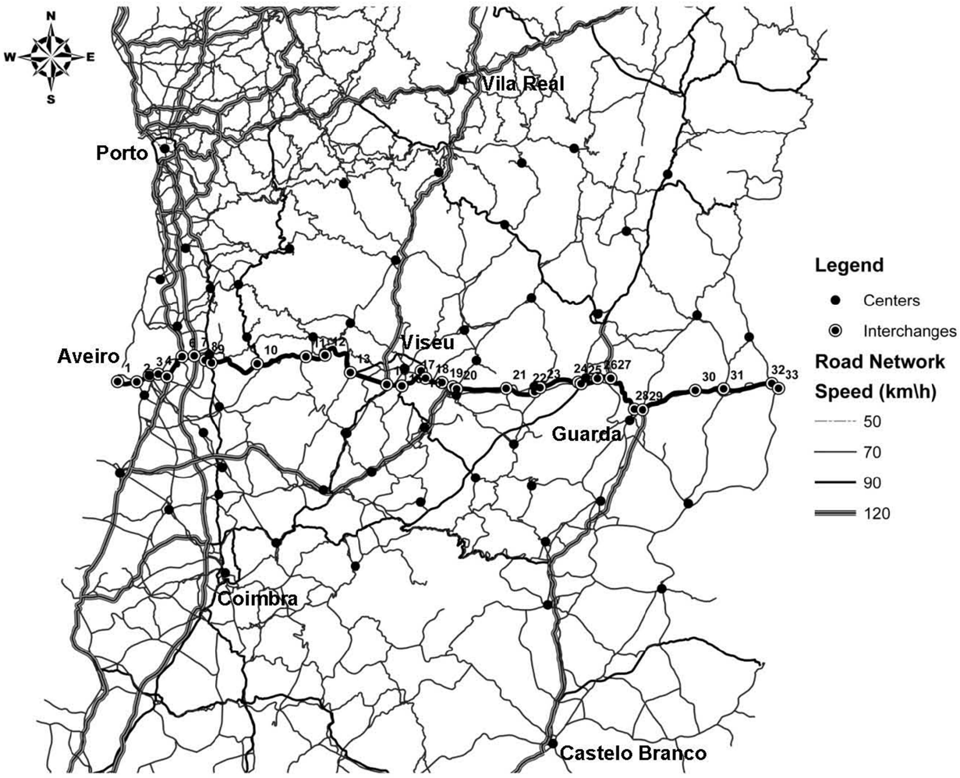

Figure 3.2 - Location and corridor of the motorway and the municipalities

The presentation of the case study is divided in four parts. First, we present the data used as input for the models. It contains a brief explanation about the parameter values adopted and a more detailed description of road user costs. In the next three parts, we describe the results obtained, respectively, for the three MILM models introduced before. The models are solved with an Intel Core 2 Quad Processor Q9550 2.84 GHz computer with 4 GB of RAM and the FICO Xpress 7.0 optimizer (FICO, 2009).

3.5.1 Model Data

The initial traffic flow, q_{0ij}, was estimated through an unconstrained gravity model considering a power-form impedance function with α equal to 1.4 and β equal to 1.0 (these parameters were calculated using the O/D traffic data available for the north Region of Portugal).

The fixed costs were estimated considering average costs of 2.00 million € for each interchange and 2.85 million € per motorway kilometer (the motorway total length is 190 kilometers). Thus, for a lifespan of 30 years and a (real) discount rate of 4 percent, the daily fixed charges for installing and operating the interchanges and for building and maintaining the motorway are, respectively, f = 305 € and w = 82,495 €.

The road user costs (*RUC*) were calculated with the model presented in SANTOS (2007). The model incorporates four cost components: vehicle operating costs (*VOC*), accident costs (*AC*), user time costs (*UTC*), and tolling costs (*TC*). The general expression is as follows:

$$RUC = VOC + AC + UTC + TC \tag{3.24}$$

The vehicle operating costs were calculated based on the HDM-4 approach (WORLD BANK, 2010), and they include fuel consumption, tires, vehicle maintenance, and vehicle depreciation costs; the accident costs were calculated based on COBA (DFT, 2006) and HDM-4; the user time costs were calculated based on HDM-4 and the formulation adopted by the Portuguese Road Administration (GEPA, 1995); and the tolling costs correspond to the toll fees currently being applied. Four vehicle classes were considered: passenger cars (PC), light duty vehicles (LD), trucks (TRK) and buses (BUS). The percentage of each vehicle class in the Portuguese national car fleet is 76.3, 21.0, 2.4 and 0.3, respectively for the PC, LD, TRK and BUS vehicle classes (information available in IMTT, 2006a and 2006b). Because we do not have specific information regarding accident costs, we assumed that they are the same for every road and vehicle class: 0.01 €/km/vehicle (the value used in SANTOS, 2007). User time costs were calculated considering 7.50, 6.00, 9.06 and 43.56 €/h/vehicle, respectively for the PC, LD, TRK and BUS vehicle classes.

The information about the existing road network and the new motorway was handled through ArcGIS 9.2. (GORR and KURLAND, 2007). Each road segment was characterized according to: length, travel speed, and toll fee (if applied). With this information, we determined the road user cost for each road segment using expression (3.24) and the parameters defined above (considering passenger-car units). Then, using the Network Analyst extension of ArcGIS 9.2, we calculated the road user cost for the least-cost route between each pair of trip generation centers (using only the existing road network) and between each trip generation center and each candidate motorway interchange location.

Five scenarios for fuel costs were considered as shown in Table 3.1. The fuel cost scenario SCN 3 corresponds to the fuel prices being applied in Portugal at the time we made the study. The scenarios SCN 1 and 2 were obtained dividing SCN 3 fuel costs by 2.0 and 1.5, respectively, and the scenarios SCN 4 and SCN 5 were obtained multiplying SCN 3 fuel costs by 1.5 and 2.0, respectively. These fuel cost scenarios represent well enough the fuel cost variations observed in the last few years in Portugal.

Table 3.1 - Fuel cost scenarios

Fuel type	SCN1	SCN2	SCN3	SCN4	SCN5
Diesel	0.498	0.663	0.995	1.493	1.990
Gasoline	0.610	0.813	1.219	1.829	2.438

The vehicle operating cost components for each fuel cost scenario are summarized in Figure 3.3.

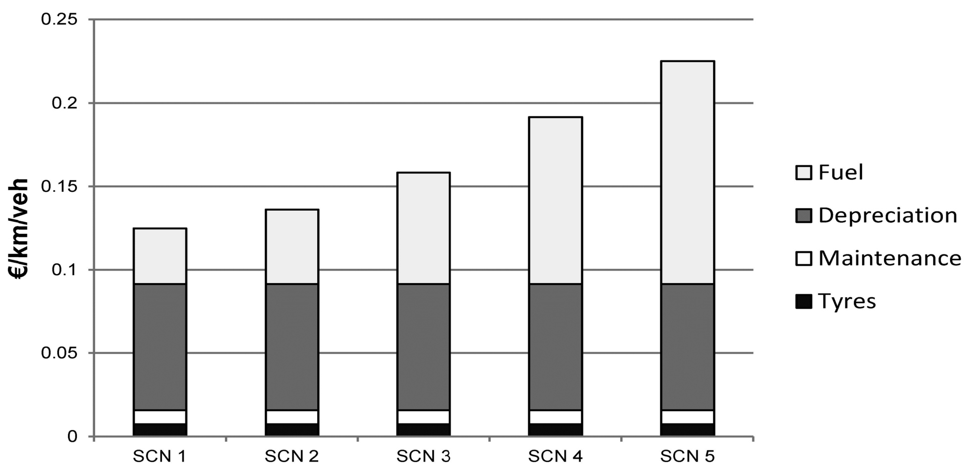

Figure 3.3 - Vehicle operating cost components for each fuel cost scenario

3.5.2 DMILM results

DMILM was solved using fuel cost scenario SCN 3. The optimum locations for the interchanges and the CPU time required to obtain the solutions for different values of toll fees are summarized in Table 3.2. For each toll fee value, the table presents the net profit generated by the DMILM model, the interchange locations selected for that toll value, the number of potentially feasible route choices (or the number of x_{ijmn} variables employed in the model) and the time needed to solve the model. Figure 3.4 shows the profit for the concessionaire according to the toll fee applied.

Table 3.2 - DMILM results for fuel cost scenario SCN 3

Toll fee (€/Km)	Interchange locations	Routes	CPU (sec)
0.030	1-3-4-6-9-10-11-12-13-14-15-16-19-20-25-26-27-28-31-33	15,929	19
0.040	1-3-4-6-7-9-10-11-12-13-14-15-17-19-20-22-23-24-27-28-31-33	13,277	13
0.045	1-3-4-6-7-9-10-11-12-13-14-15-17-20-22-23-24-26-28-29-31-33	12,059	13
0.049	1-3-4-6-7-9-10-11-13-14-15-17-20-22-24-26-28-29-31-33	11,161	11
0.050	1-3-4-6-7-9-10-11-13-14-15-17-18-22-24-26-28-29-31-33	10,890	11
0.051	1-3-4-5-6-7-8-10-11-13-14-15-17-18-22-24-26-28-29-31-33	10,598	10
0.055	1-3-4-5-6-7-8-10-11-13-14-15-18-19-20-22-24-26-28-29-31-33	9,771	9
0.060	1-3-4-5-6-7-8-10-11-14-15-19-20-22-24-26-28-29-31-33	8,786	8
0.065	1-3-5-6-7-8-9-10-11-14-15-20-22-24-26-28-29-31-33	7,789	7
0.070	1-3-5-6-7-8-9-10-11-14-15-20-24-26-28-29-31-33	6,804	6
0.080	1-3-5-6-7-8-9-10-11-15-16-17-19-20-21-24-26-28-29-31-33	5,179	6
0.081	1-3-5-6-7-8-9-10-11-13-14-15-16-19-21-24-26-28-29-31-33	5,046	4
0.090	1-3-5-6-7-8-9-10-11-15-16-19-21-24-26-28-29-31-33	4,011	5
0.100	1-3-5-6-7-8-9-10-11-15-16-19-24-26-28-29-31-33	3,073	1

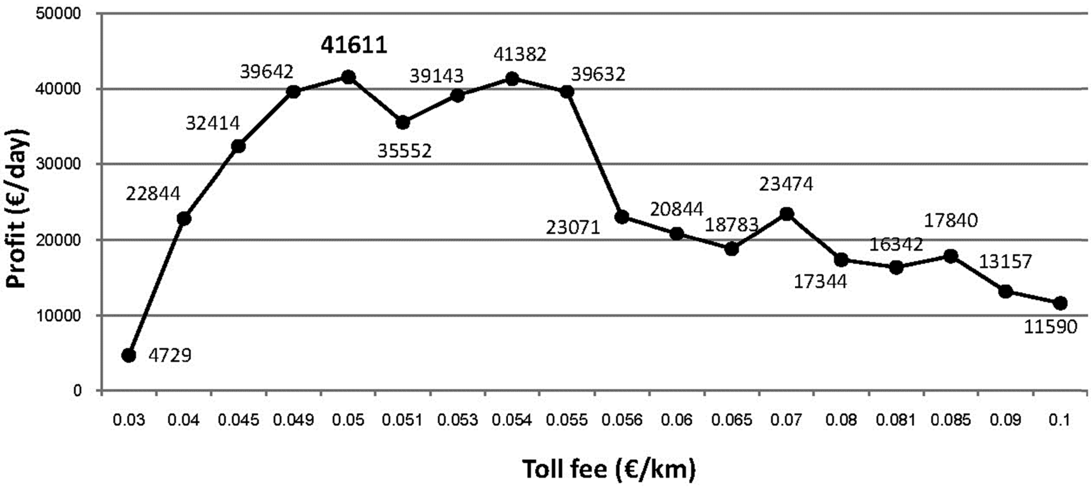

Figure 3.4 - Relationship between toll fees and concessionaire's profits

As expected, several interchanges are optimally located close to large trip generation centers (interchanges 3, 15, 28) or in the intersection of the motorway with other important roads (interchanges 5, 6, 7, 9, 10, 14, 19, 20, and 29). Other intersections are located in less obvious places – these are the ones that would have been difficult to identify if the model was not used. When the toll fee is low there are more cost-efficient routes within route choice 2 (column Routes in Table 3.2) and there are more motorway users, but the profit is relatively low. Higher values of toll fees mean fewer potential cost-efficient routes and therefore fewer motorway users but paying more. The optimum solution is found considering a trade-off between the number of motorway users and the toll fee they pay. The maximum profit is reached when a toll fee of 0.05 €/km is applied. The increase of the toll fee causes the loss of some motorway routes, while the remaining routes can be charged more before the users are lost to the existing road network. This fact justifies the irregular shape of the graph between t=0.05 €/km and t=0.054 €/km or t=0.056 €/km and t=0.07 €/km.

The solution when the toll fee is 0.05 €/km comprises 20 interchanges. Figure 3.5 shows the location of the interchanges for this toll fee, distinguishing the interchanges that are present in all optimum solutions regardless of the toll fee applied from the ones that are not present in all optimum solutions.

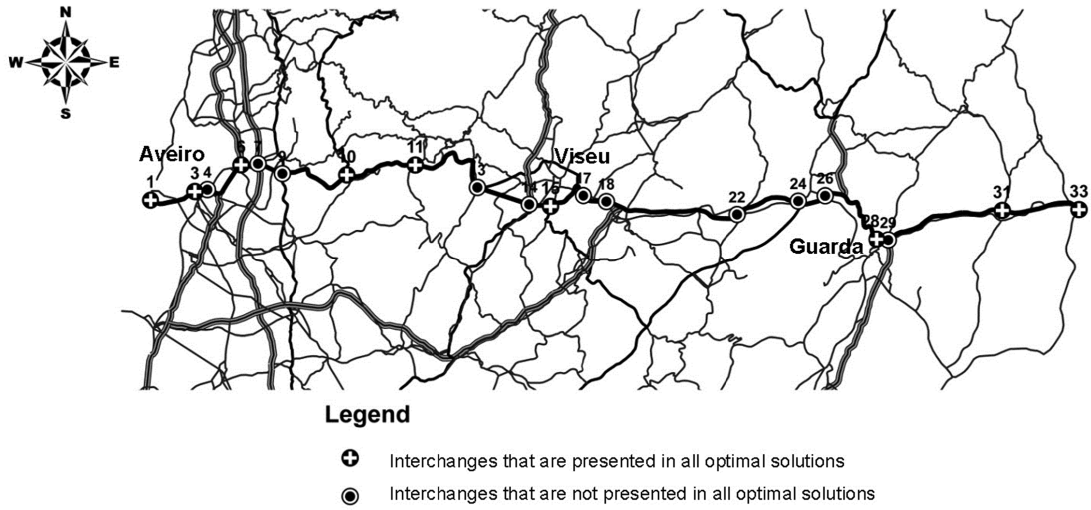

Figure 3.5 - DMILM solution for *t*=0.05€/km

More than the number of trip generation centers and interchanges, the CPU time needed to find an optimum solution depends on the number of cost-efficient routes within route choice 2 (see columns Routes and CPU in Table 3.2). As the toll fee increases, the number of cost-efficient routes decreases, and so does the CPU time needed to solve the model.

3.5.3 SMILM results

SMILM was solved using fuel cost scenario SCN 3. We considered 50 scenarios for the traffic flow. The scenarios were randomly generated from a normal distribution taking into account the population growth rate for the trip generation centers observed in the last inter-census period. All scenarios have the same probability. Table 3.3 presents the optimum interchange locations that differ from the ones obtained with DMILM for the various toll fees, and also for *t*=0.081 €/km.

For instance, when the toll fee is 0.05 €/km the SMILM solution has one more interchange (interchange 20) and interchange 18 is replaced with interchange 19. For the toll fees presented in Table 3.2 but not on Table 3.3 (except for *t*=0.081 €/km) the interchange locations are the same in both DMILM and SMILM models.

Table 3.3 - SMILM results for fuel cost scenario SCN 3

Toll fee (€/Km)	Profit (€/day)	Interchange locations	Routes	CPU (sec)
0.030	3,066	1-3-4-6-9-10-11-12-13-15-16-20-26-28-29-31-33	15,929	18
0.040	23,731	1-3-4-6-8-9-10-11-12-13-14-15-17-19-20-23-24-28-29-31-33	13,277	17
0.045	33,203	1-3-4-6-8-9-10-11-12-13-14-15-17-20-22-23-24-28-29-31-33	12,059	11
0.050	41,480	1-3-4-6-7-9-10-11-13-14-15-17-19-20-22-24-26-28-29-31-33	10,890	9
0.051	32,210	1-3-4-5-6-7-8-10-11-13-14-15-17-19-20-22-24-26-28-29-31-33	10,598	9
0.065	9,457	1-3-5-6-7-9-10-11-14-15-20-22-24-26-28-29-31-33	7,789	7
0.070	14,001	1-3-5-6-7-9-10-11-14-15-20-24-26-28-29-31-33	6,804	6
0.081	-1,804	1-3-5-6-7-8-9-10-11-13-14-15-16-19-21-24-26-28-29-31-33	5,046	7

The optimum intersection locations do not differ much across the two models, which indicates that DMILM solutions are, in general, not excessively sensitive to traffic flow uncertainty. However, it is worth noting that, when *t*=0.081 €/km, the SMILM results show that the investment is no longer profitable, while with DMILM for a single traffic flow scenario it was profitable. In this case, the consideration of uncertainty would have implications upon the very decision of making (or not) the investment.

In general, the CPU time required to solve the SMILM model did not increase (for some toll fees it even decreased) when compared to the CPU times associated with solving the DMILM.

3.5.4 *r*-SMILM results

The *r*-SMILM model was solved using the five fuel cost scenarios with a toll fee of 0.05 €/km, the value that maximizes profit using the DMILM and SMILM models. We considered the following occurrence probability set, P=[0.05, 0.225, 0.45, 0.225, 0.05], where the fuel cost scenarios SCN 1 and SCN 5, with a probability of 5 percent, are relatively unlikely to happen. The optimum solution value, V_s, for each scenario s is obtained applying the DMILM. The results obtained for t=0.05 €/km are presented in Table 3.4.

Table 3.4 - DMILM results for all fuel cost scenarios

Scenario	Profit (€/day)	Interchange locations	Routes	CPU (sec)
SCN 1	42,064	1-3-4-5-6-7-8-9-10-11-13-14-15-17-18-23-24-26-28-31-33	10,563	13
SCN 2	40,998	1-3-4-5-6-7-8-9-10-11-13-14-15-17-18-22-24-26-28-29-31-33	10,647	11
SCN 3	41,611	1-3-4-6-7-9-10-11-13-14-15-17-18-22-24-26-28-29-31-33	10,890	11
SCN 4	20,240	1-3-4-5-6-7-8-9-10-11-13-14-15-18-22-24-26-28-31-33	10,782	9
SCN 5	2,250	1-3-4-5-6-7-8-9-10-11-13-14-15-19-20-22-24-26-28-31-33	10,889	15

As fuel cost increases there are more cost-efficient routes within route choice 2, because the motorway often provides shorter itineraries (less fuel consumption). However, higher traveling costs make the traffic flow decrease (see expressions (3.2) and (3.5)). Consequently, the concessionaire profit decreases from scenario 1 to scenario 5.

Table 3.5 presents the *r*-SMILM results for *t*=0.05€/km and for three *r*-robustness levels: 1.00, 0.04 and <0.039, considering the occurrence probability set *P* defined above.

Table 3.5 - *r*-SMILM results for *t*=0.05€/km and occurrence probability set *P*

r (%)	Profit (€/day)	Interchange locations	CPU (sec)	Max. regret (%)
100.00	33,646	1-3-4-5-6-7-8-9-10-11-13-14-15-19-20-22-24-26-28-29-31-33	269	4.19
4.00	33,626	1-3-4-5-6-7-8-9-10-11-13-14-15-19-20-22-24-26-28-31-33	223	3.89
< 3.89	infeasible	-	-	-

If *r*=1.00 we essentially discard the *r*-robustness constraints (they only assure that each scenario is not non-profitable). Thus, in this case, the optimum solution maximizes expected profit according only to the scenario probabilities, *P*. For *r*=1.00, the expected profit is 33,646 €/day and the optimum solution is similar to the one obtained for the SMILM with the addition of interchanges 5 and 8 and the removal of interchange 17. The relative regret in each scenario is 3.67%, 2.51%, 3.08%, 4.02% and 4.19%, respectively.

Enforcing the *r*-robustness measure provides solutions with lower relative regret without large decreases in the expected profit. Imposing a maximum relative regret of 4% (*r*=0.040) the solution has an expected profit of 33,626 €/day, which is only 0.06% lower that the value obtained for *r*=1.000. For *r*=0.040, the solution has one less interchange (interchange 29 is removed) than the solution obtained for *r*=1.00. The relative regret in each scenario is now 3.89%, 2.72%, 3.16%, 3.72% and 0.00%, respectively. The maximum relative regret in this case is 3.89% instead of 4.19%.

For r<0.0389 there is no feasible solution, because no solution can guarantee such a maximum level of relative regret across all scenarios.

The CPU time required to solve the r-SMILM model is longer than the one required by the DMILM and SMILM models. The reason is that the r-SMILM seeks the optimum solution considering all cost-efficient routes (for route choice 2) across all scenarios. When t=0.05 €/km, the number of cost-efficient routes rises to 53771 and the CPU times required to reach the optimum solutions are 269 and 223 seconds, respectively for r=1.000 and r=0.040.

3.6 Conclusions

In this chapter, we presented three optimization models applicable to the interchange location problems faced by motorway concessionaires. The study presented in this chapter extends the analysis we initiated in Chapter 2 (REPOLHO et al., 2010), where problems of the same kind are dealt with from the perspective of road users.

With respect to Chapter 2, we have adopted the same hub location model approach, but there are a number of important differences to underline. First, we distinguish between the objectives of motorway concessionaires, who aim at maximizing profit, and the objectives of road users, who (essentially) seek to minimize travel time given the interchange locations decided by the concessionaires. Second, we employ a more sophisticated travel behavior model, where the additional traffic generated by the introduction of a motorway is considered and the role played by habit in route choice is recognized. And third, we contemplate the two major risk sources that typically affect road investment decisions (traffic flows and fuel price).

The models presented in this chapter can be, as they are, important tools to assist motorway concessionaires in their decisions about interchange locations and toll fees (or in their discussions of these issues with road administrations). The stochastic models exemplify two (among many) possible approaches for dealing with the risk issues involved in motorway interchange location problems. Though they were applied to simple scenarios, involving only one parameter, they are essentially valid for scenarios involving several parameters at the same time. However, it is worth noting that a large increase in the number of scenarios could make the models (particularly the *r*-SMILM) impossible to solve to exact optimality. In that case, heuristic algorithms would have to be used (they are being thought as a future development of our current research). The case study we include in the chapter provides, we hope, clear evidence on the potential usefulness of the models.

Still, we must acknowledge that the models have a drawback: they cannot be properly applied to congested networks. Although motorways (and motorway accesses) are typically designed to provide high levels of service, there may be congestion issues to consider particularly in segments close to major cities. These issues are not easy to deal with because their consideration has large implications on the optimization models, which become non-linear and much more difficult to solve. We plan to address them in our future research efforts regarding interchange location problems.

Chapter 4

Optimal Location of Motorway Interchanges: Social Welfare Gains versus Concessionaires' Profits

4.1 Introduction

Modern and efficient transportation networks are essential to promote and support economic development and to satisfy the increasing demands for travel of a growing population. Before the 1980s, the provision of transportation infrastructure was mainly made by governments, under the justification that most of the benefits of infrastructure provision have a public character. This tendency for central planning and control of critical public transportation infrastructure prevented the private sector from participating and investing in such developments (KUMARASWAMY and ZHANG, 2001). Since then, many countries encourage the private sector to invest in transportation infrastructure, both in the construction of new infrastructure and the renewal and maintenance of existing infrastructure (VICKERMAN, 2007). Several factors have contributed to this change, including: the tendency towards the deregulation of public monopolies, the belief that the private sector is more efficient than the public sector, the demand for better service, and the shortage of public funds to finance transportation infrastructure, which is probably the major contributing factor (CHEN and SUBPRASOM, 2007; YANG and MENG, 2000; and GOMEZ-IBANEZ et al., 1991). Financial arrangements that involve direct private sector funding in financing public sector infrastructure are generally designated as Public-Private-Partnerships (PPP). A review of the concept of PPP and related studies is available in TANG et al. (2010).

A well-accepted PPP arrangement is the Build-Operate-Transfer (BOT) scheme. According to such scheme, the government grants the concession of the transportation infrastructure to a private investor, who gets the right to build and operate the infrastructure at his own expense, receiving in turn toll revenues during the concession period. When the concession period ends the infrastructure is transferred to the government without remuneration. In the last few decades this scheme has been applied worldwide, both in developed and developing countries. A list of BOT projects can be found in WALKER and SMITH (1995), LAM (1999), and SUBPRASOM (2004). Among the existing BOT projects there are several examples of motorway concessions.

BOT projects generally involve two parties: a public entity (government) and a private investor (concessionaire). The former intends to maximize public benefits (social welfare), while the latter wants to maximize the profit generated from the investment. Such distinct goals generally lead to conflicts. Governments may be tempted to encourage BOT projects as a way to subsidize the development of public infrastructure using private funds in order to add social welfare to the society. However, given the high risk involved in such investments, the private sector will only finance a project venture if it is attractive, i.e., if it secures adequate profit. Moreover, as pointed out in PAHLMAN (1996), if something goes wrong in a BOT project it is the government (the public interest), and not the private investor, who ultimately copes with the costs of failure. For this reason when planning transportation infrastructure development all objectives should be taken into account in order to achieve a win-win solution (see KUMARASWAMY and ZHANG, 2001) for both the public and private interests, and ultimately for a successful BOT project.

The costs involved in motorway infrastructure depend on the size of the project (motorway extension and capacity and the number of interchanges), while profit depends on the combination of toll fee revenues and the volume of users captured. The latter depends on the infrastructure characteristics (layout and access points) and the toll charged. Thus, interchange location plays an essential role in costs evaluation, demand estimation and finally in public welfare calculation. The goal of this chapter is to present an optimization model for locating motorway interchanges in a public-private-partnership environment that takes into account both the public and the private interest.

The optimization model for locating motorway interchanges introduced in this chapter is based on the models formulated in REPOLHO et al. (2010 and 2011a)/Chapters 2 and 3, which formulate a set of optimization models aimed at assisting in the location of interchanges for a new motorway. The former assumes the motorway to be toll-free, and the optimization is done from the users' perspective with the objective of minimizing total travel costs. The latter, assumes the motorway is explored by a private concessionaire whose revenues are obtained from toll fees with the objective of maximizing profit.

The model here presented integrates both the users' and the concessionaires' perspectives. The model determines the number and location of motorway interchanges, as well as estimates the traffic flow using the motorway based upon the interchange locations, so that social welfare gains are maximized while ensuring a given level of profit for the concessionaire. As its predecessors (REPOLHO et al., 2010 and 2011a/Chapters 2 and 3) the model can be classified as a non-strict multiple hub-allocation model (AYKIN, 1995; EBERY et al., 2000; and O'KELLY, 1986).

The outline of this chapter is as follows. In the next section we discuss the valuation of social welfare gains in transportation projects. Consumers' surplus is presented as the benefits measure. Next the formulation of the optimization model is introduced. In the following section this model is applied to an existing data set (REPOLHO et al. 2011a/Chapter 3). The data set is briefly characterized and the results obtained through the model are compared with the ones obtained in previous studies for the same data set. Concluding remarks are presented in the last section.

4.2 Social welfare measure

The valuation of social welfare (users' benefits) in transportation has been a recurring subject in the literature (e.g., WILLIAMS, 1976; JARA-DÍAZ, 1986; JARA-DÍAZ and FARAH, 1988). Its complexity arises from the fact that the transportation sector is a peculiar economic sector which influences the entire economic system producing a multiplicity of effects (for a review the reader is referred to VICKERMAN, 1991, RIETVELD and NIJKAMP, 1993, and RIETVELD, 1994). LAKSHMANAN et al. (2001) refers to the assessment of benefits (and costs) in transport as a 'slippery ice' notion/area. For this reason and also because the subject involves economic matters that go beyond the scope of this chapter, in this section we will introduce some of the main issues and provide the social welfare measure used in our model – consumers' surplus gains.

In a strict sense, the benefits of transport infrastructure provision are related to usage, and without users there are no benefits. Thus, it is reasonable to assume that the benefits provided by the infrastructure should be given by the total benefits of the users over the life of the infrastructure. Most BOT projects use the concept of consumers' surplus to assess the users benefit (social welfare benefits) derived from the improvement of transportation infrastructure (e.g., YANG and MENG, 2000; CHEN and SUBPRASOM, 2007). Consumers' surplus was defined in MARSHALL (1920) as the 'excess of the price which the consumer is willing to pay for something rather than go without, over that which he actually does pay', i.e., the difference between total willingness to pay and actual payment.

It is logical to question at this point whether consumers' surplus is sufficiently accurate to fully reflect the social welfare or should additional external benefits be added? If this was the case, then social welfare benefits would be larger than the willingness to pay of the immediate user. However, as pointed out in MISHAN (1976), the addition of external benefits may produce double counting. JARA-DÍAZ (1986) shows that at a market level the net sum of gains and losses are fully reflected by consumers' surplus in a competitive environment and approximately in a monopolistic one.

ROTHENGATTER (1994) suggests that the external benefits, if they exist at all, would be small. LAKSHMANAN et al. (2001) analyzed a list of external effects and concluded that no clear and significant case of a positive externality of infrastructure usage was identified.

Given this basis, we have chosen to use the consumer's surplus concept to measure the social welfare benefits of an infrastructure investment. No external benefits (other than the ones captured by the demand model) are considered. The consumers' surplus gains associated with the addition of a new motorway to a road network is the sum of the consumers' surplus gains obtained for trips between each pair of traffic generation centers, *i* and *j*. The consumers' surplus gains (*CS*) are then given by the following expression:

$$CS(\boldsymbol{y}) = \sum_{i \in M} \sum_{j \in M} \left(\left[\int_{q_{2_{ij}}^{0}}^{q_{2_{ij}}} q_{2_{ij}}^{-1}(v)dv - c_{2_{ij}}(\boldsymbol{y}) \times \left(q_{2_{ij}}(\boldsymbol{y}) - q_{2_{ij}}^{0} \right) \right] + q_{2_{ij}}^{0} \times \left(c_{0_{ij}} - c_{2_{ij}}(\boldsymbol{y}) \right) \right) \quad (4.1)$$

where q_{2ij}^{-1} is the inverse demand function for an O/D pair *i/j*; q_{2ij}^{0} is the number of trips between centers *i* and *j* routed via a motorway segment when the travel costs equal the ones before the construction of the motorway, c_{0ij}; q_{2ij} is the number of trips between centers *i* and *j* routed via a motorway segment associated with the new travel costs (after the construction of the motorway), c_{2ij}.

The darker shaded area in Figure 4.1 represents the consumers' surplus gains for each O/D pair.

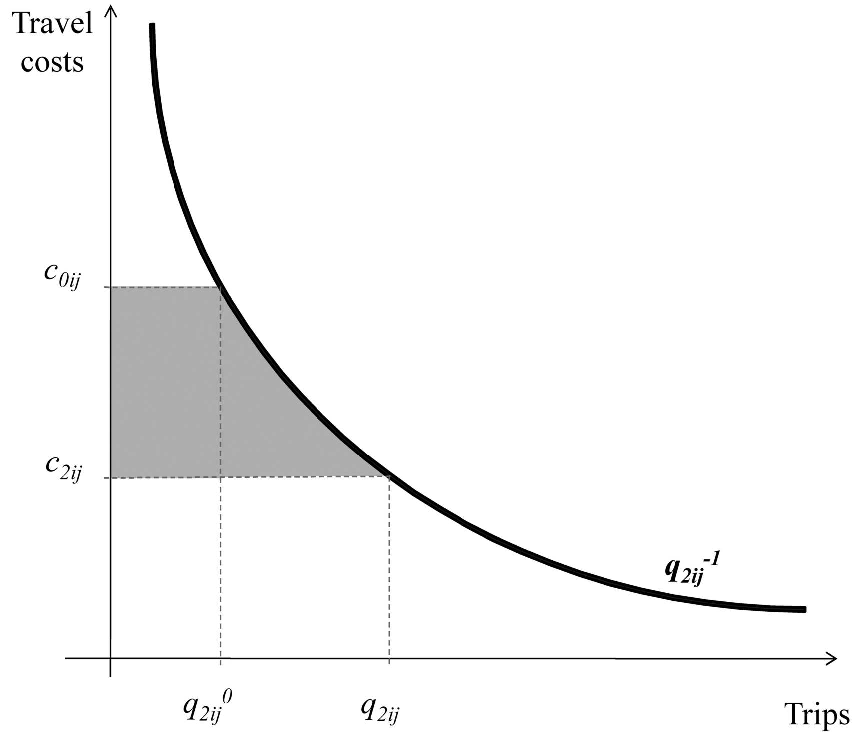

Figure 4.1 - Graphical interpretation of the consumers' surplus gains for one O/D pair *ij*

Finally, as concluded by JARA-DÍAZ and FARAH (1988), the welfare measure cannot be better than the underlying demand model. A similar warning is made in LAKSHMANAN et al. (2001). The author defends that demand functions should be estimated with accuracy in order to reflect the various indirect effects of infrastructure provision. Therefore, special attention should be given to the demand model used. The demand model should reflect the actual drivers' choices and be sensitive to pricing.

The optimization model presented later in this chapter is based on the travel behavior model introduced in REPOLHO et al. (2011a)/Chapter 3. In this model, drivers may opt between travelling through the existing road network only or traveling through a route that combines segments of the existing road network and a segment of the new motorway. The model further assumes that the introduction of cheaper routes (due to the new motorway) generates additional traffic and that the new motorway is only used if it is less costly. In fact, due to habit, a fraction of the drivers will continue to choose travelling through the existing road network even if it is more costly than the cheapest alternative route using a new motorway segment.

For a given pair of trip generation centers, *i* and *j*, the number of trips routed via a motorway segment, q_{2ij}, is given by expression (4.2.). The expression was formulated using a power-form impedance function, $f(c_{ij})=c_{ij}^{\beta}$, which as shown in FOTHERINGHAM and O'KELLY (1989) and DE VRIES et al. (2009) fits better real-world observations than exponential-form impedance functions.

$$q_{2_{ij}} = \frac{c_{0_{ij}}^{2\beta-\beta^2}}{(c_{0_{ij}}^{1-\beta} c_{2_{ij}}^{\beta} + c_{2ij})^{\beta} (c_{0_{ij}}^{\beta} + c_{2_{ij}}^{\beta})^{1-\beta}} q_{0_{ij}} \tag{4.2}$$

where c_{0ij} is the travel cost between centers *i* and *j* before the construction of the motorway; c_{2ij} is the travel cost of the best route between centers *i* and *j* that uses a segment of the new motorway; q_{0ij} is the total number of trips between centers *i* and *j* before the construction of the motorway; and β is a calibration parameter (further description on the model used to characterize travel behavior is available in REPOLHO et al., 2011a/Chapter 3).

4.3 Optimization model

The motorway interchange location model formulation presented below is principally based on the Deterministic Motorway Interchange Location Model (DMILM) presented in REPOLHO et al. (2011a)/Chapter 3. The new model optimizes a different objective function, but includes all the constraints used in the DMILM model plus a new set of constraints to account for the objectives of concessionaires. Still, all assumptions underlying the DMILM model remain valid. The model optimizes the location of the motorway interchanges such that consumers' surplus gains are maximized while guaranteeing a given level of profit for the concessionaire. By varying the level of profit parametrically, the model can be seen as the constraint form of a multi-objective optimization approach (COHON, 2004).

The proposed model applies to a region where a new motorway will be built over an existing road transportation network. The set of trip generation centers located in the region is $\boldsymbol{J}$, and the set of candidate interchange locations is $\boldsymbol{M}$. Drivers choose the least cost route according to the travel behavior model introduced in REPOLHO et al. (2011a)/Chapter 3. The notation regarding travel costs data and other parameters required to formulate the model is represented as follows:

c_{ij} — Travel cost between two centers, i and j, through the existing road network;

c_{im} — Travel cost between center i and interchange m through the existing road network;

c'_{mn} — Travel cost between two interchanges, m and n, through the new motorway;

$c_{ijmn} =$ $c_{im} + c'_{mn} + c_{nj}$	Travel cost between centers i and j through a route that includes two segments of the existing transportation network, im and nj, and a segment of the new motorway, mn;
d_{mn}	Distance between two interchanges, m and n, through the new motorway;
$R_{ijmn} =$ $\{v,b \vert c_{ijuv} > c_{ijmn}\}$	Set of potential routes ($i \rightarrow u \rightarrow v \rightarrow j$) between centers i and j that use a motorway segment uv and that cost more than the route using motorway segment mn ($i \rightarrow m \rightarrow n \rightarrow j$).
a_{ijmn}	Proportion of the original flow between centers i and j that will switch to using the new motorway if interchanges m and n are built and if the route $i \rightarrow m \rightarrow n \rightarrow j$ is less costly than the best alternative route through the existing road network;
$g^a{}_m$	Upper limit on the number of trips that may use interchange m (n) as a motorway access;
$g^e{}_n$	Upper limit on the number of trips that may use interchange n as a motorway exit;
t	Toll fee value per kilometer;
f	Fixed daily cost for installing and operating an interchange;
w	Fixed daily cost for building and maintaining the motorway;

The a_{ijmn} values are given by q_{2ij}/q_{0ij}. Thus, the product $a_{ijmn}q_{0ij}$ expresses the number of trips between centers i and j routed via the motorway segment mn. According to the notation used in this chapter c_{0ij} is equal to c_{ij} and c_{2ij} is equal to c_{ijmn}.

The main decisions that are optimized through the application of the model are the location of the motorway interchanges and the fraction of traffic between any two centers that is routed via a motorway segment. The former is represented by a binary variable, y_m, that takes the value of 1 if a motorway interchange is located at the candidate site m, and zero otherwise. The latter is represented by a set of variables x_{ijmn} that take the value of the fraction of traffic between centers i and j, routed via the motorway segment mn.

Given the entire notation described above the model can be formulated as follows:

$$\text{Max } \phi = 2\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} \int_{q_{2_{ij}}^{0}}^{q_{2_{ijmn}}} q_{2_{ij}}^{-1}(v)dv \; - \; c_{ijmn}\left(q_{2_{ijmn}} - q_{2_{ij}}^{0}\right) + \\ + q_{2_{ij}}^{0}\left(c_{ij} - c_{ijmn}\right) \tag{4.3}$$

s.t.

$$\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} x_{ijmn} \leq 1 \quad \forall i,j \in J : i<j \tag{4.4}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{n\in M:a_{ijmn}\neq 0} x_{ijmn} \leq g_m^a y_m \quad \forall m \in M \tag{4.5a}$$

$$\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M:a_{ijmn}\neq 0} x_{ijmn} \leq g_n^e y_n \quad \forall n \in M \tag{4.5b}$$

$$\sum_{u\in R_{ijmn}}\sum_{v\in R_{ijmn}} x_{ijuv} + y_m + y_n \leq 2 \quad \forall i,j\in J : i<j, \forall m,n \in M : a_{ijmn} \neq 0 \tag{4.6}$$

$$2\sum_{i\in J}\sum_{j\in J:i<j}\sum_{m\in M}\sum_{n\in M:\begin{cases}n\neq m\\ a_{ijmn}\neq 0\end{cases}} t\, d_{mn} a_{ijmn} q_{0_{ij}} x_{ijmn} - \sum_{m\in M} f y_m - w \geq \mu\pi \tag{4.7}$$

$$y_1 = 1 \tag{4.8a}$$

$$y_M = 1 \tag{4.8b}$$

$$x_{ijmn} \geq 0 \quad \forall i, j \in J, m, n \in M \tag{4.9}$$

$$y_m \in \{0,1\} \quad \forall m \in M \tag{4.10}$$

where q_{2ijmn} is the number of trips between centers i and j routed via a motorway segment mn (it corresponds to the parameter q_{2ij} used in expression 4.1); μ is the minimum percentage of profit that must be ensured (it is defined by the decision-maker and assumes a value within the interval [0,1]); and π is the highest profit value that can be achieved.

The objective function (4.3) maximizes the consumers' surplus gains, ϕ, made possible by the construction of the new motorway (it is multiplied by two to consider both traffic directions). Constraints (4.4), the assignment constraints, guarantee that trips between each *ij* pair are assigned to at most one route including a motorway segment *mn*. If this is the case, then x_{ijmn}=1 (though, since this is a multiple-allocation hub location model, if there are more than one motorway route with the same lowest travel cost, trips may be distributed among them). If trips are made only through the existing road network, then x_{ijmn}=0. Constraints (4.5) ensure that trips are only assigned to a motorway segment if two interchanges are located in both extremities. Constraints (4.6), together with the binary expressions (4.10), ensure that trips are assigned to the least-cost motorway route available. They prevent trips from being assigned to routes with longer motorway segments, thus leading to higher profit for the concessionaire, but which might be more disadvantageous for users than other available routes. The concern with concessionaire' profit is expressed through constraints (4.7). They ensure that the solution selected guarantees at least μ percent of the highest profit that the concessionaire could expect if the problem was optimized from his perspective alone, π. Profit is given as the difference between total toll fee revenues (multiplied by two to account both traffic directions) and fixed costs of the infrastructure. These costs are subdivided into costs for installing and operating the interchanges and for building and maintaining the motorway. If μ is set equal to one, than we are only maximizing profit (the model becomes equivalent to the DMILM presented in REPOLHO et al., 2011a/Chapter 3). Essentially, with μ equal to 1, the model will find the solution which optimizes consumers' surplus subject to achieving a maximum profit. If μ is set equal to zero in value, then we are focusing on the maximization of consumers' surplus gains (the model becomes equivalent – though with a different measure for social welfare benefits – to the models presented in REPOLHO et al., 2011a/Chapter 3). Constraints (4.8a) and (4.8b) ensure that there will be interchanges located at the endpoints of the motorway. Finally, expressions (4.9) and (4.10) define the domain of the decision variables.

Given that the model contains decision variables with four indexes, mid-size problems can easily become intractable to solve using available commercial software. This problem can be resolved by eliminating all unnecessary constraints and variables taking advantage of the symmetric characteristics of all traffic and travel costs, and by analyzing only motorway routes that are more cost efficient than the best existing route through the existing road network only (a_{ijmn}>0).

4.4 Model application

The optimization model proposed in the previous section was tested on the data set used in REPOLHO et al. (2011a)/Chapter 3. The data set involves a Portuguese motorway, the A25, which plays an important role in national and international road connections. The data set is comprised of 33 candidate interchange locations along the motorway and 55 trip generation centers located in the region crossed by the motorway.

The model application is presented in three parts. First, we briefly describe the REPOLHO et al. (2011a)/Chapter 3 data set that we have used as an input for our model. Next, and according to the parameters defined, we specify the final expression used to calculate consumers' surplus gains. Finally, we present and analyze the results obtained from the application of the optimization model to the data set. The implications of using the proposed model are evinced through the comparison of the results obtained in this study with the ones obtained in REPOLHO et al. (2011a)/Chapter 3 using the DMILM (where the objective is profit maximization). The model was solved using an Intel Core 2 Quad Processor Q9550 2.84 GHz computer with 4 GB of RAM and employing the FICO Xpress 7.0 optimizer (FICO Optimization, 2009). This was the same computing system as that used in REPOLHO et al. (2011a)/Chapter 3 for the profit maximization model.

4.4.1 Model data

The data used as input for the model may be grouped under two categories: data about costs and data about travel demand. There are two types of cost data involved in the model: travel costs and infrastructure costs. The former affects the routes chosen by drivers and the consumers' surplus gains, while the latter affects profit. The computation of costs was made as follows:

1. Travel costs involve time and expenses paid by road users. These costs were calculated using the model presented in SANTOS (2007), which comprises four components: vehicle operating costs, accident costs, time costs, and tolling costs. The vehicle operating costs were estimated at 16.811 Euros per 100 km per vehicle and include fuel consumption, tire usage, vehicle maintenance, and vehicle depreciation. The value was obtained considering the fuel cost scenario SCN3 characterized in REPOLHO et al. (2011a)/Chapter 3 and using the HDM-4 approach (WORLD BANK, 2010). The accident costs were assumed to be equal to 0.01 €/km/vehicle (the same value was used in SANTOS, 2007). The user time costs were estimated at 7.3306 Euros per hour. This value was obtained based on HDM-4 and the formulation adopted by the Portuguese Road Administration (GEPA, 1995), which takes into account the Portuguese national car fleet (information on this matter is available in IMTT, 2006a and 2006b). Finally, the tolling costs were considered according to the real toll fees currently being applied.

2. Infrastructure costs are comprised of the fixed costs for each interchange and for each motorway kilometer. Interchange cost was estimated at 2.00 million € each, while the cost of each kilometer of motorway was estimated at 2.85 million €. Considering a lifespan of 30 years and a real discount rate of 4 percent the daily fixed charges for installing and operating the interchanges and for building and

maintaining the motorway are, respectively, f=305 € and w=82,495 € (the motorway has 190 kilometers).

Travel demand routed via a motorway segment is given by expression 4.2., which uses travel costs data (detailed above) and the initial traffic flow, q_{0ij}, as input. The latter was computed using a power-form unconstrained gravity model (ORTÚZAR and WILLUMSEN, 2001). The impedance function, $f(c_{0ij})$, is given by the route travel cost and the mass of the origin and destination centers, m_i and m_j, is given by the population of the municipality, P_i and P_j. The calibration parameters, α and β, were set equal to 1.4 and 1, respectively. The initial traffic flow is then given by:

$$q_{0_{ij}} = \alpha \frac{m_i m_j}{f(c_{0_{ij}})} = 1.4 \frac{P_i P_j}{\left(c_{0_{ij}}\right)^1} \qquad (4.11)$$

4.4.2 Calculation of consumers' surplus gains

Given that the calibration parameter β is equal to one, the expression (4.2) for the number of trips between two centers i and j routed via a motorway segment can be simplified as follows:

$$q_{2_{ij}} = \frac{c_{0_{ij}}}{2c_{2ij}} q_{0_{ij}} \qquad (4.12)$$

The inverse demand function for an O/D pair i/j, q_{2ij}^{-1}, is then given by:

$$q_{2_{ij}}^{-1} \Rightarrow c_{2ij} = q_{0_{ij}} \frac{c_{0_{ij}}}{2} \frac{1}{q_{2_{ij}}} \qquad (4.13)$$

Finally combining equation (4.13) and the objective function (4.3), it is possible to specify the final expression used in this application to maximize the consumers' surplus gains as follows:

$$\text{Max } \phi = 2\sum_{i\in J} \sum_{j\in J:i<j} \sum_{m\in M} \sum_{n\in M:\begin{cases} n\neq m \\ a_{ijmn}\neq 0\end{cases}} q_{0_{ij}} \frac{c_{ij}}{2}\left[\ln(q_{2_{ijmn}}) - \ln(q^0_{2_{ij}})\right] - c_{ijmn}\left(q_{2_{ijmn}} - q^0_{2_{ij}}\right) + q^0_{2_{ij}}\left(c_{ij} - c_{ijmn}\right) \quad (4.14)$$

4.4.3 Model results

The model was applied to the A25 motorway considering nine toll fee value alternatives, *t*, ranging from 0.040 €/km to 0.060 €/km. The set includes the values that provide the best solutions for the concessionaire (higher profit). The calculation of the highest profit values that can be achieved for each toll fee alternative (π) was done using the DMILM model in REPOLHO et al. (2011a)/Chapter 3. The π values are presented in Table 4.1 (in the μ = 1 section). The CPU time needed to solve each model instance was always less than 20 seconds.

The optimal solution for each toll fee alternative was calculated for all values of μ between 0 and 1 with increments of 0.01. The objective here is to demonstrate the benefits of combining the two objectives, i.e., maximizing consumers' surplus gains and concessionaire's profit, into one model, and to evaluate whether it is possible to find an interesting solution taking both objectives into account. The results obtained for each toll fee alternative, with respect to consumers' surplus gains and profit, are displayed, respectively, in Figures 4.2 and 4.3. The charts are represented separately only for ease in presentation, but can and should be analyzed together in order to better understand the effect of imposing a minimum profit percentage in the value of consumers' surplus gains obtained.

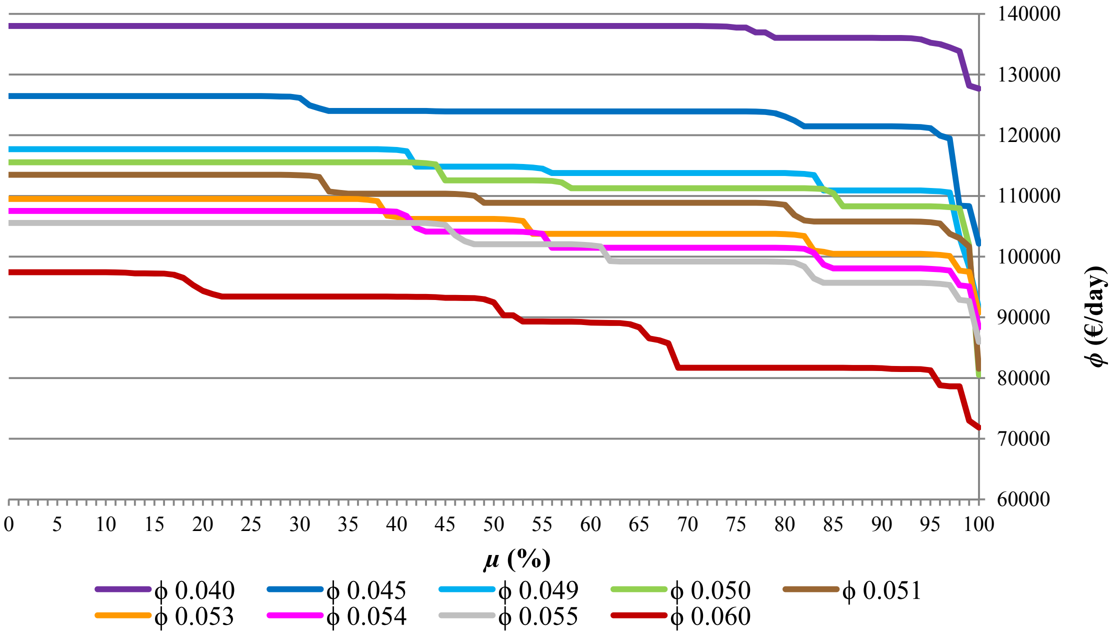

Figure 4.2 - Relationship between consumers' surplus gains and μ

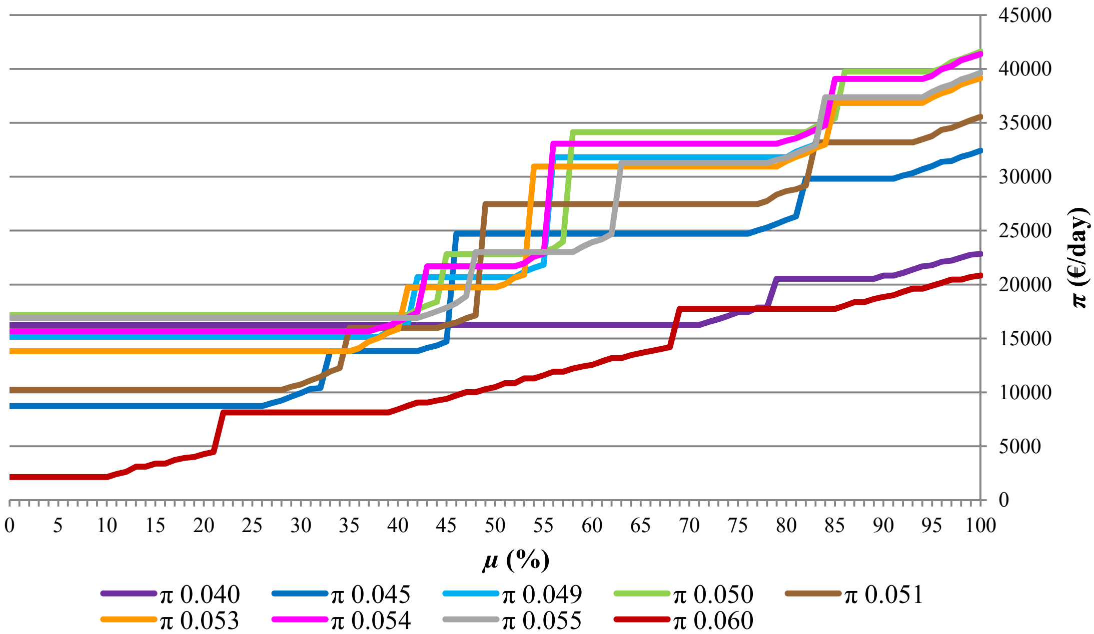

Figure 4.3 - Relationship between profit and μ

Each toll fee alternative represented in the charts defines a stratified layout which indicates that some solutions are optimal for a wide range of μ values. As expected, lower values of toll fees generate solutions with higher consumers' surplus gains. When no minimum percentage of profit is imposed (μ=0) the consumers' surplus gains obtained are: 137986, 126455, 117691, 115525, 113459, 109497, 107520, 105548 and 97413 Euros per day (see Table 4.1), respectively for each toll fee alternative (from the lowest to the highest).

If maximum profit is imposed (μ=1) we obtain the solutions given by the DMILM model in REPOLHO et al. (2011a)/Chapter 3. The solutions with higher profit are obtained for the intermediate values of toll fee alternatives tested (41611, 41382 and 39642 Euros per day, respectively for the toll fee alternatives 0.050, 0.054 and 0.049 Euros per kilometer). The reason why this occurs is clearly identified in REPOLHO et al. (2011a)/Chapter 3. The authors state that lower toll fee values attract more drivers but each paying less, while higher toll fee values attract fewer drivers but each paying more. Thus, the highest profits are obtained taking into account the trade-off between the amount of users and the total toll fees paid. The results obtained in this chapter strengthen this conclusion by showing that even when a second objective is considered and the percentage of minimum profit imposed is lower, the highest values are still obtained for the intermediate toll values. Figure 4.3 shows that when μ is set equal to a value higher than 0.5, the solutions with highest profits are mostly obtained for the toll fee alternatives 0.050 and 0.054 (the ones that provide the highest profits when μ=1).

The response to the objective outlined in the beginning of this section, i.e., finding an interesting solution where both consumers' surplus gains and concessionaire's profit are taken into account, is easier to identify if we analyze the trend in the percentage of maximum consumers' surplus gains and profit according to the minimum percentage of profit imposed (μ). Table 4.1 summarizes the percentage of maximum profit and consumers' surplus gains achieved respectively for the extreme conditions μ=0 and μ=1.

Table 4.1 - Percentage of maximum profit and consumers' surplus gains achieved for μ=0 and μ=1

t	$\mu = 0$		$\mu = 1$	
	Max. ϕ	% of π	% of Max. ϕ	π
0.040	137,986	71.1	92.5	22,844
0.045	126,455	26.9	80.8	32,414
0.049	117,691	38.2	77.7	39,642
0.050	115,525	41.3	69.7	41,611
0.051	113,459	28.8	71.8	35,552
0.053	109,497	35.3	82.9	39,143
0.054	107,520	37.8	82.2	41,382
0.055	105,548	42.6	81.4	39,632
0.060	97,413	10.2	73.7	20,844

When the concessionaire's perspective is discarded from the analysis (setting μ=0 is the same as eliminating constraints 4.7) the levels of profit the solutions guarantee are far from the maximum that could be obtained. The average percentage of maximum profit across all toll fee alternatives tested is only 36.9%. On the contrary, if the concessionaire's profit is maximized (μ=1) the average percentage of maximum consumers' surplus gains is 79.2 % (when t=0.040 Euros/km the percentage of maximum consumers' surplus gains ascends to 92.5%). The main objective then is to verify if there is any intermediate solution that provides a satisfactory level of consumers' surplus gains and profit. Figure 4.4 illustrates the tradeoff between the percentages of consumers' surplus gains and profit achieved for all integer percentages of μ between 0 and 100%.

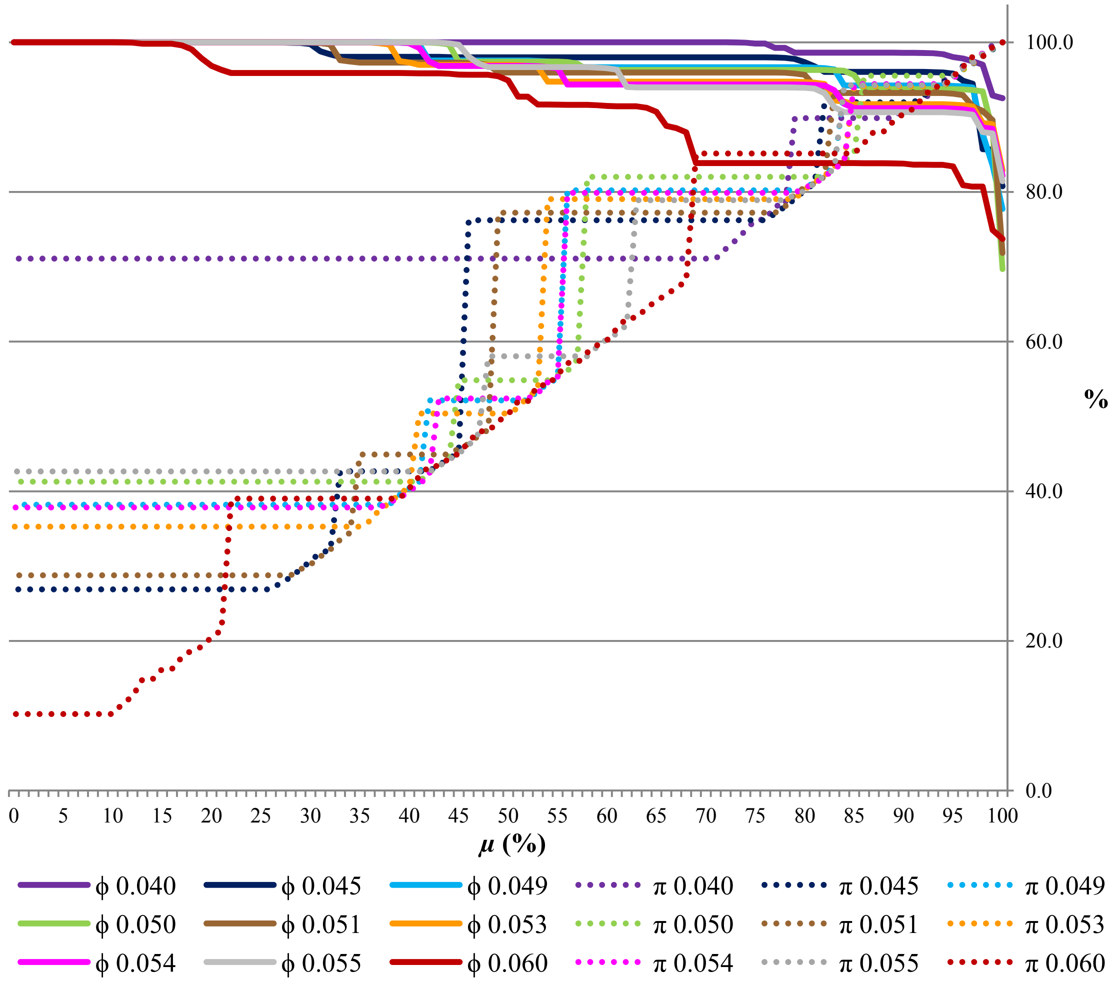

Figure 4.4 - Percentage of the maximum consumers' surplus gains and profit according to μ

The results show that there are solutions that guarantee very high levels of profit for the concessionaire while high values of consumers' surplus gains are achieved as well. There are solutions for almost all pairs of profit and consumers' surplus gain lines exhibited in the chart that ensure a percentage higher than 90% of the maximum that could be attained for each objective alone. For instance, when a minimum of 96% of the maximum profit is imposed (μ=0.96), the percentage of maximum consumers' surplus gains achieved is 97.8%, 94.9%, 94.1%, 93.7%, 92.9%, 91.6%, 91.0%, 90.5% and 80.9% respectively for the nine values of toll fees tested (from the lowest to the highest toll fee value). Additionally, Figure 4.4 also indicates that when imposing low values of μ the gains in consumers' surplus are quite small when measured against the considerably reduced levels of profit that would be obtained by the concessionaire. Thus, the approach used can indeed help to find solutions that provide highly satisfactory levels of consumers' surplus gains and concessionaire's profit simultaneously.

The consumers' surplus gains and concessionaire's profit obtained for each solution rely on the number and location of interchanges selected. Thus, it is also important to evaluate the impact of varying the value of μ in the geographic solution adopted in each case. In this sense we have analyzed the solutions obtained for the toll fee alternative 0.05 (this is the one for which most results are presented in REPOLHO et al., 2011a)/Chapter 3. The optimum interchange locations, the consumers' surplus gains, the concessionaire's profit, and respective percentages obtained for the μ values that change the solution are summarized in Table 4.2.

As we relax the minimum percentage of concessionaire's profit that must be ensured, in general, the number of interchanges located increases. When μ is set equal to zero in value, 28 interchanges are located. The remaining 5 candidate locations (2, 12, 18, 30, and 32) are never selected as they apparently do not contribute at all to increasing consumers' surplus gains. We say apparently because, as mentioned in REPOLHO et al. (2010)/Chapter 2, in reality travel demand is not all concentrated in the traffic generation centers, as it is indeed more scattered. Moreover, for the lower toll fee values (alternatives 0.040 and 0.045 Euros/km) an interchange is placed at candidate location number 12. This means that travel costs variations affect the route choices and consequently the contribution of each candidate interchange location in terms of network consumers' surplus.

Table 4.2 - Model results for *t*=0.05 Euros/km

μ (%)	ϕ (€/day)	π (€/day)	ϕ (%)	π (%)	Interchange locations
100	80,505	41,611	69.7	100.0	all except 2, 5, 8, 12, 16, 19, 20, 21, 23, 25, 27, 30, 32
99	101,851	41,240	88.2	99.1	all except 2, 5, 8, 12, 16, 18, 21, 23, 26, 29, 30, 32
98	107,966	40,918	93.5	98.3	all except 2, 12, 16, 18, 21, 23, 26, 29, 30, 32
97	108,154	40,630	93.6	97.6	all except 2, 12, 16, 18, 21, 23, 29, 30, 32
96	108,259	40,041	93.7	96.2	all except 2, 12, 16, 18, 23, 29, 30, 32
95	108,277	39,748	93.7	95.5	all except 2, 12, 16, 18, 29, 30, 32
85	110,445	35,423	95.6	85.1	all except 2, 8, 12, 16, 18, 21, 23, 26, 30, 32
84	111,134	35,005	96.2	84.1	all except 2, 12, 16, 18, 21, 23, 30, 32
83	111,196	34,633	96.3	83.2	all except 2, 12, 16, 18, 22, 23, 30, 32
82	111,257	34,123	96.3	82.0	all except 2, 12, 16, 18, 30, 32
57	112,231	23,989	97.1	57.7	all except 2, 12, 18, 21, 23, 26, 29, 30, 32
56	112,482	23,323	97.4	56.1	all except 2, 12, 18, 22, 23, 29, 30, 32
55	112,524	23,109	97.4	55.5	all except 2, 12, 18, 23, 29, 30, 32
54	112,543	22,815	97.4	54.8	all except 2, 12, 18, 29, 30, 32
44	115,203	18,392	99.7	44.2	all except 2, 12, 18, 21, 23, 26, 30, 32
43	115,402	18,065	99.9	43.4	all except 2, 12, 18, 21, 23, 30, 32
42	115,464	17,690	99.9	42.5	all except 2, 12, 18, 22, 23, 30, 32
41	115,525	17,179	100.0	41.3	all except 2, 12, 18, 30, 32
0	115,525	17,179	100.0	41.3	all except 2, 12, 18, 30, 32

The interchanges are located close to large trip generation centers or at the intersection of the new motorway with other major roads, but also in places less obvious and therefore harder to identify. Moreover, the model identifies the best options when there is more than one candidate interchange close to an attraction point (trip generation centers or major roads). Most candidate locations that figure in Table 4.2 (except the five mentioned before) have close alternatives, which helps to understand why its addition or removal from the optimal solution produces little impact on the consumers' surplus gains but may have a large effect on profit.

4.5 Conclusion

In this chapter we have presented an optimization model for locating motorway interchanges applicable to build-operate-transfer contract environment. The objectives of the two parties involved, public entity (government) and private investor (concessionaire), are taken into account. The first aims to maximize public benefit (social welfare), while the second aims to maximize profit. The two objectives considered in the model are then consumers' surplus gains (the measure for social welfare benefits) and profit. The model maximizes consumers' surplus gains such that a given level of profit is guaranteed.

The model developed extends and combines the studies done in REPOLHO et al. (2010, and 2011a)/Chapters 2 and 3, where a problem of the same kind was approached, respectively, from the users' perspective and the concessionaire's perspective.

With respect to REPOLHO et al (2010)/Chapter 2, we have used a new objective function to measure the public benefits (maximizing total travel cost savings was replaced by maximizing consumers' surplus gains) and employed the travel behavior model introduced in REPOLHO et al. (2011a)/Chapter 3. Also a major improvement in this work involves the fact that the number of interchanges to be located is no longer used as a proxy for the available budget. In the new model the costs of the project are actually calculated and the number of interchanges located is determined endogenously from the tradeoff between consumers' surplus gains and concessionaire´s profit.

The application of the model to the A25 case study demonstrated that the use of a model that considers simultaneously the interests of the two main stakeholders involved in the interchange location problem (public welfare and concessionaire) can help identify highly satisfactory solutions for both parties. Thus, it is the authors' belief that this model can be, as it is, very useful for both road administrations and motorway concessionaires.

Chapter 5

Optimal Location of Railway Stations: The Lisbon-Porto High Speed Railway Line

5.1 Introduction

Rail transportation was neglected for many years, but the situation has changed considerably in the last few decades particularly because of an increasing interest in high speed rail (HSR). The first areas that have engaged in HSR projects were Japan and Europe. In the latter area, projects were initially planned at national level, in France, Germany, and Italy, but since 1996 they are being carried out under the auspices of the European Union in the framework of the Trans-European Transport Network Program (EUROPEAN UNION, 1996; EUROPEAN COMMISSION, 2001; NASH, 2009). At present, major HSR projects are also being implemented or studied in various countries in Asia, North America, and South America. China has already the longest HSR network in the world. As of October 2010, there were 7,000 km of HSR lines in service, and 9,000 km more are expected to be built until 2020 (MORPRC, 2004; LFRC 2007; CHEN and ZHANG, 2010). In the United States, the Obama Administration recently announced a grant funding of $8 billion for projects involving 13 HSR corridors spread across 31 states, half of which will be built in California, Florida, and Illinois (US DOT, 2009; LANDERS, 2010). Brazil is expected to build a HSR line between São Paulo and Rio de Janeiro by the 2016 Olympic Games (ANTT, 2011).

The rebirth of rail transportation is mainly motivated by a recent trend that considers this transportation mode – and especially HSR – as a solution to relieving the congestion that affects roads and airports in many parts of the world (VUCHIC and CASELLO, 2002; DE RUS and NOMBELA, 2007). Rail transportation is also regarded as more environmentally friendly than road and air transportation with respect to energy consumption and greenhouse gas emissions. With respect to safety, rail transportation exhibits very low accident rates. In particular, HSR is considered – together with air transportation – to be one of the safest modes in terms of passenger fatalities per billion passenger-kilometers (CAMPOS and DE RUS, 2009). With regard to the European Union, another reason in favor of the development of HSR was the need to reduce the average travel time between capital cities, which increased significantly after the integration of former Soviet Bloc countries.

The development of a railway network is, however, a highly complex and expensive process. The success of any investment is heavily dependent on rail ridership (DE RUS and NOMBELA, 2007; CAMPOS and DE RUS, 2009), and especially on the demand captured from other transportation modes. The attractiveness for users may be measured by the travel cost savings users can make (time savings play an important role in the case of HSR), as well as by the amount of generated traffic. Those savings are dependent on the number and location of railway stations. If more railway stations are located along a line, the access time to rail transportation decreases, and more demand is attracted. However, as the number of stations increases, the number of potential intermediate stops increase for longer trips. Travel times for long distance routes may be longer (when many stations exist) due to times taken at stops at intermediate stations and the additional acceleration and deceleration phases required in making stops, which dampens demand. Thus, each additional station increases local demand but may tend to diminish global (long distance) demand.

In this chapter, we present a mixed-integer optimization model that determines the optimal number and location of stations along a railway line that will be introduced over an existing transportation network. These are important decisions to be made within the strategic planning stage of rail investment (GHOSEIRI et al., 2004). The stations are chosen within a set of possible locations defined a priori according to the objective of maximizing travel cost savings. The model takes into account the sensitivity of rail ridership due to time losses at stops at intermediate stations, as well as static competition from other modes (no response to the action of the railway line is considered). We assume that the rail corridor is already defined between the endpoints (or that the number of possible corridors is small, in such a way that the corridors can be studied separately and then compared).

The structure of the chapter is as follows. We start by presenting an overview of past optimization work on railway station location problems. Then, we formulate the model we have developed to represent such problems and apply it to a case study involving a

HSR line expected to be built in Portugal in the near future: the Lisbon-Porto line. After describing the case study data, the results obtained through the application of the model are analyzed in detail and compared with the solutions adopted in existing studies for the same line. Finally, we offer a number of concluding remarks about the model and the case study results, and point out some directions for future research.

5.2 Literature Overview

The choice of rail corridors (or alignments) and the location of railway stations are two intertwined issues arising in the strategic planning stage of rail investment. These issues have been a subject of interest in the scientific literature especially within the context of rapid transit systems (for survey articles the reader is referred to LAPORTE et al., 2000, and LAPORTE et al., 2011). Though rapid transit and rail networks have similarities, the former are set in an urban environment and usually involve a dense network with several interconnected lines, while the latter are cast at a cross-country scale and usually entail a sparse network or, particularly in the case of HSR, a single line. In this literature overview, we focus only on the location of railway stations, assuming – as is typically the case with HSR – that the rail corridor is known.

The first paper where the location of railway stations was dealt with from an optimization perspective was published almost 100 years ago by MÜLLER (1917). The results of this and other early papers on the subject were summarized and extended in a prominent paper by VUCHIC and NEWELL (1968). These authors developed a model where all the main ingredients of a railway station location problem were considered – access speed to stations, dynamic characteristics of trains (acceleration state, constant speed state, and deceleration state), standing time of trains in stations, and intermodal transfer time at stations – but within the specific context of a suburban line serving an area from which population commuted to a central point. The objective was to determine the interstation spacing that would minimize the travel time of the total population. For that specific context and assuming demand to be given by a continuous function of the distance to the central point, interstation spacing was calculated by solving the set of simultaneous difference equations specifying the optimality conditions. VUCHIC (1969) proposed a similar model, but with a different objective and introducing (static) competition. The model considered a private continuous transportation system (e.g., a freeway) that ran parallel to a public railway line classified as a discrete transportation system – the line could be boarded only at the stations as opposed to the freeway that could be accessed at any point along the line. The objective of the model was to maximize the number of passengers using the railway line assuming that the choice between the alternative transportation modes was done on the basis of shorter travel time. The solution method was similar to the one used in VUCHIC and NEWELL (1968).

After the 1960s, the subject did not catch much attention until LAPORTE et al. (1998) developed a model for locating a fixed number of stations along a railway line so that the demand covered by the stations would be maximized (an improved version of this work can be found in LAPORTE et al., 2002). The measure used to estimate the new line's ridership was, therefore, the coverage provided by stations. The impact on ridership of time losses due to intermediate stops for users in transit was not taken into account. The usefulness of the model was illustrated with an application to a rapid transit line in Seville, Spain. This work was extended in LAPORTE et al. (2005) to encompass alignment design issues in addition to station location issues.

Another significant contribution to research on the railway station location problem was given by HAMACHER et al. (2001). These authors introduced two models for the continuous stop location problem, one with the objective of maximizing accessibility to stations and the other with the objective of maximizing total travel time savings, where the positive and negative effects of placing additional railway stations in an existing railway line were studied. Time losses were taken into account in the computation of savings but their implications on ridership were ignored. The two models were tested with a "preliminary set of input data describing a situation in Germany" (the information provided does not reveal an exact location). Along the same lines, SCHÖBEL et al. (2002) formulated a discrete set covering model for the problem of minimizing the number (cost) of additional stations while ensuring coverage of all demand centers (an improved version of this work is available at SCHÖBEL et al., 2009), and KRANAKIS et al. (2002) presented a maximal covering model for a fixed number of stations. Though the latter authors discussed the need to include the additional costs imposed by stops at intermediate stations, they did not consider them in their model. Finally, SCHÖBEL (2005) extended the model presented in SCHÖBEL et al. (2002) to a bi-objective model where the maximization of demand coverage was considered in parallel with the minimization of the number of stops.

Table 5.1 - Characteristics of station/stop location models

Paper	Fixed number of stations	Objective function	Demand	Transportation environment	Competition from other modes	Travel cost (time) sensitive to new stations in transit
VUCHIC and NEWELL (1968)	No	Minimize overall transportation time	Demand distributed along the railway line	Rapid transit line	No	Yes
VUCHIC (1969)	No	Maximize ridership	Demand distributed along the railway line	Rapid transit line	Yes	Yes
LAPORTE et al. (2002)	Yes	Maximize demand coverage	Coverage provided by stations	Rapid transit system	No	No
LAPORTE et al. (2005)	Yes	Maximize ridership	O/D demand	Rapid transit system	Yes	No
HAMACHER et al. (2001)	No	1. Maximize accessibility 2. Maximize travel time savings	Coverage provided by stations	Railway network	No	Yes
SCHÖBEL et al. (2002)	No	Minimize costs while ensuring total coverage	Coverage provided by stations	Urban transit network	No	No
KRANAKIS et al. (2002)	Yes	Maximize demand coverage	Coverage provided by stations	Railway network	No	No
SCHÖBEL (2005)	No	Minimize number of stops and maximize demand coverage	Coverage provided by stations	Urban transit network	No	No

In summary, a number of optimization models for the location of railway stations are currently available (their attributes are compared in Table 5.1). Most of them rely on demand coverage as a measure of rail ridership – but, as noticed by MARÍN and JARAMILLO (2009), it is doubtful that having “a good transit network” is enough to promote its use. A few models focus on travel time/cost savings, thus making it possible to account for the behavior of users in a more accurate manner, but none of them capture all relevant features involved in a railway station location problem – in particular, the implications of the number of intermediate stops encountered on a trip upon travel demand is neglected. Overall, the original models of VUCHIC and NEWELL (1968) and VUCHIC (1969) are still quite relevant as they addressed more facets of the problem under study, but they were developed for a very specific condition associated with one major destination, the central business district.

5.3 Optimization Model

The optimization model we present in this chapter can be seen as a generalization of the VUCHIC and NEWELL (1968) and VUCHIC (1969) models. Indeed, we consider all the features of the railway station location problems identified in their work, but make the model applicable to any new railway line assuming that travel demand is concentrated at a number of trip generation centers (cities). The objective is to determine along a fixed route alignment where stations should be located in order to maximize the travel cost savings made possible by the introduction of the new railway line. The set of potential locations for the railway stations is assumed to be defined in advance. The rail service offered by the new line competes with the existing modes using the existing transportation network. Travel demand is estimated by origin-destination matrices that take into account travel costs, which, as argued in LAPORTE et al. (2000) and LAPORTE et al. (2005), is more appropriate and realistic than using the demand covered by stations. The same option is made in the combined alignment design and station location models of BRUNO et al. (1998) and LAPORTE et al. (2005). Travel costs take into account the time lost by passengers in possible intermediate stops.

The setting for the application of the model is a region whose transportation network will be augmented with a railway line. The set of trip generation centers located in the region is $\boldsymbol{J}$ and the set of possible locations for the railway stations is $\boldsymbol{M} = \{1, \ldots, M\}$. The set of possible intermediate stations between stations m and n is $\boldsymbol{R}_{mn}$, and r_{mn} is the maximum number of such stations. The distance between two possible stations, m and n, through the railway line is d_{mn}.

One of the main types of data involved in the model is the travel cost savings made possible by the use of a segment of the new railway line. Representing by c_{ij} the (least) travel cost between centers i and j through the existing transportation network only and by c^k_{imnj} the travel cost between centers i and j through a route that includes two segments of the existing transportation network, im and jn, and a segment of the new railway line, mn, and that includes k stops in transit, these savings are given by $s^k_{imnj} = c_{ij}\text{-}c^k_{imnj}$. The value of c^k_{imnj} can be computed as follows:

$$c^k_{imnj} = c_{im} + c_{mn} + c_{nj} + 2vt^e + kvt^s \qquad (4.1)$$

where c_{im} is the travel cost between center i and station m, c_{mn} is the travel cost between stations m and n through the new railway line when the train rides at maximum speed (this cost consists of ticket price and value of time, including the time lost in the acceleration phase near the origin station, m, and in the deceleration phase near the destination station, n), c_{nj} is the travel cost between station n and center j, v is the value of time, t^e is the time loss in the intermodal exchange (the multiplication by two in the term accounts for the time lost at both the access and the exit station), and t^s is the time loss associated with each intermediate stop (this includes the disembarking and boarding time, and the deceleration and acceleration time). The dynamic characteristics of train travels are therefore fully described in expression (4.1). The effect of dynamic speed of travels (acceleration, cruise speed and deceleration phases) in location modeling problems is given in DREZNER et al. (2009). Figure 5.1 illustrates the travel costs applicable to each route alternative.

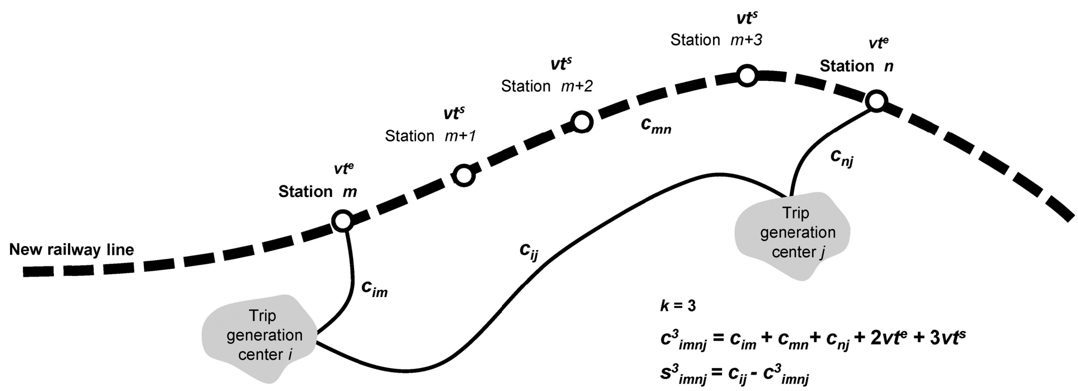

Figure 5.1 – Travel costs applicable to each route alternative

The other main type of data involved in the model is the number of trips that become less costly if a segment of the new railway line is used. This number, which is represented by q^k_{imnj} for a route $i \to m \to n \to j$ with k stops in transit, can be estimated as a function of travel costs (c^k_{imnj}) using, e.g., an unconstrained gravity model (ORTÚZAR and WILLUMSEN, 2001). If the travel costs for these trips are lower than the travel costs for trips made through the existing transportation network only ($c^k_{imnj} < c_{ij}$), the value of q^k_{imnj} will capture the additional trips generated by the decrease in travel cost. Otherwise, the value of q^k_{imnj} can be set at be zero since such trips do not lead to travel cost savings.

The key decisions to be made through the application of the model are the locations of stations. These decisions can be represented with a set of binary variables y_m, which take the value of one when candidate location m is selected for placing a railway station, and take the value of zero otherwise.

The locations of stations influence (and are influenced by) the routes that travelers need to choose to minimize their travel costs. These choices can be represented with another set of binary variables, x^k_{imnj}, which take the value of one for trips made through route $i \to m \to n \to j$ with k stops in transit, and take the value of zero otherwise. These variables have five indexes, thus their number can easily become quite large when dealing with real-world problems. In order to mitigate this, they are only defined in the following circumstances:

- $i < j$ (we assume that both the O/D trip and the travel cost matrices are symmetric, and only consider their upper triangles).
- $d_{mn} \geq d_{min}$ (we assume that travelers will only use the railway line if they are going to ride the train for a minimum distance of d_{min}).

- $q^k_{imnj} > 0$ (the number of trips that use route $i \to m \to n \to j$ with k stops in transit is positive).
- $s^k_{imnj} > 0$ (the travel costs for route $i \to m \to n \to j$ with k stops in transit are smaller than the travel costs between centers i and j using the existing transportation network only).

Additionally, $g^a{}_m$ ($g^e{}_n$) is an upper limit on the number of routes that use station m (n) as an access to (exit from) the railway line, and l_{min} is the minimal distance by which two consecutive stations must be separated.

In these conditions, the locations of railway stations that maximize the travel cost savings made possible by the introduction of the new railway line can be determined through the following mixed-integer optimization model:

$$\text{Maximize} \quad 2\sum_{i \in \boldsymbol{J}} \sum_{m \in \boldsymbol{M}} \sum_{n \in \boldsymbol{M}} \sum_{j \in \boldsymbol{J}} \sum_{k=0}^{r_{mn}} s^k_{imnj} q^k_{imnj} x^k_{imnj} \tag{4.2}$$

s.t.

$$\sum_{m \in \boldsymbol{M}} \sum_{n \in \boldsymbol{M}} \sum_{k=0}^{r_{mn}} x^k_{imnj} \le 1 \quad \forall\ i, j\ \in \boldsymbol{J} \tag{4.3}$$

$$\sum_{i \in \boldsymbol{J}} \sum_{n \in \boldsymbol{M}} \sum_{j \in \boldsymbol{J}} \sum_{k=0}^{r_{mn}} x^k_{imnj} \le g^a_m y_m \qquad \forall m \in \boldsymbol{M}: g^a_m > 0 \tag{4.4a}$$

$$\sum_{i \in \boldsymbol{J}} \sum_{m \in \boldsymbol{M}} \sum_{j \in \boldsymbol{J}} \sum_{k=0}^{r_{mn}} x^k_{imnj} \le g^e_n y_n \qquad \forall n \in \boldsymbol{M}: g^e_n > 0 \tag{4.4b}$$

$$y_m + y_{m+1} \le 1 \quad \forall\ m \in \boldsymbol{M}: d_{m,m+1} \le l_{min} \tag{4.5}$$

$$\sum_{k=0}^{r_{mn}} \left(r_{mn} - k \right) x_{imnj}^{k} \le r_{mn} - \sum_{u \in \boldsymbol{R}_{mn}} y_u \quad \forall\ i, j \in \boldsymbol{J}, m, n \in \boldsymbol{M} \colon x_{imnj}^{0} \text{ exists} \tag{4.6}$$

$$y_1 = 1 \tag{4.7a}$$

$$y_M = 1 \tag{4.7b}$$

$$x_{imnj}^{k} \in \left\{ 0,1 \right\} \quad \forall\ i, j \in \boldsymbol{J}, m, n \in \boldsymbol{M}, k = 0,1,\ldots,r_{mn} \tag{4.8}$$

$$y_m \in \left\{ 0,1 \right\} \quad \forall m \in M \tag{4.9}$$

The objective function (4.2) of this model maximizes the travel cost savings made possible by the introduction of the railway line (we multiply by two to consider both traffic directions). Constraints (4.3), the assignment constraints, ensure that trips for each O/D pair will be assigned to at most one route including a segment (*mn*) of the new railway line. If there is a route between centers *i* and *j* that includes a railway segment (*mn*) with exactly *k* intermediate stations, then x^k_{imnj}=1. When trips between centers *i* and *j* are made through the existing transportation network only, then x^k_{imnj}=0 for all *m*, *n* and *k*. Constraints (4.4) prevent trips in being assigned to a route including a segment (*mn*) of the new railway line unless railway stations are placed at locations *m* and *n*. Constraints (4.5) guarantee that two neighboring stations will be separated by a given minimum distance (l_{min}). Constraints (4.6) determine how many stops (*k*) will exist between any two stations (note that we are assuming that trains will stop in every station, as usual in the strategic planning stage of rail investment). These constraints are only formulated when x^0_{imnj} exists, i.e., when there is at least one route including a segment of the new railway line with no intermediate stations in transit (*k*=0) that is more cost efficient than the routes using the existing transportation network only. Constraints (4.7a) and (4.7b) ensure that there will be stations located at the endpoints of the railway line. Finally, expressions (4.8) and (4.9) define the domain of the decision variables.

The model therefore addresses several issues that were not dealt with, or were dealt with separately, in previous models, such as the impact on travel demand of time losses at intermediate stops, the existence of competing transportation modes, and the generation of traffic due to the decrease in travel costs.

5.4 Case study

The transportation infrastructure of Portugal has improved remarkably since 1986, the year when the country joined the European Community (later European Union). Initially, most investment was directed to the development of a modern road network. More recently, HSR has entered the national agenda, which is in line with the importance accorded by the European Union to the integration of the Iberian Peninsula in the Trans-European Transport Network (MATEUS et al., 2007).

The general layout for the HSR network of Portugal was established by the government in 2003, after agreeing on the international links with the government of Spain (MOPTH/MF, 2003). It consists of six corridors, two of which are within the Portuguese territory (Lisbon-Porto and Évora-Faro) and the four others involve the two countries (Porto-Vigo, Aveiro-Salamanca, Lisbon-Madrid, and Faro-Huelva). Figure 5.2 depicts the general layout of the network.

Figure 5.2 - Layout of the HSR network of Portugal

In order to illustrate the application of the model presented in the previous section, we developed a case study focusing on the Lisbon-Porto HSR line, an important component of the "high-speed rail axis of south-west Europe" – included as priority axis number 3 within the 30 priority axis and projects defined in EUROPEAN COMMISSION (2005). It crosses the most populated and economically developed areas of Portugal, and therefore the areas that might attract more people for the high standard service that HSR provides. These areas are served by a very good road network, which means that HSR will face significant competition from the automobile. Also, there are at present conventional rail services and frequent flights between Lisbon and Porto (the scheduled time is 55 min), but it is doubtful they will survive the introduction of HSR.

The final corridor for the Lisbon-Porto HSR line has been modified several times since the initial draft and remains to be fully defined. The study done by ATKEARNEY (2003) for RAVE – Rede Ferroviária de Alta Velocidade S.A. – the company responsible for the implementation of HSR in Portugal, and the work of ANCIÃES (2005) describe existing conflicts over the corridor for the southern part of the line. The basic alternatives are between the east and the west side of Serra dos Candeeiros. Furthermore, the decision to build the line through Leiria or to the east of Leiria has yet to be made. In regard to the area of Aveiro, two alternatives for the location of the station are considered in a study done by SDG (2007) for RAVE: the city center of Aveiro and the town of Albergaria-a-Velha (15 kilometers east of Aveiro). Doubts are also mentioned in a more recent study done by SDG (2009) concerning the possible adoption of a solution combining the new HSR line with the existing conventional line between Coimbra and Porto. Another important source of uncertainty is the location of the new Lisbon airport (to be built in the next few years). The airport was originally planned to be located in the Ota area, north of Lisbon, and to be served by the Lisbon-Porto HSR line. Recently, the government has opted to move the new airport to the Alcochete area, east of Lisbon, which is located on the other side of the Tagus River and clearly outside of any likely Lisbon-Porto HSR corridor. But, it is not certain that this decision is final. The last document released by RAVE refers to a corridor between Lisbon and Porto with a length of 292 km and intermediate stations located in Oeste (somewhere between Lisbon and Leiria), Leiria, Coimbra, and Aveiro or Albergaria-a-Velha (RAVE, 2011).

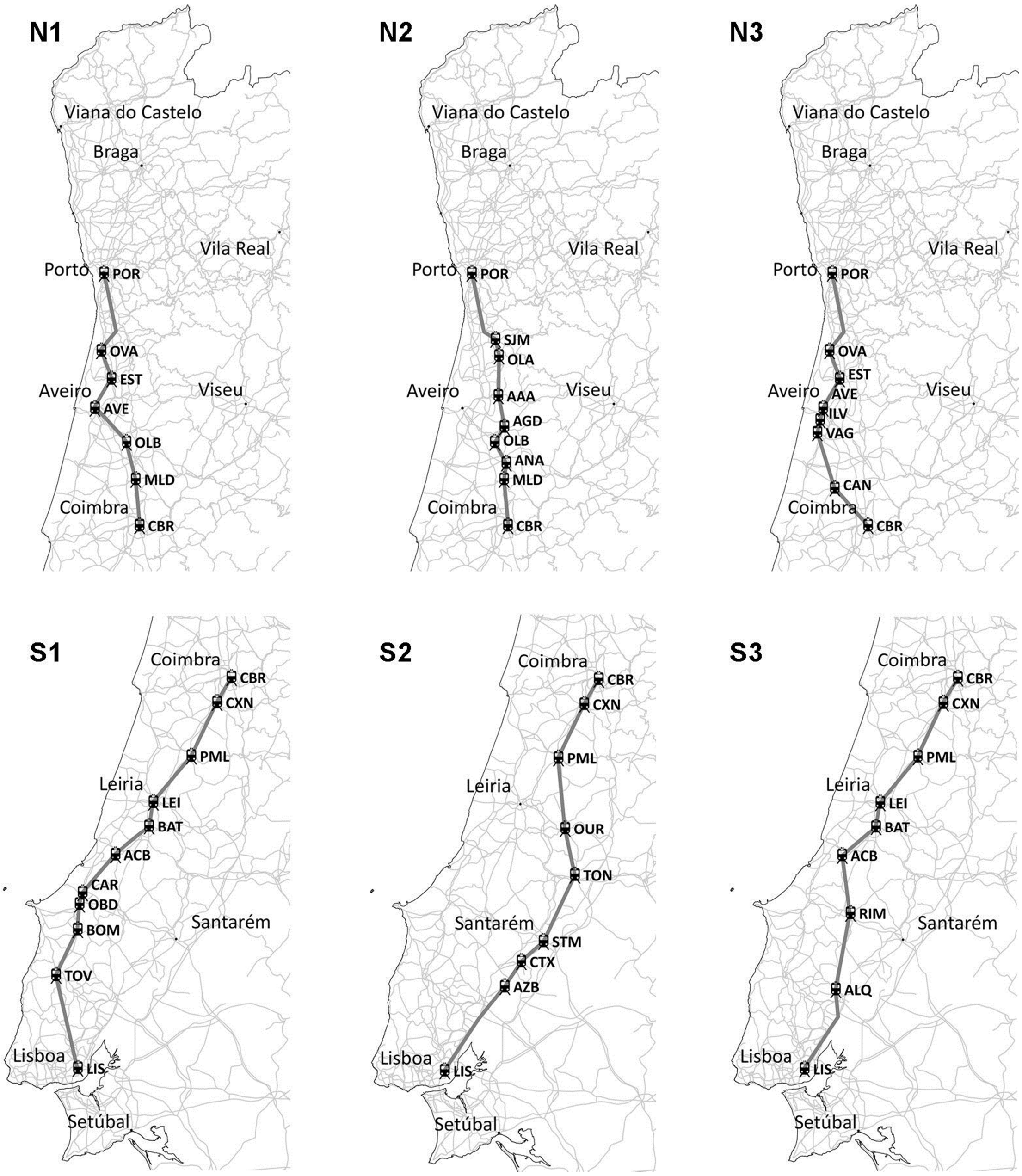

Figure 5.3 - Possible north and south corridors and stations

In the face of all these uncertainties, we have considered in our study three possible corridors north of Coimbra (N1, N2 and N3), and another three possible corridors south of Coimbra (S1, S2 and S3). The north and south corridors are represented in Figure 5.3. Along these corridors there are 32 municipalities, each one being a possible location for a station. The names of these municipalities (and respective abbreviations) are specified in Table 5.2. The combination of the possible north and south corridors leads to nine possible Lisbon-Porto corridor alignments. Table 5.3 shows how these corridors are formed, as well as the length and the number of possible stations for each corridor. The length of the corridor alternatives ranges between 293 km (COR 8) and 302 km (COR 1 and COR 3). The number of possible stations varies between 15 (COR 4 and COR 7) and 19 (COR 2).

Table 5.2 - Locations of possible stations

Locations	Abb.	Locations	Abb.	Locations	Abb.
Águeda	AGD	Cartaxo	CTX	Ourém	OUR
Albergaria-a-Velha	AAA	Coimbra	CBR	Ovar	OVA
Alcobaça	ACB	Condeixa-a-Nova	CXN	Pombal	PML
Alenquer	ALQ	Estarreja	EST	Porto	POR
Anadia	ANA	Ílhavo	ILV	Rio Maior	RIM
Aveiro	AVE	Leiria	LEI	Santarém	STM
Azambuja	AZB	Lisboa	LIS	São João da Madeira	SJM
Batalha	BAT	Mealhada	MLD	Torres Novas	TON
Bombarral	BOM	Óbidos	OBD	Torres Vedras	TOV
Caldas da Rainha	CAR	Oliveira de Azeméis	OLA	Vagos	VAG
Cantanhede	CAN	Oliveira do Bairro	OLB		

Table 5.3 - Layout, length, and number of possible stations along possible corridors

Corridor	COR1	COR2	COR3	COR4	COR5	COR6	COR7	COR8	COR9
South	S1	S1	S1	S2	S2	S2	S3	S3	S3
North	N1	N2	N3	N1	N2	N3	N1	N2	N3
Length (Km)	302	297	302	298	293	299	298	293	298
Number of possible stations	17	19	18	15	17	16	15	17	16

The case study is carried out with the purpose of comparing the various possible corridors for the Lisbon-Porto HSR line, when optimizing travel cost savings. This comparison is made with respect to three performance measures: travel cost savings, rail ridership, and ticket revenues.

5.5 Model data

The application of the model involves two basic data sets: data about the travel cost savings that can be made by using a segment of the new railway line; and data about the travel demand between the municipalities of the region served by the HSR line.

The computation of travel cost savings was made as follows:

- Road user costs were calculated considering three components: vehicle operating costs, time costs, and tolling costs.
- Vehicle operating costs were estimated at 16.478 Euros per 100 km per vehicle. This value was obtained using the HDM-4 approach (WORLD BANK, 2010), and includes fuel consumption, tire usage, vehicle maintenance, and vehicle depreciation.
- Time costs were computed considering the value of time (VOT) to be 12 Euros per hour.
- Tolling costs were calculated considering the toll fees currently being applied.
- Travel speed in the railway line was considered to be 250 kph (except in the acceleration and deceleration phases).

- Tickets for HSR trips were assumed to cost 0.16 Euros per kilometer, which means a price between 46.88 and 48.32 Euros for a trip between Lisbon and Porto, depending on the length of the corridor. The value used in SDG (2009) for the same trip was 49 Euros.
- Time loss in an intermodal exchange (t^e) was estimated to be 12 min.
- Time loss associated with each intermediate stop (t^s) was estimated to be 9 min, corresponding to 3 min for the acceleration and deceleration phases and 6 min for the boarding and disembarking phases. This time loss is consistent with the difference of 18 min between a non-stop and a two-stop Lisbon-Porto trip mentioned in SDG (2009).

The computation of travel demand was made using a power-form unconstrained gravity model (the power form works generally better than the exponential form for interurban trips, see e.g. FOTHERINGHAM and O'KELLY, 1989). According to this model, the travel demand after the introduction of HSR is given by:

$$q_{imnj}^{k} = \alpha \frac{w_{im} w_{nj}}{\left(c_{imnj}^{k}\right)^{\beta}} \tag{4.10}$$

where w_{im} (w_{nj}) is a mass parameter reflecting the importance of municipality i(j) as a trip generation center when the trips with origin (destination) in that municipality are made through a station located at m(n), and α and β are calibration parameters.

The mass of a municipality, i, for trips originated in the municipality that are made through station m, were assumed to be given by the population (p_i) of the municipality multiplied by a linear decay factor reflecting the distance of the municipality to the station and the impact distance limit (or cutoff) of a station, d_{max}; that is:

$$w_{im} = p_i \left(1 - \frac{d_{im}}{d_{max}}\right), i \in \boldsymbol{J}, m \in \boldsymbol{M} : d_{im} \le d_{max} \qquad (4.11a)$$

Similarly, the mass of a municipality, j, for trips destined to the municipality that are made through station n, is given by:

$$w_{nj} = p_j \left(1 - \frac{d_{nj}}{d_{max}}\right), j \in \boldsymbol{J}, n \in \boldsymbol{M} : d_{nj} \le d_{max} \qquad (4.11b)$$

The impact distance limit of a station (d_{max}) was considered to be 50 km, that is, the same value as used in SDG (2007).

Finally, we have assumed a minimum train trip distance, d_{min}, of 50 km and a minimum station interspacing, l_{min}, of 30 km (to prevent the HSR service of being degraded to regular service, as accelerating to the maximum speed of 250 kph in a high speed train and then decelerating to stop takes a distance of approximately 20 km).

5.6 Model results

The optimization model was applied to the nine corridors and solved on an Intel Core 2 Quad Processor Q9550 2.84 GHz computer with 4 GB of RAM using the FICO Xpress 7.0 optimizer (FICO, 2009). The results obtained for the nine corridors with respect to travel cost savings per day, rail ridership per day, ticket revenues per day, locations of intermediate stations, and CPU time required to obtain the solution are displayed in Table 5.4.

Table 5.4 - Model results for the case study

COR	Travel cost savings (€/day)	Rail ridership (pax/day)	Ticket revenues (€/day)	Locations of intermediate stations	CPU time (sec)
1	291,063	24,974	845,827	LEI-CBR-OVA	762
2	316,069	25,860	855,938	LEI-CBR-OLA	3,855
3	287,043	24,900	845,688	LEI-CBR-OVA	809
4	301,673	22,946	793,832	TON-CBR-OVA	1,334
5	325,455	23,794	804,016	TON-CBR-OLA	1,472
6	297,849	22,874	793,414	TON-CBR-OVA	1,077
7	310,797	25,432	847,883	LEI-CBR-OVA	8,054
8	336,126	26,334	858,195	LEI-CBR-OLA	2,128
9	306,750	25,352	847,486	LEI-CBR-OVA	807

The best optimal solution obtained with the model is COR8 (Figure 5.4). It yields the highest travel cost savings, the highest rail ridership, and the highest ticket revenues. This solution comprises three intermediate stations, located in Leiria, Coimbra, and Oliveira de Azeméis. With respect to the RAVE corridor (the one they currently refer in their website) there are two basic differences: the Oeste station is removed; and the station in Aveiro is moved to Oliveira de Azeméis. The ridership for COR8 is estimated at 26,334 passengers per day, which is about 6.8 percent more than the 24,658 passengers per day considered in SDG (2009). It is worth noting here that the ridership for COR1, which is quite similar to the RAVE corridor, is 24,974 passengers per day. This indicates that our study and the study underlying the RAVE corridor are quite consistent with respect to demand estimation.

The optimal solutions for the other corridor alignments also involve three intermediate stations. There is always a station in Coimbra and there is never a station in Oeste. The decision of locating (or not) a station in Leiria was classified in the initial studies made by RAVE as mostly political (see ANCIÃES, 2005). However, Leiria is always chosen in our study except for corridors that do not include this municipality (COR4, COR5, and COR6). In contrast, Aveiro, that was set to receive a station in all studies commissioned by RAVE (including SDG, 2007, 2009), is never included in the optimal solutions identified in our study, being replaced either by Oliveira de Azeméis or Ovar. This is probably due to the fact that the areas surrounding Oliveira de Azeméis and Ovar are much more populated than Aveiro (they cover more population than Aveiro), and therefore more people are attracted to the HSR service.

Figure 5.4 - Optimal station locations for corridor COR8

The three best optimal solutions with respect to travel cost savings, COR2, COR5, and COR8, have in common the fact that they share the same corridor north of Coimbra – corridor N2. Thus, it can be said that N2 is the most advantageous north corridor (Table

5.5). Similarly, it can be said that the best south corridor is S3, since COR7, COR8, and COR9 outperform the corridors that do not include it.

Table 5.5 - Travel costs savings (€/day) for the possible combinations of north and south corridors

Corridor	N1	N2	N3
S1	COR1	**COR2**	COR3
	291,063	316,069	287,043
S2	COR4	**COR5**	COR6
	301,673	325,455	297,849
S3	**COR7**	**COR8**	**COR9**
	310,797	**336,126**	306,750

5.7 Sensitivity Analysis

In order to deepen our study of the Lisbon-Porto HSR line, we performed a sensitivity analysis on the impact of three key parameters and two critical options upon the results described in the previous section. The parameters considered are the value of time, the station impact distance limit, and the ticket price, and the options are the location of a station in the Aveiro area and the construction of the line east or west of Serra dos Candeeiros.

5.7.1 Value of time

The computation of travel costs was made assuming the VOT of 12 Euros per hour, for both car and train trips. In recent transportation studies done in Portugal, the VOT has usually ranged between 10 and 15 Euros per hour. For instance, SDG (2009) adopted VOTs of 15.10 and 13.75 Euros per hour, respectively for car and train trips (2008 was the reference year), and TIS.pt (2007) adopted VOTs of 13.95 and 14.04 Euros (2006 was the reference year).

Therefore, we have chosen to recalculate the optimal solution for the nine corridors using VOTs of 10 and 15 Euros per hour. Also, we have used a VOT of 30 Euros. The reason for using such a high VOT (similar to the one applicable to Germany and unlikely to be attained in Portugal before many years) was to ascertain whether, in such conditions, the opinion sometimes heard in Lisbon that having no stops in Lisbon-Porto HSR trips could make sense.

The conclusion was that, for a VOT of 10 Euros, the optimal solutions (number and location of stations) would remain exactly the same for all corridors, and for a VOT of 15 Euros, the only changes would occur for COR4 and COR6 (see Table 5.6, where the symbol √ means that the location of stations are the same as for the reference VOT of 12 Euros). In both cases, Torres Novas is not chosen and Ovar is replaced with Estarreja, which means that there would be only two intermediate stations. Though potential demand decreases when the VOT increases (travel costs are higher, see expression 4.10), the travel cost savings increase – for COR8, the best optimal solution, these savings were 317,210 Euros, 336,126 Euros and 346,577 Euros, respectively for a VOT of 10, 12 and 15 Euros per hour. For a VOT of 30 Euros, COR2, COR5, and COR8 (the ones yielding the higher travel cost savings) would involve two intermediate stations (in Coimbra and Oliveira de Azeméis), while the other possible corridors would involve only one (in Coimbra). This clearly indicates that the idea of having only non-stop Lisbon-Porto HSR services is unreasonable.

Table 5.6 - Optimal station locations for various VOTs

COR	Value of time (€/h)			
	10	12	15	30
1	√	LEI-CBR-OVA	√	CBR
2	√	LEI-CBR-OLA	√	CBR-OLA
3	√	LEI-CBR-OVA	√	CBR
4	√	TON-CBR-OVA	CBR-EST	CBR
5	√	TON-CBR-OLA	√	CBR-OLA
6	√	TON-CBR-OVA	CBR-EST	CBR
7	√	LEI-CBR-OVA	√	CBR
8	√	LEI-CBR-OLA	√	CBR-OLA
9	√	LEI-CBR-OVA	√	CBR

5.7.2 Station impact distance limit

The station impact distance limit influences the amount of traffic that the HSR can capture from other modes. For the sensitivity analysis we considered a limit of 30 km (and the VOT of 12 Euros per hour) instead of the reference limit of 50 km. The model was recalculated for the nine corridors, yielding the travel cost savings mentioned in Table 5.7. The table shows that COR8 continues to be the best alternative and that the number of intermediate stations continues to be three, with Oliveira de Azeméis being always replaced with São João da Madeira (as expected the difference in the two solutions is very small given the close proximity of these two centers) and Ovar being replaced with Estarreja in some corridors. The reason for this replacement has to do with the fact that Aveiro, a large trip generation center, is not covered by a station located in Ovar, but is partly covered if the station is located in Estarreja (while the coverage of all other large centers in the area is not affected).

Table 5.7 - Model results for a station impact distance limit of 30 km

COR	Travel cost savings (€/day)	Locations of intermediate stations
1	260,555	LEI-CBR-EST
2	282,506	LEI-CBR-SJM
3	256,763	LEI-CBR-OVA
4	265,147	TON-CBR-OVA
5	285,561	TON-CBR-SJM
6	261,904	TON-CBR-EST
7	278,251	LEI-CBR-EST
8	300,517	LEI-CBR-SJM
9	274,719	LEI-CBR-EST

5.7.3 Ticket price

The price users pay for tickets is an important component of travel costs in HSR trips. Minor variations in this parameter may turn user cost efficient HSR routes into non-efficient ones (when compared with routes made through alternative transportation modes) or vice-versa.

In order to assess the effect of ticket price changes, we first focused our analysis on COR8 (always the best corridor up to now), and considered a range of prices between 0.06 and 0.26 Euros per kilometer (that is, minus or plus 0.1 Euros than the reference price of 0.16 Euros per kilometer). The results we have obtained are summarized in Figure 5.5.

As one could expect, travel cost savings increase as ticket prices decrease. The same occurs with the number of stations, which goes up to six when the price is 0.06 Euros per kilometer (and would not increase from there even if the price was nil). The highest values for ticket revenues occur when prices are 0.12 and 0.16 Euros per kilometer, reaching respectively 861,180 and 858,195 Euros per day, but changes are minimal for prices in the range between 0.11 and 0.18. Since the number of stations is larger for 0.12 Euros per kilometer than for 0.16, this ticket price may well be the most favorable for RAVE (and is indeed very close to the price considered in the latest studies commissioned by this company).

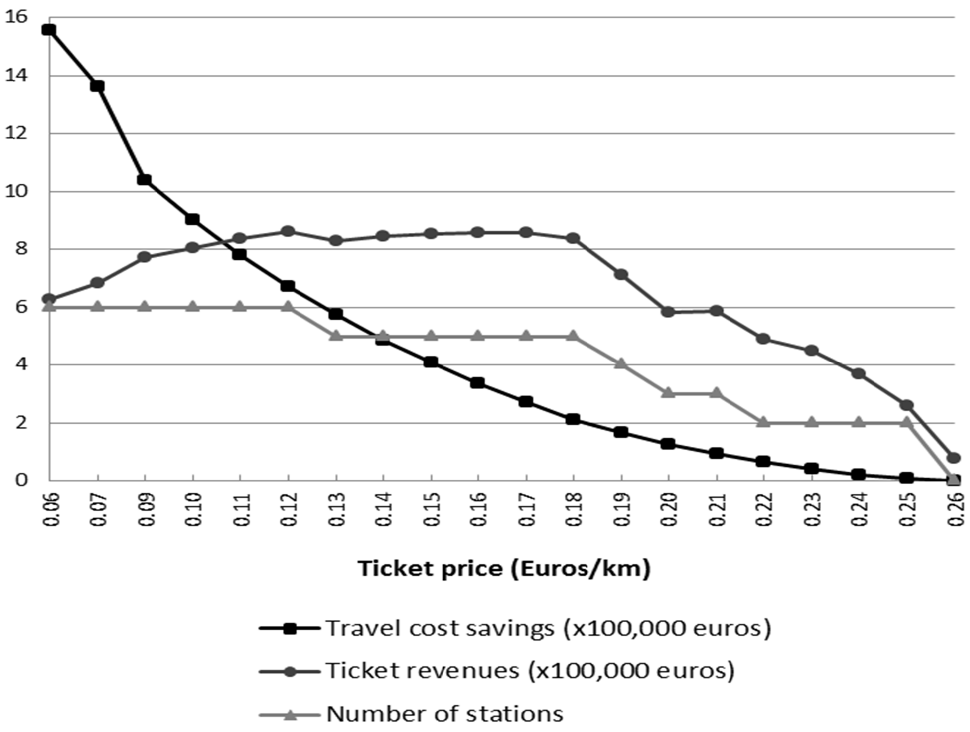

Figure 5.5 - Relationship between travel cost savings, ticket revenues, number of stations, and ticket prices

We have also analyzed the impact of ticket price changes on the other corridor options. Specifically, we have considered the prices of 0.13 and 0.18 Euros per kilometer as an alternative to the reference price of 0.16. As shown in Table 5.8 (and Table 5.4), travel cost savings and ticket revenues are, in general, higher for the lower ticket price (the only exception is COR8). The decrease of ticket revenues with the increase of ticket prices is in particular due to the fact that, in general, the best solutions for the price of 0.18 Euros per kilometer involve only two intermediate stations, and imply the loss of the demand from the Leiria area (or, in the case of COR2, the Coimbra area).

Table 5.8 - Model results for ticket prices of 0.13 and 0.18 Euros per km

COR	Ticket Price 0.13 €/km			Ticket Price 0.18 €/km		
	Travel cost savings (€/day)	Ticket revenues (€/day)	Locations of intermediate stations	Travel cost savings (€/day)	Ticket revenues (€/day)	Locations of intermediate stations
1	519,956	816,856	LEI-CBR-OVA	175,941	685,809	CBR-OVA
2	550,967	829,912	LEI-CBR-OLA	195,842	707,785	LEI-OLA
3	515,626	817,530	LEI-CBR-OVA	172,986	681,606	CBR-OVA
4	520,336	765,478	TON-CBR-OVA	190,106	695,876	CBR-EST
5	550,427	779,991	TON-CBR-OLA	210,252	720,740	CBR-OLA
6	516,060	765,632	TON-CBR-OVA	187,068	695,992	CBR-EST
7	542,514	815,218	LEI-CBR-OVA	191,000	695,936	CBR-EST
8	574,484	829,631	LEI-CBR-OLA	212,747	838,280	LEI-CBR-OLA
9	538,068	815,659	LEI-CBR-OVA	187,952	695,875	CBR-EST

5.7.4 Location of a station in the Aveiro area

All studies commissioned by RAVE refer the area of Aveiro as a certain location for a station of the Lisbon-Porto HSR line (though there is some hesitation on the exact location of the station). However, according to our study, locating a station in that area is never the most advantageous option. In order to quantify the implications of this option, we have run the model imposing the location of a station in Aveiro (COR1, COR3, COR4, COR6, COR7, and COR9) or in the nearby town of Albergaria-a-Velha (COR2, COR5, and COR8). The results are displayed in Table 5.9.

Table 5.9 - Model results for a station in the Aveiro area

COR	Travel cost savings (€/day)	Travel cost savings losses (%)	Ticket revenues (€/day)	Ticket revenues losses (%)	Locations of intermediate stations
1	284,794	2.15	832,131	1.62	LEI-CBR-AVE
2	306,278	3.10	843,928	1.40	LEI-CBR-AAV
3	280,724	2.20	831,790	1.64	LEI-CBR-AVE
4	295,608	2.01	780,976	1.62	TON-CBR-AVE
5	316,544	2.74	793,256	1.34	TON-CBR-AAV
6	291,863	2.01	780,683	1.60	TON-CBR-AVE
7	304,271	2.10	833,976	1.64	LEI-CBR-AVE
8	326,551	2.85	847,077	1.30	LEI-CBR-AAV
9	300,315	2.10	833,594	1.64	LEI-CBR-AVE

They reveal that Albergaria-a-Velha would be a better choice than Aveiro, but still 2.01 to 3.10 per cent worse than the solutions obtained when stations are freely chosen to maximize travel cost savings. The best optimal solutions with a station in Aveiro or in Albergaria-a-Velha are respectively COR7 and COR8. When compared to the best solution of the study (COR8 when stations are freely chosen), they signify daily losses of 31,855 and 9,575 Euros with regard to travel cost savings, and 3,875 and 1,779 Euros with regard to ticket revenues, respectively.

5.7.5 Construction of the line east or west of Serra dos Candeeiros

According to our previous results, the Lisbon-Porto HSR line should pass west of Serra dos Candeeiros. The fact that no station is located between Lisbon and Leiria justifies this choice, since the railway line can be shorter (and trips faster). The east of Serra de dos Candeeiros alternative (S2) was discarded perhaps because it does not include Leiria as a possible location for a station. However, when possible, Leiria is a component of all optimal solutions. Hence, we have decided to consider a new corridor, COR10, combining the best north corridor (N2) and a new south corridor, S4, passing east of Serra dos Candeeiros with a detour to Leiria (Figure 5.6).

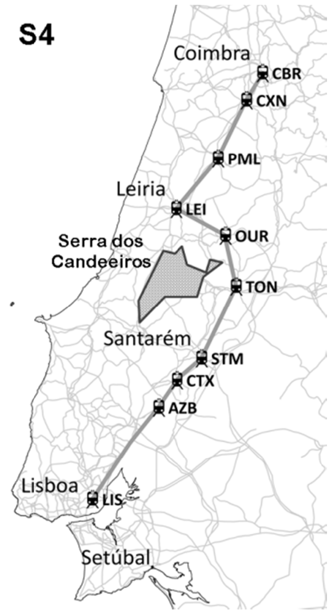

Figure 5.6 - Alternative south corridor S4

The optimal solution for this corridor would involve the same intermediate stations as COR 8, that is, Leiria, Coimbra, and Oliveira de Azeméis, but the travel cost savings would go down by 23% (from 336,126 to 258,416 Euros) and the ticket revenues would be 3% lower (833,173 instead of 858,195 Euros). The poor performance of COR10 with respect to COR8 is because the stations are the same but the line is 16 km longer (indeed, with 309 km, COR10 is the longest corridor of all). Another important result is reached when the corridors that pass east of Serra dos Candeeiros – COR4, COR5, COR6 and COR10 – are compared. Among these scenarios, COR10 is the one that presents the lowest travel cost savings, which indicates that if the Lisbon-Porto HSR line is eventually built east of Serra dos Candeeiros, then Leiria is not an advantageous location for a station.

5.8 Conclusions

In this chapter, we have presented a new railway station location model and the results of its application to the Lisbon-Porto high speed railway line, an important component of the high-speed rail axis of south-west Europe.

The objective of the model is to maximize the travel cost savings made possible by the introduction of a new railway line over an existing transportation network. The model combines a number of features that were either addressed separately or not addressed at all in previous models. In particular, it takes into account simultaneously the impact on travel demand of time losses due to intermediate stops, the (static) competition from other transportation modes, and the generation of traffic due to the decrease in travel costs. Other features considered within the model include the access speed to stations, the dynamic characteristics of trains, the standing time of trains in stations, and the intermodal transfer time at stations.

The case study carried out with respect to the Lisbon-Porto high speed railway line clearly illustrates the kind of results that can be obtained through the application model. Specifically, we have been able to conduct a thorough discussion not only about the best location of stations but also about the best corridor for building the line. This discussion made clear that, under the assumptions we have considered, the solution adopted in a document recently released by RAVE (the company responsible for the implementation of HSR in Portugal) is not the most advantageous one.

Rail transportation planning is a highly complex process, and is usually divided into several stages. The model we have presented in this chapter applies to the strategic stage of this process. However, as pointed out in BUSSIECK et al. (1997), some subsequent stages of the process, classified as tactical, should also be taken into account in the evaluation of possible strategies. This should include, in particular, the case of rolling stock planning and train scheduling. As future work, we intend to develop a model that addresses these strategic and tactical decisions simultaneously. The future model should not only locate train stations along a railway line in the best possible way, but also determine the optimal fleet characteristics and the optimal train schedules (considering different stop-schedules for different trains).

Chapter 6

High Speed Rail - An Optimization Model for Locating Stations and Scheduling Trains

6.1 Introduction

Railway transportation began at the end of the 18th century with the invention of the steam engine. Although at the beginning European railway traffic was essentially for freight transportation, by the end of the first half of the 19th century several European railway networks were already operating for passenger transportation. Regarding operational issues passengers and freight traffic are quite different since they are based on different assumptions. The first and perhaps most visible difference is that freight trains are dispatched on demand, while passenger trains operate according to pre-fixed schedules (BUSSIECK et al., 1997).

The target of this study is the European reality, in particularly the new high speed rail (HSR) lines which are mainly oriented for passenger transportation. Thus, we focus our study on railway transportation planning for passengers, discarding some important issues for freight trains such as car blocking, train makeup, train routing or empty car distribution. A survey on the whole spectrum of railway planning for passenger and freight transportation can be found in ASSAD (1980) and CORDEAU et al. (1998).

The railway network infrastructure can be used by one operator or shared by several. Furthermore, the infrastructure may be owned by the operator(s), by an independent organization or by the State itself. The complexity of the planning process in each of these cases is quite different. The study presented in this paper is developed using Portugal as an example. In Portugal, there is only one public operator controlling the railway network that belongs to the Portuguese State. Thus, the focus of this paper is a railway network owned and operated by the same public entity. This is an important assumption to take into account for the remainder of this chapter.

The entire railway transportation planning process can be divided, with respect to the planning horizon and the objectives, following three classical major planning stages proposed in ANTHONY (1965) and the time horizons proposed in GHOSEIRI et al. (2004):

a. Strategic – resource acquisition and definition of the service level provided to customers (up to 20 years);
b. Tactical – resource allocation and operating policies (up to 5 years);
c. Operational – daily tasks and final details on timetable (one day up to one year).

Given the complexity of the railway transportation planning process, it can also be decomposed into a hierarchical planning process formed by sub-problems. The planning process is usually preceded by a demand analysis step in order to assess the passenger volume from many-to-many origin/destination trips (this step is sometimes viewed as a sub-problem of the strategic stage). Figure 6.1 illustrates one possible hierarchically defined planning process (based on GHOSEIRI et al., 2004, HUISMAN et al., 2005, and CAPRARA et al., 2007).

Demand analysis	
Strategic stage	Network planning
	Rolling stock management
	Line planning
Tactical stage	Train scheduling (basic)
	Rolling stock planning
	Crew planning
Operational stage	Train scheduling (details)
	Rolling stock circulation
	Crew roastering

Figure 6.1 - Hierarchical railway transportation planning process

The various steps of the hierarchical planning process are described in detail in BUSSIECK et al. (1997) (particularly line planning, train scheduling and rolling stock scheduling), CAPRARA et al. (1997) (crew scheduling methods), HUISMAN et al. (2005) (general survey and arising topics in railway planning), TÖRNQUIST (2005) (railway traffic scheduling) and finally CAPRARA et al. (2007) (general survey).

Most existing studies concentrate on tactical and operational stages regarding real-time applications, while train scheduling for planning applications (especially for inter-city passenger services) has not received much attention (ZHOU and ZHONG, 2005). Also, long term capacity planning of infrastructure, rolling stock and crew management through optimization processes has not been dealt with adequately (CAPRARA et al., 2007). The integration between the three major stages and even between the sub-problems of the hierarchical railway planning process is limited. The sub-problems are usually solved separately in the same hierarchical order based on available optimization models and calculation methods. Indeed strategic issues, particularly the ones related to infrastructure, are modeled without recurring to important potential information regarding the future services provided by the railway operator. The price for limited integration in the basic problem components is that the search for a global optimum is compromised, but in return the planner takes advantage of the reduced size of the individual sub-problems.

This chapter responds to the integration concerns raised in BUSSIECK et al. (1997). They state that despite the fact that network planning problems are viewed as the main strategic issues, it is imperative, in order to evaluate possible strategic alternatives, to consider at least the subsequent stages: line planning and train scheduling. In this sense, the focus of this study is the strategic stage, especially infrastructure location decisions, and the subsequent tactical sub-problems that may influence strategic decisions, such that the economic viability of the investment may be evaluated with more accuracy. In detail, we develop an optimization model that determines the optimal location for stations, the fleet characteristics, the service provided and the volume of ridership in such a way that social net benefits are maximized.

The remainder of the chapter is organized as follows. The problem dealt with in this chapter is presented in the next section. The following section presents the optimization model we have developed to represent such a problem. Afterwards, we describe a case study involving a future HSR line in Portugal and provide an empirical dataset required to run the model. Results are then thoroughly analyzed. In the final section we provide some concluding remarks and point out directions for future research.

6.2 Problem description

Investment on a railway network is related to infrastructure (lines and stations) and rolling stock acquisition. The success of the railway investment is highly depend on rail ridership (DE RUS and NOMBELA, 2007; CAMPOS and DE RUS, 2009), which relies not only on the existing infrastructures and train units but also on the level of service provided by the railway network system. The goal of this study is then to integrate and optimize all features that may influence optimal investment decisions at a strategic level. Four main aspects are handled: travel demand, infrastructure, service provided and rolling stock. Detailed descriptions on each aspect and the way they are dealt with in this chapter are found below.

6.2.1 Travel demand

Demand analysis is probably the first step to be assessed in any railway plan. Usually, strategic decisions and the subsequent stages are based on estimations of long-term demand. However, as pointed out in CAPRARA et al. (2007) there is a bidirectional relationship between demand and the operated rail service. In an inter-city environment, as in the case presented here, mode choice (and therefore railway ridership) is mainly affected by four service features: travel cost, frequency, in transit time travelling and waiting time to board the transport or to transfer (KPMG, 1990; BHAT, 1995). In the railway mode all these features are determined by, or at least depend on, the service provided, particularly train timetables and stop-schedules (ZHOU and ZHONG, 2005) and on the infrastructure used to provide the services. The dynamic relationship between passenger demand and each of the four service features mentioned is clearly shown in the study of FU et al. (2009).

Despite evidence of a strong relationship between demand for rail and service features, the existing literature on train service plan design is usually based on static methods where demand is seen as a constant (FU et al., 2009). In such cases train service is optimized regardless of its dynamic relationship with demand. The model presented in this study takes into account the sensitivity of rail ridership to the rail service offered.

6.2.2 Infrastructure

We consider a HSR network consisting of a single double track railway line (each track is reserved for one direction) between two terminal stations known a priori. The track system is to be operated on an exclusive exploitation model (CAMPOS et al., 2009a), i.e. there is a complete separation between conventional and HSR services. Thus, the new track system is operated only for HSR trains. The corridor outline is already defined, except for the location of intermediate stations, which must be chosen from within a given set of possibilities. The number and location of stations influences (and is influenced by) the ridership captured by the rail service. As referred in REPOLHO et al. (2011b)/Chapter 5 more stations imply less access time to the rail service and therefore more demand, but also additional travel time for users of the train (time spent in disembarking and alighting operations and additional accelerating and braking phases at intermediate stops) and consequently less demand. Hence, each additional station increases local demand but diminishes global (long distance) demand. For a review of optimization-based work on railway station location problems the reader is referred to REPOLHO et al. (2011b)/Chapter 5.

The existing literature considers infrastructure elements, such as railway tracks and stations, as fixed for the subsequent strategic line planning problem (e.g. GOOSSENS et al., 2006). Our objective is to integrate infrastructure decisions about station locations within the subsequent strategic design problem.

6.2.3 Service Provided

The service provided to customers, referred to as the “main product of the railway company” in HUISMAN et al. (2005), is essentially characterized by two aspects: line system and the timetable. The first is dealt with at the line planning sub-problem and is classified as a strategic issue while the second is dealt with at the train scheduling sub-problem and is classified as a tactical issue. Most line planning models frequently consider the quality of service but do not generate simultaneously a timetable (KASPI, 2010). Thus, they neglect an important feature for assessing service level, i.e., total travel time of the passengers (including waiting time at origin, intermodal transference time and time in transit). An exception is LINDNER (2000) where a line planning model is developed along with a model for finding a cyclic timetable.

The line-planning problem consists of determining a set of lines (sequence of segments, stations and sidings between two terminal stations), their frequencies, and their stop-schedule patterns, such that some operational constraints (e.g. demand satisfaction or minimization of operational costs) are met. The stop-schedule pattern specifies the subset of stations along the railway line at which a train stops, when using that schedule. The best planning outcome is achieved by considering a flexible number of stop-schedule patterns not restricted by specific stopping schemes set by the planner (CHANG et al., 2000). GOOSSENS et al. (2006) solved a discrete optimization line planning problem in which lines can have different stop-schedule patterns. The number of papers in the literature dealing with line-planning problems is limited. To our understanding, the first paper on this subject was published in PATZ (1925). Other important works on line planning optimization are DIENST (1978), BUSSIECK et al. (1996), BUSSIECK (1998), CLAESSENS et al. (1998), CHANG et al. (2000), GOOSSENS et al. (2004), SCHÖBEL and SCHOLL (2005) and BONDÖRFER et al. (2007). In this study the line-planning sub-problem is simplified since we know a priori the sequence of segments connecting the stations at the endpoints of the new HSR line. Thus, the decisions to be made regarding this issue are the service frequency (number of trains serving the route) and the stop-schedule patterns.

Different levels of train scheduling problems have been proposed in the literature. TÖRNQUIST (2005) distinguishes tactical scheduling, operational scheduling and re-scheduling according to the level of accuracy and the time frame within which the decision is made (tactical scheduling may be done up to a year in advance while re-scheduling might have to be done in a few minutes or even seconds). Regarding passenger transportation, train scheduling models aim to generate suitable plans of arrival and departure times for trains at each station using, in general, cyclic models (i.e. schedules are operated in a periodic pattern). These models generate schedules such that train conflicts are prevented (preventing trains to meet within a block at the same time), and are mostly based on the "Periodic Event Scheduling Problem", PESP, formulated in SERAFINI and UKOVICH (1989). In this chapter, the train scheduling problem is dealt with at a strategic level with the objective of generating a master timetable that characterizes the service provided and therefore the ridership captured by the new HSR line. The planning horizon is analyzed on a day-to-day basis and is divided in fixed time demand intervals (e.g. on an hourly basis) in such a way that they reflect the various operating periods of the day (e.g. peak and off-peak periods). The master timetable generated must be seen as a reference that might need further detailing while in operation to deal with possible train conflicts. Nevertheless, it should have enough detail to characterize the service provided to customers and the ridership that is attracted.

6.2.4 Rolling stock

Management rolling stock decisions should be made at the strategic level. First, because rolling stock involves a considerable amount of investment that should last for a long lifetime (usually they operate during several decades). Second, because rolling stock has direct implications upon the rail service characterization. Nevertheless, rolling stock management has not received adequate attention in the literature. Most existing studies focus on operational issues such as circulation and allocation. An exception is found in FOLKMANN et al. (2007), where the required units and types of rolling stock for a certain timetable are calculated.

Railway transportation systems may operate two types of trains: locomotive hauled carriages and train units. Locomotive hauled carriages require larger shunting times but may vary its length during service by coupling and decoupling carriages. Train units have constant capacity but simplify rolling stock circulation planning (HUISMAN et al., 2005). The problem presented in this chapter only considers train units, since for security reasons HSR lines only operate this type of trains.

This study deals with the rolling stock management problem such that, upon the generation of the master timetable the fleet characteristics (type and size) required to assure the service plan are determined. Moreover, the units and types of rolling stock are assigned to each planned train trip, taking into account the system's availability in each interval at each departing station. This planning method makes possible the calculation of general costs regarding the train fleet.

We also address some general issues regarding the shunting problem. Shunting is defined in HUISMAN et al. (2005) as a local problem that involves choosing the "configurations and locations of the trains at the shunt tracks in such a way that the railway process can start up as smoothly as possible the next morning." We assume trains always start and end their trips at the stations located at the endpoints of the railway line, which also work as shunt yards (places where trains are kept when not operating). When generating a master timetable, we determine how many trains of each type should be placed in each of the endpoint stations in the first period of the day. The scheduling table must be made in such a way that the number and type of trains located at the shunt yards by the end of the day is the same as in the first period so that a new cycle can begin the next day.

6.3 Optimization model

To the best of our knowledge there is no model that simultaneously optimizes infrastructure location decisions, rolling stock management and level of service provided (the latter concerns line planning, train scheduling and stop-schedules). Still it is worth mentioning here two studies whose principles and methods are a reference for the model we are proposing. REPOLHO et al. (2011b)/Chapter 5 presented a strategic model related to infrastructure planning. The objective of the model is to determine the optimal number of intermediate stations along a single railway line that maximizes total travel cost savings. Two interesting features are considered in the model. First, forecasted demand is not a constant, as it is sensitive to time losses due to stops at intermediate stations; second, the railway transportation mode competes with alternative transportation means. It should be noted though, that they do not respond to the railway actions (static competition). CHANG et al. (2000) proposed a line planning optimization model for an inter-city HSR line without branches. They formulated a multi-objective linear programming model that minimizes both the operator's total operating costs and the passenger's total travel-time loss. The output of the model is a train service plan that includes the train stop-schedule plans, services frequency and fleet characteristics. However, no timetable is generated or used to compute total travel time loss.

The model we introduce here combines the station location problem (part of the network planning problem), the train scheduling problem and the rolling stock management problem. The new rail service competes with the modes that use the existing transportation network. The attractiveness of the rail service may be measured by several indicators. FU et al. (2009) suggested five: safety, riding comfort, price, convenience (it is related to passengers' waiting time, i.e., with train services frequency) and promptness (it is viewed as passengers' time on transit). Among those, safety can be neglected (together with air transportation, HSR is considered the safest mode in terms of passenger fatalities per billion passenger-kilometers - CAMPOS and DE RUS, 2009) and riding comfort cannot be easily quantified as it is quite subjective. The remaining factors, convenience, price and promptness may be converted to travel costs. We assume that users always choose the cheapest (measured by travel costs) transportation mode.

The model applies to a region where a new railway line will be built near an existing transportation network. The set of possible locations for the railway stations is also the set of trip generation centers and is given by $\boldsymbol{M}=\{1,\ldots,M\}$. The distance between two candidate sites, i and j, is d_{ij}.

An important type of data involved in the model is associated with the characterization of the line system. Since we are dealing with a single railway line, the number of line services in the study is the same as the number of stop-schedule patterns considered. The set of stop-schedule patterns is $\boldsymbol{R}$, where each element specifies a subset of stations where the train stops. The stop-schedule patterns are defined using a matrix a, where each matrix element, a_{ri}, takes the value of one if a train operating in stop-schedule pattern r stops at station i and zero otherwise (this technique was used in XIE et al., 2009). The number of intermediate stops between two stations, i and j, served in stop-schedule pattern r, is S_{rij}. Defining a segment as the track section between two consecutive stops, the number of segments of a stop-schedule r is $F(r)$. Both directions of the line are independent, which means that a train may adopt a certain stop-schedule pattern on one direction and a different one when returning on the opposite direction. In this sense, trips may begin either at station 1 or station M, and end, respectively, at station M or station 1. The intervals needed to get from a starting station to a station i in transit in stop-schedule pattern r is b^{1}_{ri} (direction $1 \rightarrow M$) or b^{M}_{ri} (direction $M \rightarrow 1$). The daily operational horizon is divided into P fixed time intervals (e.g. on a half an hourly basis), such that $p \in \{1,..,P\}$. Regarding rolling stock and knowing that HSR lines operate train units (instead of locomotive hauled carriages) the fleet must be chosen from within a set of $\boldsymbol{T}$ train types. Each unit type t is characterized by a given seat capacity $v(t)$.

Another main type of data needed in the model involves the computation of travel costs through the existing transportation network and through the new railway line. The least travel cost between sites i and j through the existing transportation network is represented by c'_{ij}, while c_{rij} represents the travel cost between the same sites but through the new railway line on a train operating a stop-schedule pattern r. The value of c_{rij} can be computed as follows:

$$c_{rij} = c_{ij} + 2vt^e + S_{rij}vt^s \quad (5.1)$$

where c_{ij} is the travel cost between site i and j through the new railway line when the train rides at maximum speed (this cost includes the ticket price for using the HSR service, the value of time lost in the acceleration phase near the origin station, i, and in the deceleration phase near the destination station, j), v is the value of time, t^e is the time loss in the intermodal exchange (the multiplication by two accounts for the time lost in both the access to and exit from the station), and t^s is the time loss associated with each intermediate stop (this includes the disembarking and boarding time, and the deceleration and acceleration time in accommodating a stop). When users do not board in the desired interval, l, but on interval p, there is an additional travel cost of abs$(l-p)\cdot h\cdot v$, where h is the fixed time (in hours) of an interval. According to the site where traffic originates, the access station where passengers potentially board the train and whether or not it occurs in the desired time interval, we may define three types of trips through the HSR line and respectively three ways of calculating travel cost savings. First, when users from site i travel on the railway line between stations located at sites i and j in a train operating a stop schedule pattern r in the desired time interval the travel cost savings are given by $s^x_{rij} = c'_{ij} - c_{rij}$. Second, for the same situation, but when users take the train on time interval p instead of the desired interval l, travel cost savings are given by $s^z_{rijlp} = c'_{ij} - c_{rij}$ - abs$(l-p)\cdot h\cdot v$. Third, when users take a train operating a stop schedule pattern r in the desired time interval, but have to use the existing transportation network to travel from the origin site o to the access station located at site i, travel cost savings are given by $s^k_{roij} = c'_{oj} - c'_{oi} - c_{rij}$. Figure 6.2 illustrates the travel costs applicable to each of the three types of trips and the respective road route alternatives.

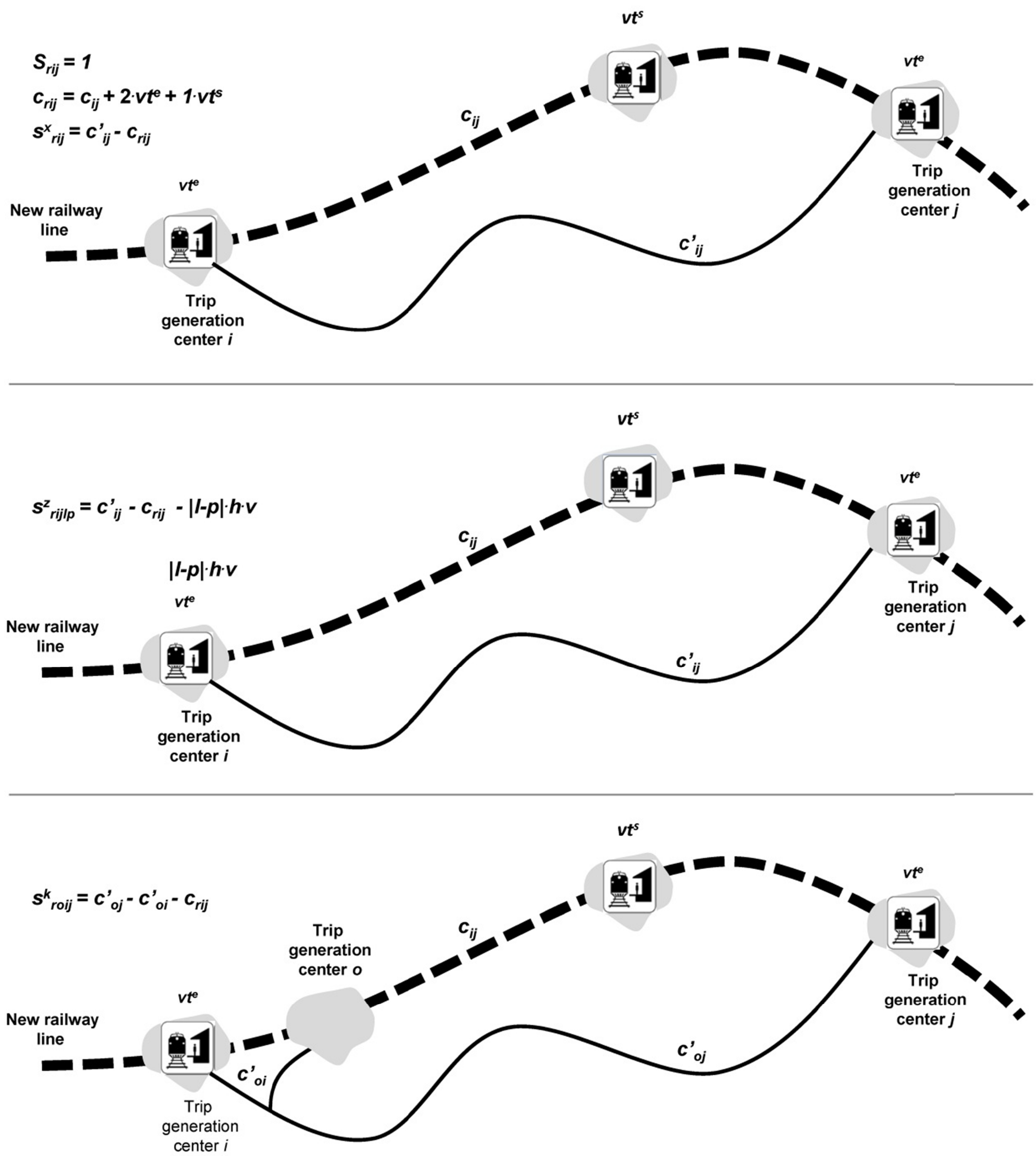

Figure 6.2 - Travel costs applicable to each trip type and alternative routes

The last main data type used in the model is the amount of trips that become less costly if made through the HSR line. According to the three types of trips that use a segment of the new railway line defined above, the amount of cost efficient trips is then represented by: q^x_{rijp} for trips between sites i and j, respectively the locations of the access and exit stations, made in the desired interval p in a train operating a stop schedule pattern r; q^z_{rijlp} for trips between sites i and j, respectively the locations of the access and exit stations, and that are not made in the desired interval l but on interval p in a train operating a stop schedule pattern r; and q^k_{roijp} for trips that include a segment of the existing transportation network oi to reach the access station, and a segment of the new railway line ij, made in the desired interval p in a train operating a stop schedule pattern r. The numbers q^x_{rijp}, q^z_{rijlp} and q^k_{roijp} are estimated as a function of the respective travel costs, c_{rij}, c_{rij} + abs$(l-p) \cdot h \cdot v$, and $c'_{oi} + c_{rij}$, using an unconstrained gravity model (ORTÚZAR and WILLUMSEN, 2001). If the travel costs savings for these trips are positive, i.e., $s^x_{rij}>0$, $s^z_{rijlp}>0$, and $s^k_{roij}>0$, then the value of q^x_{rijp}, q^z_{rijlp}, and q^k_{roijp}, respectively, will capture the additional trips generated by the decrease in travel costs. However, if travel costs savings are zero or negative the value of q^x_{rijp}, q^z_{rijlp}, and q^k_{roijp} are zero because the respective trips do not lead to travel cost savings.

The main decisions that are optimized through the application of the model are represented through eight sets of decision variables: one dealing with location, two dealing with allocation and five dealing with assignments. Station locations decisions are represented with a set of binary variables y_i, which take the value of one when candidate location i is selected for placing a railway station, and take the value of zero otherwise. The decisions regarding the number of trains of each type allocated to terminal stations 1 and M in the first operating interval are represented with two sets of integer variables N^1_t and N^M_t, respectively. Train assignment decisions are represented with two sets of binary variables x^1_{prt} and x^M_{prt}, respectively for trips running in direction $1 \rightarrow M$ and $M \rightarrow 1$. The variable x^1_{prt} (x^M_{prt}) takes the value of one when a train operating a stop-schedule pattern r is set to depart the initial station 1 (M) on period p.

The two sets are independent between each other. The travel options made by travelers in order to minimize their travel costs are represented through three sets of variables, each one corresponding to one of the three types of trips defined. Thus, x_{rijp} represents the fraction of trips made through route $i \to j$ using a train operating a stop-schedule pattern r in the desired interval p; z_{rijlp} represents the fraction of trips made through route $i \to j$ using a train operating a stop-schedule pattern r on the interval p instead of the desired interval l; and finally k_{roijp} represents the fraction of trips made through route $o \to i \to j$ using a train operating a stop-schedule pattern r in the desired interval p.

Given that we are dealing with eight types of decision variables, some of them with five indexes, a detailed pre-processing analysis is required in order to reduce the size of the problem and make possible its resolution through optimization processes. The objective is to eliminate all superfluous variables and associated constraints. Thus, regarding the assignment variables we opted to work with dynamic sets of variables, whose creation relies on the fulfillment of certain conditions. The following list of conditions details in which circumstances each type of assignment variables are defined.

The variable x^1_{prt} is defined when:

1) $p + b^1_{rM} \leq P$ (a train type t operating a stop-schedule r that departs from station 1 must arrive at station M by the latest time interval, P).

The variable x^M_{prt} is defined when:

2) $p + b^M_{r1} \leq P$ (a train type t operating a stop-schedule r that departs from station M must arrive at station 1 by the latest time interval, P).

The variable x_{rijp} is defined when:

3) $a_{ri}.a_{rj} = 1$ (stop-schedule pattern r stops at the stations i and j).

4) Direction $1 \rightarrow M$ ($i<j$): $p + b^1_{rM} - b^1_{ri} \leq P$ (a train operating a stop-schedule r that departs from station 1 in interval p, stopping at i in interval $p + b^1_{ri}$ must arrive at station M by the latest interval, P); Direction $M \rightarrow 1$ ($i>j$): $p + b^M_{r1} - b^M_{r1} \leq P$ (a train operating a stop-schedule r that departs from station M in interval p, stopping at i in interval $p + b^M_{r1}$ must arrive at station 1 by the latest interval, P).

5) $q^x_{rijp} > 0$ (there is traffic between sites i and j on interval p for a train operating a stop-scheduling r).

6) $s^x_{rij} > 0$ (the route between sites i and j using a HSR train operating a stop-schedule r that stops at i in interval p is less costly than the existing alternative route).

The variable z_{rijlp} is created when:

Conditions (3) and (4).

7) $q^z_{rijlp} > 0$ (there is traffic between sites i and j from interval l that it is willing to travel only in interval p in a train operating a stop-scheduling r).

8) $s^z_{rijlp} > 0$ (the route between sites i and j using a HSR train operating a stop-schedule r that stops at i in interval p for traffic that were desiring to travel in interval l in the first place is still less costly than the existing alternative route).

9) $(t_{ij} \cdot S_{rij} \cdot t^s + 2 \cdot t^e)/n \geq \text{abs}(l-p) \cdot h$ (users only travel on interval l, different from the one they desire, p, if the time difference between both periods is at most $1/n$ of the total HSR trip time between stations i and j).

The variable k_{roijp} is created when:

Conditions (3) and (4).

10) $o \neq i$ (the site where demand is originated cannot be coincident with the boarding station site.

11) $d_{oi} < d_k$ (maximum attraction distance between a station and a site without station).

12) $q^k_{roijp} > 0$ (there is traffic between sites *o* and *j* on interval *p* that are willing to board at station *i* in a train operating a stop-schedule *r*).

13) $s^k_{roij} > 0$ (the route between sites *i* and *j* using a HSR train operating a stop-schedule *r* that stops at *i* in interval *p* for traffic originated in site *o* going to site *j* is still less costly than the existent alternative route);

The objective of the model is to determine how many and where (within a set of candidate locations) should the railway stations be located, determine how many trains and of which type should be placed in the terminal stations, determine which stop-schedule patterns should be selected, design a master timetable, and determine when demand is served, such that social net benefits are maximized. Social net benefits are given by the difference between travel costs savings made possible upon the introduction of the new railway line and the investment required to build the stations and acquire the rolling stock fleet. Operational and maintenance costs are assumed to be supported by ticket revenues.

Given the entire notation described above the station location and train scheduling problem can be formulated through the following mixed-integer optimization model:

$$Max\ \pi = \sum_{i\in\boldsymbol{M}} \sum_{j\in\boldsymbol{M}} \sum_{p\in\boldsymbol{P}} \sum_{r\in\boldsymbol{R}} q^x_{rijp} s^x_{rij} x_{rijp} + \sum_{i\in\boldsymbol{M}} \sum_{j\in\boldsymbol{M}} \sum_{l\in\boldsymbol{P}} \sum_{p\in\boldsymbol{P}} \sum_{r\in\boldsymbol{R}} q^z_{rijlp} s^z_{rijlp} z_{rijlp} + \sum_{o\in\boldsymbol{M}} \sum_{i\in\boldsymbol{M}} \sum_{j\in\boldsymbol{M}} \sum_{p\in\boldsymbol{P}} \sum_{r\in\boldsymbol{R}} q^k_{roijp} s^k_{roij} k_{roijp} - \sum_{i\in\boldsymbol{M}} f^s_i y_i - \sum_{t\in\boldsymbol{T}} f^{rs}_t \left(N^1_t + N^M_t\right) \tag{5.2}$$

s.t.

$$\sum_{r\in\boldsymbol{R}} \sum_{t\in\boldsymbol{T}} x^1_{prt} \le 1 \quad \forall p \in \boldsymbol{P} \tag{5.3a}$$

$$\sum_{r\in\boldsymbol{R}} \sum_{t\in\boldsymbol{T}} x^M_{prt} \le 1 \quad \forall p \in \boldsymbol{P} \tag{5.3a}$$

$$\sum_{t\in\boldsymbol{T}} a_{ri} x^1_{prt} \le y_i \quad \forall i \in \boldsymbol{M}, \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : a_{ri} = 1 \tag{5.4a}$$

$$\sum_{t\in\boldsymbol{T}} a_{ri} x^M_{prt} \le y_i \quad \forall i \in \boldsymbol{M}, \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : a_{ri} = 1 \tag{5.4b}$$

$$\sum_{p\in\boldsymbol{P}} \sum_{r\in\boldsymbol{R}} \sum_{t\in\boldsymbol{T}} x^1_{prt} \le n \tag{5.5a}$$

$$\sum_{p\in\boldsymbol{P}} \sum_{r\in\boldsymbol{R}} \sum_{t\in\boldsymbol{T}} x^M_{prt} \le n \tag{5.5b}$$

$$x_{riju} \le \sum_{t\in\boldsymbol{T}} x^1_{prt} \quad \forall i, j \in \boldsymbol{M} : i < j, \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall u \in P : u = p + b^1_{ri} \tag{5.6a}$$

$$x_{riju} \le \sum_{t\in\boldsymbol{T}} x^M_{prt} \quad \forall i, j \in \boldsymbol{M} : i > j, \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall u \in P : u = p + b^M_{ri} \tag{5.6b}$$

$$z_{rijlu} \le \sum_{t\in\boldsymbol{T}} x^1_{prt} \quad \forall i, j \in \boldsymbol{M}, \forall p, l, u \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : u = p + b^1_{ri} \tag{5.7a}$$

$$z_{rijlu} \le \sum_{t\in\boldsymbol{T}} x^M_{prt} \quad \forall i, j \in \boldsymbol{M}, \forall p, l, u \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : u = p + b^M_{ri} \tag{5.7b}$$

$$\sum_{r\in\boldsymbol{R}} x_{rijp} + \sum_{r\in\boldsymbol{R}} \sum_{u\in\boldsymbol{P}} z_{rijpu} \le 1 \quad \forall i, j \in \boldsymbol{M}, \forall p \in \boldsymbol{P} \tag{5.8}$$

$$k_{roijp} \le 1 - y_o \quad \forall i,j,o \in \boldsymbol{M}, \forall p \in P, \forall r \in \boldsymbol{R} \tag{5.9}$$

$$k_{roiju} \le \sum_{t \in \boldsymbol{T}} x^1_{prt} \quad \forall i,j,o \in \boldsymbol{M}, \forall p,u \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : u = p + b^1_{ri} \tag{5.10a}$$

$$k_{roiju} \le \sum_{t \in \boldsymbol{T}} x^M_{prt} \quad \forall i,j,o \in \boldsymbol{M}, \forall p,u \in \boldsymbol{P}, \forall r \in \boldsymbol{R} : u = p + b^M_{ri} \tag{5.10b}$$

$$\sum_{i \in \boldsymbol{M}} \sum_{r \in \boldsymbol{R}} k_{roijp} \le 1 \quad \forall j,o \in \boldsymbol{M}, \forall p \in \boldsymbol{P} \tag{5.11}$$

$$N^1_t - \sum_{r \in \boldsymbol{R}} \sum_{l \in \boldsymbol{P}: l \le p} x^1_{lrt} + \sum_{r \in \boldsymbol{R}} \sum_{l \in \boldsymbol{P}: l + b^{south}_{r1} + G \le p} x^M_{lrt} \ge 0 \quad \forall p \in \boldsymbol{P}, \forall t \in \boldsymbol{T} \tag{5.12a}$$

$$N^M_t - \sum_{r \in \boldsymbol{R}} \sum_{l \in \boldsymbol{P}: l \le p} x^M_{lrt} + \sum_{r \in \boldsymbol{R}} \sum_{l \in \boldsymbol{P}: l + b^{north}_{rM} + G \le p} x^1_{lrt} \ge 0 \quad \forall p \in \boldsymbol{P}, \forall t \in \boldsymbol{T} \tag{5.12b}$$

$$\sum_{r \in \boldsymbol{R}} \sum_{p \in \boldsymbol{P}} x^1_{prt} = \sum_{r \in \boldsymbol{R}} \sum_{p \in \boldsymbol{P}} x^M_{prt} \quad \forall t \in \boldsymbol{T} \tag{5.13}$$

$$\sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} < f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i < j \\ \sum_{u=1}^{j} a_{ru} > f \end{cases}} q^x_{rijp+b^1_{ri}} x_{rijp+b^1_{ri}} + \sum_{o \in \boldsymbol{M}} \;\; \sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} < f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i < j \\ \sum_{u=1}^{j} a_{ru} > f \end{cases}} q^k_{oijp+b^1_{ri}} k_{roijp+b^1_{ri}} +$$

$$\sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} < f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i < j \\ \sum_{u=1}^{j} a_{ru} > f \end{cases}} \sum_{l \in \boldsymbol{P}} q^z_{ijlp+b^1_{ri}} z_{rijlp+b^1_{ri}} \le \sum_{t \in \boldsymbol{T}} v_t x^1_{prt}$$

$$\forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall f \in \{1, \ldots, F(r)\} : p + b^1_{rM} \le P \tag{5.14a}$$

$$\sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} > f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i > j \\ \sum_{u=1}^{j} a_{ru} < f \end{cases}} q^x_{rijp+b^M_{ri}} x_{rijp+b^M_{ri}} + \sum_{o \in J} \;\; \sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} > f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i > j \\ \sum_{u=1}^{j} a_{ru} < f \end{cases}} q^k_{roijp+b^M_{ri}} k_{roijp+b^M_{ri}} +$$

$$\sum_{i \in \boldsymbol{M}: \sum_{u=1}^{i} a_{ru} > f} \;\; \sum_{j \in \boldsymbol{M}: \begin{cases} i > j \\ \sum_{u=1}^{j} a_{ru} < f \end{cases}} \sum_{l \in \boldsymbol{P}} q^z_{rijlp+b^M_{ri}} z_{rijlp+b^M_{ri}} \le \sum_{t \in \boldsymbol{T}} v_t x^M_{prt}$$

$$\forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall f \in \{1, \ldots, F(r)\} : p + b^M_{ri} \le P \tag{5.14b}$$

$$y_1 = 1 \tag{5.15a}$$

$$y_M = 1 \tag{5.15b}$$

$$x^1_{prt} \in \{0,1\} \quad \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall t \in \boldsymbol{T} \tag{5.16a}$$

$$x^M_{prt} \in \{0,1\} \quad \forall p \in \boldsymbol{P}, \forall r \in \boldsymbol{R}, \forall t \in \boldsymbol{T} \tag{5.16b}$$

$$y_i \in \{0,1\} \quad \forall i \in \boldsymbol{M} \tag{5.17}$$

$$N^1_t \text{ is integer} \quad \forall t \in \boldsymbol{T} \tag{5.18a}$$

$$N^M_t \text{ is integer} \quad \forall t \in \boldsymbol{T} \tag{5.18b}$$

where f^s is the fixed daily cost of building an intermediate station; $f^{rs}{}_t$ is the fixed daily cost for acquiring one unit of rolling stock type t; and n is the maximum number of trains scheduled per day defined by the decision-maker.

The objective function (5.2) maximizes the social net benefits given by the difference between travel costs savings and the investment made to build stations and acquire the rolling stock fleet. Constraints (5.3) ensure that only two trains at most (one per direction) depart from the starting stations 1 and M in each interval. Constraints (5.4) prevent a stop-schedule pattern r to be selected unless a station is located in every site i where the stop-schedule pattern r stops. Constraints (5.5) ensure that only n trains at most are schedule per day in each direction. Constraints (5.6) ensure that passengers wanting to travel from station i to station j in interval u can only be served if a train with a stop-schedule plan r departs from the initial station in interval p, such that it stops at station i in interval u (u is therefore equal to p plus the additional intervals, $b^1{}_{ri}$ – or $b^M{}_{ri}$ according to the trip direction – needed for a train operating a stop-schedule plan r to get to i). Constraints (5.7) follow the same logic but for passengers wanting to travel in interval l are only served in interval u. Constraints (5.8) prevent demand do be considered more than one time. If demand is all served in interval p then x_{rijp}=1 and z_{rijpu}=0 (for all values of u). If demand is only served in interval u then x_{rijp}=0 and z_{rijpu}=1. If for capacity reasons demand is partially served in interval p and interval u then, $0< x_{rijp} <1$ and $0< z_{rijpu} \leq 1 - x_{rijp}$. If no demand is served then x_{rijp}=0 and z_{rijpu}=0 (for all values of u). Constraints (5.9) ensure that passengers from site o will only visit a nearby station i to get to station j if no station is located at o. Constraints (5.10) work the same way constraints (5.7) do, but for demand from a site o without a station and going to station i to get to station j in interval u. Constraints (5.11) ensure that demand from a site with no station is only considered at most once in moving to nearby stations (it prevents unrealistic multiplication of demand). Constraints (5.12), the equilibrium constraints, keep track of the number and type of trains operating in the system. A train of type t can only be selected for a trip if there is at least one train type t available at the station. Note also that after finishing a trip a train is only available after G intervals of time (defined as the terminal time required in preparing the train for subsequent operations). Constraints (5.13) ensure that the number of trains of each type placed at each of the terminal stations (1 and M) by the end of the day is the same as the starting conditions. Constraints (5.14), the capacity constraints, ensure that the seat capacity of each train is not exceeded in any segment of the railway line. The control is made by segment which allows a seat to be used by more than one passenger per train journey if the segments do not overlap. Constraints (5.15a) and (5.15b) ensure that there will be stations located at the endpoints of the railway line. Finally, expressions (5.16), (5.17) and (5.18) define the domain of the decision variables.

6.4 Case study

To illustrate the usefulness of the model presented in the previous section we applied it to a case study involving the future HSR line between Lisbon and Porto in Portugal. The line is still under study but it is planned to be built in the next few years. The new railway line is one of the 30 priority projects defined in EUROPEAN COMMISSION (2005) in order to integrate the Iberian Peninsula in the Trans-European Network. More specifically the Lisbon-Porto HSR line makes part of the priority axis number 3 – “high-speed rail axis of south-west Europe” – which also comprehends the links between Aveiro-Salamanca, Lisboa-Madrid and the links between Madrid and the French HSR lines. More information on the Lisbon-Porto HSR line is available in REPOLHO et al. (2011b)/Chapter 5. For the purpose of this study we will consider the corridor COR8 defined in the same study. The corridor has an extension of 293 km and 17 possible locations for HSR stations: Lisboa (LIS), Alenquer (ALQ), Rio Maior (RIM), Alcobaça (ACB), Batalha (BAT), Leiria (LEI), Pombal (PML), Condeixa-a-Nova (CXN), Coimbra (CBR), Mealhada (MLD), Anadia (ANA), Oliveira do Bairro (OLB), Águeda (AGD), Albergaria-a-Velha (AAV), Oliveira de Azeméis (OLA), São João da Madeira (SJM) and Porto (POR). Figure 6.3 portrays the HSR line corridor and the possible station locations.

Figure 6.3 - Possible station locations for the Lisbon-Porto HSR line

The areas crossed by the new HSR line are served by a dense and very good road network and by conventional rail services. While the competition between the HSR rail mode and the automobile is expected to be significant, the competition between HSR rail and conventional rail services is considered non-existent as HSR rail will replace the existing rail services along this corridor.

6.5 Model data

The application of the model basically requires three data sets: data about costs (travel costs, intermediate stations installation costs and rolling stock acquisition costs), data to characterize the line system (more precisely the stop-schedule patterns and types of rolling stock units), and finally data about travel demand between the HSR stations based upon the three types of trips described.

The travel costs through the existing road network and through the new HSR line were computed using the following data:

- Road user costs estimation took into account three components: vehicle operating costs, time costs, and tolling costs.
- Vehicle operating costs were estimated at 16.478 Euros per 100 km per vehicle. The estimation was done using the HDM-4 approach (WORLD BANK, 2010), which includes fuel consumption, tire usage, vehicle maintenance, and vehicle depreciation.
- Time costs were calculated considering a value of time (VOT) set equal to 12 Euros per hour.
- Tolling costs were considered according to the toll fees currently being applied.
- Travel speed in the railway line was considered to be 250 kph (except in the acceleration and deceleration phases).

- Tickets for HSR trips were assumed to cost 0.16 Euros per kilometer, which amounts a total of 46.88 Euros for trips between Lisbon and Porto. A similar value, 49.00 Euros, was used in SDG (2009) for the same trips.

- Time loss in an intermodal exchange (t^e) was estimated to be 12 min.

- Time loss associated with each intermediate stop (t^s) was estimated to be 9 min, corresponding to 3 min for the acceleration and deceleration phases and 6 min for the boarding and disembarking phases. In SDG (2009), the time difference between a Lisbon-Porto non-stop HSR service and a two intermediate stop service was 18 min, thus strengthening the value we use.

The fixed costs for building the stations of Lisbon and Porto were taken from SDG (2009) and are equal to 219.579 million € and 135.559 million €, respectively. As for intermediate stations we assumed an average value of 28.955 million € per station. The value was estimated considering the global value used in SDG (2009) for all intermediate stations and sub-stations (115.819 million €). Regarding the acquisition of rolling stock, the fixed costs were calculated in terms of the passenger capacity. However, as mentioned in CAMPOS et al. (2009b), rolling stock acquisition costs are determined not only by its technical specifications, (where capacity plays a major role) but also by other factors such as the contractual relationship between the manufacturer and the rail operator, delivery and payment conditions, specific rolling stock configurations required by the rail operator, etc. Thus, following the methodology used in CAMPOS et al. (2009b) we considered three cost alternatives: "best" – 30.000 € per seat, "medium" – 50.000 € per seat, and "worst" – 65.000 € per seat. We consider four types of rolling stock units with the following passenger capacity 1000, 800, 600 and

400. For a lifespan of 40 years (the same value is used in CAMPOS et al., 2009b, for HSR projects) and a (real) discount rate of 4 percent, the daily fixed charges for installing the stations, f_i^s, are 29225 €, 18042 € and 3854 € (respectively for Lisbon, Porto and each intermediate station). The daily fixed acquisition costs of each type of rolling stock unit, $f^{rs}{}_t$, according to the cost alternative are summarized in Table 6.1.

Table 6.1 - Train unit costs under the best, medium and worst rolling stock cost alternatives

Passenger capacity	Rolling stock unit daily cost (Euros)		
	Best	Medium	Worst
1,000	3,993	6,655	8,651
800	3,194	5,324	6,921
600	2,396	3,993	5,191
400	1,597	2,662	3,461

The results obtained in REPOLHO et al. (2011b)/Chapter 5 revealed that the optimal number of intermediate stations in the Lisbon-Porto HSR line should be three when assuming that trains stop in every station. Thus, in this study we designed stop-schedule patterns with one, two or three intermediate stops at most. Additionally we considered a direct line (non-stop service) between the two terminal stations, Lisbon and Porto. All combinations of one, two and three stations among the fifteen possible intermediate stops were considered with the following restrictions: 1) the sum of the gravitational potentials of the stations included in the pattern should be at least 100, 200 and 300 thousand people, respectively for one, two and three intermediate stops; 2) the distance between two consecutive stations must be at least of 30 kilometers. This minimum distance was set to ensure that the HSR service is not degraded to a regular train service and taking into account that a HSR train takes a distance of approximately 20 km to accelerate to the maximum speed of 250 kph and then decelerating till it stops. The outcome is a set of a hundred and ten alternative stop schedule patterns.

Travel demand for each of the three types of trips described above was estimated using an unconstrained gravity model that uses a power-form impedance function. The choice of the power form instead of the exponential form is justified in the literature (e.g. FOTHERINGHAM and O'KELLY, 1989) for providing a better representation of the interurban trips reality. According to the travel costs involved in each trip type, the travel demand after the introduction of the HSR line is given by:

$$q_{rijp}^{x} = \mu_p \alpha \frac{w_i w_j}{\left(c_{rij}\right)^{\beta}} \quad (5.19a)$$

$$q_{rijlp}^{z} = \mu_l \alpha \frac{w_i w_j}{\left(c_{rij} + |l-p|uv\right)^{\beta}} \quad (5.19b)$$

$$q_{roijp}^{k} = \mu_p \alpha \frac{w_o w_j}{\left(c'_{oi} + c_{rij}\right)^{\beta}} \quad (5.19c)$$

where w_i and w_j are the gravitational potential of sites i and j, μ_p (μ_l) is a weight parameter used to define the fraction of the total daily demand traveling at period p (l), α is a proportional constant and β is a parameter of transport friction.

The parameter n (used in condition 10) was set equal to 2, i.e., passengers not traveling at the desired period are willing to anticipate or delay their travel for no more than half of the time the HSR trip would take. Regarding condition 11), the maximum attraction distance between a station and a site without station, d_k, was set equal to 20 km. Thus, q^k_{roijp} is only considered if the distance between site o and station i through the existing road network is at most 20 km.

We assume the gravitational potential of a station located at site i, both as origin and destination of trips, is given by the sum of populations (p_h) of the municipalities covered by station i (the set of municipalities covered by station i is represented by $\boldsymbol{J_i}$) multiplied by a linear decay factor that reflects the distance between the municipality and the station and the maximum impact distance limit of a station, d_{max}. The expression for the gravitational potential of station i is:

$$w_i = \sum_{h \in \boldsymbol{J}_i} p_h \left(1 - \frac{d_{ih}}{d_{max}}\right), i \in \boldsymbol{M} \tag{5.20}$$

The parameters α and β were calibrated using the O/D traffic data for the north Region of Portugal, and were set to be equal to 0.42 and 1.2 respectively. The set of municipalities covered by each station was defined on a shortest path basis and assumed that the maximum impact distance limit of a station, d_{max}, to be 50 km. The same value was used in SDG (2007).

The planning horizon is analyzed on a day-to-day basis, where each day is divided in fixed time intervals of half an hour. The trains are expected to operate between 06:00 AM and 24:00 PM, which makes a total of thirty six intervals. Demand is not distributed homogenously along the day. We considered the morning peak period (between 07:00 AM and 10:00 AM) and the afternoon peak period (between 17:30 PM and 20:00 PM) having two and a half times more demand than the regular intervals.

Additionally we considered the lunch period (between 12:00 PM and 15:00 PM) having one and a half times more demand than the regular intervals. The daily demand distribution is represented in Figure 6.4.

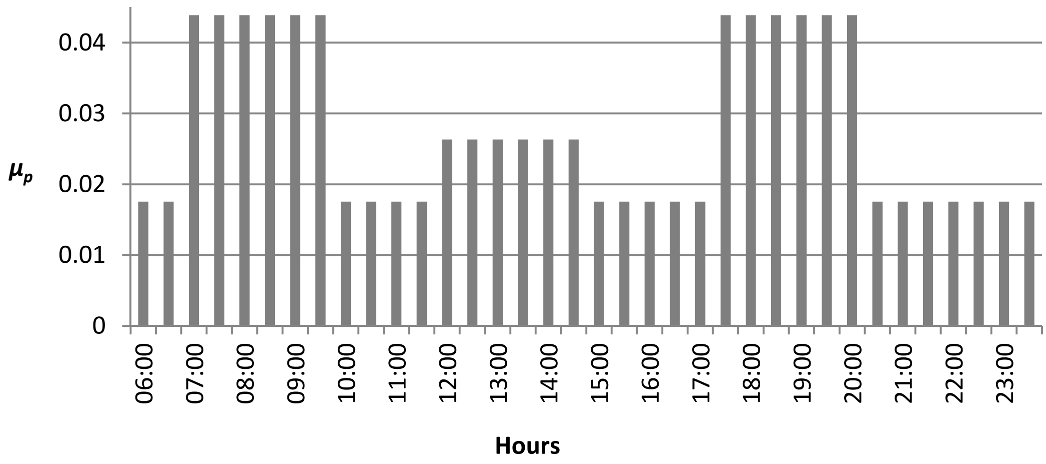

Figure 6.4 - Demand distribution per time interval per day, μ_p

Finally, the time required to set a train operational again after one trip between terminal stations, *G*, was set equal to 30 min (i.e., one fixed time interval). The maximum number of trains possible of scheduling per day in each direction, *n*, is assumed to be eighteen (this information can be found in the website of RAVE).

6.6 Model results

The model was applied to the Lisbon-Porto new HSR line (specifically to corridor COR8 described above), considering the three rolling stock cost alternatives and using an Intel Core 2 Quad Processor Q9550 2.84 GHz computer with 4 GB of RAM and the FICO Xpress 7.1 optimizer (FICO, 2009). The results obtained for all rolling stock cost alternatives with respect to social net benefits, investment, ridership, average load factor and locations of intermediate stations are summarized in Table 6.2.

Table 6.2 - Model results for the rolling stock cost alternatives: "best", "medium" and "worst"

	Rolling stock cost alternatives		
	Best	Medium	Worst
Social net benefits (€/day)	375,390	362,079	353,470
Investment (€/day)	78,793	92,104	95,564
Rail ridership (pax/day)	26,856	26,856	26,342
Average load factor (%)	74	74	76
Location of intermediate stations	LEI-CBR-OLA	LEI-CBR-OLA	LEI-CBR-OLA

The optimal solution obtained for the cost alternatives "best" and "medium" is the same (except for the value of the objective function). The optimal fleet is composed by four trains of 800 passengers (one located in Lisbon and three located in Porto) and three trains of 600 passengers (two located in Lisbon and one located in Porto). The effect of the rolling stock cost is only visible in the cost alternative "worst". In this case the optimal solution comprises one less train unit of 800 passengers (only two trains of this type are located in Porto). As a consequence, the cost alternative "worst" serves 514 fewer passengers per day than the solution obtained for the other cost alternatives.

The trains average load factor is greater than or equal to 74 percent. This result is important with regard to the environmental impact. According to the literature (e.g. CE DELFT, 2003; NASH, 2009; DE RUS and NASH, 2009) energy consumption per seat km of a HSR train is highly dependent on the load factor. HSR trains pollute less than air transports even for lower load factors. However, when compared to cars, trains emissions only start to become similar to cars for load factors of 70 per cent or higher.

Regarding the number and location of intermediate stations, the optimal solutions obtained for the three cost alternatives were comprised of three intermediate stations located in Leiria, Coimbra and Oliveira de Azeméis. This solution was also generated in the study REPOLHO et al. (2011b)/Chapter 5 for the same HSR line where the authors considered only one stop-schedule pattern (trains stop in every station). In both studies the area of Aveiro (represented in COR8 by Albergaria-a-Velha) is not selected as a station location, despite being set to receive a station in all studies commissioned by RAVE (e.g. SDG, 2009).

The optimal train timetable for cost alternative "medium" is illustrated in Figure 6.5.

Trains are distributed along all operational periods of the day, though with more frequency during the morning and afternoon peak intervals. The earliest train departs in the 6:30 interval in both directions and the last train departs from Lisbon station in the 22:30 period. Despite forty five percent of the passengers (12,080 out of 26,856) travel between Lisbon and Porto or vice-versa there is only one direct train between these two stations in the direction Lisbon to Porto. All the other stop-schedule patterns selected comprise two or three intermediate stops. These results indicate that having mainly non-stop Lisbon-Porto HSR service is unreasonable with respect to all potential users.

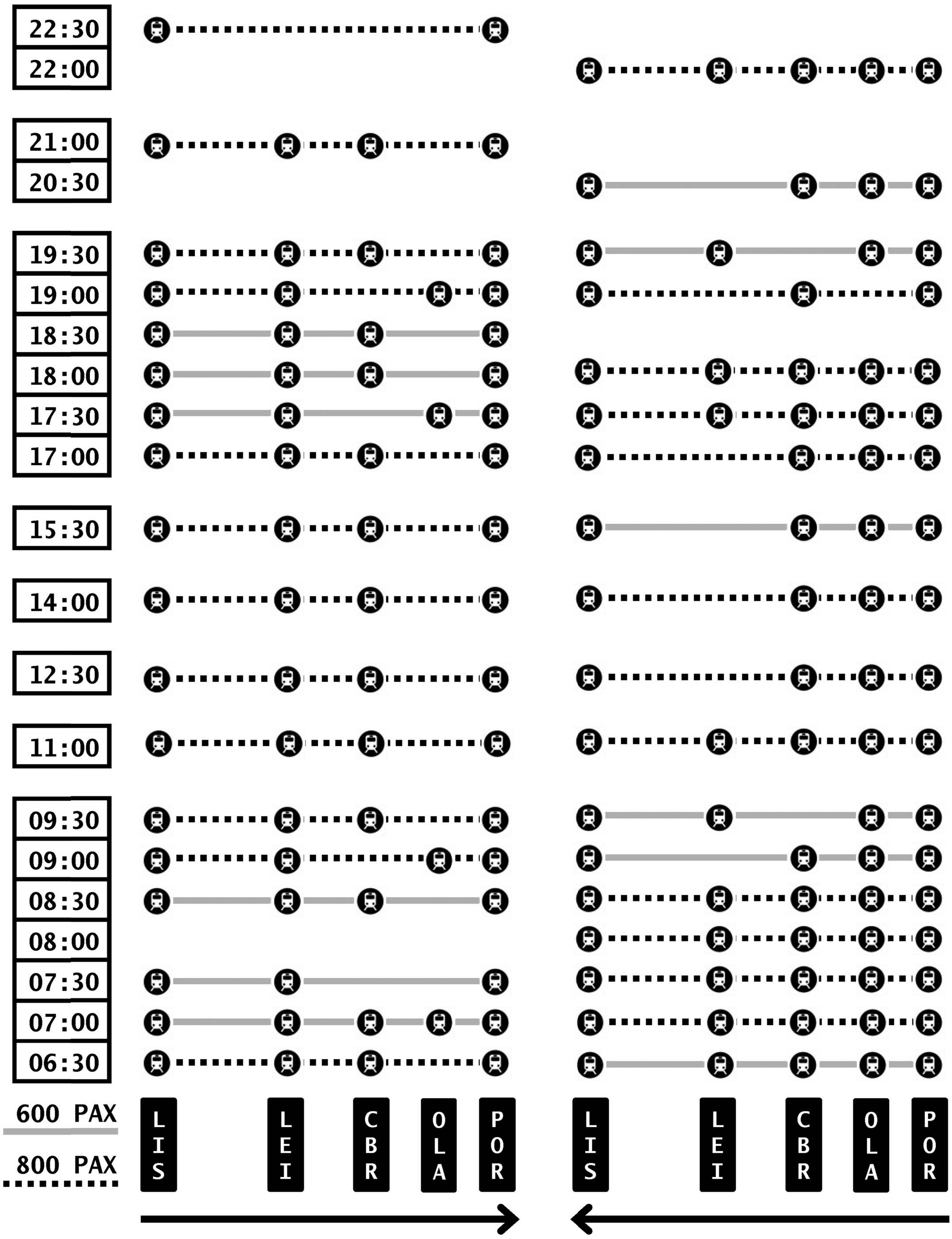

Figure 6.5 - Train timetable for the rolling stock cost alternative "medium"

Another interesting analysis is related to the origin of the passengers. Once again for the cost alternative "medium", the optimal solution indicates that 58.4 per cent of the passengers (15,689) board at a station located in their origin site in the desired time interval; 23.2 per cent of the passengers (6,229) board at a station located in their origin site but not in the desired time interval; and finally, 18.4 per cent of passengers travel to a nearby station to access HSR service.

Even though train conflicts were not considered upon the design of the master timetable, the solution can be easily implemented. Since we are using half an hour time intervals there is a considerable leeway to schedule trains operating in consecutive intervals. Moreover, the maximum travel time difference between a stop-schedule pattern with three stops and one with no stops is 27 min, thus, less than half an hour.

6.7 Sensitivity analysis

The application of the model depends on a set of parameters and data, whose values may vary during the lifespan of the project. In order to validate the solution found for the Lisbon-Porto HSR line we studied its sensitivity to changes in the value of two key factors: value of time and estimated demand. Additionally, we performed a sensitivity analysis on the effects of the level of investment upon the optimal solution and studied the optimal solution when the number and location of intermediate stations are the same as in the studies commissioned by RAVE for the Lisbon-Porto HSR line. For the analysis that follows we assume the “medium” cost alternative for rolling stock acquisition. The solution obtained in the previous section for the “medium” cost alternative is from now on designated as the “*base solution*”.

6.7.1 Value of time

The valuation of travel costs is highly important as passengers' route selection is made based on the route travel cost. Within travel costs, the value of time plays a major role. The value of time used in the previous sections, 12 Euros per hour, is within the range of values (10 to 15 Euros per hour) usually adopted in recent transportation studies in Portugal (e.g. SDG, 2009; TIS.pt, 2007).

In order to cover the range of values used in Portuguese transportation studies we have recalculated the optimal solution for the case study using values of time of 10 and 15 Euros per hour. Additionally, we have also used a value of time of 30 Euros per hour to simulate the German standards (though this seems quite high with respect to current conditions in Portugal) as to assess the implications such standards could have.

For the VOTs of 15 and 30 Euros per hour the optimal solution (number and location of intermediate stations) would be the same obtained for a VOT of 12 Euros per hour, i.e., three stations located in Leiria, Coimbra and Oliveira de Azeméis. The changes in the value of time would only affect the optimal intermediate station locations for a VOT of 10 Euros per hour. In this case, the solution would comprise one additional intermediate station located in Rio Maior. It is important to note that the fleet characteristics and the timetable vary significantly over all values of VOT tested. Table 6.3 summarizes the optimal locations of intermediate stations, ridership (total and regarding trips between Lisbon and Porto or vice-versa), investment, fleet characteristics and total number of intermediate stops (in both directions) obtained for each value of VOT tested.

Table 6.3 - Model results for various VOTs

VOT (€/h)	10	12 (base solution)	15	30
Location of the intermediate stations	RIM-LEI-CBR-OLA	LEI-CBR-OLA	LEI-CBR-OLA	LEI-CBR-OLA
Rail ridership (pax/day)	32,593	26,856	23,234	13,801
Ridership LIS POR (pax/day)	12,775	12,080	10,942	7,542
Investment (€/day)	95,958	92,104	84,118	78,794
Number of Trains 400 Pax	0	0	0	6
Number of Trains 600 Pax	0	3	5	1
Number of Trains 800 Pax	5	4	1	0
Number of Trains 1000 Pax	1	0	0	0
Total # of intermediate stop	96	78	75	53

The increase in the value of time leads to a situation with less ridership. The ridership obtained for a VOT of 30 Euros per hour is about half of the one obtained for a VOT of 12 Euros per hour. Consequently, the capacity of the train units selected decreases as well. However, the proportion of passengers traveling between Lisbon and Porto increases when the value of time is increased. The percentage of ridership between Lisbon and Porto is 39.2%, 45.0%, 47.1% and 54.6% respectively for VOTs of 10, 12, 15 and 30 Euros per hour. Regarding the stopping patterns, increases in the value of time favors trips with less intermediate stops. For a VOT of 12 Euros per hour the optimal solution comprises a total of 78 intermediate stops, while for a VOT of 30 Euros per hour the optimal solution comprises a total of 53 intermediate stops. Moreover, there are more non-stop services between Lisbon and Porto for a VOT equal to 30 Euros per hour than for the other VOTs. As an example, Figure 6.6 illustrates the train timetable obtained for a VOT of 10 Euros per hour and a VOT of 30 Euros per hour, respectively, in the direction of Lisbon to Porto.

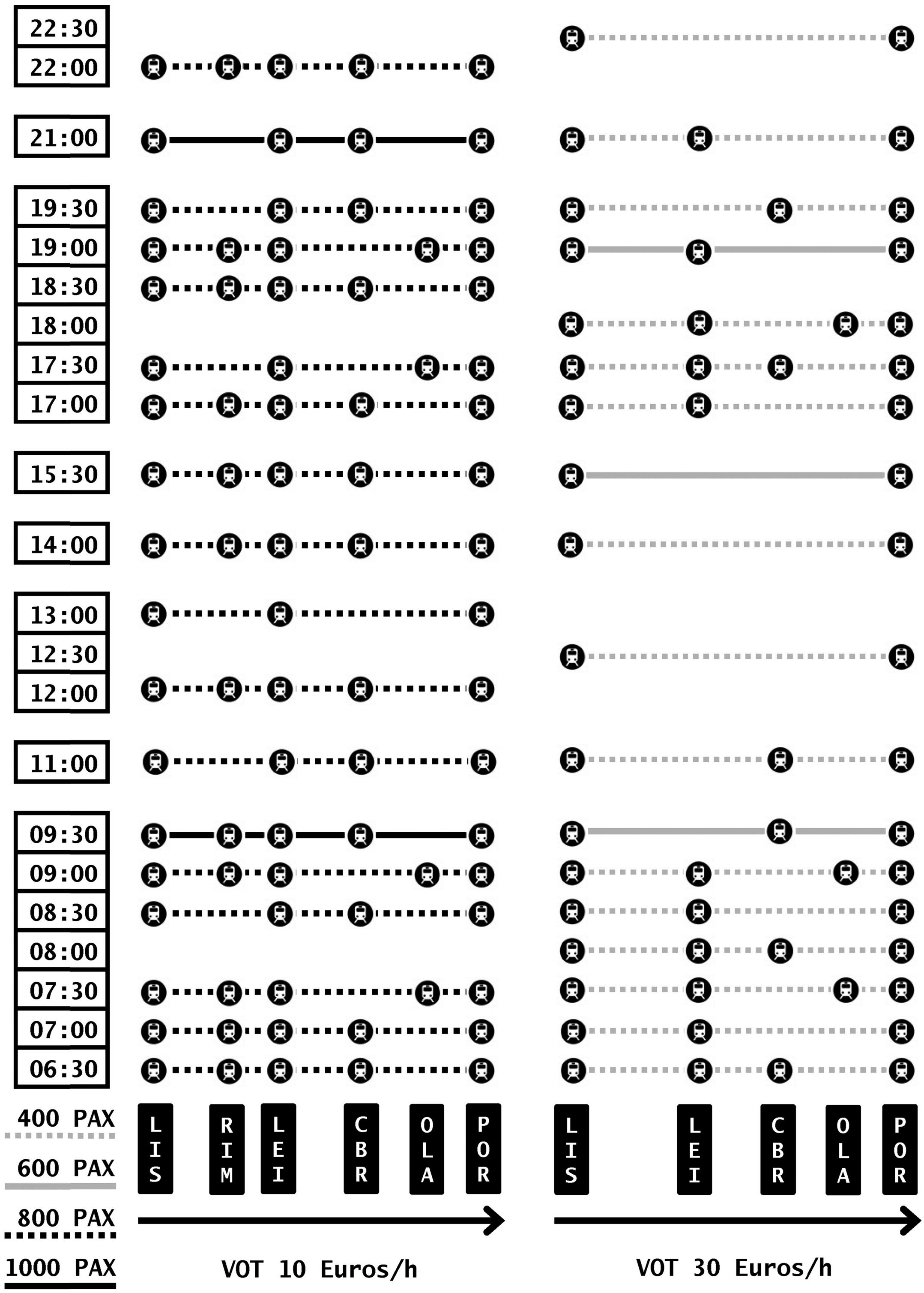

Figure 6.6 - Train timetable for a VOT of 10 and 30 Euros (Direction 1→*M*)

6.7.2 Demand

The HSR line ridership is expected to grow during the lifespan of the project. The ridership for the case study, COR 8, was estimated at 26,342 passengers per day, which is almost the same value obtained in REPOLHO et al. (2011b)/Chapter 5 (26,334 passengers per day) for the same HSR line and the same number and location of intermediate stations. This level of ridership is consistent with the number of passengers per day estimated in SDG (2009) for the first years of operation of the HSR line. However, the last documents released by RAVE estimate that in 2033 the ridership will be equal to 33,425 passengers per day.

In order to assess the impact of ridership variations upon the optimal solution we have run the model setting the value of the proportional constant, α, used in the unconstrained gravity model equal to 0.52 and 0.32. The latter value is used to simulate a scenario where the new HSR line does not capture the level of ridership predicted in the studies underlying the RAVE corridor.

The ridership values for α equal to 0.52 and for α equal to 0.32 are estimated at 32,803 and 20,230 passengers per day, respectively. These values represent respectively 22.1 percent more and 24.7 percent less than the ridership estimated for the *base solution*. Nevertheless, the changes in ridership do not change the optimal location for the intermediate stations, since in both cases Leiria, Coimbra and Oliveira de Azeméis are still the sites selected to receive stations. However, ridership variations affect the optimal investment regarding rolling stock acquisition. For α equal to 0.52 the rolling stock investment is 34606 Euros per day corresponding to four trains of 800 passengers and two of 1,000 passengers, while for α equal to 0.32 the investment is 23,958 Euros per day corresponding to three trains of 400 passengers and four of 600 passengers.

The results obtained for α equal to 0.52 and 0.32 are summarized in Table 6.4.

Table 6.4 - Model results for various levels of demand

	α = 0.32	α = 0.42 (base solution)	α = 0.52
Social net benefits (€/day)	309,217	409,346	510,080
Investment (€/day)	82,787	91,504	93,435
Rail ridership (pax/day)	20,230	26,856	32,803
Number of Trains 400 Pax	3	0	0
Number of Trains 600 Pax	4	3	0
Number of Trains 800 Pax	0	4	4
Number of Trains 1000 Pax	0	0	2
Average load factor (%)	0.77	0.76	0.78
Location of intermediate stations	LEI-CBR-OLA	LEI-CBR-OLA	LEI-CBR-OLA

6.7.3 Level of investment

The investment issues studied in this study are related to station construction and rolling stock acquisition. The objective function optimizes the travel cost savings simultaneously with the number of intermediate stations and the number and type of rolling stock units needed to fulfill the rail services. Thus, the optimal solution provides one single option regarding the selection of intermediate stations and fleet characteristics. However, if we allow other levels of investment it is possible to assess the effect of the level of investment on the optimal solution. To pursue this goal we have considered an alternative objective function (5.21) that maximizes the travel costs savings made possible upon the introduction of the new HSR line, and two additional constraints. Constraint (5.22) sets an upper bound (defined by the decision maker) on the investment made to build the intermediate stations and to acquire the train fleet. Constraints (5.23) prevent a station to be located at site *i* unless there is at least one train stopping at *i*.

All the other constraints formulated for the base model are also used in this case.

$$Max\ \pi = \sum_{i\in \boldsymbol{M}} \sum_{j\in \boldsymbol{M}} \sum_{p\in \boldsymbol{P}} \sum_{r\in \boldsymbol{R}} q^x_{rijp} s^x_{rij} x_{rijp} + \sum_{i\in \boldsymbol{M}} \sum_{j\in \boldsymbol{M}} \sum_{l\in \boldsymbol{P}} \sum_{p\in \boldsymbol{P}} \sum_{r\in \boldsymbol{R}} q^z_{rijlp} s^z_{rijlp} z_{rijlp} + \sum_{o\in \boldsymbol{M}} \sum_{i\in \boldsymbol{M}} \sum_{j\in \boldsymbol{M}} \sum_{p\in \boldsymbol{P}} \sum_{r\in \boldsymbol{R}} q^k_{roijp} s^k_{roij} k_{roijp} \tag{5.21}$$

s.t. (5.3) – (5.18) and

$$\sum_{i\in \boldsymbol{M}} f_i^s y_i - \sum_{t\in \boldsymbol{T}} f_t^{rs} \left(N_t^1 + N_t^M \right) \leq I \tag{5.22}$$

$$\sum_{p\in P} \sum_{r\in R: a_{ri}=1} \sum_{t\in T} a_{ri} x^1_{pr} + \sum_{p\in P} \sum_{r\in R: a_{ri}=1} \sum_{t\in T} a_{ri} x^M_{pr} \geq y_i \qquad \forall i \in M \tag{5.23}$$

where *I* is the maximum limit of money available to spend in non-pre-fixed options, i.e., to build intermediate stations and acquire rolling stock units. To obtain the total investment we should add the building cost of terminal stations Lisbon and Porto (47,267 Euros per day).

The application was recomputed using the new objective function (5.21) and the additional constraints (5.22) and (5.23) considering fourteen investment levels, *I*, ranging between 10,000 and 75,000 Euros per day. The results obtained with respect to travel cost savings, investment in intermediate stations and train fleet, social net benefits, rail ridership, trains load factor, locations of intermediate stations and fleet characteristics are summarized in Table 6.5.

Table 6.5 - Model results for various levels of investment

Level of Investment (€/day)	Travel cost savings (€/day)	Intermediate stations and fleet investment (€/day)	Social net benefits (€/day)	Rail ridership (pax/day)	Average load factor (%)	Intermediate stations location	Number of trains			
							400 Pax	600 Pax	800 Pax	1000 Pax
≤10,000	335,107	9,317	278,523	12,359	79	-	2	1	0	0
≤15,000	361,519	14,502	299,750	14,577	94	CBR	4	0	0	0
≤20,000	388,067	19,826	320,974	17,446	85	CBR	3	2	0	0
≤25,000	404,133	23,680	333,186	21,210	75	LEI-CBR	0	4	0	0
≤30,000	420,527	29,004	344,256	23,384	77	LEI-CBR	0	4	1	0
≤35,000	437,546	34,189	356,090	24,577	74	LEI-CBR-OLA	0	3	2	0
≤40,000	448,635	39,513	361,855	26,342	76	LEI-CBR-OLA	0	3	3	0
≤45,000	454,183	44,837	362,079	26,856	74	LEI-CBR-OLA	0	3	4	0
≤50,000	455,103	48,691	359,145	28,498	77	RIM-LEI-CBR-OLA	0	3	4	0
≤55,000	457,985	54,015	356,703	28,855	76	RIM-LEI-CBR-OLA	0	3	5	0
≤60,000	461,429	59,200	354,962	29,548	76	ALQ-RIM-LEI-CBR-OLA	0	2	6	0
≤65,000	462,725	63,193	352,265	30,175	70	ALQ-RIM-LEI-CBR-OLA	0	2	6	0
≤70,000	462,940	68,709	346,964	30,011	67	ALQ-RIM-LEI-CBR-OLB-OLA	0	0	5	3
≤75,000	462,940	72,371	343,302	30,011	62	ALQ-RIM-LEI-CBR-OLB-OLA	0	0	3	5

For a level of investment of ≤45,000 Euros per day we obtain the *base solution* (it is the one with highest social net benefits – 362,079 Euros per day). If we increase the available budget in 25,000 Euros (≤70,000) the social net benefits decrease 4.17% (from 362,079 to 346,964 Euros), while, if we decrease the available budget in the same amount (≤20,000) the social net benefits reduction is quite significant, 11.17% (from 362,079 to 320,974) Euros. As one could expect, travel cost savings increases with investment. The maximum travel cost savings, 462,940 Euros (more 1.93% than 454,183 Euros) is obtained when the investment is 68,709 Euros (≤70,000). However, the ridership is lower (less 164 passengers) than the previous investment level, ≤65,000. From ≤70,000 on, the augmentation of the available budget would not increase the travel cost savings (see level ≤75,000). For an investment below 10,000 Euros no intermediate stations are built. The rolling stock acquired in this case is not enough to ensure eighteen trips per day in each direction (only seventeen train trips are made in each direction).

Figure 6.7 illustrates the budget invested to build intermediate stations and to acquire rolling stock units for each level of investment.

The number of intermediate stations selected goes up to six for an investment of 68,709 Euros per day (21,924 Euros of which are for intermediate stations). The optimal solution adds the stations Alenquer, Rio Maior and Oliveira do Bairro to the sites selected in the base solution (Leiria, Coimbra and Oliveira de Azeméis). Regarding the train fleet, as the available budget increases more train units or units with more capacity are selected. The average load factors vary accordingly to the fleet, but ensuring always percentages above seventy percent (except for level ≤70,000). The increase of the rolling stock capacity and the number of intermediate stations is the reason for the increase in train ridership.

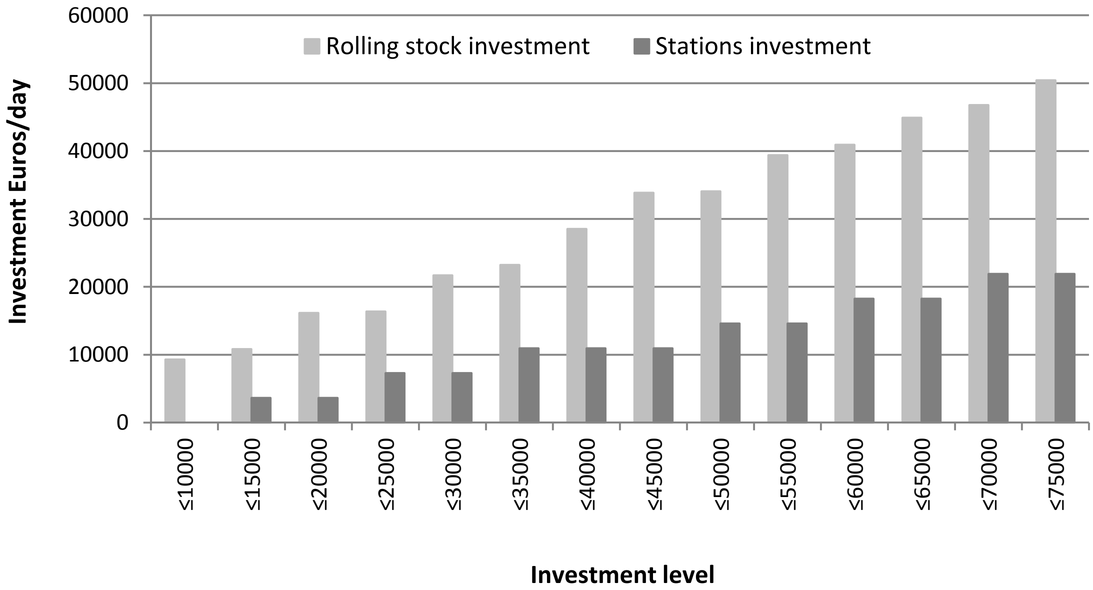

Figure 6.7 - Expenses in intermediate stations and fleet for various investment levels

6.7.4 RAVE solution

The *base solution* differs from the solution presented in most studies commissioned by RAVE that considers four intermediate stations: West Region, Leiria, Coimbra and the area of Aveiro. Though the West Region is not selected in the *base solution*, including Rio Maior (it is located in the West Region) in the solution would only represent a decrease of 0.81 per cent in the social net benefits with the same fleet (see Table 6.5). However, the area of Aveiro is never chosen as a station location. Furthermore, even the studies commissioned by RAVE (e.g. ATKEARNEY, 2003; SDG, 2007) raise some concern as to the exact location of the station in the area of Aveiro. Two alternatives are expressed: the city center of Aveiro and the town of Albergaria-a-Velha situated 15 kilometers east of Aveiro. Between the two alternatives REPOLHO et al. (2011b)/Chapter 5 show that Albergaria-a-Velha produces better results than the city center of Aveiro. In order to analyze the RAVE solution we have run the model imposing the location of the intermediate stations in Leiria, Coimbra, Albergaria-a-Velha and a forth in the West Region. Since the location of the station in the West Region is not yet defined in the studies commissioned by RAVE, we did not assume such a location. Instead, we added constraint (5.24) to the model to seek a compromise solution where a station in one of the sites located in the West Region (Alenquer, Rio Maior, Alcobaça and Batalha) is selected:

$$y_2 + y_3 + y_4 + y_5 + y_6 = 1 \qquad (5.24)$$

The results are displayed in Table 6.6.

Table 6.6 - Comparison between the RAVE solution and the *base solution*

	RAVE solution	Base solution
Social net benefits (€/day)	349,888	362,079
Investment (€/day)	89,303	92,104
Tickets revenues (€/day)	912,640	939,633
Rail ridership (pax/day)	27,126	26,856
Number of Trains 400 Pax	0	0
Number of Trains 600 Pax	4	3
Number of Trains 800 Pax	2	4
Number of Trains 1000 Pax	0	0
Average load factor (%)	82	74
Location of intermediate stations	RIM-LEI-CBR-AAV	LEI-CBR-OLA

Under these circumstances, the site selected to receive a station in the West Region is Rio Maior. With an investment that is less than three percent different from the *base* *solution*, the optimal solution comprises one additional station and one less train: two of 800 passengers and four of 600 passengers. The increase in one per cent of ridership (more than 260 passengers) and the use of trains in average with less capacity leads to a higher average load factor (82 per cent instead of 74 per cent). Nonetheless, the social net benefit decreases three per cent.

The optimal train timetable obtained for the RAVE solution (Figure 6.8) shows that most intermediate stops occur in Leiria or in Coimbra. The stations of Rio Maior and Albergaria-a-Velha are served by a fewer number of trains. Moreover, Rio Maior is mostly served in the direction Lisbon to Porto and Albergaria-a-Velha in the direction Porto to Lisbon. The total number of intermediate stops north of Coimbra, i.e. in Albergaria-a-Velha, is only eight while in the *base solution* there are twenty one stops in Oliveira de Azeméis.

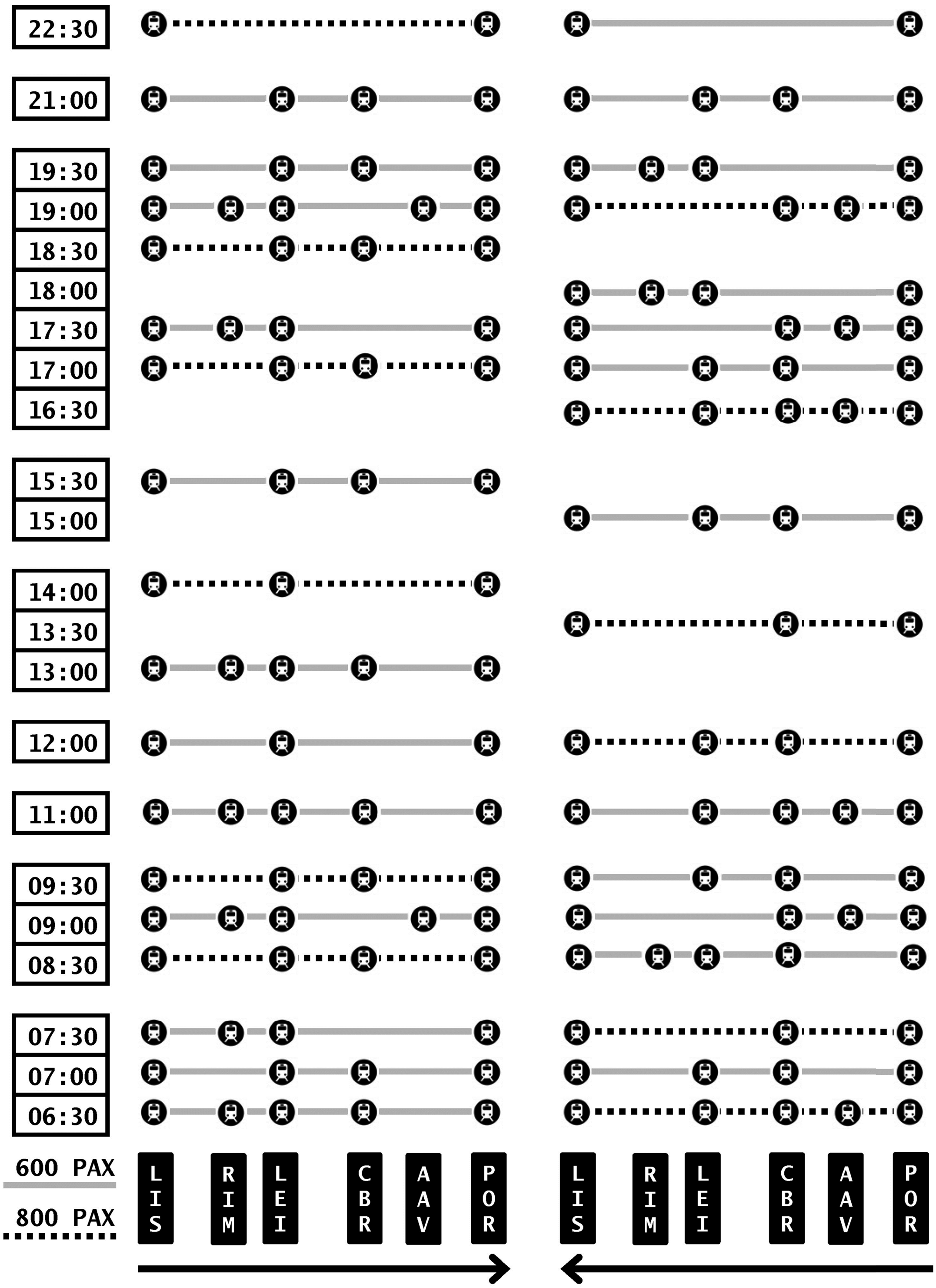

Figure 6.8 - Train timetable for RAVE solution

6.8 Conclusions

Effective railway strategic planning requires the integration of all the subsequent stages that may influence optimal investment. In this chapter we have presented a strategic railway planning model for infrastructure and fleet decisions that takes into account the dynamic relationship with demand and rail service issues. The study described in this chapter extends the analysis initiated in Chapter 5 (REPOLHO et al., 2011b), where only intermediate station locations were optimized.

The model integrates a number of railway planning sub-problems that, to the best of our knowledge, have never been dealt with simultaneously. In particular, investment decisions on the number and location of intermediate stations and fleet characteristics are optimized simultaneously with the design of the HSR line system, the master timetable, and the estimated volume of ridership captured by the new HSR line services. Regarding demand capture, three types of trips are considered based on the site where traffic originates, the access station where passengers take the train and whether or not it occurs in the desired time interval. Other important features considered within the model include the effect of travel time delays due to intermediate stops on travel demand, the (static) competition from other transportation modes, different stop-schedule patterns, dynamic characteristics of trains, standing time of trains in stations and intermodal transfer time at stations.

The results that can be obtained through the application of the model are well-illustrated through the application to the Lisbon-Porto new high speed line. This chapter provides a solution for the best location of stations and fleet characteristics along with the design of the optimal high speed rail service that should be provided in the Lisbon-Porto line. The results also call into question the solution adopted in a document recently released by RAVE.

Although we have integrated in this model several important features, there are a few that were not broached. The first and perhaps most important is the train conflict problem upon the design of the timetable. Also, it may be important to consider different construction costs for each intermediate station (based on total capacity of the station, land value, characteristics of the ground, natural adversities, etc.). This may affect the choice in the number and location of stations. Finally, we believe that it may be important to include constraints that reflect the expectation that passengers selecting service in one direction between two stations must be adequately served in the opposite direction.

Chapter 7

Conclusion

This thesis addressed the strategic planning of transportation infrastructure in the context of controlled entry transportation networks, specifically motorway and railway networks. The main problems dealt with were the determination of the optimal location for motorway interchanges and railway stations. Because of the long life span of transportation infrastructures, the large amount of money required for the investments, the difficulty to reverse, and the economic and social impact of such decisions, transportation infrastructure decisions need to be made carefully and if possible supported by analytical tools. The major contribution of this thesis is the development of a set of tools (optimization models) that can be used by transportation administrations or any other decision-makers for the planning of the location of the access points to controlled entry transportation networks.

The first objective defined in the research objectives section was fully accomplished. A set of optimization models applicable to the motorway interchange location problem was developed in Chapters 2, 3 and 4, and another set of optimization models applicable to the railway station location problem was developed in Chapters 5 and 6.

In Chapter 2 the motorway interchange location problem was modeled from the users' perspective. Three optimization models were formulated with the objective of determining the location for a given number of interchanges such that the total cost incurred by road users is minimized. Two of the models were formulated based on existing hub location models (not applied before to motorway interchange location problems). The third one is a new model based on the concept of a prescreened list of viable route alternatives and was formulated as a response to the computational difficulties encountered in solving the first two models. The application showed that this new model performs better than the other two models.

Chapter 3 extended the analysis initiated in Chapter 2 by changing the perspective from which the analysis was done and by including additional features to the analysis. Indeed, the models formulated in Chapter 3 are based in a hub location approach similar to the one used in Chapter 2 but with the objective of maximizing profit. Road users' travel behavior was also taken into account by using a travel behavior model where the additional traffic generated by the introduction of a motorway is considered and the role played by habit in route choice is recognized (in Chapter 2 travel demand was assumed to be inelastic, i.e. demand did not change according to the location of motorway interchanges).

Chapter 3 discussed several sources of risk and uncertainty that typically affect facility location decisions. The two stochastic models formulated, the SMILM and the *r*-SMILM, exemplify how one can evolve from a deterministic model to models that can cope with the risk inherent to motorway investments. The second stochastic model, *r*-SMILM, went even beyond the scope of traditional stochastic models by incorporating a robustness measure (relative regret). The potential relevance of the models is established and verified through the case study results.

Chapter 4 addressed the second major objective defined for the motorway interchange location problem, i.e. developing a model that takes simultaneously into account the public and private perspective in motorway interchange location problems. It combines and extends the models formulated in Chapters 2 and 3. The main body (constraints) of the DMILM model presented in Chapter 3 was used to formulate a new model. The objective function of the DMILM model was recast into a new set of constraints to ensure that a certain level of profit must be reached by the optimal solution. The objective function of the model maximizes the social welfare benefits through a consumers' surplus measure. The application of the model to the A25 case study allowed to identify highly satisfactory solutions for both public and private interests. The results proved that the model can be very useful to address the frequent conflict of interests that usually arise between the parties involved in BOT contracts, the government (public entity) and the concessionaire (private investor).

The railway station location problem was dealt with in Chapters 5 and 6. In Chapter 5 an optimization model was developed that determines the optimal location of railway stations such that the travel cost savings made possible by the introduction of a new railway line over an existing transportation network is maximized. The model developed in that chapter takes into account the impact on travel demand of time losses due to intermediate stops explicitly, the (static) competition from other transportations modes, and the generation of traffic due to the decrease in travel costs along with other features/characteristics of the railway mode such as access speed to stations, the dynamic characteristics of trains, the standing time of trains in stations, and the intermodal transfer time at stations. The combination of all of these features in one single optimization model had never been accomplished before in the literature and is therefore a major contribution of this thesis.

Chapter 6 added important features to the railway station location problem. The strategic infrastructure location model developed in Chapter 5 evolved into a strategic model with supporting tactical model components. The subsequent tactical problems that may influence strategic decisions were integrated in the optimization model. Specifically, the model optimizes the investment decisions on the number and location of intermediate stations and the fleet characteristics along with the design of the HSR line system (line planning) and a master timetable and the assessment of the volume of ridership captured by the new HSR line services. To the best of the author's knowledge there is no model that simultaneously optimizes infrastructure location decisions, fleet management and level of service provided (the latter concerns line planning, train scheduling and stop-schedules). The resulting model is therefore, we believe, an important asset to use in railway transportation network planning.

Hub location theory has been used in the literature in a wide variety of fields such as air transportation planning, telecommunications or rapid transit design (especially in a urban or suburban environment), but to the best of the author's knowledge it has never been applied to motorways or interurban railway lines. The content of chapters 2, 3, 4 and 5 pinpoint specific characteristics of these types of networks that make them ideal for applying hub theory. Indeed, in motorways or in railway lines (especially in high speed railway lines) the possibility of travelling much faster than in the alternative modes gives the inter-hub links (motorway or railway segments) the flow-independent discount.

Overall, the specific objectives defined for each type of controlled entry transportation network considered in this thesis (motorways and railway lines) were fulfilled.

The usefulness of the models proposed in this thesis was illustrated through the application to two academic examples based on real-world networks. The models formulated in Chapters 2, 3 and 4 for motorways were applied to one of the most important Portuguese motorways, the A25, formerly the IP5 (the conversion of the IP5 into A25 was concluded in 2006). The solution implemented converted 33 intersections of the old IP5 with other roads into motorway interchanges. The purpose of the case study was to assess whether it made sense to convert all those intersections into interchanges. The results obtained through the users' perspective model clearly show that most of the travel time savings could have been achieved by converting only a selected subset of the intersections. With just 11 interchanges (out of the 33 considered) the travel time savings would amount to almost 85% of the maximum possible savings. Using the concessionaires' perspective model (the DMILM) the maximum profit is obtained for a toll fee of 0.05 €/km and a solution with 20 interchanges. The multi-objective model (Chapter 4) was applied under the same circumstances and showed that this solution only guarantees 69.7% of the maximum achievable social welfare benefits (80,505 out of 115,525 Euros per day). By only diminishing the level of profit 1.7% (from 41,611 to 40,918 Euros per day) it is possible to guarantee 93.5 % (107,966 out of

115,525 Euros per day) of the possible social welfare benefits. These results are accomplished by locating three additional interchanges and moving the locations of a few others. Either way, the results demonstrate, once more, that the number of interchanges implemented in reality might have been excessive.

The models formulated in Chapters 5 and 6 were also applied to a Portuguese academic example based on a real-world case, the future Lisbon-Porto high speed railway line. Though the line has not been built yet, it has been the subject of several studies. Moreover there is already an outline for the line proposed by RAVE, the company responsible for the implementation of the HSR in Portugal. The optimal solution obtained through the models developed in this thesis does not match with the solution proposed by RAVE. The solutions differ in the number and location of the stations. With respect to the RAVE solution, the Oeste station is removed and the station in Aveiro is moved to Oliveira de Azeméis.

Though promising, the results obtained must be taken with caution because some of the academic case study assumptions might be a bit restrictive as mentioned in the respective chapters. Still, the results obtained clearly show that the optimization models formulated in this thesis may be quite useful during the planning process in order to examine transportation infrastructure investments in detail.

Finally, some comments about model solving issues. The models developed throughout this thesis had in common two types of decision variables: location and assignment. The latter frequently involve a considerable number of indexes. For instance: the MILM-C model developed in Chapter 2 uses assignment variables with four indexes to fully describe the road users' routes; the *r*-SMILM model developed in Chapter 3 uses assignment variables with five indexes to describe the road users' routes and respective fuel cost scenario; the model developed in Chapter 5 requires assignment variables with five indexes in order to characterize the passengers itinerary and the number of stops in transit; and the models developed in Chapter 6 make use of assignment variables with up to five indexes in order to characterize the trip origin center, the access station, the destination station, the type of train and the pattern of stop-schedule. When applied to real-world examples, as is the case in this thesis, such models become extremely large. Nevertheless, all models were solved optimally without resorting to the use of heuristic methods. Instead, we invested in searching for suitable and efficient alternative formulation structures and pre-processing techniques. The MILM-L is a good example of an alternative formulation that allowed solving the motorway interchange location problem to optimality. In the other chapters, we relied on special pre-processing and reductions techniques. These techniques were used with the objective of eliminating all superfluous variables and constraints, so that the models could be solved through optimization processes, such as off the shelf optimization software.

It is the author's belief that the models presented in this thesis can be, as they are, used to assist transportation administrations in their decisions about access points' location in controlled entry transportation networks. Nevertheless, at the end of each chapter several topics were raised that deserve further research. Some of the topics mentioned in the conclusions section of Chapters 2 and 5 have been addressed in Chapters 3 and 6, respectively. Still, some topics were left for future research.

The models presented in Chapters 2, 3 and 4 are based on the assumption that the road system is uncongested. Although, in general, this assumption may be valid for motorways (and motorway accesses) as they are typically designed to ensure high levels of service, there may be congestion issues to consider particularly in segments near large cities. Also, the road network that simultaneously feeds and competes with the motorway is more susceptible to suffer from congestion issues. The consideration of congestion would however make the models much more complex since they would have to be integrated with a road network design model (YANG and BELL, 1998). The resulting models would be nonlinear and much more difficult, if not impossible, to solve to exact optimality. Still, the development of such models cannot be dismissed because of the computational complexity alone and is an appealing research direction for future work.

Another key issue regarding the motorway interchange location models has to do with the uncertainty that characterizes long-term planning. Some risk issues involved in motorway interchange location problems were considered in Chapter 3 through the development of stochastic models. However, they were applied to simple scenarios, involving only one parameter. Real-world application studies would benefit from considering uncertainty in several parameters and a larger number of scenarios at the same time. Though the models here described are still essentially valid for scenarios involving several parameters, such expansion could make the models impossible to solve to exact optimality. Thus, the development of a heuristic algorithm is a potentially fertile area for future research.

A major gap in the rail transportation planning literature regards the integration of all sub-problems that may influence optimal investment decisions at a strategic level (CAPRARA et al., 2007). The models presented in this thesis introduced important innovations by combining several important features (dynamic demand, rolling stock management, line planning, train scheduling) on the pursuit of the integration goal. However, there are a few elements that were not considered. Probably, the most prominent is the train conflict problem. One of the outputs of the model presented in Chapter 6 is an optimized master timetable. Given the assumptions made in this study the train conflict problem could be neglected without losses upon the design of the timetable. However, for other applications this may not be true. That is the case of HSR lines with very frequent trains or track systems that are not exclusively exploited by HSR trains (such as Spain's AVE – *Alta Velocidad Española*).

There are also other improvements that can be made in order to better characterize reality and obtain more suitable solutions: consider different construction costs for each intermediate station based on the total capacity or throughput of the stations, land value, characteristics of the ground, natural adversities, etc.; include constraints to reflect the will of passengers to be served between two stations in opposite directions in different intervals of the day; and consider dynamic competition. With regard to the latter, the models developed in Chapters 5 and 6 do not consider any response from alternative transportation modes to the railway actions, i.e., only static competition is considered. Including dynamic competition is a hard task but would make the models more realistic and the solutions more reliable.

The research directions identified for both the motorway interchanges and the railway stations problems are certainly worth being pursued in order to make the models more accurate. Still, the author believes that the present thesis already offers a valuable contribution to the controlled access points' location planning problem. The case studies carried out with respect to the A25 motorway and the Lisbon-Porto high speed line clearly illustrate the capacity of the models already developed to support real-world decisions made by transportation network administrations or any other decision-makers.

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