

# A STUDY ON THE IMPROVEMENT OF THE SECONDARY ROAD NETWORK OF THE CENTRO REGION OF PORTUGAL

## UM ESTUDO SOBRE O MELHORAMENTO DA REDE RODOVIÁRIA SECUNDÁRIA DA REGIÃO CENTRO DE PORTUGAL

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### ABSTRACT/RESUMO

In last three decades, very large investments were made in the transformation of the main road networks of Portugal and Spain. In contrast, during the same period, little has been done with regard to the secondary roads. In this paper, we present a study aimed at determining the best way of improving the secondary road network of the Centro Region of Portugal. This is one of the regions of the country where some accessibility problems persist. The study was made using a multi-objective road network planning model. In relation to the road network planning models available in the literature, the one we applied has a number of important, distinctive features. The objectives considered were efficiency (evaluated by four different measures: average travel speed; weighted travel cost; consumers' surplus gains; and weighted aggregate accessibility), equity (evaluated by the Gini Index), and energy (evaluated by fuel consumption). An overview of the measures used in the past to evaluate road network efficiency and a discussion of the implications of adopting the four efficiency measures considered are also provided. The results for the Centro Region of Portugal indicate that solutions can be significantly different when using each of the efficiency measures. As a conclusion of this study, a brief reflection about how to incorporate the perspectives, interests and budgets of different countries in a border network is presented.

Keywords: Accessibility, multi-objective approach, optimization, road network planning.

*JEL Codes: R42 e C61.*

Na últimas três décadas, grandes investimentos foram feitos no melhoramento das redes rodoviárias principais de Portugal e Espanha. Em contraste, durante o mesmo período, pouco foi feito no que diz respeito às estradas secundárias. Neste artigo, apresentamos um estudo que visa determinar a melhor maneira de melhorar a rede de estradas secundárias da Região Centro de Portugal. Esta é uma das regiões do país onde alguns problemas de acessibilidade persistem. O estudo foi feito usando um modelo multiobjetivo de planeamento de redes rodoviárias. Em relação aos modelos de planeamento de redes rodoviárias presentes na literatura, o modelo usado tem uma série de características distintas importantes. Foram considerados objetivos de eficiência (avaliada por quatro medidas diferentes: velocidade média de viagem; custos de viagem ponderados; ganhos no excedente do consumidor; e acessibilidade total ponderada), de equidade (avaliada pelo índice de Gini) e de energia (avaliada pelo consumo de combustível). Apresenta-se uma revisão geral das medidas utilizadas no passado para avaliar a eficiência da rede rodoviária e é feita uma discussão sobre as implicações da adoção das quatro medidas de eficiência. Os resultados para a Região Centro de Portugal indicam que as soluções podem ser significativamente diferentes quando se usa cada uma das medidas de eficiência. Como conclusão deste estudo, é apresentada uma breve reflexão sobre como incorporar as perspetivas, interesses e orçamentos de diferentes países em redes de regiões transfronteiriças.

Palavras-chave: Acessibilidade, abordagem multiobjetivo, otimização, planeamento de redes rodoviárias.

*Códigos JEL: R42 e C61.*

## INTRODUCTION

The perspective of economic and geographic space has been always changing over time, people are traveling more and farther, job and labor dynamics have turned international, and commerce has become worldwide. Road transportation is probably one of the transportation sectors most affected with travel demand variations. Due to its high flexibility and the unique capability to provide door-to-door transportation, roads are the backbone of most transportation systems.

In the last three decades, very large investments were made in the transformation of the main road networks of Portugal and Spain. In contrast, during the same period, little has been done with regard to the secondary roads. The improvement of some of these roads will allow a significant increase in the accessibility to many of the population centers that have gained less from the investments already made.

In this paper, we present a study aimed at determining the best way of improving the secondary road network of the Centro Region of Portugal. This is one of the regions of the country where some accessibility problems persist. The analysis is carried out assuming that solutions are established by solving a road network design problem (RNDP). The RNDP is a widely studied optimization problem that consists in determining the best way of improving a road network according to some objective or objectives (Yang *et al.*, 1998). In the paper, we assume that the RNDP is handled through the multi-objective approach proposed in Santos *et al.* (2005), which is consistent with the planning framework adopted in the Highway Capacity Manual (TRB: 2000).

Several objectives are usually considered in the evaluation of road network planning solutions. One of the most important ones is efficiency – that is, in a simple definition for a complex concept, the ability of making the maximum possible benefits with the minimum possible costs (or given benefits at minimum costs, or maximum benefits at given costs). As it often happens with complex concepts, efficiency can be difficult to assess. This certainly is the reason why there is no single, standardized measure to assess the efficiency of a road network. Instead, there are several measures, highlighting different attributes of the road network. In this paper, we provide an overview of the measures used in the past to evaluate road network efficiency and discuss the implications of adopting the four measures of efficiency considered in the analysis (average travel speed; weighted travel cost; consumers' surplus gains; and weighted aggregate accessibility). In addition to the efficiency of the network, in our case study we consider two other objectives, maximization of equity (measured by the Gini Index) and minimization of energy (measured by fuel consumption), to take into account other important features of regional road network planning.

The structure of the paper is as follows. In the next section, we describe the optimization model used to represent the RNDP under consideration. Then, we provide

an overview of the efficiency measures used in the past and specify the efficiency measures considered in our study. Afterward, we present and discuss the implications of adopting different efficiency measures for a real-world case study: the improvement of the road network of the Centro Region of Portugal. In the last section, we offer some concluding remarks.

## OPTIMIZATION MODEL

The approach presented in Santos *et al.* (2009) upon which our study of efficiency measures is based relies on a multi-objective optimization model. The model has a number of particular features. First, as already mentioned, it is consistent with the planning framework of the Highway Capacity Manual. Second, it takes into account the fact that road capacity increases are discrete, defined according to a set of road levels (whereas most RNDP models assume them to be continuous). Third, it relies on an assignment principle different from the traditional user equilibrium principle, which we believe to be more appropriate when dealing with interurban trips: drivers will follow least-cost paths if the minimum level of service is verified for every link of the paths. Fourth and last, it assumes that travel demand is elastic with respect to both trip distribution and traffic induction. The model can be formulated as follows:

$$\max OF = w_z \times \frac{Z - Z_0}{Z_B - Z_0} + \sum_{i \in \mathcal{G}} w_{V^i} \times \frac{V_i - V_0^i}{V_B^i - V_0^i} \quad (1)$$

subject to

$$Z = \eta(\mathbf{y}) \quad (2)$$

$$V^i = \xi^i(\mathbf{y}) \quad (3)$$

$$T_{jk} = \theta \times P_j \times P_k \times C_{jk}(\mathbf{y})^{-\beta}, \forall j, k \in \mathbf{N} \quad (4)$$

$$Q_l = \sum_{j \in \mathbf{N}} \sum_{k \in \mathbf{N}} T_{jk} \times x_{jlk}, \forall l \in \mathbf{L} \quad (5)$$

$$\sum_{m \in \mathbf{M}_l} y_{lm}, \forall l \in \mathbf{L} \quad (6)$$

$$Q_l \leq \sum_{m \in \mathbf{M}_l} Q_{\max_m} \times y_{lm}, \forall l \in \mathbf{L} \quad (7)$$

$$\sum_{l \in \mathbf{L}} \sum_{m \in \mathbf{M}_l} e_{lm} \times y_{lm} \leq b \quad (8)$$

$$T_{jk}, Q_l \geq 0, \forall j, k \in \mathbf{N}, l \in \mathbf{L} \quad (9)$$

$$x_{jlk}, y_{lm} \in \{0, 1\}, \forall j, k \in \mathbf{N}, l \in \mathbf{L}, m \in \mathbf{M}_l \quad (10)$$

where (in order of appearance):  $OF$  is the normalized value of a solution;  $w_z$  is the weight attached to the efficiency objective;  $Z$  is the value of a solution in terms of the efficiency objective;  $Z_B$  is the best value obtained for the efficiency objective;  $Z_0$  is the worst value obtained for the efficiency objective;  $\mathcal{G}$  is the set of objectives considered in addition to the efficiency objective (e.g., maximization of equity, maximization of robustness, and minimization of fuel consumption);  $w_{V^i}$  is the weight attached to objective  $i$ ;  $V_i$  is the value of a solution in terms of objective  $i$ ;  $V_B^i$  is the best value obtained for objective  $i$ ;  $V_0^i$  is the worst value obtained for objective  $i$ ;  $\eta$  is the efficiency measure;

$y = \{y_{lm}\}$  is a matrix of binary variables equal to one if link  $l$  is set at road level  $m$  and equal to zero otherwise;  $\xi_i$  is the measure for assessing objective  $i$ ;  $T_{jk}$  is the estimated traffic flow from center  $j$  to center  $k$ ;  $\theta$  and  $\beta$  are statistical calibration parameters;  $P_j$  is the population of center  $j$  (or any other measure of the size of the center);  $C_{jk}$  is the (generalized) cost of traveling between centers  $j$  and  $k$ ;  $\mathbf{N}$  is the set of traffic generation centers;  $Q_l$  is the estimated traffic flow on link  $l$ ;  $x_{jke}$  are binary variables equal to one if link  $l$  belongs to the least-cost route between centers  $j$  and  $k$  and equal to zero otherwise [their values are obtained by solving a lower-level optimization model, see (Yang and Bell: 1998)];  $\mathbf{L}$  is the set of links;  $\mathbf{M}_l$  is the set of possible road types for link  $l$ ;  $Q_{max,m}$  is the maximum service flow for a link of road type  $m$ ;  $e_{lm}$  is the expenditure required to set link  $l$  at road type  $m$ ; and  $b$  is the budget.

The objective-function (Equation 1) of this combinatorial non-linear optimization model represents the maximization of the normalized value of the road network planning solution. This solution is obtained through the application of weights to the normalized values of the solutions. The weights are included to reflect the relative importance of the different objectives under consideration. The normalization of solution values is made considering the range of variation of solutions, but other normalization procedures could be used. The values of the solutions for the three objectives, as well as the normalized values, depend on the decisions made with regard to road types (which are represented with variables  $y$ ). Constraint (2) defines the efficiency measure as being dependent on the road type assigned to the various links of the network. Constraints (3) specify that the measures used to assess other objectives are also dependent on the road type assigned to the various links of the network. Traffic demand is calculated according to constraints (4) and the number of trips on each link is calculated according to constraints (5). Constraints (6) are included to guarantee that each link will be set at one, and only one, road type. For some links, it may be impossible or, particularly because of environmental concerns, undesirable to choose some road types. This is the reason why the set of road types ( $\mathbf{M}_l$ ) is indexed in the link. Constraints (7) are used to ensure that the maximum service flow is not exceeded by the traffic flow estimated for each link. Constraint (8) is included to guarantee that the cost of improving the network does not exceed a given budget. Expressions (9) and (10) define the domain for the decision variables.

## EFFICIENCY MEASURES

### LITERATURE OVERVIEW

Throughout time, a vast number of efficiency measures have been used for the assessment of transportation efficiency. These measures are surveyed in Levinson (2003), being classified there according to the perspective

of engineers, economists, managers, and planners. Below, we focus on measures that have been used within the context of RNDP.

Travel time is one of the efficiency measures considered more often. In particular, this is the measure retained in Leblanc (1975), the first article devoted to the RDNP. In this article, congestion is identified as the major cause for the poor performance of a (urban) road network and a model is proposed to define the optimum set of links that should be added to some network in order to minimize travel time. The same objective is used, for instance, in Abdulaal and Leblanc (1979) and, more recently, in Solanki *et al.* (1998), Poorzahedy and Abulghasemi (2005), and Kim *et al.* (2008). The latter addresses the RNDP from a multi-period perspective. In other articles, the minimization of travel time is combined with other objectives. Feng and Wu (2003) includes an equity objective together with the efficiency objective. The equity objective is to minimize the intraregional and interregional differences in the average travel speed at which trips between cities and their respective regional capitals take place. Chen and Alfa (1991) and Chiou (2005) consider the minimization of investment costs, measured in equivalent time units, together with the minimization of travel time. Cantarella and Vitetta (2006) addresses a multi-modal RNDP where CO emissions and travel time are both to be minimized. Ukkusuri *et al.* (2007) considers the minimization of travel time as the efficiency objective in a robustness approach to the RNDP with demand uncertainty.

Another efficiency measure widely present in the RDNP literature is travel costs (or user costs). The minimization of travel costs is the objective retained in Boyce and Janson (1980) under a budget constraint on investment costs. Janson *et al.* (1980) considers travel costs (shipping costs) within a multi-period planning approach developed to define future expansions and improvements of the U.S. interstate highway network. The studies described in Friesz *et al.* (1992), Tzeng and Tsaur (1997), and Meng *et al.* (2001) take investment costs not as a constraint but as a minimization objective, simultaneously with travel costs. In Ben-Ayed *et al.* (1992) and Friesz *et al.* (1993), other costs are added. The former contemplates the minimization of operating costs and accident costs, and the latter the minimization of travel distance and property expropriation. A recent study described in Kim and Kim (2006) presents a comprehensive cost approach to the multi-modal RNDP. This study assumes construction costs as a constraint, and considers the minimization of travel costs, vehicle-operating costs, accident costs, environmental costs, and maintenance costs as the objective.

In relatively recent years, consumers' surplus has often been used as an efficiency measure within the RNDP, following ideas first proposed in (Jara-Diaz: 1982; Kocur: 1982). It expresses the amount of money by which consumers value a good or service (trips) over and above its purchase price (travel cost). Jara-Diaz and Farah (1988) and William and Lam (1991) were the first to use it within a RNDP model.

Chen and Subprasom (2007) and Szeto and Lo (2008) consider the maximization of consumers' surplus together with the maximization of operator profits in the analysis of government policies to improve road networks. Yang and Bell (1997) and Szeto and Lo (2006) consider consumers' surplus as the efficiency measure to deal with the problem of defining the optimum toll pattern for a road network (the latter presents an interesting intergeneration equity approach to define tolling strategies and road investments).

Other efficiency measures have been used more rarely within an RNDP. These include average accessibility (Antunes *et al.*: 2003) and connectivity (Scaparra and Church: 2005). The concept of accessibility can be defined as the "potential of opportunities for interaction" (Hansen: 1959) or, more precisely, as a "measure of spatial separation of human activities, which denotes the ease with which activities may be reached using a particular transportation system" (Morris: 1969). The concept of connectivity can be defined as the easiness with which it is possible to reach all travel destinations from all travel origins (by a given type of road).

SELECTED MEASURES

For our study, we have selected the following four efficiency measures: average travel speed; weighted travel cost; consumers' surplus gains; and weighted aggregate accessibility. These measures are explained below in separate subsections.

AVERAGE TRAVEL SPEED

One of the main reasons to improve a road network is to increase the average travel speed at which trips are made. The average travel speed for a road network (ATS) is the ratio between the total travel length and the corresponding total travel time, and can be calculated through the following expression:

$$ATS(\mathbf{y}) = \frac{\sum_{j \in N} \sum_{k \in N} T_{jk}(\mathbf{y}) \times d_{jk}}{\sum_{j \in N} \sum_{k \in N} T_{jk}(\mathbf{y}) \times t_{jk}(\mathbf{y})} \quad (11)$$

where  $d_{jk}$  is the travel distance by the least-cost route between centers  $j$  and  $k$ ; and  $t_{jk}$  is the travel time by the least-cost route between centers  $j$  and  $k$ .

WEIGHTED TRAVEL COST

Travel costs are one of the main road network efficiency measures. However, the importance of these costs may be different depending on the travel destinations. In particular, it is important to distinguish the trips made from the different population centers of some study area to the respective national and regional capitals, because this is where the more specialized public services are provided. The weighted travel cost for a road network (WTC) is the weighted sum of travel costs involved in traveling to major

population centers, considering their functional hierarchic level. Weights are used to represent the relative importance of hierarchic levels. The WTC can be calculated through the following expression:

$$WTC(\mathbf{y}) = \sum_{j \in N} \frac{P_j}{P} \times \left[ \sum_{m \in H} w_m \times C_{jm}(\mathbf{y}) \right] \quad (12)$$

where  $P$  is the total population of the study area;  $H$  is the set of hierarchic levels;  $w_m$  is the weight assigned to hierarchic level  $m$ ;  $C_{jm}$  is the (generalized) cost of traveling by the least-cost route between center  $j$  and its respective capital at hierarchic level  $m$ .

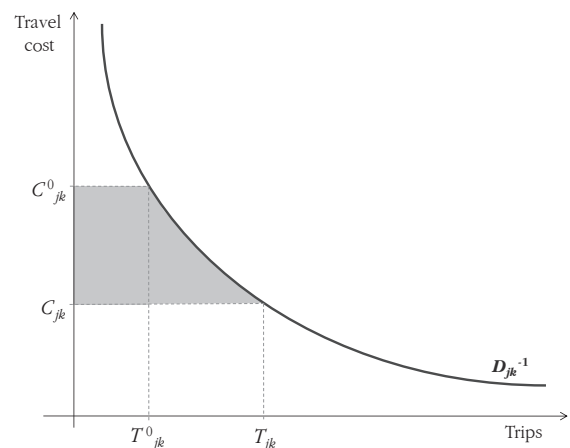
CONSUMERS' SURPLUS GAINS

Consumers' surplus is widely considered in the economic literature, as the measure upon which the assessment of the net social benefits derived from public investments should be based. The consumers' surplus gains (CSG) associated with the improvement of a road network is the sum of the consumers' surplus gains obtained for each center of the network considering the trips made to all other centers. The gain for each O/D pair is the shaded area in Figure 1. The CSG can be calculated as follows:

$$CSG(\mathbf{y}) = \sum_{j \in N} \sum_{k \in N} \left[ \int_{T_{jk}^0}^{T_{jk}} D_{jk}^{-1}(v) dv - C_{jk}(\mathbf{y}) \times (T_{jk}(\mathbf{y}) - T_{jk}^0) \right] + T_{jk}^0 \times (C_{jk}(\mathbf{y}) - C_{jk}^0) \quad (13)$$

where  $T_{jk}^0$  is the initial traffic flow from center  $j$  to center  $k$  (before improvement);  $D_{jk}^{-1}$  is the inverse demand function for O/D pair  $j/k$  ( $D_{jk}^{-1} = [\theta \times P_j \times P_k / T_{jk}]^{1/\beta}$ ); and  $C_{jk}^0$  is the initial cost of traveling between centers  $j$  and  $k$ .

FIGURE 1. CONSUMERS' SURPLUS GAIN FOR EACH O/D PAIR



WEIGHTED AGGREGATE ACCESSIBILITY

Accessibility is a measure used very often in geographic studies involving the improvement of road networks (Holl: 2007; Keeble *et al.*: 1982; Vickerman *et al.*: 1999).

The accessibility of a population center is a gravity-based measure that increases with the population of neighboring centers (or any other suitable indicator of the importance of the activities carried out there), and decreases with the travel time or cost needed to reach the centers. The weighted aggregate accessibility (WAA) is the sum of the accessibilities of the centers weighted by their population and divided by the total population of the study area, and can be calculated as follows:

$$ACC(\mathbf{y}) = \sum_{j \in N} A_j \times \frac{P_j}{P}, \text{ with } A_j = \sum_{k \in N \setminus j} \frac{P_k}{C_{jk}(\mathbf{y})^\beta} \quad (14)$$

where  $A_j$  is the accessibility of center  $j$ .

## CASE STUDY

### PRESENTATION

A (hypothetical) case study based on the road network of the Centro Region of Portugal is used to illustrate the implications of adopting different efficiency measures. The Centro Region of Portugal is one of the five planning regions of Continental Portugal. The main road network of the region was significantly improved in the last 20 years within the framework of PRN 2000 (PRN are the initials of *Plano Rodoviário Nacional*). The plan defined the national (and international) road corridors connecting the major Portuguese cities, borders and ports. However, the Centro Region secondary network, which is necessary to ensure the connection of smaller cities to the main road network and is deemed to be of great importance for the economic vitality of the region, has not been changed accordingly. The case study consists in discussing the road investments that should be done to enhance the quality of the region's secondary network. Possible improvements of the main road network are also discussed. This case study was firstly introduced and presented in detail in Santos (2009).

The Centro Region of Portugal involves eight administrative districts. The districts, their capitals, and the other population centers are depicted in Figure 2. Some population centers located in the south of the Centro Region have their district capitals outside the Centro Region (Santarém and Lisboa). This happens because the regional borders, and in particular the Centro Region border, are not coincident with the borders of administrative districts.

The reference road network adopted in this study is shown in Figure 3. The figure depicts the main roads connections between the municipalities of the Centro Region (represented by their main towns), the rest of Portugal (represented by the main cities of the other regions), Spain (represented by the capitals of autonomous communities, except for País Vasco, La Rioja, and Navarra, which are represented by a single center), and the rest of Europe (represented by Paris). This network comprises 196 nodes (124 population centers plus 72 nodes corresponding to

road intersections) and 334 links (261 inside the Centro Region and 73 outside).

The size of the population centers was assumed to be equal to their population forecasts for 2015 (Eurostat: 2006; INE-P: 2004; INE-S: 2005), multiplied by 0.15 in the case of foreign population centers to reflect cross-border traffic decay effects.

The current Centro Region road network (2007) has a total length of 3794.2 kilometers (km) – 2429.0 km of slow two-lane roads, 429.4 km of fast two-lane roads, and 935.8 km of four-lane freeways. The reference road network includes an additional 82.8 km, corresponding to projected national roads (which are included in PRN 2000 but are yet to be built). A synthesis of the design characteristics of the different road levels is presented in Table 1.

The budget for road infrastructure investment was taken to be 3500 monetary units, which is the cost of building 1750 km of new fast two-lane highways on flat terrain. The costs per kilometer for road construction and upgrading in flat terrain are presented in Table 3.2. In mountainous areas (that is, all the region except for a stretch of land of approximately 50 km along the Atlantic coastline) these unit costs were doubled to represent the additional difficulties of construction.

Travel costs were calculated assuming average vehicle costs of 0.36 Euros per kilometer and average time costs of 6.0 Euros per hour.

Traffic volumes were calculated assuming an impedance parameter ( $\beta$ ) of 1.5, as proposed by Antunes *et al.* (2003) for the Portuguese national road network. The scaling parameter ( $\theta$ ) was calibrated using the traffic counts provided by the Portuguese road authority – EP [9] – and was taken equal to 0.35.

FIGURE 2. CENTRO REGION DISTRICTS



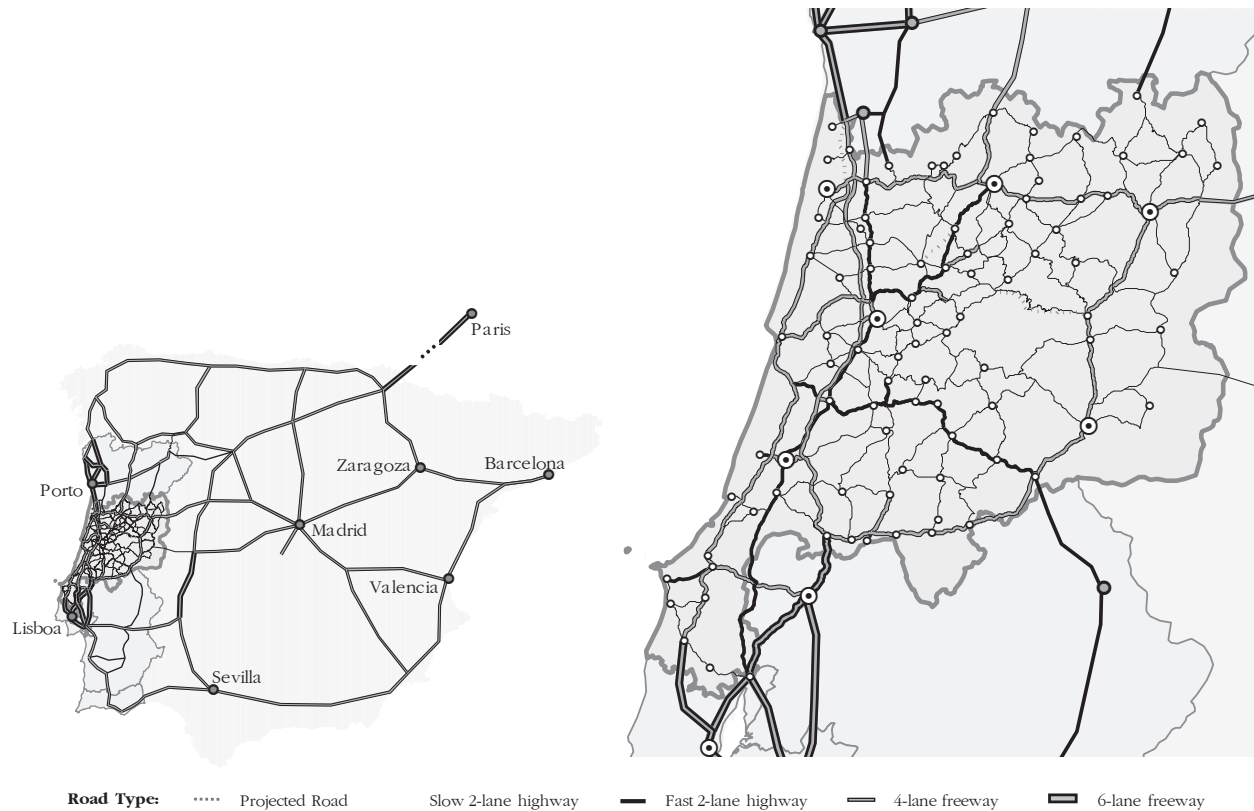
The discussion of road network investments in the Centro Region is made considering not only efficiency objectives (assessed through the four measures presented in the previous section, that is, average travel speed, weight-



ed travel costs, consumers' surplus gains, and weighted aggregate accessibility), but also equity objectives and energy objectives. Half of the priority is given to the efficiency

objective and the other half is given to the two other objectives (weights of 50/100 for the efficiency objective and 25/100 for the other objectives).

**FIGURE 3. REFERENCE ROAD NETWORK**



**TABLE 1. DESIGN CHARACTERISTICS FOR THE DIFFERENT ROAD TYPE**

Road type	Free-flow speed	Capacity	Level of service	Maximum service flow	Maximum service speed
	[km/h]	[pcu/h/lane]		[pcu/h/lane]	[km/h]
Slow two-lane highway	70	1 700	D	255	55
Fast two-lane highway	90	2 100	C	1 428	90
Four-lane freeway	120	2 400	B	1 320	120
Six-lane freeway	120	2 400	B	1 320	120

**TABLE 2. ROAD CONSTRUCTION AND UPGRADING COSTS PER KILOMETER**

From	to			
	Slow two-lane highway	Fast two-lane highway	Four-lane freeway	Six-lane freeway
Projected road	1	2	3	4
Slow two-lane highway	–	1,5	2,5	3,5
Four-lane highway	–	–	2	3
Six-lane highway	–	–	–	1

The weighted travel costs were calculated considering the following weights: 40% for the district capital, 25% for the Centro Region capital (the city of Coimbra), 25% for the Portuguese capital (the city of Lisboa), and 10% for the closest population center located abroad.

The equity measure used in the study was the Gini Index, one of the measures used more often in social and economic inequality studies (Santos *et al.*: 2009; Xu: 2004). This coefficient takes values in the interval [0, 1], with zero corresponding to a fully equitable situation. It can be calculated through the following expression:

$$\xi^1(\mathbf{y}) = \frac{\sum_{j \in N} \sum_{k \in N} |Z_j(\mathbf{y}) - Z_k(\mathbf{y})|}{2n^2 \bar{Z}} \quad (15)$$

where  $\xi^1$  is the Gini Index value (objective 1);  $Z_j$  is the efficiency solution value for center  $j$  (e.g., the average speed for travel between center  $j$  and the other centers of the network);  $n$  is the number of centers that belong to  $N$ ; and  $\bar{Z}$  is the average efficiency value of the centers that belong to  $N$ .

The energy measure used in the study was the average fuel consumption in the network, given through the following expression:

$$\xi^2(\mathbf{y}) = \frac{\sum_{l \in L} F_l(\mathbf{y}) \times Q_l(\mathbf{y}) \times L_l}{\sum_{l \in L} Q_l(\mathbf{y}) \times L_l} \quad (16)$$

where  $\xi^2$  is the average fuel consumption in the network (objective 2);  $F_l$  is the average fuel consumption for link  $l$ ; and  $L_l$  is the length of link  $l$ .

The average fuel consumption for each link was calculated using the well-known COPERT model (European Commission: 1999). We considered the current composition of the Portuguese fleet and run COPERT assuming different average (steady) speeds in highways and rural roads. With the values of fuel consumption obtained for the different speeds, we calibrated a quadratic function to measure the relationship between fuel consumption and speed. The result was as follows:

$$F = 97.055688 - 1.273995 \times S + 0.008036 \times S^2 \quad (R^2 = 0.938) \quad (17)$$

where  $F$  is the fuel consumed (expressed in grams of oil equivalent per kilometer);  $S$  is the average speed; and  $R^2$  is the correlation coefficient (note that, according to this expression the lowest fuel consumption is achieved for a travel speed of 79.3 km/h).

## RESULTS

The optimization model presented above was applied to the case study. For solving the model we used the enhanced genetic algorithm (EGA) presented in Santos *et al.* (2005). The computation of the optimum solution for each one of the four efficiency measures under consideration

took 3 to 6 days on an Intel Dual Core 6700 microprocessor running at 2.66 GHz.

The optimum solutions are depicted in Figure 4. Some similarities can be found in the solutions. For example, the fast two-lane highway between Leiria and Lisboa is upgraded to a four-lane freeway (and even to a six-lane freeway in the southern part of the Centro Region). The four-lane freeway connection between Lisbon and Porto is widened to a six-lane freeway in the north of Aveiro and next to Coimbra. Other similarity is the construction of the road projected near Aveiro as a four-lane freeway. None of the solutions involves the construction of the projected road in the south of Viseu. The projected road located in the edge of the districts of Guarda, Castelo Branco, and Coimbra, would be built as a fast two-lane highway if accessibility is selected as the efficiency measure (Figure 4b).

A summary of the results obtained for the four efficiency measures is presented in Table 3. The solution that maximizes average speed is the one with largest length of freeways – 1314.8 km of four-lane freeways and 60.1 km of six-lane freeways –, closely followed by the solution that minimizes weighted travel costs – 1296.1 km of four-lane freeways and 70.7 km of six-lane freeways. The solution with the largest length of two-lane highways is, by far, the one that maximizes consumers' surplus – 1419.7 km, more 225.4 km than the solution that maximizes accessibility (which is the one with the second largest length of two-lane highways).

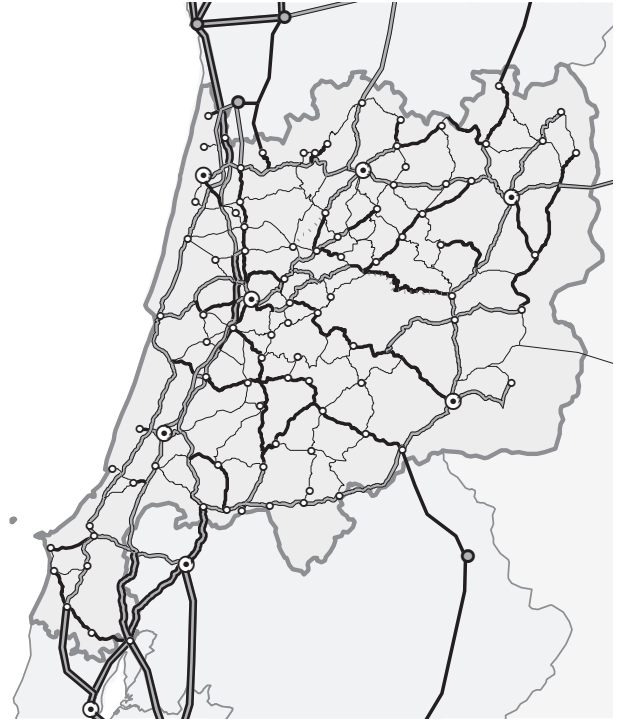
The maximum possible gain for average speed is approximately 4.0% (obtained when the efficiency measure is the average speed). The gain reduces to 2.9% when the objective is to maximize consumers' surplus. With regard to weighted travel costs, the maximum possible gain is also 4.0%. The gain falls down to 3.6% when the efficiency measures are consumers' surplus or accessibility. The maximum possible consumers' surplus gain is 41.65 units. This gain reduces to 39.41 when the efficiency measure is accessibility. Finally, with regard to accessibility, the maximum possible gain is 9.8%. This gain shrinks to 7.7% when the objective is to maximize consumers' surplus. From these results, it can be concluded that, for this particular case study, consumers' surplus was the more comprehensive measure, with good results regardless of the measures used to express the efficiency objective.

The largest gains for the equity objective are obtained when the efficiency measure is average speed – the Gini Index decreases by 60.2%. Comparatively, the weighted travel cost and the accessibility measures lead to very small gains. In terms of the energy objective, the two solutions with the largest length of freeways are the worst ones – fuel consumption increases by 0.3% in the weighted travel cost solution and by 0.9% in the average speed solution. In contrast, for the consumers' surplus and the accessibility solutions, fuel consumption decreases by 0.4 and 0.3%, respectively.

FIGURE 4. BEST SOLUTION FOR THE DIFFERENT EFFICIENCY OBJECTIVES



(a) Average Speed, Gini Index, and fuel consumption



(b) Weighted travel costs, Gini Index, and fuel consumption



(c) Consumers' surplus, Gini Index, and fuel consumption



(d) Accessibility, Gini Index, and fuel consumption

**Road Type:**    ..... Projected Road    — Slow 2-lane highwas    — Fast 2-lane highway    — 4-lane freeway    — 6-lane freeway

In order to compare pairs of road network solutions, we defined the following similarity index:

$$S(u,v) = \frac{\sum_{l \in L} L_l \times \Delta_l^{uv}}{\sum_{l \in L} L_l} \quad (18)$$

where  $S$  is the similarity index,  $u$  and  $v$  are a pair of solutions (the optimum networks obtained for two different efficiency measures) and  $\Delta_l^{uv}$  is the difference of levels for link  $l$  in solutions  $u$  and  $v$ . The value of this index is always higher or equal to zero. The lower its value is, the closer the two solutions are of being exactly similar.



TABLE 3. SUMMARY OF RESULTS FOR DIFFERENT EFFICIENCY MEASURES

Reference Network			Solution							
			1		2		3		4	
			Value	Variation	Value	Variation	Value	Variation	Value	Variation
Road type length	Projected road	82,8	64,8	-21,7%	64,8	-21,7%	64,8	-21,7%	19,8	-76,1%
	Slow two-lane highway	2 429,0	1 451,6	-40,2%	1 448,4	-40,4 %	1 222,5	-49,7%	1 400,8	-42,3%
	Fast two-lane highway	429,4	985,7	129,5%	997,1	132,2%	1 419,7	230,6%	1 194,3	178,1%
	Four-lane freeway	935,8	1 314,8	40,5%	1 296,1	38,5%	1 099,4	17,5%	1 191,5	27,3%
	Six-lane freeway	0,0	60,1	-	70,7	-	70,0	-	70,7	-
Efficiency measures	Average speed	111,24	115,64	4,0%	113,86	2,4%	114,52	2,9%	114,30	2,8%
	Weighted travel cost	66,75	64,39	-3,5%	64,11	-4,0%	64,35	-3,6%	64,38	-3,6%
	Consumers' surplus gains	0,0	38,91	-	33,90	-	41,65	-	39,41	-
	Accessibility	7,91	8,49	7,3%	8,33	5,3%	8,52	7,7%	8,69	9,8%
Other objectives	Equity (Gini Index)	-	-	-60,2%	-	-6,8%	-	-	-	-3,2%
	Fuel consumption	57,75	58,28	0,9%	57,93	0,3%	57,53	-0,4%	57,58	-0,3%

Note: Solution 1 – average speed, Gini Index, and fuel consumption; Solution 2 – weighted travel costs, Gini Index, and fuel consumption; Solution 3 – consumers' surplus gains, Gini Index, and fuel consumption; Solution 4 – weighted aggregated accessibility, Gini Index, and fuel consumption.

The similarity indexes for the Centro Region case study are presented in Table 4. The solutions more different from the initial network is the one obtained for the accessibility measure, which is quite similar to the one obtained for the

consumers' surplus measure. The two less similar solutions are obtained for the weighted travel cost and the average speed measures (despite being two solutions with similar lengths for roads of the same type).

TABLE 4. SIMILARITY INDEX FOR EACH PAIR OF SOLUTIONS

Current Network		Solution				
		1	2	3	4	
Current Network	-	0,390	0,392	0,399	0,400	
Solution	1	0,390	-	0,400	0,272	0,279
	2	0,392	0,400	-	0,368	0,348
	3	0,399	0,272	0,368	-	0,201
	4	0,400	0,279	0,348	0,201	-

Note: Solution 1 – average speed, Gini Index, and fuel consumption; Solution 2 – weighted travel costs, Gini Index, and fuel consumption; Solution 3 – consumers' surplus gains, Gini Index, and fuel consumption; Solution 4 – weighted aggregate accessibility, Gini Index, and fuel consumption.

## CONCLUSION

In this paper, we present a study aimed at determining the best way of improving the secondary road network of the Centro Region of Portugal. The study was based on a multi-objective model developed for helping road authorities in their strategic decisions regarding the improvement of road network planning.

The road network of the Centro Region of Portugal was used as case study for testing the sensitivity of road network planning solutions to four measures that can be adopted for assessing their efficiency: average travel speed; weighted travel costs; consumers' surplus gains; and weighted aggregate accessibility. The analysis was carried out assuming that solutions are established by solving

a road network design problem. Equity and energy objectives were added to the efficiency objective to take into account other important features of road network planning. The results show that, depending on the efficiency measure used, the optimum solution can be considerably different. The solutions obtained when average speed and weighted travel costs were used as efficiency measures included the largest length of freeways. However, the roads improved in the two cases are quite different and, in fact, these are the less similar of the solutions obtained for the four measures. The accessibility solution is the more different in comparison with the initial network. The consumers' surplus solution was characterized with the best results with regard to the other efficiency measures.

The case study allows us to conclude that caution is required when defining road network efficiency. The choice of the measure should reflect the goals and the concerns for the specific network and territory under analysis. The simultaneous consideration of more than one efficiency measure can be recommendable. This issue will be addressed in future works.

A future enhancement of the proposed approach would be to consider transboundary networks, in which different national or regional authorities would rule contiguous sub-networks. The study of a transboundary road network would be possible with the model presented, needing only some minor adaptations. The budget should be subdivided and assigned each part to some specific sub-networks of the transboundary road network. The objective function should reflect the interest of both states from the different sides of the border and the common interest of increasing the cross-border accessibility. This could be done, for instance, by considering the increase of accessibility between population centers of the two countries as one of the objectives.

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