OPTROAD: A COMPUTER PROGRAM FOR INTERURBAN ROAD NETWORK PLANNING

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ABSTRACT

In this paper, we present *OptRoad*, a user-friendly, optimization-based computer program aimed at helping transportation authorities in the long-term interurban road network planning. The core of *OptRoad* is an optimization model with a multi-level (discrete) nature, in which roads are defined according to some hierarchy (e.g., freeways, fast highways, and slow highways). Road investments are decided taking into account the planning framework typically used in practice, which is based on the concept of level of service. In addition, the optimization model can enclose more than one objective – equity, robustness, and energy objectives can be added to the traditional efficiency objective. The applicability of *OptRoad* is illustrated through an academic example based on a main road network of the state of Parana, Brazil. This case study was included to clarify the type of results that can be expected when the proposed approach is used. As illustrated by the Brazilian case study, we believe that *OptRoad* can be a helpful computational tool to help decision makers in the long-term planning of interurban road networks. Although it is not yet in a final version, *OptRoad* has already a stable version and, with few improvements, can easily be used by third party users.

1 INTRODUCTION

Road transportation is a key factor in modern economies. While most developed countries already have very good road networks, this is certainly not the case with countries like Brazil, China, India, and most Eastern European countries. The high economic growth rates that characterized these countries in the recent past will be difficult to sustain if their road networks are not strongly improved. The renovation of these road networks requires a huge amount of money, and therefore should be carefully planned.

The alternatives involved in the improvement of a road network are often extremely large and can only be handled efficiently with recourse to optimization modeling. The optimization models applicable to network planning (or design) problems, which are often considered to be among the most difficult to solve, have been the object of intense research over the last thirty years (Yang and Bell 1998). Road network planning models are typically aimed at determining the best way of allocating a limited budget to the improvement of a road network, in order to achieve some objective or objectives. For most studies on the subject reported in the literature, the objective is to minimize costs (see, e.g., Janson *et al.* 1991). But other objectives have been considered, including accessibility

(Antunes *et al.* 2003), connectivity (Scaparra and Church 2005), equity (Feng and Wu 2003), and robustness or reliability (Chootinan *et al.* 2005).

In this paper, we present *OptRoad*, a user-friendly, optimization-based computer program for long-term interurban road network planning. The paper is organized as follows. In the next section, we explain the planning approach upon which *OptRoad* is built. Then, we introduce *OptRoad* through a detailed description of the data inputs it requires, the solution methods it can apply, and the result outputs it provides. Next, we describe an example of application of *OptRoad* to the road network of the state of Parana, Brazil. In the final section, we provide some concluding remarks.

2 PLANNING APPROACH

The approach to road network planning adopted within *OptRoad* has the following four main features (explained in detail in Santos *et al.* 2009).

First, the road networks are represented with a set of nodes connected by a set of links. The nodes correspond to the urban centers served by the network, as well as to road intersections located outside them. The links correspond to existing (direct) road connections between nodes, as well as to possible future connections. The existing links are classified according to previously defined road types, e.g.: slow two-lane roads; fast two-lane roads (with passing lanes, truck lanes, grade-separated intersections, etc.); four-lane roads; etc. The set of road levels that can be assigned to links may differ from link to link. For example, for links located (or to be built) in environmentally sensitive areas, the road levels with higher speeds may be disabled.

Second, the solution for the improvement of the road network is determined assuming that trips are made through least-cost paths at the minimum service speed (MSS) consistent with the level of service (LOS) required for each road type. According to the Highway Capacity Manual (TRB 2000), LOS is a qualitative measure of the operational conditions of a traffic facility, and is characterized with a maximum traffic flow, a maximum traffic density, and a maximum average speed. The planning solution must be feasible from the budgetary standpoint. That is, the total expenditure involved in the planning solution must not exceed the available budget.

Third, the travel demand of the (improved) road network is estimated through one of two methodologies: the first, by using an unconstrained gravity model calibrated for reference hourly traffic volume – e.g., the 30th highest hourly traffic volume as proposed by the Highway Capacity Manual; the second, by introducing the estimated O/D matrix with the current travel demand and using the gravity model to estimate the trips induced by road improvements. As stated before, trips are assumed to be made through least-cost paths at the MSS consistent with the LOS required for each road type. Therefore, after the traffic assignment, the LOS required for each link (which depends on the level of the link) must be checked. If the LOS is violated for any link, the solution is unfeasible and a penalty is applied to the solution value.

Fourth, the determination of the best solution is made by solving a non-linear combinatorial optimization model (Santos *et al.* 2009). The decision variables of the model represent the construction of new links of a given type, and the upgrading of existing links to a better type and the objective-function evaluates the solution in terms of efficiency, equity, robustness, and fuel consumption measures, using the well-know weighting method (Cohon 2004). In this manner, the solution value, *V*, is calculated as follows:

$$V = w_Z \times \left(\frac{Z - Z_{\min}}{Z_{\max} - Z_{\min}} \right) + w_E \times \left(\frac{E - E_{\min}}{E_{\max} - E_{\min}} \right) + w_R \times \left(\frac{R - R_{\min}}{R_{\max} - R_{\min}} \right) + w_F \times \left(\frac{F - F_{\min}}{F_{\max} - F_{\min}} \right) \qquad (1)$$

where *Z*, *E*, *R*, and *F* are the values of the solution in terms of efficiency, equity, robustness, and fuel consumption measures, respectively; w_Z, w_E, w_R, and w_F, are the weights attached to each objective; Z_{max}, E_{max}, R_{max}, and F_{max}, are the best values for the solution in terms of each objective in previous iterations; Z_{min}, E_{min}, R_{min}, and F_{min}, are the worst values for the solution in terms of each objectives in previous iterations. The initial best and worst values are obtained through the generation of an initial sample of random solutions (with a number of solutions equal to five times the number of links in the network).

3 THE OPTROAD PROGRAM

OptRoad is a user-friendly, optimization-based program coded with *Microsoft Visual Basic*®. Within this section, we will present the program with the help of a small academic example that we will call Country Y (Figure 1). This example considers the road network of a hypothetical country of six centers, A, B, …, F, as well as the linkages with a foreign country represented with the node W.
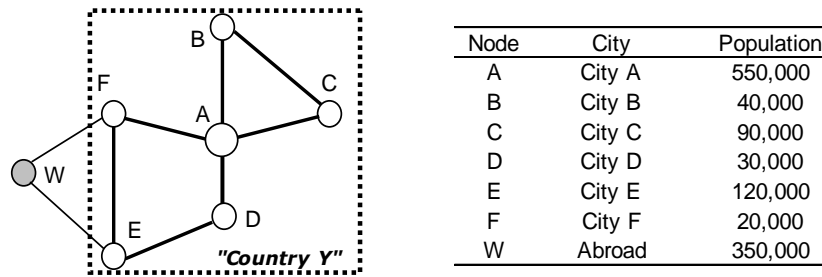

Node	City	Population
A	City A	550,000
B	City B	40,000
C	City C	90,000
D	City D	30,000
E	City E	120,000
F	City F	20,000
W	Abroad	350,000

Fig. 1 - Country Y example

3.1 Problem Data

Once the program starts, after an introduction window, the Main Window of *OptRoad* appears to the user (Figure 2). The core of the program is controlled through this window. All other windows will come from or into this main window.

Most of the information needed to run *OptRoad* should be input through a *Microsoft Excel*® file or any other compatible format. This is the case of data relative to the nodes (location and population), the links (start and end nodes, length, road type and land type) of the road network, the objectives considered and the corresponding measures, the budget available, the construction costs, and the gravity model parameters. A schematic picture of the network is shown on the left side of the window once the file is uploaded.

The information related to the problem to be solved can be edited through the Problem Data Window, which can be activated in the Data menu of the Main Window. The Problem Data Window consists of four tab windows: Objective Settings; Network Settings; Road/Travel Settings; and Cost/Budget Settings.
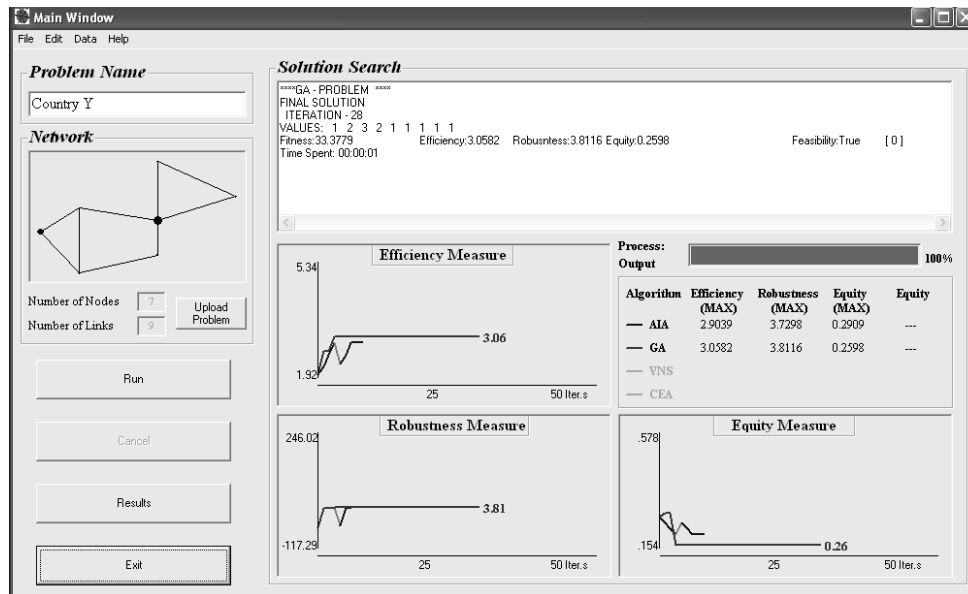
Fig. 2 Main Window

In the Objective Settings tab window (Figure 3a), the user can specify the measures and weights to associate with the objectives. Several measures can be chosen for each objective. For the efficiency objective, the user can choose either to maximize the weighted accessibility of urban centers, to maximize the average speed for the road network, to maximize consumers' surplus, or to minimize the weighted distance between urban centers and the closest capitals (at maximum, four different administrative levels). For the robustness objective, the user can choose either to maximize the number of links with a given percentage of spare capacity, to maximize the capacity of evacuation in each city, or to minimize the network vulnerability. For the equity objective, the user can choose to maximize the gains of the urban centers with the lower efficiency, to maximize the Gini Index of urban centers efficiency, or to minimize the standard deviation of centers efficiency. Finally, for the fuel consumption objective, the user can add the minimization of fuel consumption to the previous objectives.
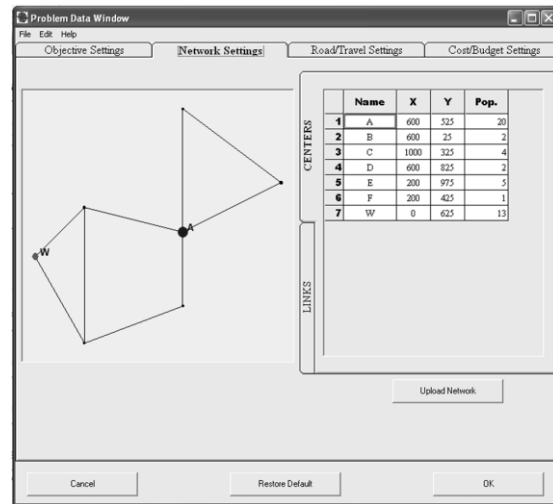
In the Network Settings tab window (Figure 3b), the user can see the display of the network, in addition to the information previously input to define the network.

In the Road/Travel Settings tab window (Figure 3c), the user can define the road types, and the number of lanes, the practical capacity per lane, the free flow speed, and the level of service (LOS) required for each road type. The user can also define in this tab window the parameters of the unconstrained gravitational model employed to predict the traffic flow changes that can be expected to occur as a consequence of road network improvements.
In the Cost/Budget Settings tab window (Figure 3d), the user can introduce the unit costs of construction and upgrading for roads of the different types considered, as well the budget available for the improvement of the road network.
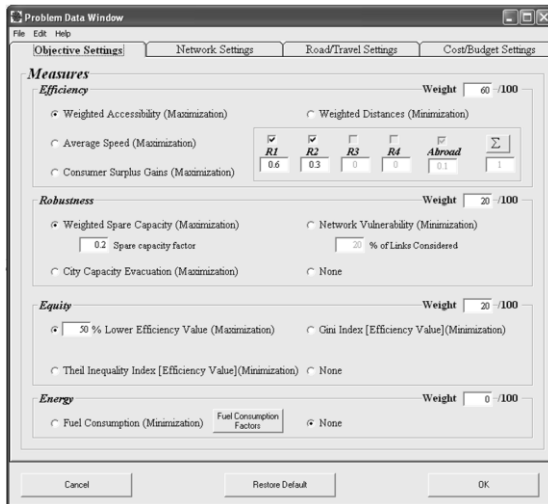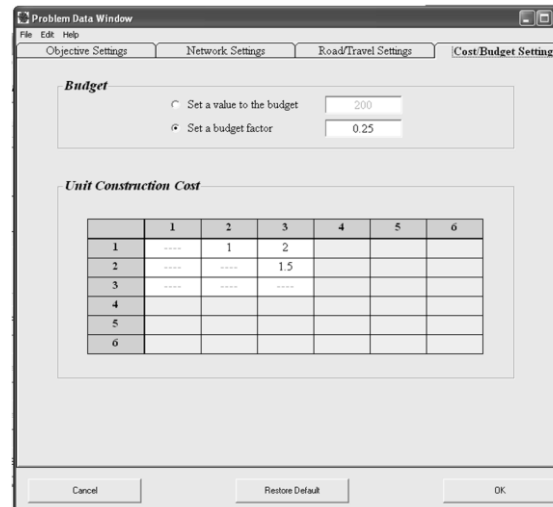
(a) Objective Settings tab window

(b) Network Settings tab window

(c) Road/Travel Settings tab window

(d) Cost/Budget Settings tab window

Fig. 3 Problem Data Window

3.2 Solution methods

The main component of *OptRoad* is a non-linear combinatorial optimization model. In general, this type of model is extremely difficult to solve. Except for small-size problems (up to, say, 15 nodes), it is necessary to resort to heuristic methods. These methods do not guarantee an optimum solution. However, if properly developed, they will often lead to the identification of optimum or near-optimum solutions. Within *OptRoad* three heuristics methods are available: a Local Search Algorithm – LSA; a Variable Neighborhood Search algorithm – VNSA (Hansen and Mladenović 2003); and an Enhanced Genetic Algorithm – EGA (Michalewicz 1996, Aarts and Lenstra 2003). For small-size problems, a Complete Enumeration Algorithm is also available (which evaluates all feasible solutions, therefore allowing the identification of a guaranteed optimum solution). Details on the algorithms, solution quality and computation time for the various algorithms is presented in Santos et al. 2005.

The information on the solution method to apply is input through the Solution Method Window, which can also be activated in the Data menu of the Main Window (Figure 4).
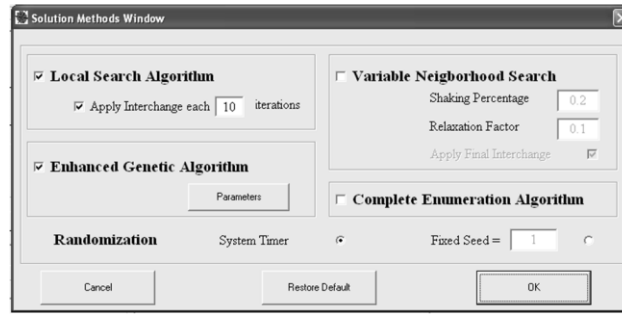
Fig. 4 Solution Methods Window

3.3 Results output

After defining the problem data and the solution method to apply, the solution search starts by pressing the button Run in the Main Window. During the search, the user receives information on the evolution of the best solutions found, both in text and graphic format (Figure 2). When the search ends, by pressing the button Results, the Problem Results window appears (Figure 5, Left). This window contains information about the objective-function gains, the budget use, the value for the various measures for each objective (even if not chosen for the optimization), and computational time. It also contains information on the objective-function gains for each urban center, the average speed for the trips started at each urban center, the evacuation capacity of each urban center, the road type change in each link, and the flow/capacity changes for each link. By pressing the button Graphic on the same window, the user can open the Graphic Solution window, where a schematic picture of the best solution is displayed (Figure 5, Right). There, the centers are represented by dark circles with diameter proportional to population, and the links are represented with lines of different color and width, according to the settings previously define by the user for each road type.
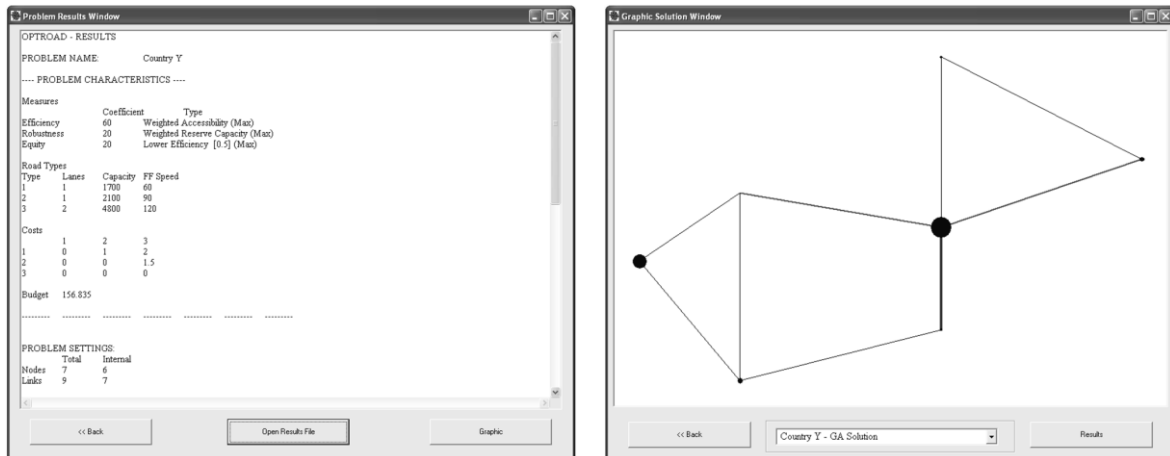

Fig. 5 Problem Results Window (left) and Graphic Solution Window (right)

The results are saved in the computer in text and graphic formats in a folder with the name of the problem. These files can be open and edited by most Windows or Macintosh text and graphic editors. However, as the graphic created by the *OptRoad* is a raster graphic, its manipulation is difficult. Thus, together with the results files, is saved an extra text file with general information about the network and with a synthesis of the results obtained. This file can be loaded in *ArcGIS*, the ESRI geographic information system (GIS) software, by using a script coded by the authors. Once the network is loaded in *ArcGIS* it

can be easily edited, manipulated, and exported as a vectorized graphic. Additionally, if the nodes coordinates are based on geographical coordinates, the network can be display together with other *ArcGIS* shapefiles. This feature can be particularly useful to enhance the raw network image, consisting only of nodes and links, with some geographical information that would allow a better interpretation of the results.

4 APPLICATION EXAMPLE

In order to illustrate the practical usefulness of *OptRoad*, we present below an application of the program to the road network of the state of Parana, Brazil (Figure 6). In 2002, the total length of this network was 6,781 km – 820 km of roads planned to be built in the future by the Brazilian Ministry of Transportation, 441 km of existing unpaved roads, 3,183 km of paved slow two-lane roads, 1,970 km of paved fast two-lane roads and only 370 km of four-lane freeways, all located next to Curitiba (Figure 7). In total, the network was represented with 76 nodes (39 internal urban centers, 26 intersections, and 11 external urban centers representing the neighboring countries) and 133 links (100 internal and 33 external). The reference network has more 6,772 km of roads located outside the state of Parana.
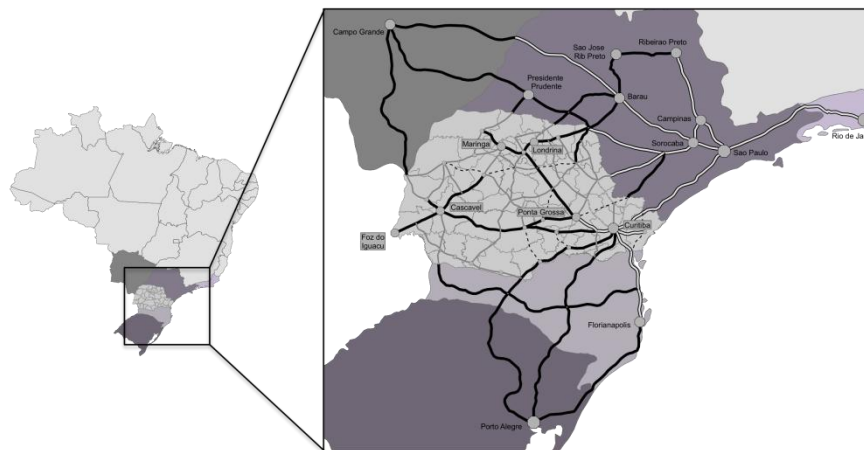

Fig. 6 Reference road network

Fig. 7 Road network of the state of Parana, Brazil, in 2002

The application consisted in determining an optimum solution for the evolution of the network for a budget of 3,884 monetary units. This budget corresponds to the money necessary to improve the unpaved roads and the slow two-lane roads to fast two-lane roads. The relative unit costs for road upgrading are presented in Table 1.

Table 1 Relative unit cost for road upgrading

From	To			
	Unpaved roads	Slow two-lane roads	Fast two-lane roads	Four-lane freeway
Planned roads	0.5	1.0	2.5	4.0
Unpaved roads	-	0.5	1.5	3.0
Slow two-lane roads	-	-	1.0	2.0
Fast two-lane roads	-	-	-	1.5

Initially, a single objective was considered for the network optimization: the maximization of the weighted accessibility of all centers. The concept of weighted accessibility was defined as follows (Keeble *et al.* 1982):

$$Z = \sum_{j \in N} P_j \times A_j, \text{ with } A_j = \sum_{k \in N \setminus j} \left(\frac{P_k}{C_{jk}^{\beta}} \right) \tag{2}$$

where Z is the weighted accessibility (efficiency objective); A_j is the accessibility of center j; N is the set of urban centers; P_j is the population of urban center j; C_{jk} is the generalized cost for traveling between centers j and k; and β is a calibration parameter that was considered to be 1.2.

The solution to the initial problem is depicted in Figure 8a. With regard to the 2002 network, the total length of freeways would increase from 370 km to 1,758 km, while the fast and slow two-lane roads would decrease from 1,971 km to 1,887 km and from 3,183 km to 2,048 km, respectively. The main changes to the initial network would be: a freeway corridor from Curitiba to Londrina and Maringa; a new freeway connection between Curitiba and the south border of the state of Parana; a connection by freeway between Foz do Iguacu and Cascavel; a fast two-lane road connection between Curitiba and the northeast border of Parana; a fast two-lane corridor between the southwest border and the northwest border, through Cascavel and Maringa; and the construction of 115 km of planned roads as unpaved roads, all located at the east of Curitiba. The weighted accessibility would increase from 2.446 to 2.557 (an increase of 5.0%).

To test the impact of taking different objectives simultaneously into account, we added three other different objectives to the accessibility maximization objective. For the sack of simplicity, we chose to add each new objective at a time (with weights of 50% for the accessibility objective and 50% for the additional objective).

The first objective that we added was equity maximization. This objective was expressed through the maximization of the accessibility of the 20-percent centers with lower accessibility (Santos et al. 2008):

$$E = \sum_{j \in N_{P20}} P_j \times A_j \tag{3}$$

where *E* is the weighted sum of the accessibility of the 20-percent centers with lower accessibility (equity objective) and N_{P20} is the set of 20-percent centers with lower accessibility.

The best solution for the efficiency (accessibility) and equity objectives is depicted in Figure 8b. With regard to the solution where only the accessibility objective was considered, the total length of freeways would increase from 1,758 km to 1,903 km and the fast two-lane roads would decrease from 1,887 km to 1,563km. The main changes to the accessibility-maximization solution would be: less freeways around Curitiba; a freeway corridor connecting Curitiba to Cascavel, and from Cascavel to Foz do Iguacu, Maringa, Londrina and the border in the northeast; a set of new freeway connection at the west of Cascavel and Maringa; and only one of the planned roads would be constructed. The weighted accessibility would increase from 2.446 in the initial network to 2.557 (an increase of only 3.8%) and the accessibility of the 20-percent centers with lower accessibility would increase 4.4% (in the solution for accessibility maximization, this increase would only be of 1.5%).

The next objective to be tested was network vulnerability minimization. The vulnerability of the network was defined as follows (Santos *et al.* 2010):

$$R = \sum_{l \in N_p} \frac{\sum_{j \in N} \sum_{k \in N} C_{jk}^l \times T_{jk} - \sum_{j \in N} \sum_{k \in N} C_{jk} \times T_{jk}}{N_p} \tag{4}$$

where *R* is the network vulnerability (robustness objective); N_p is the set of links with the *p* largest vulnerability; C_{jk}^l is the generalized cost for traveling between centers *j* and *k* when link *l* is closed; T_{jk} is the traffic flow between centers $_j$ and $_k$; and N_p is the number of links in the N_p set. Expression (4) defines network vulnerability as the average increase on travel costs when the links with the largest vulnerability are closed separately. The vulnerability of each link was estimated according to two aspects: the number of least-cost routes where the link is included and the traffic flow on the link (explained in detail in Santos et al. 2010).

The best solution when vulnerability minimization is taken into account, together with accessibility maximization, is depicted in Figure 8c. In this solution roads that could provide alternative paths between some major cities would be improved or constructed, for instance, roads between Curitiba and Ponta Grossa and roads between Maringa and Londrina. Planned roads at the north and east of Curitiba would also be constructed has slow two-lane roads. When compared with the solution for accessibility maximization, more 184 km of planned roads would be constructed. The length of freeways would decrease from 1,758 km to 1,639 km, while the length of fast two-lane roads would increase from 1,887 km to 1,907 km. The weighted accessibility would increase from 2.446 in the initial network to 2.559 (an increase of 4.6%) and the vulnerability of the network would decrease in 51.1% (while in the accessibility maximization solution would only decrease 35.2%).
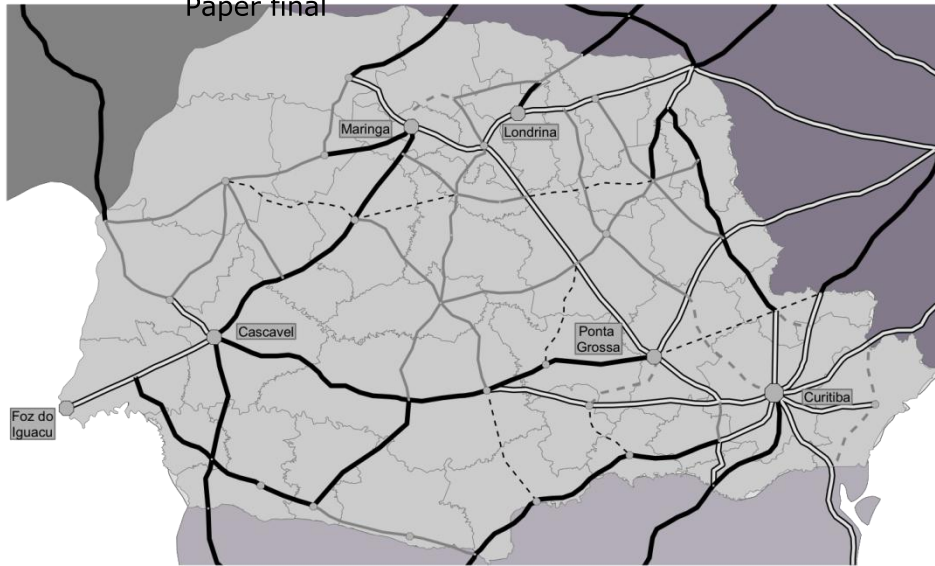
(a) Accessibility maximization

(b) Accessibility maximization and equity maximization

(c) Accessibility maximization and vulnerability minimization

(d) Accessibility maximization and fuel consumption minimization

Fig. 8 Best solutions for different objectives

Finally, we considered fuel consumption minimization. The average fuel consumption in the network was calculated as follows:

$$F = \frac{\sum_{l \in L} FC_l(\mathbf{y}) \times Q_l(\mathbf{y}) \times L_l}{\sum_{l \in L} Q_l(\mathbf{y}) \times L_l} \tag{5}$$

where F is the average fuel consumption in the network (fuel consumption objective); FC_l is the average fuel consumption for link l; Q_l is the estimated traffic volume in link l; and L_l is the length of link l. Average fuel consumption in each link was considered to be a function of the maximum service speed in the link. The lower fuel consumption was assumed to be around 80 km/h.

Figure 8d depicts the best solution obtained when accessibility maximization and fuel consumption minimization were considered together. With regard to the accessibility-maximization solution, this solution has more 2,404 km of fast two-lane roads but less 1,351 km of freeways. The fast two-lane roads have the maximum service speed closer to the lower fuel consumption speed and thus are wide spread in the network. When compared with the accessibility-maximization solution, there would be a higher number of unpaved roads that would be paved (more 202 km) and more planned roads would be constructed (more 288 km). The weighted accessibility would increase from 2.446 in the initial network to 2.488 (an increase of only 3.4%) and the fuel consumption would decrease by 7.2% (in the solution for accessibility maximization there would be an increase of 5.5%).

5 CONCLUSION

In this paper, we presented *OptRoad*, a user-friendly, optimization-based computer program for long-term interurban road network planning. The program is aimed at determining the best way of allocating a limited budget to the improvement of a road network, in order to achieve some objective or objectives. Four objectives are available in the *OptRoad*: efficiency, equity, robustness, and fuel consumption measures. An optimization model with a multi-level (discrete) nature is used by *OptRoad* to decide how to improve the road network. These improvements can be achieved both through the construction of new roads or the upgrading of existing roads. In the optimization model, roads are defined according to some hierarchy (e.g., freeways, fast highways, and slow highways) and traffic conditions in the roads are estimated following the concept of level of service as defined by the Highway Capacity Manual. Within *OptRoad* three different heuristic methods are available to solve the optimization model.

The type of results that can be obtained through the application of *OptRoad* in a real-world context was illustrated with a study of the development of the road network of the state of Parana, Brazil. We verified that, depending on the objectives taken into consideration, the results could be considerably different, highlighting the fact that the optimization of the network according to some measure does not necessarily mean that the network is optimized with regard to the other measures. Although it is not yet in a final version, *OptRoad* has already a stable version and, with few improvements, can easily be used by third party users.

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