OptRoad: A COMPUTER PROGRAM FOR INTERURBAN ROAD NETWORK PLANNING

Bruno Santos [1], **António Antunes** [2], **and Eric Miller** [3]

ABSTRACT

Road network planning is still a major concern in many parts of the World. The high economic growth rates observed in the recent past in countries such as Brazil, China, or India, as well as in most Eastern European countries, will be difficult to sustain if their road networks are not strongly improved. In this article, we present *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. This improvement can be achieved both through the construction of new roads or the upgrading of existing roads. Possible solutions are assessed according to various efficiency, equity, and robustness measures. The type of results that can be obtained through the application of *OptRoad* in a real-world context is illustrated with a study of the development of the national road network of Poland.

KEY WORDS

Transportation planning, road network, computer program, optimization model, genetic algorithm

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

---

[1] PhD Student, Civil Engineering Department, University of Coimbra, 3030 – 290 Coimbra, Portugal, Phone (+351) 239 797131, FAX (+351) 239 797142, bsantos@dec.uc.pt

[2] Professor, Civil Engineering Department, University of Coimbra, 3030 – 290 Coimbra, Portugal, Phone (+351) 239 797139, FAX (+351) 239 797142, antunes@dec.uc.pt

[3] Professor, Department of Civil Engineering, University of Toronto, 35 St. George Street, M5S 1A4, Toronto, Ontario, Canada, Phone 416-978-4076, FAX 416-978-5054, miller@civ.utoronto.ca

thirty years (for a relatively recent review, see 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 (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 article, we present *OptRoad*, a user-friendly, optimization-based computer program for long-term interurban road network planning. The article 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 and example of application of *OptRoad* to the road network of Poland. In the final section, we refer the improvements to the program that will be made available in the near future.

PLANNING APPROACH

The approach to road network planning adopted within *OptRoad* consists of the following three steps.

First, the road network is 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-way roads; fast two-way roads (with passing lanes, truck lanes, grade-separated intersections, etc.); four-way roads; etc.

Second, the best 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. The solution must be feasible from the budgetary, the technical, and the environmental standpoints (e. g., roads should not be upgraded, or should be downgraded, if they have abundant side construction, roads should not be upgraded if they cross natural parks, etc.). The determination of the best solution is made by solving a non-linear combinatorial optimization model (Santos *et al*., 2005). 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. The objective-function of the model evaluates the solution in terms of efficiency, equity, and robustness measures, using the well-know weighting method (Cohon, 2004). In this manner, the value of a solution, *V*, is calculated as follows:

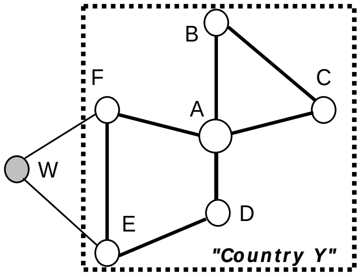
$$V = w_Z \times \left(\frac{Z_{\max} - Z}{Z_{\max} - Z_{\min}} \right) + w_E \times \left(\frac{E_{\max} - E}{E_{\max} - E_{\min}} \right) + w_R \times \left(\frac{R_{\max} - R}{R_{\max} - R_{\min}} \right) \quad (1)$$

where Z, E, and R are the values of the solution in terms of efficiency, equity and robustness measures, respectively; w_Z , $w_{E,}$, and w_R, are the weights attached to each objective; $Z_{\max}$, $E_{\max}$, and $R_{\max}$, are the maximum possible values for the solution in terms of each objective when the solution is determined disregarding the other objectives; $Z_{\min}$, $E_{\min}$, and $R_{\min}$ are the minimum possible values for the solution in terms of each objective when the solution is determined to optimize one of the remaining objectives.

Third, the traffic flows on the links of the (improved) road network are estimated using an unconstrained gravitational model calibrated for the 30th highest hourly traffic volume (TRB, 2000). As before, trips are assumed to be made through least-cost paths at the MSS consistent with the LOS required for each road type. If the traffic flows on some links entail a travel speed smaller than the MSS for the road type of the links, the solution found previously is not feasible. Hence, a new solution must be found. Various strategies may be pursued to determine it. The simplest strategy (which is the only one currently implemented in *OptRoad*) consists in upgrading the links for which the travel speed is smaller than the MSS to a better road type and downgrading (some of) the other links to a worse road type, to keep outlays consistent with the budget available. Starting from the resulting network, the non-linear combinatorial optimization model is then solved again. This procedure is repeated until a fully feasible solution is found.

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 by the node *W*.

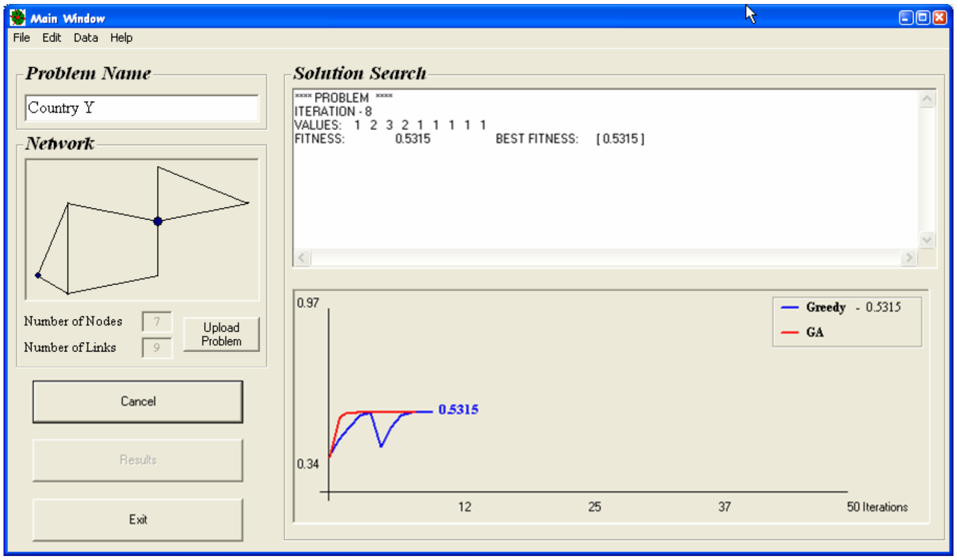


Node	City	Population
A	City A	550,000
B	City B	40,000
C	City C	90,000
D	City D	30,000
E	City E	120,000
F	City F	20,000
W	Abroad	350,000

Figure 1: Country Y Example

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 and into this main window.



Problem Name: Country Y

Number of Nodes: 7

Number of Links: 9

Solution Search

```
**** PROBLEM ****
ITERATION - 8
VALUES:  1  2  3  2  1  1  1  1  1
FITNESS:          0.5315            BEST FITNESS:    [ 0.5315 ]
```

Figure 2: Main Window

Part 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) and the links (start and end nodes, length, road type and land type) of the road network. A schematic picture of the network is shown on the left side of the window once the file is uploaded.

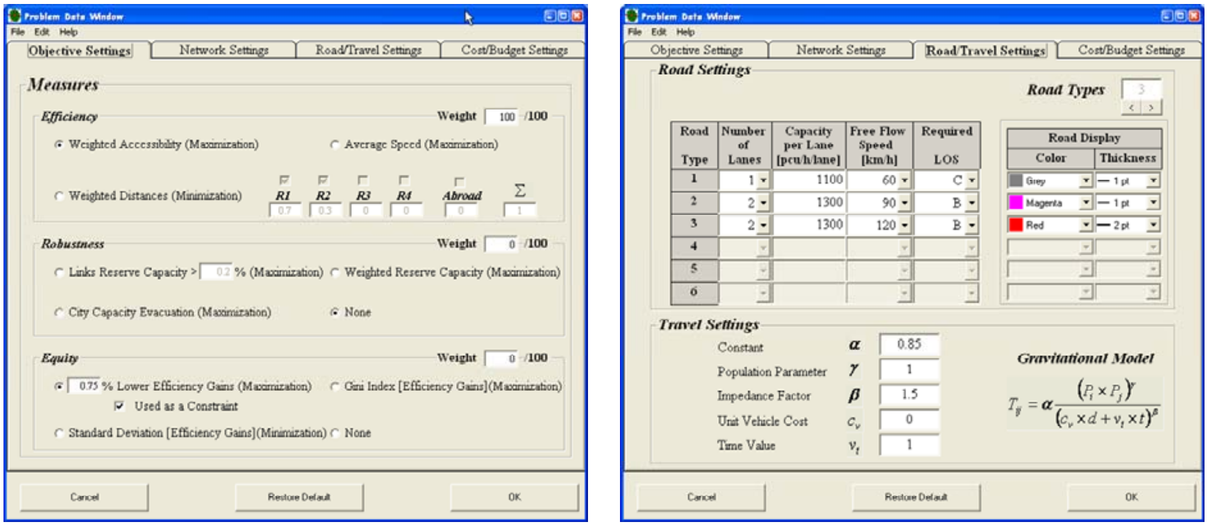
The remaining information should be input through the Problem Data Window, which can be activated in the Data menu of the Main Window. The Problem Data Window consists of four tab windows: Objective Settings; Network Settings; Road/Travel Settings; and Cost/Budget Settings.

In the Objective Settings tab window (Figure 3, Left), the user can specify the measures and weights to associate with the objectives. Three 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, or to minimize the weighted distance between urban centers and the closest capitals (at four different administrative levels). For the robustness objective, the user can choose either to maximize the number of links with a given percentage of reserve capacity, to maximize a weighted reserve capacity measure over all the links, or to maximize the capacity of evacuation in each city. Finally, for the equity objective, the user can choose to maximize the gains of the urban centers with the lower efficiency gains, to maximize the Gini Index of efficiency gains, or to minimize the standard deviation of efficiency gains. The first measure of equity can be used as a constraint to ensure that only the efficiency gains of the urban centers where the gains are smaller are taken into account.

In the Network Settings tab window, 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 3, Right), 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, 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.



Measures

Efficiency Weight 100 /100

● Weighted Accessibility (Maximization) ○ Average Speed (Maximization)

○ Weighted Distances (Minimization) ☑ R1 0.7 ☑ R2 0.3 ☐ R3 0 ☐ R4 0 ☐ Abroad 0 Σ 1

Robustness Weight 0 /100

○ Links Reserve Capacity > 0.2 % (Maximization) ○ Weighted Reserve Capacity (Maximization)

○ City Capacity Evacuation (Maximization) ● None

Equity Weight 0 /100

● 0.75 % Lower Efficiency Gains (Maximization) ○ Gini Index [Efficiency Gains](Maximization)

☑ Used as a Constraint

○ Standard Deviation [Efficiency Gains](Minimization) ○ None

Road Settings

Road Types 3

Road Type	Number of Lanes	Capacity per Lane [pcu/h/lane]	Free Flow Speed [km/h]	Required LOS	Road Display Color	Road Display Thickness
1	1	1100	60	C	Grey	1 pt
2	2	1300	90	B	Magenta	1 pt
3	2	1300	120	B	Red	2 pt
4						
5						
6						

Travel Settings

Constant α 0.85
Population Parameter γ 1
Impedance Factor β 1.5
Unit Vehicle Cost c_v 0
Time Value v_t 1

Gravitational Model

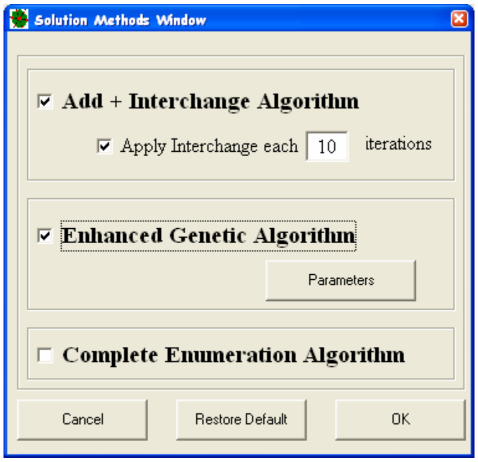
$$T_{ij} = \alpha \frac{(P_i \times P_j)^{\gamma}}{(c_v \times d + v_t \times t)^{\beta}}$$

Figure 3: Problem Data Window - Objective Settings (Left) and Road/Travel Settings (Right)

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, 12 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* two heuristics methods are available: a classic Add+Interchange algorithm (AIA); and a modern Enhanced Genetic Algorithm (EGA) (Aarts and Leenstra, 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). 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).

The EGA is an evolutionary algorithm that comprises the standard selection, crossover, mutation and invasion procedures described for instance in Michalewicz (1996), as well as some additional procedures that largely improve its performance (for details, see Santos *et al.* 2005). The comparison of the results obtained with the two heuristic methods for a representative sample of randomly-generated road network planning problems clearly revealed the superiority of the EGA over the AIA. In fact, for 20 networks with up to 12 nodes (the largest for which a guaranteed optimum solution could be found) the EGA always identified the optimum solution, while the AIA only identified the optimum solution on 12 occasions. For 80 networks of 20 to 100 nodes, the EGA always outperformed the AIA. As it could be expected since the EGA is far more complex than the AIA, the computing time required by the EGA is high compared to the computing time required by the AIA. However, in this regard, it is worth noting that the computing time advantage of the AIA in relation to the EGA diminished quite rapidly as the size of the network increased.



☑ Add + Interchange Algorithm

☑ Apply Interchange each 10 iterations

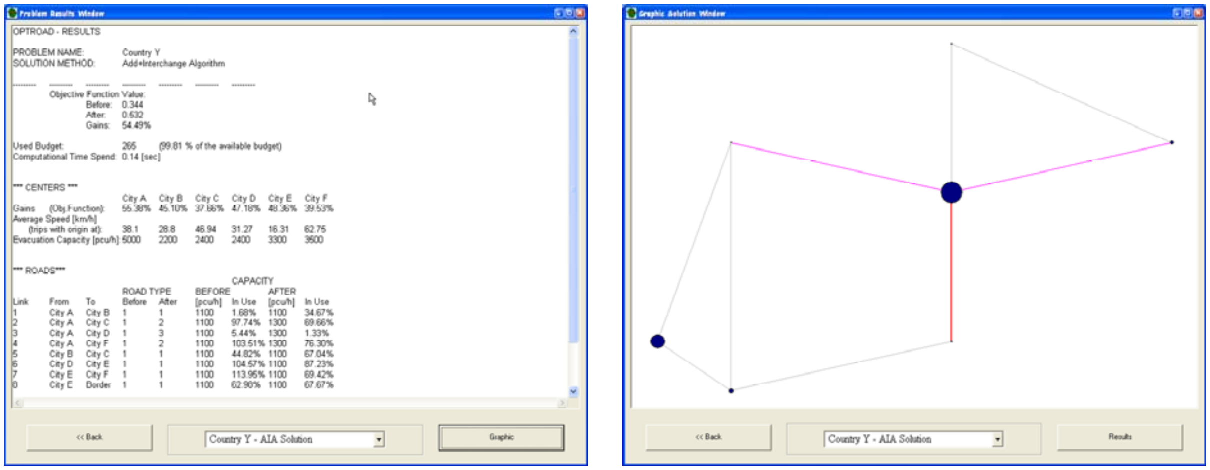
☑ Enhanced Genetic Algorithm

☐ Complete Enumeration Algorithm

Figure 4: Solution Methods Window

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 (Figure 2). When the search ends, pressing the button *Results*, the *Problem Results* window appears (Figure 5, Left). This window contains information about the objective-function gains, budget use, and computing 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 black 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. Both the results and the graphic are saved in a folder with the name of the problem.



```
OPTROAD - RESULTS

PROBLEM NAME:            Country Y
SOLUTION METHOD:         Add+Interchange Algorithm

--------   --------   --------   --------   --------   --------   --------
           Objective Function Value:
                      Before:  0.344
                      After:   0.632
                      Gains:   54.49%

Used Budget:                   265      (99.81 % of the available budget)
Computational Time Spend:      0.14 [sec]


*** CENTERS ***
                               City A   City B   City C   City D   City E   City F
Gains      (Obj.Function):     55.38%   45.10%   37.66%   47.18%   48.36%   39.53%
Average Speed [km/h]
     (trips with origin at):   38.1     28.8     46.94    31.27    16.31    62.75
Evacuation Capacity [pcu/h]:   5000     2200     2400     2400     3300     3500


*** ROADS***
                                                          CAPACITY
                               ROAD TYPE         BEFORE            AFTER
Link       From       To       Before   After    [pcu/h]  In Use   [pcu/h]  In Use
1          City A     City B   1        1        1100     1.68%    1100     34.67%
2          City A     City C   1        2        1100     97.74%   1300     69.66%
3          City A     City D   1        3        1100     5.44%    1300     1.33%
4          City A     City F   1        2        1100     103.51%  1300     76.30%
5          City B     City C   1        1        1100     44.82%   1100     67.04%
6          City D     City E   1        1        1100     104.57%  1100     87.23%
7          City E     City F   1        1        1100     113.95%  1100     69.42%
8          City E     Border   1        1        1100     62.96%   1100     67.67%
```

Figure 5: Problem Results Window (Left) and Graphic Solution Window (Right)

APPLICATION EXAMPLE

Though some of the features of *OptRoad* described above are not yet available, the program can already be used to help solving some real-world interurban road network planning problems.

Below, we present an application of the program to the main road network of Poland (Figure 6). In 2000, the total length of this network was 11,132 km (5763 km of slow two-way roads, 4901 km of fast two-way roads, and 468 km of four-way roads). The network was represented with 85 nodes (48 internal urban centers, 30 intersections, and 7 external urban centers representing the neighboring countries) and 159 links (146 internal and 13 external).

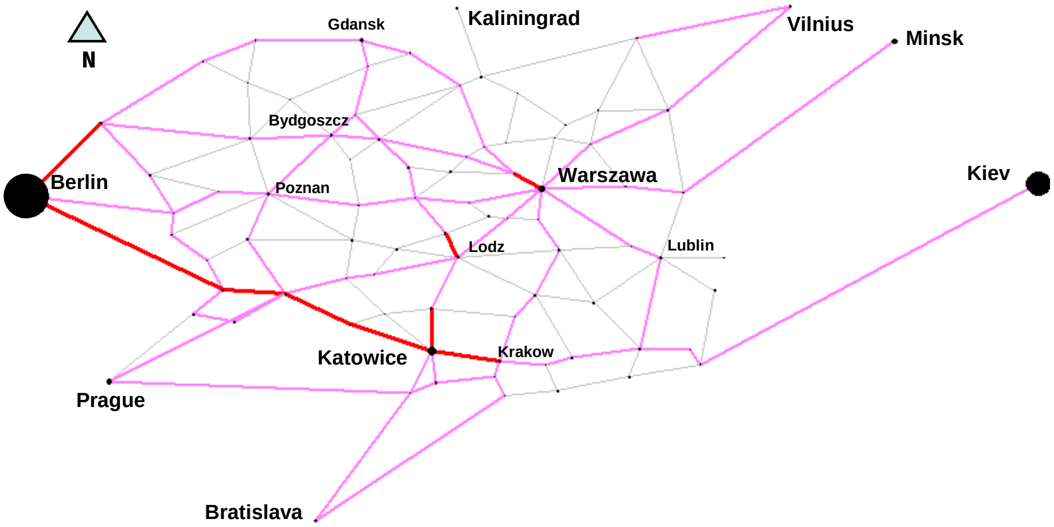


Figure 6 - Main Road Network of Poland in 2000

The application consisted, initially, in determining an optimum solution for the evolution of the network for a budget of 5,520 monetary units (that is, 20% of the budget required to upgrade all links to the four-way road type). The cost of upgrading a two-way road from slow to fast was assumed to be equal to one on average, and half the cost of upgrading a slow two-way road to a four-way road. The objective was to maximize weighted accessibility gains with no equity constraint. Then, we analyzed the change to the solution consecutive to a 50% increase of the budget and to the inclusion of an equity constraint of 50% (that is, considering the 50% centers with lower accessibility gains). Robustness issues were not taken into account because they can not yet be handled by *OptRoad*.

The concept of weighted accessibility gains is defined as follows (Keeble *et al*., 1982):

$$\Delta A = \sum_{j \in \boldsymbol{U}} P_j \sum_{k \in \boldsymbol{U} \setminus j} \frac{P_k}{\Delta c_{jk}} \quad (2)$$

where ΔA are weighted accessibility gains; $\boldsymbol{U}$ is the set of urban centers; P_j is the population of urban center j; and Δc_{jk} is the change in the cost of traveling between urban centers j and k.

The solution to the initial problem is depicted in Figure 7 (Top). With regard to the 2000 network, the total length of four-way roads would increase from 468 km to 2905 km, while the total length of fast two-way roads would decrease from 4901 km to 3323 km (this means that a very significant part of the transformation of the network would be achieved by upgrading fast two-way roads). The main changes to the existing network would be: the connection of Warszawa to Berlin (Germany) by four-way road, through Bydgoszcz; the connection of Warszawa to Katowice and Poznan by four-way road, through Lodz; and the connection of Warszawa to Kaliningrad (Russia). The weighted accessibility gains for this solution would be 1.403 (accessibility units).

If the budget was increased 50% in relation to the previous value, the total length of four-way roads would increase to 4206 km, while the total length of fast two-way roads would decrease to 2418 km All the roads upgraded with the initial budget would be upgraded again (Figure 7, Middle). Additionally, there would be connections by four-way road between Warszawa and Gdansk, and Warszawa and Wroclaw. After Germany and Russia (Kaliningrad), also the borders with Ukraine, Czech Republic and Byelorussia would be connected to Warszawa by a four-way road. The weighted accessibility gains for this solution would be 1.523. This means that a budget increase of 50% would lead to an accessibility increase of only 8.5%.

If an equity constraint of 50% was considered, the total length of four-way roads would be 2979 km, which is approximately the same as if no equity concerns were considered. However, in comparison with the solution to the initial problem, there would be two main differences (Figure 7, Bottom): the four-way roads would be distributed across the country instead of being concentrated around Warszawa; and the connection of Warszawa to Berlin would be through Gdansk (instead of Bydgoszcz). The weighted accessibility gains for this solution would be 0.520. This means that the equity increase would be accompanied with a massive 63% decrease in accessibility.

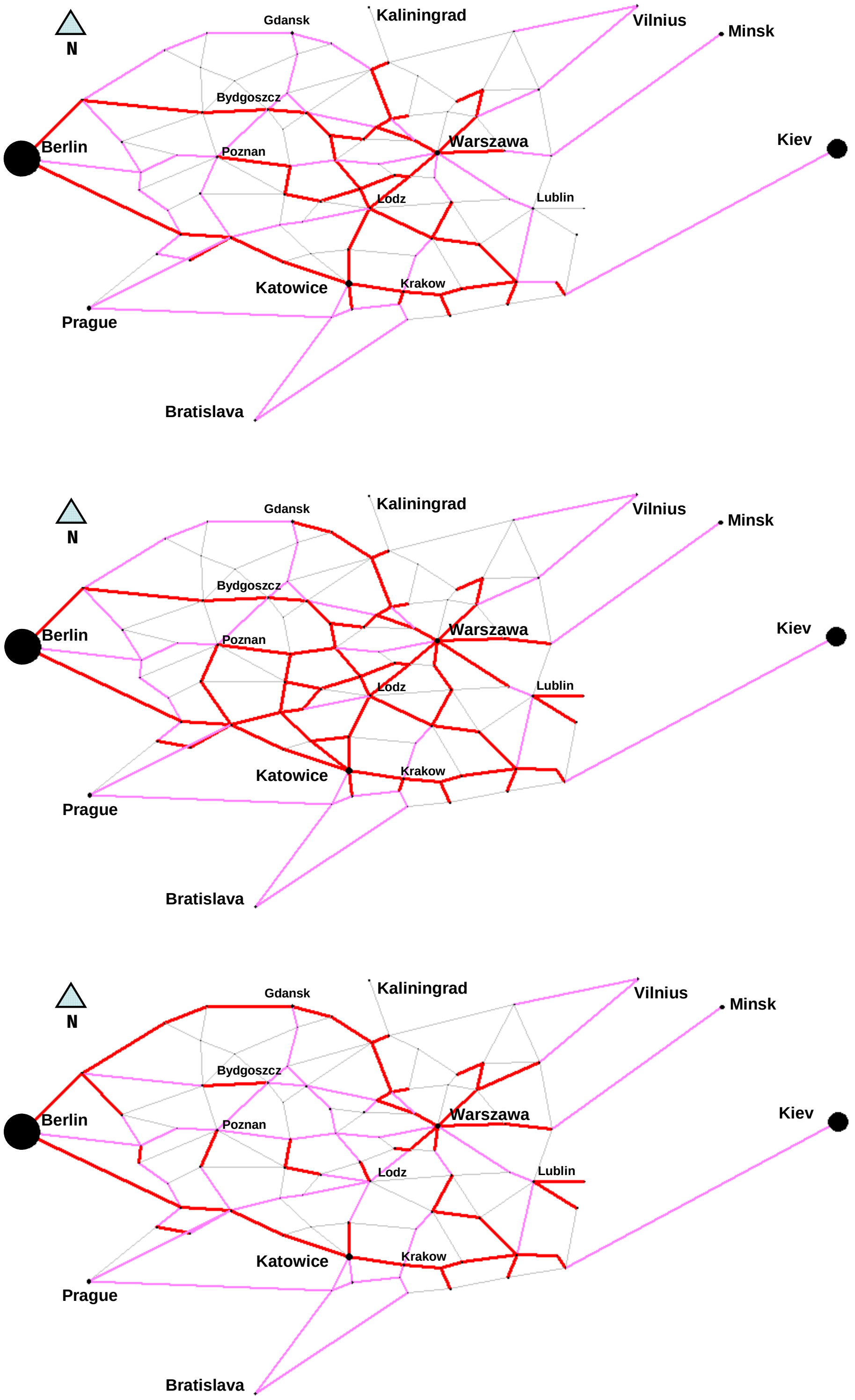


Figure 7: Solution for the Initial Problem (Top), Solution with Increased Budget (Middle), and Solution with an Equity Constraint (Bottom)

CONCLUSION

In this article, 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 accomplish some objective or objectives. The improvement can be achieved both through the construction of new roads or the upgrading of existing roads. At present, some features of the program are not yet available to the user. This is, in particular the case of features relating to equity and robustness objectives, which will be dealt with in the near future. Despite this, *OptRoad* can already be useful to help solving with real-world problems, as illustrated through its application to the road network of Poland.

ACKNOWLEDGMENT

The participation of the first author in the study reported in this article has been supported by Fundação para a Ciência e Tecnologia through grant SFRH/BD/16407/2004.

REFERENCES

Aarts, E. and Lenstra, J. (2003). *Local Search in Combinatorial Optimization*. Princeton University Press, Princeton, NJ, USA, 536 pp.

Antunes, A., Seco, A. and Pinto, N. (2003). “An accessibility-maximization approach to road network planning.” *Computer-Aided Civil and Infrastructures Engineering* 18 (3) 224-240.

Chootinan P., Wong S., and Chen, A. (2005). “A Reliability-Based Network Design Problem.”. *Journal of Advanced Transportation* 39 (3) 247-270.

Cohon, J. (2004). *Multiobjective Programming and Planning*. Dover Publications, Mineola, NY, USA, 333 pp.

Feng, C. and Wu, J.Y. (2003). “Highway Investment Planning Model for Equity Issues.” *Journal of Urban Planning and Development* 129 (3) 161-176.

Janson, B., Bruckels, L., and Peterson, B. (1991). “Network design programming of U.S. highway improvement, Journal of Transportation Engineering.” 117 (4) 457-468.

Keeble, D., Owens, P., Thompson, P. and Thompson, C. (1982). “Regional Accessibility and Economic Potential in the European Community.” *Regional Studies* 16 (6) 419-432.

Michalewicz, Z. (1996). *Genetic Algorithms + Data Structures = Evolution Programs.* Springer-Verlag, Berlin, Germany, 409 pp.

Santos, B., Antunes, A., and Miller, E. (2005). “Solving an Accessibility-Maximization Road Network Design Model: A Comparison of Heuristics.” In Jaszkiewicz, A., Kaczmarek, M., Zak, J., Kubiak, M. (eds). *Advanced OR and AI Methods in Transportation*. Publishing House of Poznan University of Technology, Poznan, Poland, 692-697.

Scaparra, M. and Church, R. (2005). “A GRASP and Path Relinking Heuristic for rural Road Network Development.” *Journal of Heuristics* 11 (1) 89-108.

TRB – Transportation Research Board (2000). *Highway Capacity Manual*. Washington, DC, USA, 1134 pp.

Yang, H. and Bell, M. (1998). “Models and Algorithms for Road Network Design: A Review and Some New Development.” *Transportation Reviews*, 18 (3) 257-258.