A Multi-objective Approach to Long-term Interurban Multi-level Road Network Planning

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

Abstract

This article presents a multi-objective approach to long-term interurban multi-level road network planning. In addition to the efficiency objectives dealt with in the vast majority of the literature where the subject is addressed, the approach takes into account robustness and equity objectives. For achieving the objectives, two types of action can be performed: the construction of a new road of a given level; and the upgrading of an existing road to a higher level. The approach is consistent with the planning framework of the Highway Capacity Manual, using the concept of level of service to assess traffic flow conditions. The application of the approach is illustrated for a case study involving the main road network of Poland.

CE Database keywords: transportation networks; planning; highways and roads; network design; multiple objective analysis; optimization models.

---

[1] Assistant Professor, Dep. of Civil Engineering, University of Coimbra, Polo II, 3030-290 Coimbra, Portugal

[2] Professor, Dep. of Civil Engineering, University of Coimbra, Polo II, 3030-290 Coimbra, Portugal

[3] Bahen-Tanenbaum Professor, Dep. of Civil Engineering, University of Toronto, 35 St. George Street, M5S 1A4, Toronto, Ontario, Canada

Introduction

Modern economies are highly dependent upon transportation systems. As an important component of the transportation system, road networks play a vital role for the sustainability of these economies. While for most developed countries the main concern is the improvement of their already good interurban road networks, this is certainly not the case with countries like China, India, Brazil, and most Eastern European countries. The high economic growth rates that have characterized these countries in recent years will be difficult to maintain without a strong development of their road networks. Given the major social implications and massive financial outlays involved in the renovation of road networks, the decisions to be made by transportation authorities with regard to the construction of new roads and the upgrading of existing roads need to be carefully planned.

In practice, interurban road network planning is typically made through a trial-and-error approach using simulation models based on the classic (or four-step) transportation model (see Daly, 2000). Trial-and-error does not allow full exploration of possible planning solutions. This can only occur if an optimization-based approach is used. But the real-world application of optimization to road network planning is difficult because the corresponding models – often considered among the most challenging optimization models – could only be handled through powerful mainframes. This situation is now changing, thanks to recent evolutions in computing hardware and software.

The optimization-based, multi-objective approach to interurban road network planning presented in this article is intended at helping transportation authorities in their strategic reflections regarding the long-term (say, 20 years) evolution of a national or regional network. In addition to the efficiency objectives dealt with in the vast majority of the literature where the subject is addressed, the approach presented in this article takes into account robustness and equity objectives. Indeed, from road network improvements, transportation authorities want (or should want) more than just better accessibility or faster speed in current, everyday situations.

They also require road network improvements to enhance the way abnormal traffic peaks and unexpected disruptive events are coped with. Moreover, transportation authorities want the accessibility and speed benefits derived from the improvement of road networks to be fairly distributed across the different parts of a country or a region, because excessively uneven welfare gains are not consistent with sustainable development principles.

An important feature of the model is its compatibility with the planning framework adopted in the Highway Capacity Manual - HCM (TRB 2000). This manual, published by the United States Transportation Research Board, is an important reference for highway engineers working in Departments of Transportation all over the world. In our opinion, planning solutions which are consistent with the HCM framework will, in principle, be more easily accepted by practitioners and more likely to be adopted in real-world studies.

The article is organized as follows. In the following section, we provide a brief overview of the literature on optimization-based road network planning models. Next, we describe the essential features of the proposed planning approach. Then, we present the model upon which the approach is based and supply information on the algorithm developed to solve it. Afterward, we illustrate the type of results that can be obtained through the approach for a case study involving the main road network of Poland. In the final section, we make some concluding remarks and point out directions for future research.

Literature overview

Over the last thirty years, significant research efforts have been devoted to optimization-based road network planning (or design) models.

The vast majority of these efforts were oriented towards two models: the discrete road network design (DRND) model and, especially, the continuous road network design (CRND) model. The former focus on the addition of new links to a road network, whereas the latter concentrates on the (continuous) expansion of capacity of existing links. A related model that appears in the literature is the mixed road network design (MRND) model, which is a combination of the

DRND model with the CRND model. Among the best-known articles dealing with these models are LeBlanc (1975) and Boyce and Janson (1980) regarding the DRND model, and Abdulaal and LeBlanc. (1979) and Friesz et al. (1992) regarding the CRND model. One interesting, early application of this kind of models to a national road network is provided in Ben-Ayed et al. (1992). For a relatively recent review of this literature, see Yang and Bell (1998).

The models referred to above can be classified in respect to three main issues: travel demand; traffic assignment; and planning objective. Travel demand – that is, the O/D matrix – is, in many cases, assumed to be known in advance (inelastic). This certainly is a poor assumption because, at least in the long-term, it is rather unlikely that the addition of new links and/or the improvement of existing links will not induce new trips and will not change the distribution of existing trips. Traffic assignment is typically made according to the user-equilibrium principle: "traffic arranges itself in such a way that no individual trip maker can reduce his path costs by switching routes" (Wardrop 1952). However, some early studies, as well as studies dealing with rural road networks, use the "all-or-nothing" principle, according to which trips are assigned to the shortest-route. Planning objectives vary widely. The most frequent are efficiency objectives, such as user cost minimization or user benefit maximization (as measured by the consumer surplus). Other important objectives that have been dealt with in previous studies include robustness (Lo and Tung 2003) and equity (Meng and Yang 2002). A number of articles address multi-objective road network design models. The first one reported in the literature is due to Friesz and Harker (1983). More recently, Friesz et al. (1993) and Tzeng and Tsaur (1997) contemplated user costs and construction costs as simultaneous minimization objectives (the former also took into account the minimization of travel distance and the minimization of property expropriation). Ukkusuri et al. (2007) consider a robustness objective in addition to an efficiency objective (travel time minimization), Feng and Wu (2003) considered horizontal and vertical equity objectives, and Cantarella and Vitetta (2006) considered environmental objectives (minimization of CO emissions).

Despite being extremely appealing from a theoretical standpoint, none of the RND models referred to above explicitly address a very important issue of real-world road network planning: the multi-level, discrete nature of capacity expansion. Indeed, capacity increases considerably when some road is upgraded to a higher level (or replaced with a better road, or complemented with a new road). When a road is upgraded from two to four lanes, its capacity more than doubles. This kind of issue has rarely been handled through optimization-based road network planning models. The only two examples of multi-level models we are aware of are Janson et al. (1991) and Antunes et al. (2003). The model described in Janson et al. (1991) is based on an efficiency objective (the minimization of shipping costs). Traffic is assigned to the network according to the user-equilibrium principle. The model applies to previously selected routes and several planning periods. The procedure for selecting the routes, which are typically composed of a large number of links, is not specified. One of the two versions of the model assumes travel demand to be elastic, but only with regard to trip distribution (which is estimated through a constrained gravity model). Induction of traffic is not taken into account. The model presented in Antunes et al. (2003) combines accessibility and equity objectives, and assumes travel demand to be elastic with regard to both trip distribution and traffic induction. Traffic is assigned to the network through an iterative "all-or-nothing" approach that takes into account the capacity of roads of different levels.

Planning approach

The approach to long-term interurban road network planning proposed in this article is based on the following main principles:

- Planning decisions involve the construction of new road links of given levels (types) or the upgrading of existing road links to a higher level.
- Efficiency, robustness, and equity objectives are simultaneously taken into account.
- Environmental concerns may limit the set of road levels that can be assigned to links included (or to be built) in environmentally-sensitive areas.

– Total expenditure involved in the planning decisions must not exceed the available budget.

– Travel demand is elastic with road network changes.

– Planning decisions are consistent with the planning framework adopted in the Highway Capacity Manual.

For the implementation of these principles we developed an approach involving an iterative process with seven steps in each iteration (Figure 1).

(Locate Figure 1 approximately here)

First, we generate a set of solutions for the improvement of the road network consistent with environmental concerns and budgetary constraints. Each solution specifies the links to build or upgrade, and the road levels to assign to these links. Each road level is associated with a level of service (LOS) that must be guaranteed. LOS is a qualitative measure of the operational conditions of a traffic facility (TRB 2000), and is characterized with a maximum traffic flow, a maximum traffic density, and a maximum average speed. Among other alternatives, the LOS of a road can be measured through volume to capacity ratio, which is given by the ratio between the traffic flow and the maximum traffic flow for the road. For generating solutions, one may resort either to local or population (including evolutionary) search procedures, or to a combination of both.

Second, we apply an unconstrained gravity model to calculate the aggregate O/D matrix in the improved network for some reference hourly traffic volume (Ortúzar and Willumsen 2001). If desired, different models can be used to calculate separate passenger and freight traffic O/D matrices. The HCM proposes the reference hour to be the one with the 30th highest traffic volume, indicating a method for computing it (TRB 2000). The same method can be used with any reference hourly traffic volume. The unconstrained gravity model defines the expected number of trips between two traffic generation centers to be proportional to the size of the centers (population, employment, etc.) and inversely proportional to the (generalized) travel cost between the centers. Drivers are assumed to follow least-cost paths, traveling at the maximum average speed consistent with the LOS defined for the road levels of the links included in their routes.

Third, we assign the O/D matrix to the improved road network. This can be done according to the user-equilibrium assumption. However, many drivers on an interurban road network are not fully aware of the route alternatives they have – they just follow road signs and/or, more and more often, GPS instructions. Therefore, to be on the safe side, we decided to rely on the assumption that drivers will follow the least-cost route they can choose if travel is made at the maximum average speed consistent with the LOS immediately below the LOS defined for the road level of the links included in the route. Or, in other words, we use the average speed for the worst conditions within which the LOS for the road level of the link is still guaranteed – hereafter called guaranteed average speed. This assumption can be clarified with a simple example. Suppose a driver wants to travel from X to Y, and has two alternatives (Figure 2): a main road (four-lane freeway, length 30 km, design LOS B, and guaranteed average speed 115 km/h) and a secondary road (two-lane road, length 20 km, design LOS D, and guaranteed average speed 50 km/h). According to our assumption, and further assuming that generalized travel costs are assessed through travel time, the driver will choose the main road if the traffic there takes place at LOS B with a travel time of 15.7 minutes at most, even if the secondary road is operating at LOS A (i.e., a better LOS) with a travel time of 15.0 minutes. That is, the driver will not exchange a main road with a secondary road if, for trips made at the guaranteed average speed, the traffic conditions offered by the main road are what they are planned to be (or better). We say that this is a safe side assumption because it leads to solutions where drivers can travel at the average speed guaranteed for the road they are using, but at least some of them can change to worse roads and save travel time.

(Locate Figure 2 approximately here)

Fourth, we assess the solutions with regard to efficiency, robustness, and equity objectives. In the literature, these objectives have been expressed in many different forms. Some examples of alternative (or complementary) objectives taken into account in transportation studies, as well as in other infrastructure studies, are as follows:

- Efficiency: maximization of the accessibility of urban centers (as defined by Keeble et al. 1982); maximization of the average speed in the road network; minimization of a weighted distance to national, state, and regional capitals; and maximization of road users surplus (Jara-Diaz and Friesz 1982).
- Robustness: maximization of the reserve capacity of the network; maximization of the evacuation capacity of cities; and minimization of the vulnerability of the network (D'Este and Taylor 2003).
- Equity: maximization of accessibility (or other efficiency measure) for the urban centers with the lowest accessibility; maximization of the Gini Index of accessibility; and minimization of Theil Inequality Index of the accessibility to urban centers (for information on these and other equity/inequality measures see Kokko et al. 1999).

Fifth, we perform a multi-objective evaluation of the solutions using the well-know weighting method (Cohon and Rothley 1997). According to this method, the overall value of a solution is calculated through the application of weights (or priorities) to the normalized values of the solutions for each objective. Solution values need to be normalized because the degree of achievement of the objectives is assessed in different units and/or different scales of measure. The weights for the objectives are to be established by the policy-makers according to the relative importance they attach to them. Several methods are available for helping policy-makers at eliciting weights, among which are MACBETH (Bana e Costa and Vansnick 1997) and the methods used within the Analytic Hierarchy Process (Saaty 1994). The weighting method can be especially useful if applied through an interactive process, within which weights are reformulated by policy-makers as they get a better insight into the problems to solve and into the implications of their choices.

Sixth, we check whether the LOS required for each link (which depends on the level of the link) is violated. If this is the case, the solution is unfeasible and a penalty is applied to the solution value. The penalty is the sum of the differences between maximum traffic flow and estimated traffic flow for the links where the LOS is violated.

Seventh, we compare the solutions assessed in this iteration with the best solution obtained in previous iterations – the incumbent solution. If the best of the new solutions is better than the previous best solution, it becomes the incumbent solution and a new iteration is performed. If not, after a given number of non-improving iterations, the iterative process is stopped.

Optimization model

In order to accomplish the planning approach described in the previous section, it is necessary to solve an optimization model in each iteration. The essential ingredients of this optimization model are:

$$\max V = w_Z \times \frac{Z(\boldsymbol{y}) - Z_0}{Z_B - Z_0} + w_R \times \frac{R(\boldsymbol{y}) - R_0}{R_B - R_0} + w_E \times \frac{E(\boldsymbol{y}) - E_0}{E_B - E_0} \tag{1}$$

subject to

$$T_{jk} = \theta \times P_j \times P_k \times C_{jk}(\boldsymbol{y})^{-\beta}, \forall j,k \in \boldsymbol{N} \tag{2}$$

$$Q_l = \sum_{j \in \boldsymbol{N}} \sum_{k \in \boldsymbol{N}} T_{jk} \times x_{ljk}, \forall l \in \boldsymbol{L} \tag{3}$$

$$\sum_{m \in \boldsymbol{M}_l} y_{lm} = 1, \ \forall l \in \boldsymbol{L} \tag{4}$$

$$Q_l \leq \sum_{m \in \boldsymbol{M}_l} Q_{\max_m} \times y_{lm}, \forall l \in \boldsymbol{L} \tag{5}$$

$$\sum_{l \in L} \sum_{m \in M_l} e_{lm} \times y_{lm} \leq b \tag{6}$$

$$T_{jk}, Q_l \geq 0, \forall j,k \in \boldsymbol{N}, l \in \boldsymbol{L} \tag{7}$$

$$x_{ljk}, y_{lm} \in \{0,1\}, \forall j,k \in \boldsymbol{N}, l \in \boldsymbol{L}, m \in \boldsymbol{M} \tag{8}$$

where (in order of appearance) V is the normalized value of a solution; w_Z , w_R, and w_E are the weights attached to efficiency, robustness, and equity objectives; Z, R, and E are the values of a solution in terms of each objective; Z_B, R_B, and E_B are the best values obtained for each objective in previous iterations; Z_0, R_0, and E_0 are the worst values obtained for each objective in previous iterations; T_{jk} is the estimated traffic flow from center j to center k; θ is a scaling parameter; P_j is the population of center j; C_{jk} is the (generalized) cost of traveling between centers j and k; $\boldsymbol{y} = \{y_{lm}\}$ is a matrix of binary variables equal to one if link l is set at road level m and equal to zero otherwise; β is a calibration parameter (usually called impedance or attrition parameter);Q_l is the estimated traffic flow on link l; x_{ljk} are binary variables equal to one if link l belongs to the least-cost path between centers j and k and equal to zero otherwise (which are obtained by solving a lower-level optimization model, see Yang and Bell, 1998); $\boldsymbol{L}$ is the set of links; $\boldsymbol{M}_l$ is the set of possible road levels for link l; $Q_{\max_m}$ is the maximum service flow for a link of road level m; e_{lm} is the expenditure required to set link l at road level m; and b is the budget.

The objective-function (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 three 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 levels (which are represented with variables $\boldsymbol{y}$). Traffic demand is calculated according to constraints (2) and the number of trips on each link is calculated according to constraints (3). Constraints (4) are used to guarantee that each link will be set at one, and only one, road level. For some links, it may be undesirable to choose some road levels because of environmental concerns. This is the reason why the set of road levels ($\boldsymbol{M_l}$) is indexed in the link. Constraints (5) are included to ensure that the traffic flow estimated for each link, which depends on the decisions made with regard to road levels for all links, does not exceed the maximum service flow. Constraint (6) is used to guarantee that the budget available for improving the road network will not be exceeded. Expressions (7) and (8) define the domain for the decision variables.

Solution algorithm

The optimization model described in the previous section is extremely difficult to solve to exact optimality. Except for small-size instances, it must be handled through heuristic methods. A large number of classic and modern heuristic methods are available (Gendreau and Potvin 2005; Michalewicz and Fogel 2004). For solving the model we developed three different algorithms, an add plus interchange algorithm (AIA), a variable neighborhood search algorithm (VNS), and an enhanced genetic algorithm (EGA). This algorithm improves on the traditional genetic algorithm in several respects (Figure 3). First, it includes local search (add and drop) procedures in order to 'repair' solutions which do not take full advantage of the budget available or do not comply with it. Second, it uses interchange procedures for the best solution found after a given number of iterations and for the best solution found immediately before ending the algorithm. Third, it utilizes an intervention procedure after a given number of iterations, through which the parameters governing the selection, crossover, mutation, and invasion operations may change slightly.

(Locate Figure 3 approximately here)

The three algorithms were evaluated on a representative sample of partly-random test problems. The EGA outperformed the other algorithms (using the following parameters: population, 100 solutions; crossover probability, 85 percent; mutation probability, 1 percent; invasion probability, 1 percent; stop criterion, 50 non-improving iterations). When applied to small networks (with up to 20 links), for which we were able to find optimum solutions through a complete enumeration search only after several hours of computation, the EGA needed no more than a few seconds and was the only one of the three algorithms that was always able to identify the optimum solutions. When applied to larger networks (with up to 200 links), the EGA provided, on average, clearly better solutions. In terms of computing effort, the EGA is approximately equivalent to the VNS and is more time consuming than the AIA. However, the difference relative to the AIA decreases as the number of links in the network increases. On an Intel Dual Core 6700 microprocessor running at 2.66 GHz, the application of the EGA to problems with 50, 100, and 200 links took, on average, 3.7, 62.0, and 1025.5 minutes, respectively. This represents 5.0 times more than the average computing effort required by the AIA for a problem with 50 links, 3.3 times more for a problem with 100 links, and only 2.2 more for a problem with 200 links. More details on algorithm design, calibration procedures, and algorithm performance can be found in Santos et al. (2005).

Case study

The results that may be obtained through the application of the approach presented in this article are illustrated in this section with an academic example based on the main road network of Poland. In the year 2000, this network had a total length of 11,358 km (5,894 km of slow two-lane roads, 4,992 km of fast two-lane roads, and 472 km of two-lane freeways).

For the application of the approach, the network was represented with 86 nodes (49 Polish traffic generation centers, 30 main intersections, and 7 foreign traffic generation centers representing the neighboring countries) and 164 links (147 internal and 17 external). A scheme of the network is depicted in Figure 4.

(Locate Figure 4 approximately here)

The application consisted in determining the best assignment of 8,712 monetary units (which represent 25% of the budget required to upgrade all links to a six-lane freeway) to the improvement of the existing road network. The design characteristics of road levels are presented in Table 1. Due to the lack of specific information for Polish roads, the parameters of the HCM were used. Other parameters could certainly be used without compromising the applicability of the approach. The relative unit costs for road upgrading are presented in Table 2. These costs apply to roads built in flat land. For roads built in hilly and mountainous ground, unit costs were increased by 30 and 60 percent, respectively. Generalized transportation costs were calculated through the expression $C_{jk} = 0.40\, d_{jk} + 0.35\, t_{jk}$ (Euros), where d_{jk} and t_{jk} are the travel distance and the travel time between centers j and k, expressed in kilometers and minutes, respectively. The impedance parameter β was taken equal to 1.4.

(Locate Table 1 approximately here)

(Locate Table 2 approximately here)

All computations were made using OptRoad, a user-friendly program developed by the authors to implement the approach proposed in this article (Santos et al. 2006). The computing time for solving the instances described below on an Intel Dual Core 6700 microprocessor running at 2.66 GHz varied between 3,5 and 4,0 hours.

Results for a single efficiency objective

We first considered only an efficiency objective. Specifically, the objective was to maximize the weighted average accessibility of the Polish traffic generation centers. The accessibility of a center was defined as (proportional to) the spatial interaction between the center and all other centers. This is a notion of accessibility that has been used in many studies (Keeble et al. 1982; Vickerman et al. 1999). The expression used to calculate weighted average accessibility was:

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

where N is the set of traffic generation centers; N_P is the set of Polish traffic generation centers; P is the total population; and A_j is the accessibility of center j;.

The best solution obtained for this objective is depicted in Figure 5(a). In comparison to the network of 2000, the total length of four-lane freeways would increase from 472 kilometers to 3,067 kilometers, whereas the total length of fast two-lane highways would decrease from 4,992 to 4,528 kilometers. Three links of six-lane freeways, with a total length of 213 kilometers, would be included in the network, along the least-cost path between Warszawa and Katowice, the largest traffic generation centers.

(Locate Figure 5 approximately here)

Impact of adding a robustness objective

We then added a robustness objective to the efficiency objective, giving equal weights (50/100) to both objectives. The robustness objective was to maximize the weighted reserve capacity of the network. The reserve capacity of a link was defined as the traffic flow that the link can still accommodate within the LOS required for its road level (this is essentially the same definition used by Chen et al. 1999). The expression used to calculate the (weighted) reserve capacity of the network was:

$$R(\boldsymbol{y}) = \frac{\sum_{l \in \boldsymbol{L}} \left(Q_{\max_l} - Q_l \right)^{\alpha} \times Q_l \times L_l}{\sum_{l \in \boldsymbol{L}} Q_l \times L_l}$$

where α is a weighting parameter; and L_l is the length of link l. Parameter α is introduced to reflect the importance attached to reserve capacity. Values of α greater than one lead to solutions where reserve capacity is concentrated on a small number of links, being large in these links. On the other hand, values of α less than one lead to solutions where reserve capacity is more evenly distributed across the network, being small for each link. In this study, a value of α equal to 0.5 was used.

The best solution obtained for the two objectives is depicted in Figure 5(b). The freeway network would now be composed of 345 kilometers of six-lane freeways and 2,814 of four-lane freeways. Overall, the solution is very similar to the accessibility-maximization solution, the most significant difference being the larger investment effort placed on high-traffic roads (132 additional kilometers).

Impact of adding an equity objective

We next replaced the robustness objective with an equity objective. The equity objective was implemented by limiting the computation of accessibility to the 20-percent of Polish traffic generation centers with the lowest accessibilities (note that the fewer centers that are considered, the more emphasis is given to equity). The expression used to calculate equity was:

$$E(\boldsymbol{y}) = \sum_{j \in \boldsymbol{N}_{P20}} P_j \times A_j$$

where $\boldsymbol{N}_{P_{20}}$ is the set of 20-percent of Polish traffic generation centers with the lowest accessibilities.

The best solution obtained for the efficiency and equity objectives is depicted in Figure 5(c). The freeway network would now be composed of 2,727 kilometer of four-lane freeways and 290 kilometers of six-lane freeways. This solution is achieved by improving the links serving smaller traffic generation centers, such as Bydgoszcz, Gdansk, and Olsztyn, which were not improved in the previous solutions. In addition, some roads next to the Polish border would be improved to four-lane freeways, thus creating a freeway connection between Poznan and Kiev. Also, in the south of Poland, there would be a freeway connection between Berlin and Kiev via Katowice. In contrast to the previous solutions, the length of the fast two-lane highways would, in this case, be larger than in the network of 2000 (by 96 kilometers).

Results for efficiency, robustness, and equity objectives

We finally included the three objectives together, assigning equal weights (33.3/100) to the objectives. The best solution obtained for the efficiency, robustness, and equity objectives is depicted in Figure 5(d). The freeway network would now be composed of 230 kilometers of six-lane freeways and 2,783 kilometers of four-lane freeways. As one could expect, this solution is a compromise solution between the previous solutions, with more six-lane freeways than the solution obtained when only the efficiency objective was considered and with some smaller cities, such as Gdansk, connected to close centers by freeway. In this solution, a four-lane freeway connection between Warszawa and the north border is added to the previous freeway border connections.

Comparison of Results

The impact of the improvement of the network upon the different assessment measures – accessibility, reserve capacity, and accessibility of the 20 percent centers with the lower accessibilities – for the different combinations of objectives is summarized in Table 3. In relation to the initial situation, accessibility would increase by 10.12 percent if only the efficiency objective was taken into account. This value would decrease if robustness or equity objectives were added. The inclusion of robustness would involve a slight deterioration of accessibility in 0.06 percent (from 10.12 to 10.06), but the reserve capacity would increase 4.16 percent (from 31.48 to 32.79). The value for the reserve capacity measure would increase by 110.51, from -77.72 (i.e., initially the capacity of some roads is not enough to properly accommodate the flows on these roads) to 32.79 units. The inclusion of equity would have much more significant implications. Indeed, accessibility would only increase 8.95 percent (instead of 10.12). In contrast, the accessibility of the 20 percent centers with the lowest accessibilities would increase 11.96 percent, whereas it would increase only 8.00 percent if equity objectives were not considered. For the solution obtained when the three objectives were included, accessibility would increase 9.15 percent, the value for the reserve capacity measure would increase 107.56 units (from -77.72 to 29.84), and the accessibility of the 20 percent centers with lower accessibilities would increase 11.86 percent.

(Locate Table 3 approximately here)

With regard to the changes referred to above, it is important to recognize here that the differences between solution values are quite small, despite the differences between the solutions obtained for the various objectives being noticeable. The main reason for this is the fact that reductions in travel costs were assumed to be exclusively due to savings in travel time, whose value is relatively low in Poland (the fraction of travel costs proportional to travel distance was assumed to remained unchanged). A second reason has to do with the importance of cross-border traffic in a country surrounded by several countries, including a large country like Germany. Parts of the roads used by this traffic are located outside Poland and were not considered for improvement.

The total length of the different levels of roads is given in Table 4. All the solutions would involve a decrease in highway length and an increase in freeway length, but the length of fast two-lane highways would increase for the two solutions involving the equity objective. Also, for these same solutions the reduction of slow two-lane highways length would be close to 45 percent while for the other two solutions the decrease of slow two-lane highways length would be smaller than 40 percent. For the four solutions, the length of freeways would exceed 3,000 kilometers. Nonetheless, it would be again for the solutions considering equity that we would have the lower freeway length, with a difference of about 260 kilometers for the solution obtained considering only the efficiency objective and 140 km for the solution obtained considering also the robustness objective.

(Locate Table 4 approximately here)

Sensitivity Analysis

To test the sensitivity of the solutions to a budget reduction, two budget levels were considered for the case of including the three objectives together: 75 percent and 50 percent of the initial budget. The two solutions were compared with the solution obtained for the full budget (Figure 6). The results reveal that few links which would not be upgraded in the full budget solution would be upgraded in the lower budget solutions. The exceptions would be the links connecting Warszawa to Bialystok and some links located in peripheral regions of Poland. The three six-lane freeways of the full budget solution remain in the lower budget solutions. This happens because the traffic on these links is high and a six-lane freeway is necessary to guarantee the LOS constraints. Amongst the links that were not upgraded in the lower budget solutions, the most noticeable is the freeway connection between Poznan and Kyiv. It is interesting to note that, in the full budget solution, some of these links would be at almost 80 percent of their maximum service flow (1320 pcu/h/lane), serving traffic between Berlin, Poznan, Lodz, Kielce, and Kyiv. In the lower budget solutions this traffic is spread across the network, some of it going through Warszawa or Wroclaw.

The accessibility gains obtained with the lower budget solutions would be considerably lower than the gains obtained for the full budget solution: 2.59 percent (from 9.15 to 6.56 percent) for a 75-percent reduction of the budget and 4.18 percent for a 50-percent reduction (Table 5). With regard to reserve capacity, the differences to the full budget solution would be of less 3.61 units in the case of 75 percent of the budget (from 29.84 to 26.23 units) and 4.38 in the case of 50 percent of the budget. The differences between the lower budget solutions and the full budget solutions are significantly larger when comparing the accessibility of the 20-percent centers with lower accessibility. In fact, the value of the equity measure for the solution with 75 percent of the budget would be almost half the value of the equity measure for the full budget solution (11.86 versus 6.09 percent). The difference to the solution with 50 percent of the budget is only slightly larger (11.86 versus 5.14 percent).

(Locate Figure 6 approximately here)

(Locate Table 5 approximately here)

Conclusion

In this article, we presented a multi-objective approach to long-term interurban road network planning. It applies to multi-level roads, assuming travel demand to be elastic, and considering robustness and equity objectives in addition to the traditional efficiency objectives. The decisions derived from the application of the approach are consistent with the planning framework adopted in the Highway Capacity Manual. Taken separately all these features of road network planning have been addressed before within the framework of an optimization approach (some of them very rarely, e.g. multi-level roads). But, to the best of our knowledge, they were never dealt with simultaneously.

The approach is aimed at helping policy-makers in their strategic reflections regarding the long-term evolution of a national or regional network. Using a top-market personal computer, it can handle road networks large enough for most practical cases, since it is superfluous to be very detailed in the representation of the road network when the long-term travel demand forecasts required by the application of the approach are, inevitably, highly uncertain. As some planning theorists put it, from models representing very complex problems, we need meaningfulness more than accuracy (Batty and Torrens 2005; Guhathakurta 2002). This is particularly true when the long-term is the focus of analysis. We believe our approach can give meaningful results to long-term interurban road network planning problems, and provide good a starting point for the study of detailed solutions.

The application of the approach is illustrated for a case study involving the main road network of Poland. This case study was included to clarify the type of results that can be expected when the proposed approach is used. It was also included to clarify the implications for road network planning of taking efficiency, robustness, and equity objectives simultaneously into account.

As illustrated by the Polish case study, we believe that the proposed approach is already useful in practical applications. Nevertheless, we recognize that it can be improved with regard to a number of features. In particular, we identify four important lines of improvement. The first line relates to multi-modal integration. Our approach applies only to road transportation. We plan to extend it to incorporate rail transportation (high-speed and "regular") and modal split issues. The second line relates to environment concerns. Our approach considers them only as constraints to the improvement of road links above a certain level. We plan to extend it to encompass environmental objectives (namely, CO_2 emissions) in parallel with efficiency, robustness, and equity objectives. The third line relates to investment scheduling. Our approach seeks a long-term planning solution for a road network without paying attention to the evolution of the road network over time. We plan to extend it to allow the definition of an optimum schedule for investment in the transportation network. The fourth line relates to investment finance. Our approach relies on the assumption that the transformation of the road network is made with funds external to the road system (e. g., funds coming from the government budget). We plan to extend it to include internal funding from rail tickets and turnpike tolls. Once these extensions will be added, a decision support tool based on the approach can be extremely helpful to transportation authorities, because it will handle the essential aspects they must take into account when making strategic decisions on the improvement of transportation networks.

Acknowledgments

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

Abdulaal, M., and Leblanc, L. J. (1979). "Continuous Equilibrium Network Design Models." *Transportation Research Part B-Methodological*, 13(1), 19-32.

Antunes, A., Seco, A., and Pinto, N. (2003). "An Accessibility-Maximization Approach to Road Network Planning." *Computer-Aided Civil and Infrastructure Engineering*, 18(3), 224-240.

Bana e Costa, C. A., and Vansnick, J. C. (1997). "Applications of the Macbeth Approach in the Framework of an Additive Aggregation Model." *Journal of Multi-Criteria Decision Analysis*, 6(2), 107-114.

Batty, M., and Torrens, P. M. (2005). "Modelling and Prediction in a Complex World." *Futures*, 37(7), 745-766.

Ben-Ayed, O., Blair, C. E., Boyce, D. E., LeBlanc, L. J. (1992). "Construction of a Real-World Bilevel Linear Programming Model of the Highway Network Design Problem." *Annals of Operations Research*, 34, 219-254.

Boyce, D. E., and Janson, B. N. (1980). "A Discrete Transportation Network Design Problem with Combined Trip Distribution and Assignment." *Transportation Research Part B-Methodological*, 14(1-2), 147-154.

Cantarella, G. E., and Vitetta, A. (2006). "The Multi-Criteria Road Network Design Problem in an Urban Area." *Transportation*, 33(6), 567-588.

Chen, A., Yang, H., Lo, H. K., and Tang, W. H. (1999). "A Capacity Related Reliability for Transportation Networks." *Journal of Advanced Transportation*, 33(2), 183-200.

Cohon, J. L., and Rothley, K. (1997). "Multiobjective Methods." Design and Operation of Civil and Environment Engineering Systems, C. S. Revelle and A. E. McGarity, eds., Wiley, New York, USA.

Daly, A. (2000). "National Models." Handbook of Transport Modelling, D. A. Hensher and K. J. Button, eds., Elsevier Science, Oxford, UK.

D'Este, G. M., and Taylor, M. A. P. (2003). "Network Vulnerability: An Approach to Reliability Analysis at the Level of National Strategic Transport Networks." The Network Reliability of Transport, M. G. H. Bell and Y. Iida, eds., Elsevier, Oxford, UK, 23-44.

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

Friesz, T. L., Anandalingam, G., Mehta, N. J., Nam, K., Shah, S. J., and Tobin, R. L. (1993). "The Multiobjective Equilibrium Network Design Problem Revisited - a Simulated Annealing Approach." *European Journal of Operational Research*, 65(1), 44-57.

Friesz, T. L., and Harker, P. T. (1983). "Multi-Objective Design of Transportation Networks - the Case of Spatial Price Equilibrium." *Lecture Notes in Economics and Mathematical Systems*, 209, 86-93.

Friesz, T. L., Hsun-jung, C., Mehta, N. J., Tobin, R. L., and Anandalingam, G. (1992). "A Simulated Annealing Approach to the Network Design Problem with Variational Inequality Constraints." *Transportation Science*, 26(1), 18-26.

Gendreau, M., and Potvin, J. Y. (2005). "Metaheuristics in Combinatorial Optimization." *Annals of Operations Research*, 140(1), 189-213.

Guhathakurta, S. (2002). "Urban Modeling as Storytelling: Using Simulation Models as a Narrative." *Environment and Planning B-Planning & Design*, 29(6), 895-911.

Janson, B. N., Buckels, L. S., and Peterson, B. E. (1991). "Network Design Programming of United-States Highway Improvements." *Journal of Transportation Engineering-Asce*, 117(4), 457-478.

Jara-Diaz, S., and Friesz, T. L. (1982). "Measuring the Benefits Derived from a Transportation Investment." *Transportation Research Part B-Methodological*, 16(1), 57-77.

Keeble, D., Owens, P. L., and Thompson, C. (1982). "Regional Accessibility and Economic-Potential in the European-Community." *Regional Studies*, 16(6), 419-431.

Kokko, H., Mackenzie, A., Reynolds, J. D., Lindström, J., and Sutherland, W. J. (1999). "Measures of Inequality Are Not Equal." *The American Naturalist*, 154(3), 358-382.

Leblanc, L. J. (1975). "Algorithm for the Discrete Network Design Problem." *Transportation Science*, 39(1), 63-79.

Lo, H. K., and Tung, Y. K. (2003). "Network with Degradable Links: Capacity Analysis and Design." *Transportation Research Part B-Methodological*, 37(4), 345-363.

Meng, Q., and Yang, H. (2002). "Benefit Distribution and Equity in Road Network Design." *Transportation Research Part B-Methodological*, 36(1), 19-35.

Michalewicz, Z., and Fogel, D. B. (2004). *How to Solve It: Modern Heuristics*, Springer-Verlag, Berlin, Germany.

Ortúzar, J. D., and Willumsen, L. G. (2001). *Modelling Transport*, John Wiley & Sons Ltd, Chichester, England.

Saaty, T. L. (1994). "How to Make a Decision - the Analytic Hierarchy Process." *Interfaces*, 24(6), 19-43.

Santos, B., Antunes, A., and Miller, E. J. "Solving an Accessibility-Maximization Road Network Design Model: A Comparison of Heuristics." *Advanced OR and AI Methods in Transportation*, Poznan, Poland, 692-697.

Santos, B., Antunes, A., and Miller, E. J. "Optroad: A Computer Program for Interurban Road Network Planning." *Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, Montreal, Canada, 996-1005.

TRB. (2000). "Highway Capacity Manual." Transportation Research Board, National Research Council, Washington, D.C., USA.

Tzeng, G. H., and Tsaur, S. H. (1997). "Application of Multiple Criteria Decision Making for Network Improvement." *Journal of Advanced Transportation*, 31(1), 49-74.

Ukkusuri, S. V., Mathew, T. V., and Waller, S. T. (2007). "Robust Transportation Network Design under Demand Uncertainty." *Computer-Aided Civil and Infrastructure Engineering*, 22(1), 6-18.

Vickerman, R., Spiekermann, K., and Wegener, M. (1999). "Accessibility and Economic Development in Europe." *Regional Studies*, 33(1), 1-15.

Wardrop, J. G. "Some Theoretical Aspects of Road Traffic Research." *Institute of Civil Engineers*, 325-378.

Yang, H., and Bell, M. G. H. (1998). "Models and Algorithms for Road Network Design: A Review and Some New Developments." *Transport Reviews*, 18(3), 257-278.

Table 1. Design characteristics for the different road levels (TRB, 2000)

Road level	Free-flow speed [km/h]	Capacity [pcu/h/lane]	Level of service	Maximum service flow [pcu/h/lane]	Maximum service speed [km/h]
Slow two-lane highway	70	1700	E	1428	55
Fast two-lane highway	90	2100	C	1428	90
Four-lane freeway	120	2400	B	1320	120
Six-lane freeway	120	2400	B	1320	120

Table 2. Relative unit costs for road upgrading

From	To		
	Fast two-lane highway	Four-lane freeway	Six-lane freeway
Slow two-lane highway	1.5	2.5	3
Fast two-lane highway	-	2	2.5
Four-lane freeway	-	-	1

Table 3. Impact of the improvement of the road network

Assessment measure	Initial network	Objective							
		Efficiency		Efficiency and robustness		Efficiency and equity		Efficiency, robustness, and equity	
	Value	Value	Variation	Value	Variation	Value	Variation	Value	Variation
Weighted accessibility	1.442	1.588	10.12%	1.587	10.06%	1.571	8.95%	1.574	9.15%
Reserve capacity	-77.72	31.48	-----	32.79	-----	29.34	-----	29.84	-----
Accessibility of the 20% centers with the lower accessibilities	10.12	10.93	8.00%	10.92	7.91%	11.33	11.96%	11.32	11.86%

Table 4. Length of the different road levels

Road level	Initial network	Objectives							
		Efficiency		Efficiency and robustness		Efficiency and equity		Efficiency, robustness and equity	
	km	km	Variation	km	Variation	km	Variation	km	Variation
Slow two-lane highways	5894	3550	-39,8%	3608	-38,8%	3253	-44,8%	3209	-45,6%
Fast two-lane highways	4992	4528	-9,3%	4591	-8,0%	5088	1,9%	5136	2,9%
Four-lane freeways	472	3067	549,8%	2814	496,2%	2727	477,8%	2783	489,6%
Six-lane freeways	0	213	-----	345	-----	290	-----	230	-----

Table 5. Sensitivity of the solution to budget reduction

Assessment measure	Initial network	Budget					
		50 percent		75 percent		Full	
	Value	Value	Variation	Value	Variation	Value	Variation
Weighted accessibility	1.442	1.514	4.97%	1.537	6.56%	1.574	9.15%
Reserve capacity	-77.72	25.46	----	26.23	----	29.84	----
Accessibility of 20% centers with the lower accessibilities	10.12	10.64	5.14%	10.74	6.09%	11.32	11.86%

Figure captions

Fig. 1. Schematic representation of the approach

Fig. 2. Example of route alternatives

Fig. 3. Flowchart for the Enhanced Genetic Algorithm

Fig. 4. Main road network of Poland in the year 2000

Fig. 5. Best solutions for the different objectives

Fig. 6. Sensitivity of solution to budget reduction