FCTUC DEPARTAMENTO DE ENGENHARIA CIVIL
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

Planeamento de redes rodoviárias:
Aplicações em Portugal e no Brasil

Workshop Optimização de Transportes
Coimbra – 26 de Novembro de 2010

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Outline

- Introduction
- Research Goal
- The Proposed Approach
- The Optimization Model
- Solution Techniques
- Objectives and Measures
- Results
- Conclusion
- Future Research

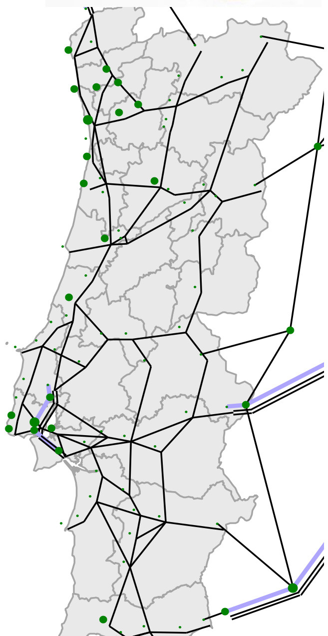
Introduction

- **Modern economies** are highly dependent upon **transportation systems.**
- Due to its high flexibility and the unique capability to provide door-to-door transportation, **roads play a vital role** in the transportation systems.

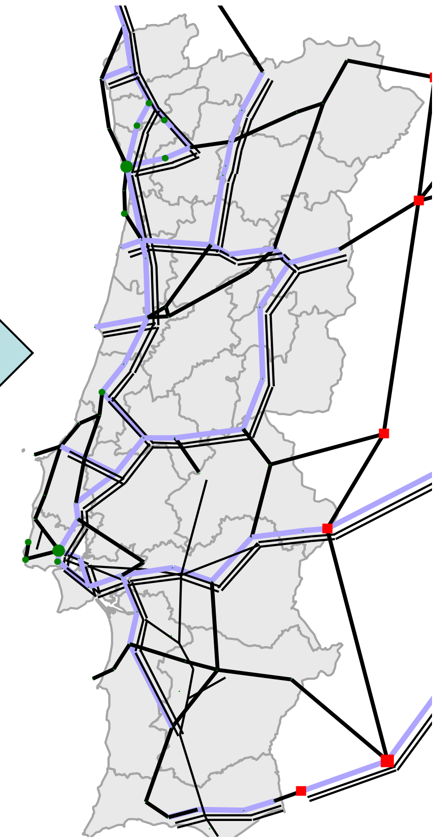
- **Road network plans** are typically developed following a **trial-and-error approach.**
- Although widely studied, **optimization-based approaches** have rarely (or never) been used in practical applications.

Introduction

What is the problem about?



How to apply a given budget in the improvement of a road network?



PRN 2000

Introduction

The Road Network Design Problem (RNDP)

- The problem consists of:
  - defining the **best investment decisions on the expansion of a street and highway system** in response to a growing demand (Yang and Bell 1998).

- Decisions can include:
  - the **improvement** of existing roads (Continuous RNDP);
  - the **addition** of new roads to the existing road network (Discrete RNDP).

Introduction

Bibliography

- RNDP models:
  - **Discrete RNDP**:
    - LeBlanc (1975); Boyce and Janson (1980); Drezner and Salhi (2002); Kim et al. (2008).
  - **Continuous RNDP:**
    - Abdulaal and LeBlanc. (1979); Friesz et al. (1992); Meng et al. (2001); Gao et al. (2007).

- RNDP objectives:
  - **User costs and construction costs:**
    - Friesz et al. (1993); Tzeng and Tsaur (1997).
  - **Robustness/reliability:**
    - Lo and Tung (2003); Ukkusuri et al. (2007).
  - **Equity:**
    - Meng and Yang (2002); Feng and Wu (2003).
  - **CO_2 emissions:**
    - Cantarella and Vitetta (2006).
  - **Accessibility:**
    - Antunes et al. (2003).

Introduction

<u>Long-term planning of interurban road networks</u>

- The weaknesses of the planning approach that underlies traditional RNDP:
  - does not take into account the **long-term influence** of the investments **on travel demand;**
  - **road capacity** is assumed **continuous;**
  - does not take into account the **planning framework** typically used in practice;
  - does not take into account the fact that road network investments are aimed at fulfilling **objectives of various types.**

Research Goal

- Goal:
  - To address the RNDP in such a way that **decision makers and practitioners would be more likely to use it.**

- Objectives:

1. To **develop a multi-objective approach** for long-term interurban road network planning and to test the influence that each planning objective will have on the solutions.
2. To **develop efficient techniques to solve the model.**
3. To **develop a computer program** for implementing the multi-objective approach

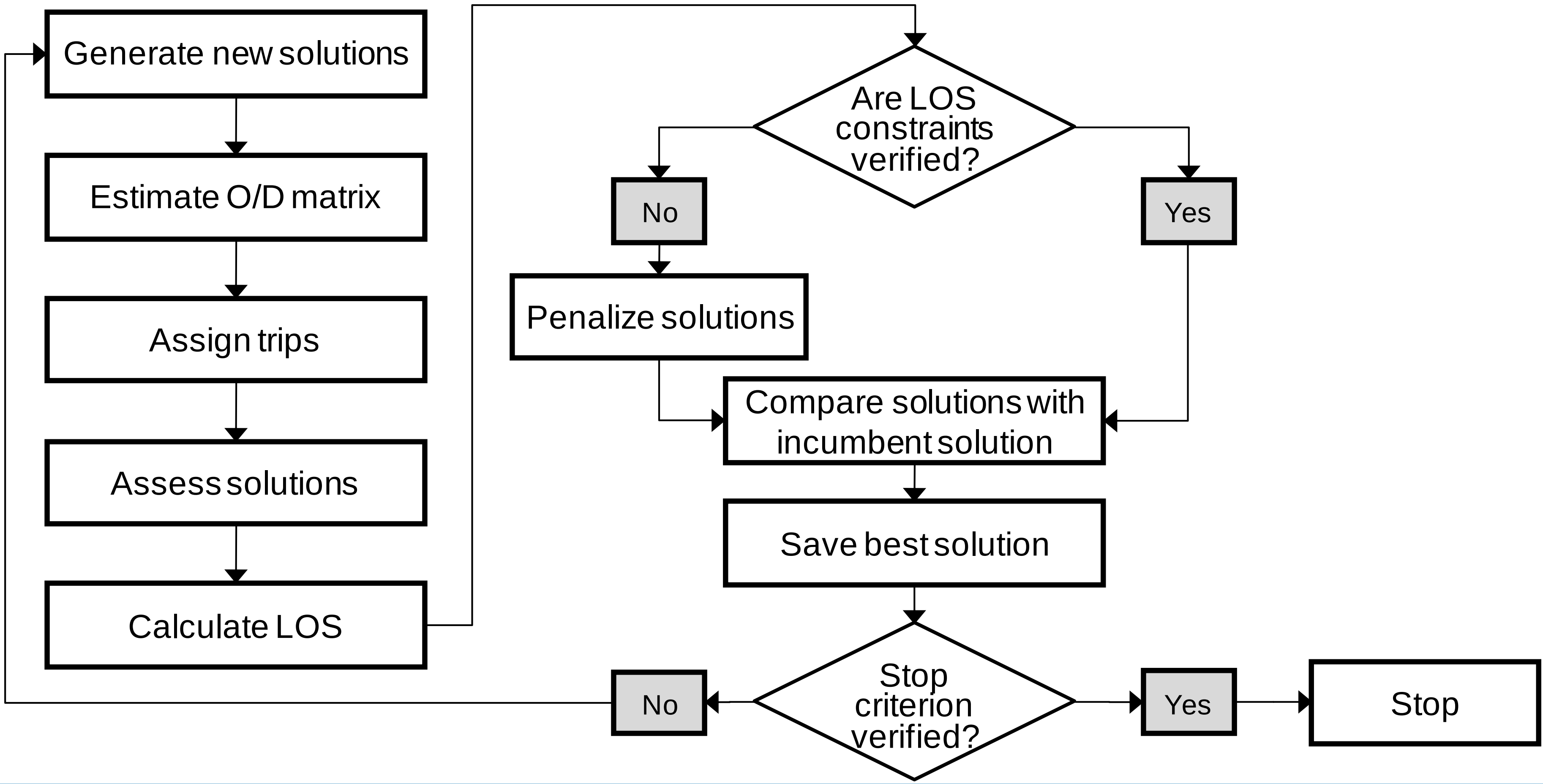
The Proposed Approach

Main principles:

- Planning decisions are defined according to a **road hierarchy:**
  - the construction of new road links of a given level (type);
  - the upgrading of existing road links to a higher level.
- **Efficiency, robustness, equity, and energy consumption objectives** are simultaneously taken into account.
- **Travel demand is elastic** with road network changes.
- Planning decisions are consistent with the planning framework adopted in the **Highway Capacity Manual.**

The Proposed Approach

- Schematic representation of the approach



The Optimization Model

- Upper-level Problem – Road improvements decisions:

$$\max V = w_Z \times \frac{Z - Z_0}{Z_B - Z_0} + w_E \times \frac{E - E_0}{E_B - E_0} + w_R \times \frac{R - R_0}{R_B - R_0}$$

[1] Objective function
(maximization of weighted normalized values)

subject to:

$$Z = \eta(\boldsymbol{y}) \text{ and } E = \mu(\boldsymbol{y}) \text{ and } R = \xi(\boldsymbol{y})$$

[2] Objectives measures

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

[3] Single decision per link

$$\sum_{l \in \mathbf{L}} \sum_{m \in \mathbf{M}_l} e_{lm} . y_{lm} \leq b$$

[4] Budget constraint

$$T_{ij} = \theta \times P_i \times P_j \times c_{ij}(\boldsymbol{y})^{-\beta}, \forall i, j \in \boldsymbol{N}$$

[5] Demand function

$$Q_l = \sum_{i \in N} \sum_{j \in N} T_{ij} \times x_{lij}, \forall l \in \boldsymbol{L}$$

[6] Traffic on each link

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

[7] LOS constraint

$$y_{lm} \in \{0,1\}, \forall l \in \mathbf{L}, m \in \mathbf{M}_l \text{ and } a_i, T_{ij}, Q_l \geq 0, \forall i, j \in \mathbf{N}, \forall l \in \mathbf{L}$$

The Optimization Model

- Lower-level Problem – Driver's route choice for each (r, d) pair of centers:

$$\min c_{rd} = \sum_{l \in \mathbf{L}} \sum_{m \in \mathbf{M}_l} z_{lm} \times y_{lm} \times x_{lrd}$$

[8] Objective function
(minimization of travel costs)

subject to:

$$\sum_{l \in \mathbf{R}(k)} x_{lrd} = v_{krd}, \ \forall k, r, d \in \mathbf{N}, \ \mathbf{R}(k) = \{(i, j) \in \mathbf{L} : i = k \vee j = k\}$$

$$v_{krd} = \begin{cases} 1, \ k = r \vee k = d \\ 2 \times u_{krd}, \ k \in N \setminus \{r, d\} \end{cases}$$

[9,10] Continuous optimum route

$$u_{krd}, x_{lrd} \in \{0,1\}, \ \forall k, r, d \in N, l \in L$$

$$v_{krd} \in \{0,1,2\}, \ \forall k, r, d \in N$$

Solution Techniques

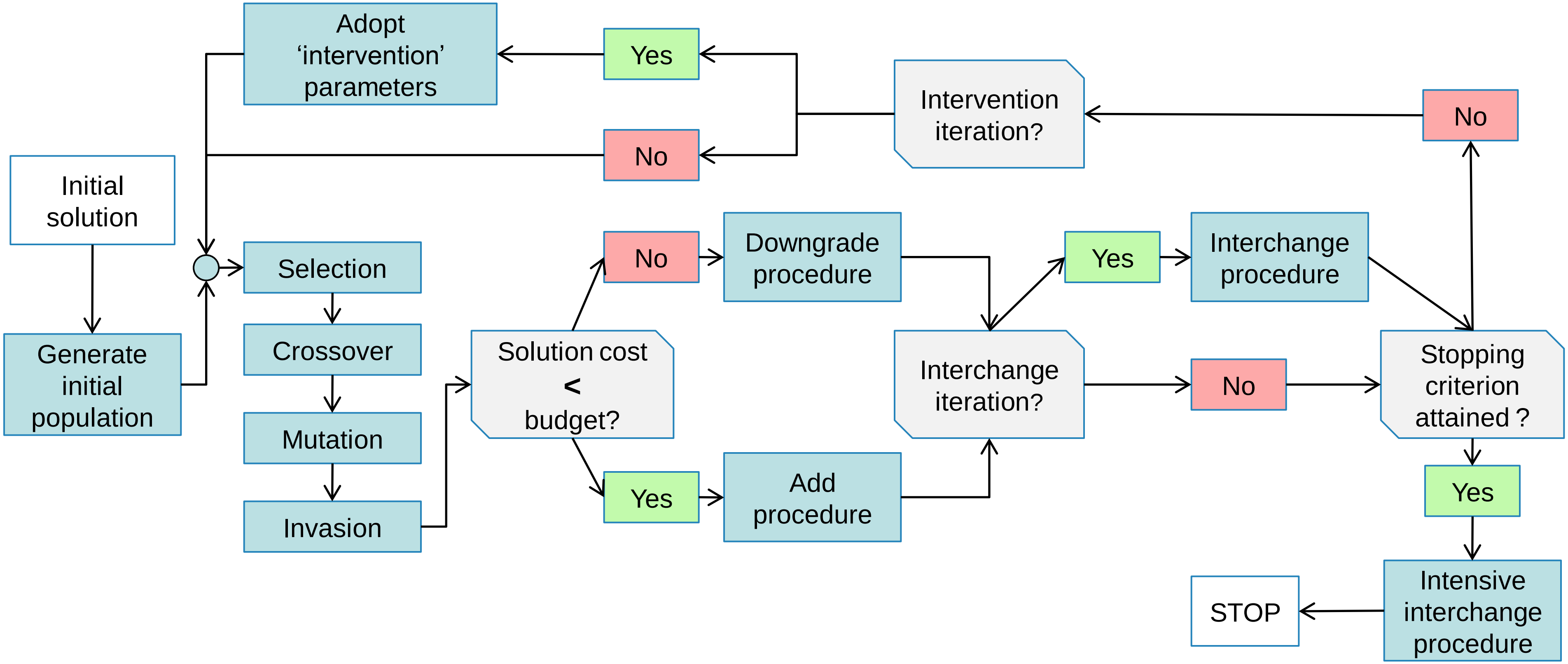
Three heuristics were developed:

- A Local Search Algorithm (LSA),
- A Variable Neighborhood Search Algorithm (VNSA), and
- An Enhanced Genetic Algorithm (EGA).

Santos, B., Antunes, A. and Miller, E. (2005)
"Solving an Accessibility Maximization Road Network Design Model: A Comparison of Heuristics".
Advanced OR and AI Methods in Transportation, Proceedings pp. 692-697, Poznan, Poland, 13-16 September, 2005.

Solution Techniques

- Enhanced Genetic Algorithm (EGA)



Solution Techniques

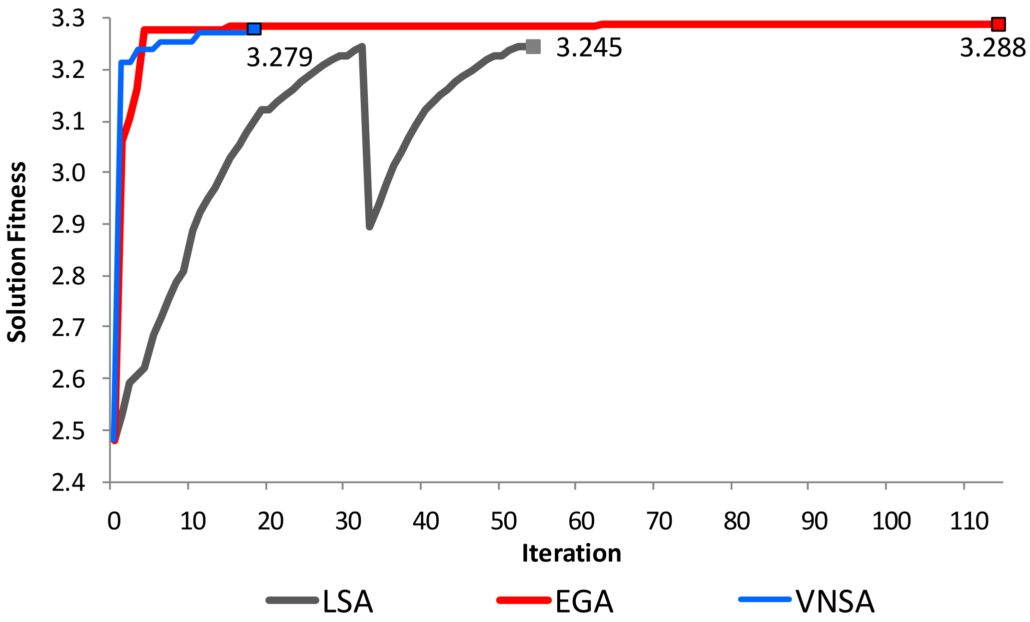
The three heuristics were tested on a sample of randomly generated test networks.

- <u>Solution quality</u>:
  - **20 small networks** (10-24 links) – exact optimum solution known:
    - **LSA** found **4 of the 20** optimum solutions
    - **VNSA** found **8 of the 20** optimum solutions
    - **EGA** found **17 of the 20** optimum solutions
  - **40 larger networks** – heuristics compared between them:
    - **LSA never found** the best solution and was, on average, **1.01% worse**
    - **VNSA** found **9 of the 40** best solutions and was, on average, **0.23% worse**
    - **EGA** found **32 of the 40** best solutions and was, on average, **0.14% worse**

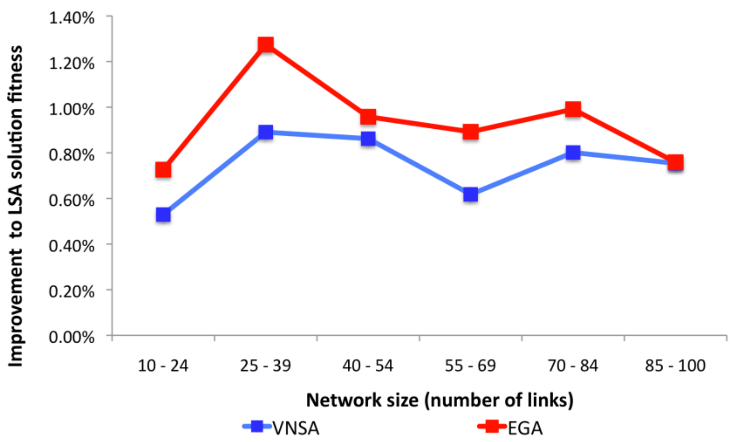
- <u>Computational effort</u>:
  - The **LSA** is **more than 10 times faster** than the other algorithms for small networks (10-39 links).
  - The **EGA**:
    - **much slower** than the other heuristics for **smaller size networks**
    - for **networks with 70 links or more**, became **faster than the VNSA**

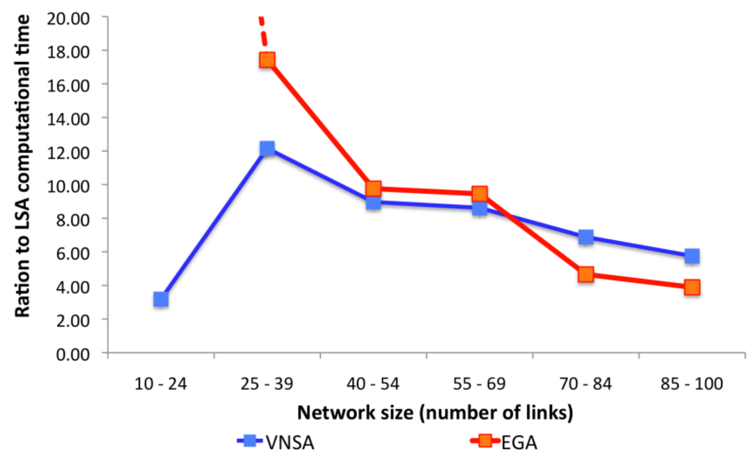
Solving Techniques

Example of evolution of solution fitness during the application of the heuristics



Impact of network size on the performance of the VNSA and the EGA





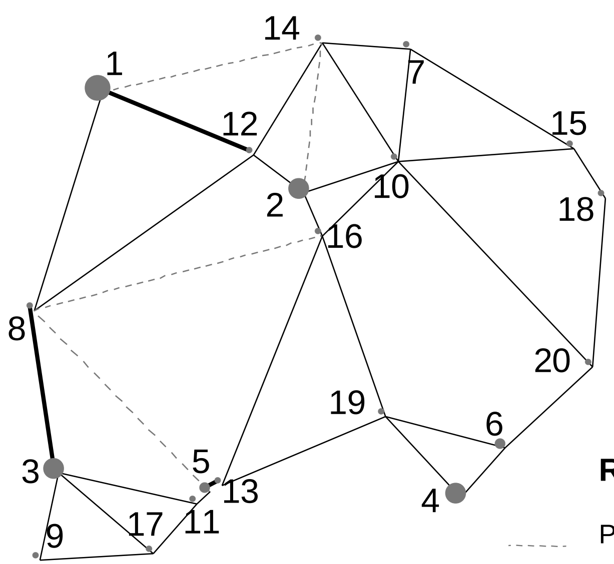
Objectives and Measures

- **Efficiency:**
  - Weighted accessibility
  - Average speed
  - Consumer's surplus
  - Weighted travel costs to major centers (capitals)
- **Equity:**
  - Accessibility of centers with lower accessibility
  - Gini index
  - Theil's inequality index
- **Robustness:**
  - Spare capacity
  - Evacuation capacity
  - Network vulnerability
- **Energy consumption**
  - Average fuel consumption (maximum service speed)

Results

Random Networks

- Randomly generated networks of different sizes were used to analyze the impact of considering equity objectives.



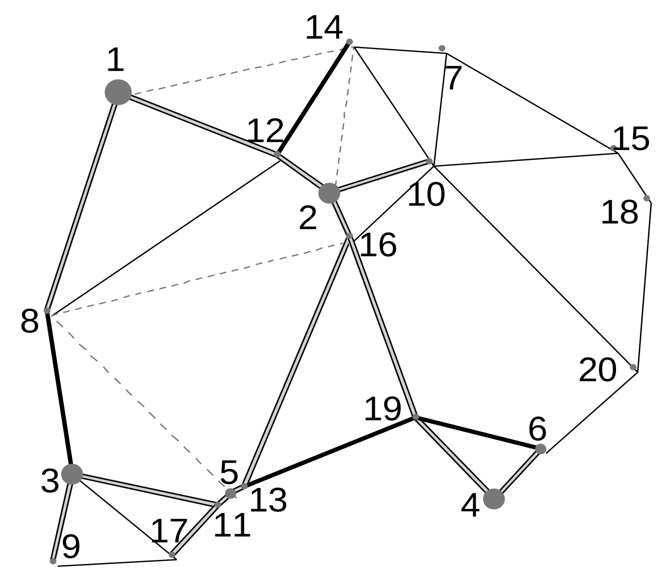
Initial network

Population Centers

- 80 000 inhabitants
- 150 000 inhabitants
- 250 000 inhabitants
- 650 000 inhabitants

50 km

Road Type	Service flow (pcu/h)	Free flow speed
Possible Road	0	0 km/h
Slow 2-lane highway	1428	70 km/h
Fast 2-lane highway	1869	90 km/h
4-lane freeway	2640	120 km/h



Accessibility maximization solution

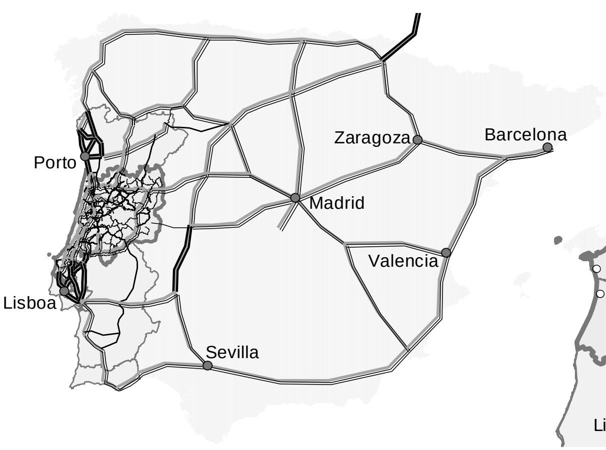
Santos, B., Antunes, A., Miller, E. (2008)
"Integrating Equity Objectives in a Road Network Design Model".
Transportation Research Record - Issue Number: 2089.

Centro Region Road Network (PT)

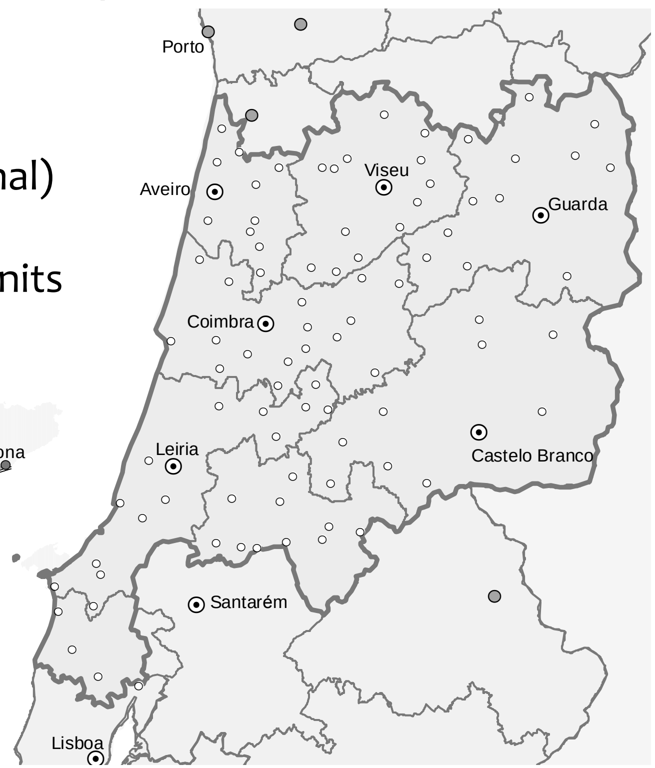
- The main road network of the Centro Region was improved in the last 20 years. How to improve the secondary road network?

Network with:
- 196 nodes
- 334 links (261 internal)

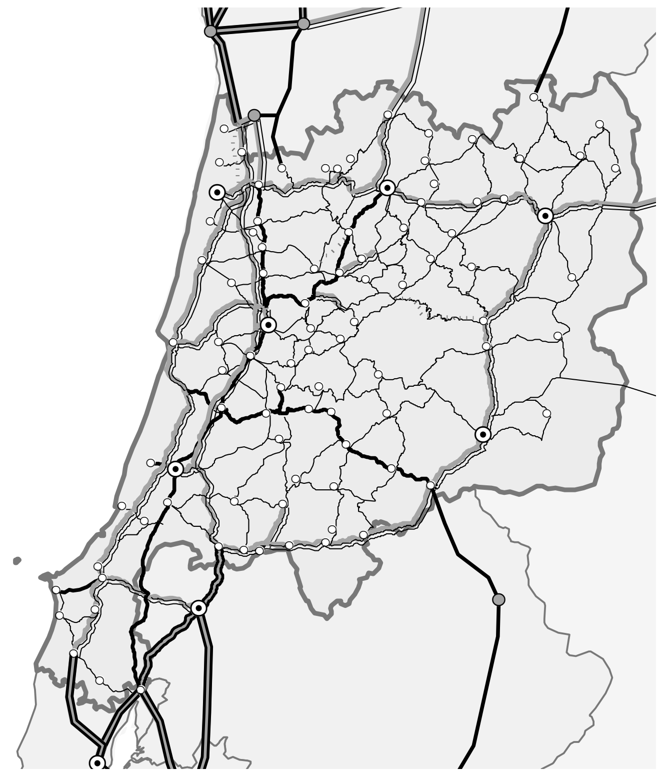
Budget: 3,500 monetary units



(a) Refence network



(b) Centro Region – Districts and major cities

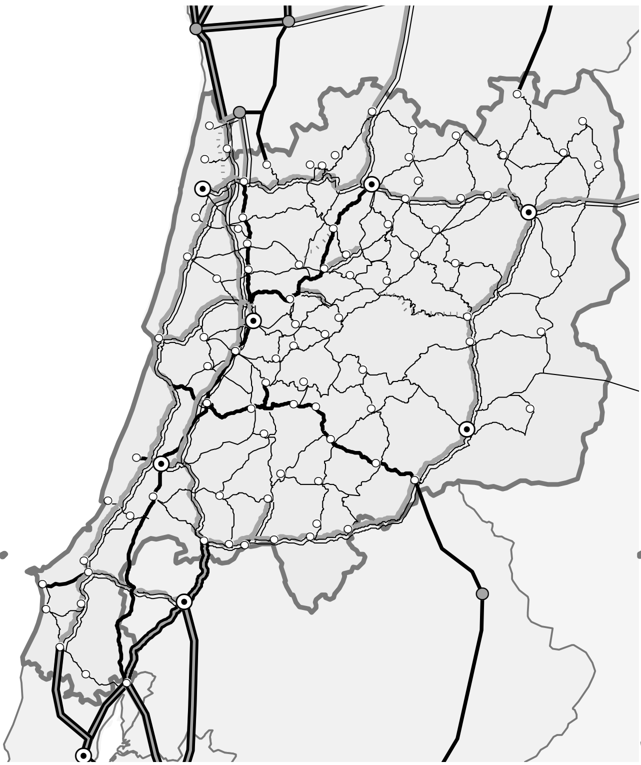


(c) Centro Region current road network

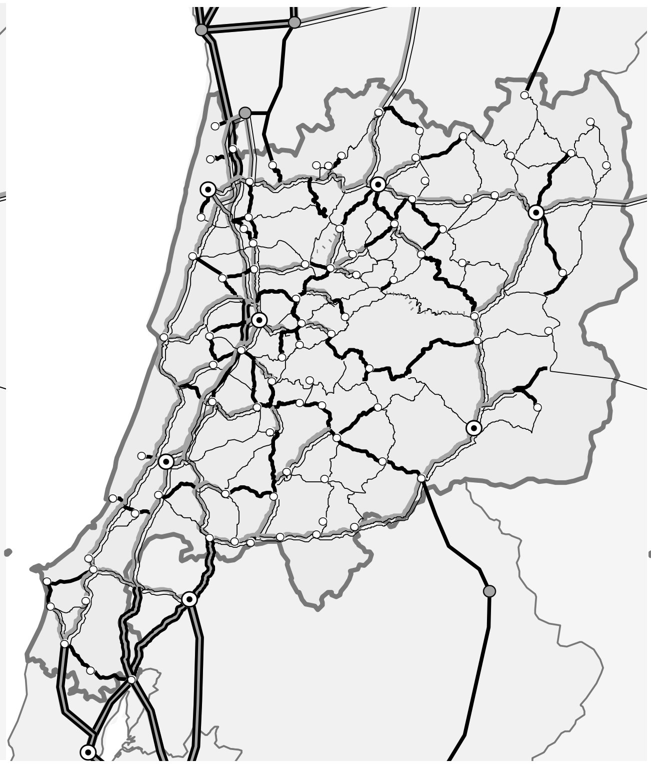
Centers — Centro Region: District capitals; Other population centers. Outside Centro Region: NUTS III main cities. Centro Region

Road Type — Possible Road; Slow 2-lane highway; Fast 2-lane highway; 4-lane freeway; 6-lane freeway

Centro Region Road Network (PT)



Centro Region current road network

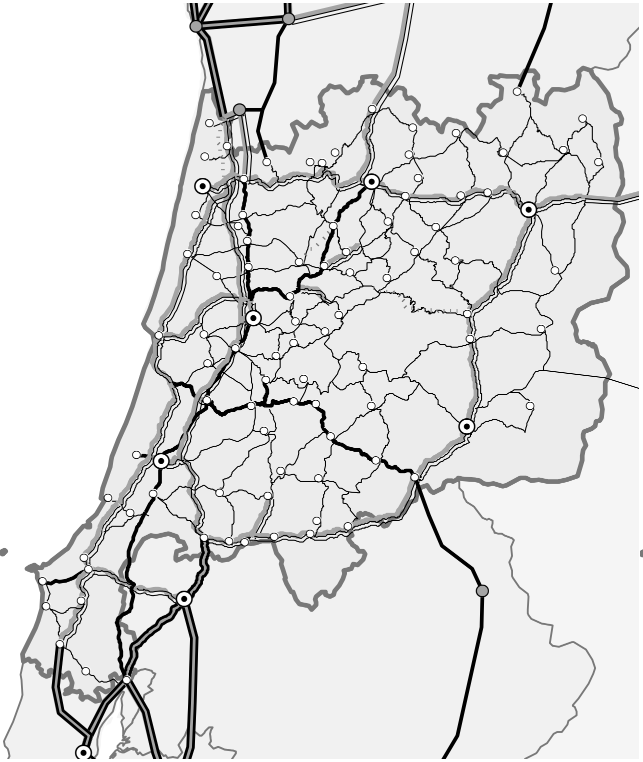


(1) Average speed, gini index, and fuel consumption

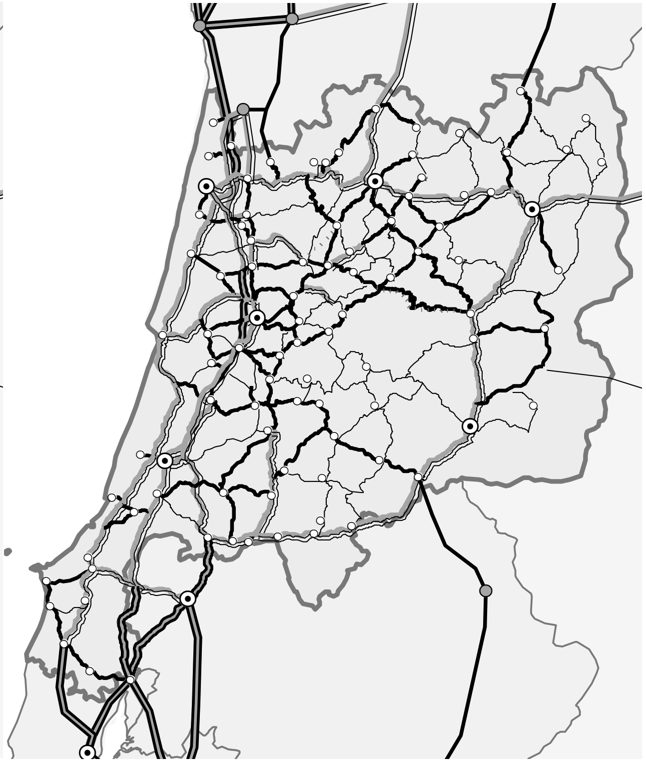
(2) Weighted travel cost, gini index, and fuel consumption

Road Type: ···· Possible Road —— Slow 2-lane highway ▬ Fast 2-lane highway ▭ 4-lane freeway ▭ 6-lane freeway

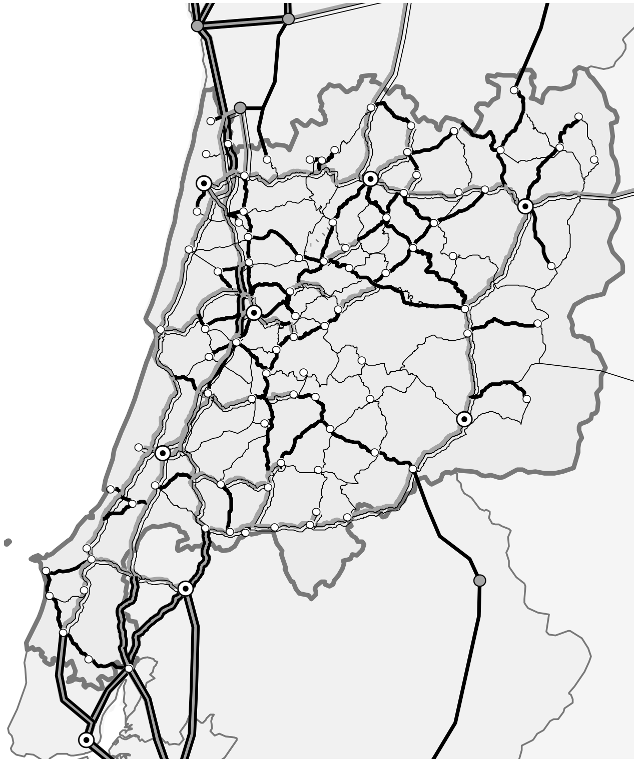
Centro Region Road Network (PT)



Centro Region current road network



(3) Consumer's surplus, gini index, and fuel consumption



(4) Weighted accesibility, gini index, and fuel consumption

Road Type: ···· Possible Road — Slow 2-lane highway — Fast 2-lane highway — 4-lane freeway — 6-lane freeway

Centro Region Road Network (PT)

- In order to compare pairs of road network solutions, the following similarity index was considered:

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

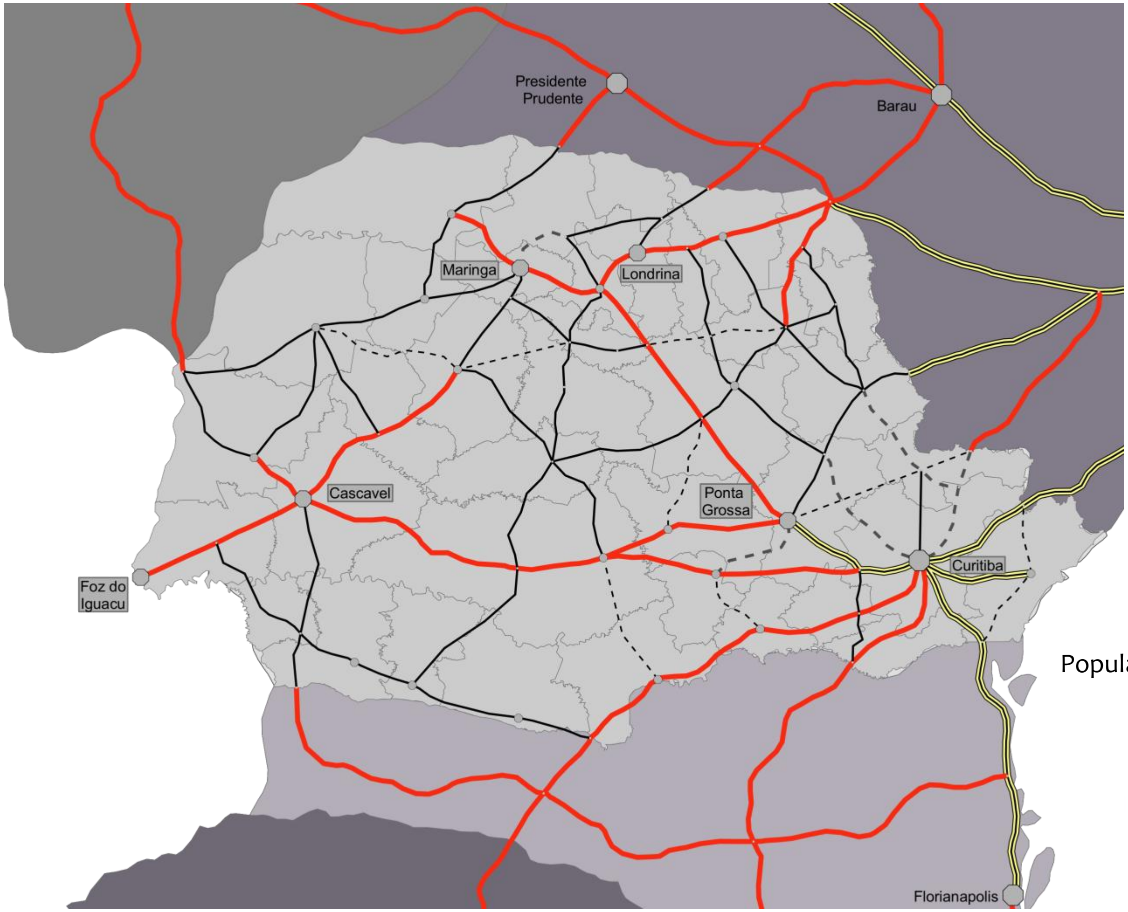
		Current Network	Solution			
			1	2	3	4
Current Network		----	0.390	0.392	0.399	0.400
Solution	1	0.390	----	0.400	0.272	0.279
	2	0.392	0.400	----	0.368	0.348
	3	0.399	0.272	0.368	----	0.201
	4	0.400	0.279	0.348	0.201	----

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

- The "**accessibility**" solution is **similar** with the "**consumer's surplus**" solution and it is the most different from the initial network.
- The two **less similar** solutions are obtained for the **weighted travel cost** and the **average speed** measures (despite being two solutions with similar lengths for roads of the same type).

Case Study – Paraná (Brazil)

- Improvement of the road network of the state of **Paraná** (Brazil)

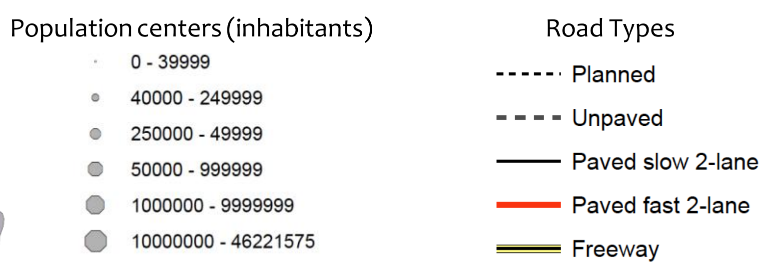


The Paraná road network in 2007

Network with:

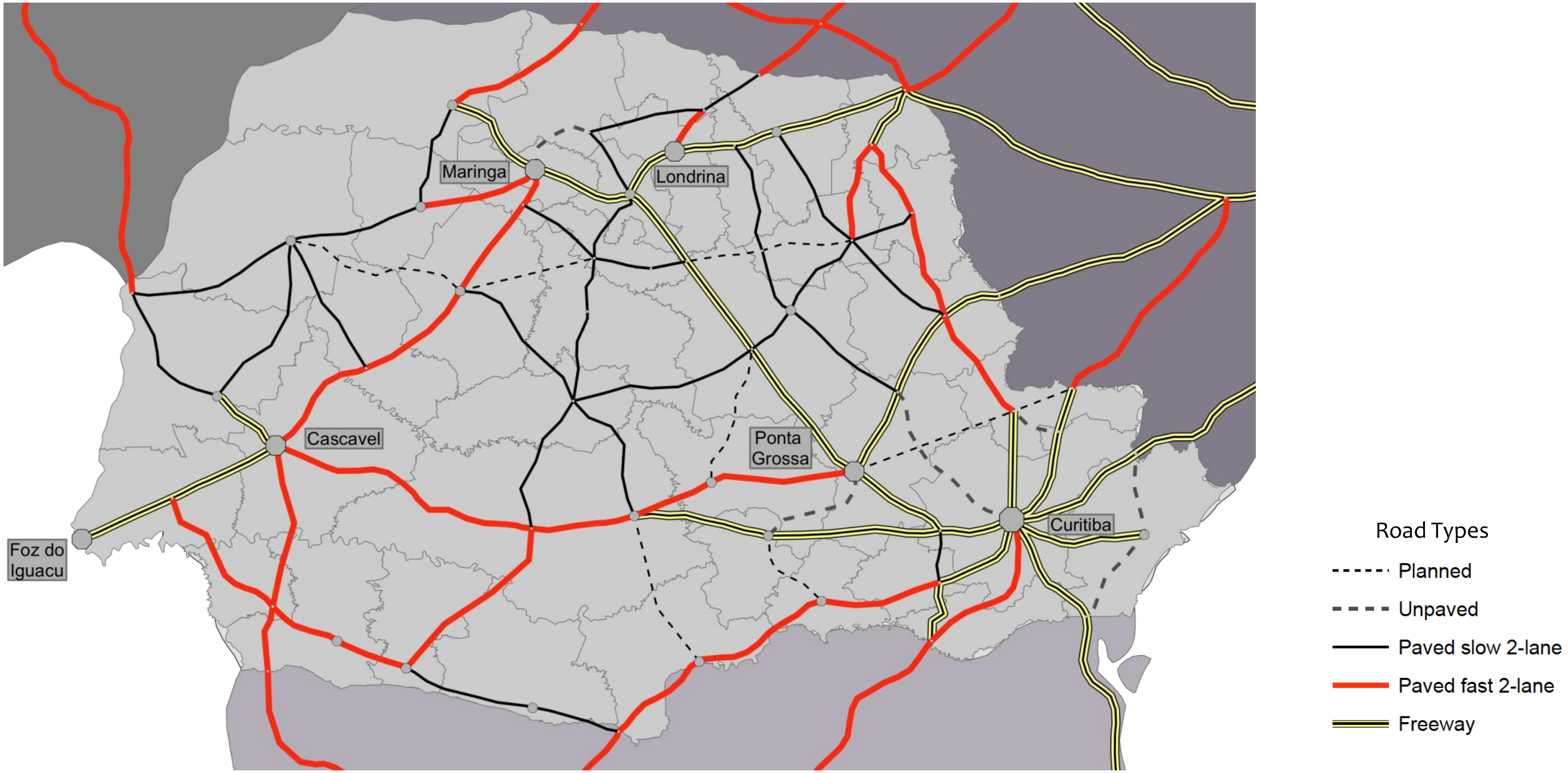
- 76 nodes
- 133 links (100 internal)

Budget: 4,700 monetary units



Case Study – Paraná (Brazil)

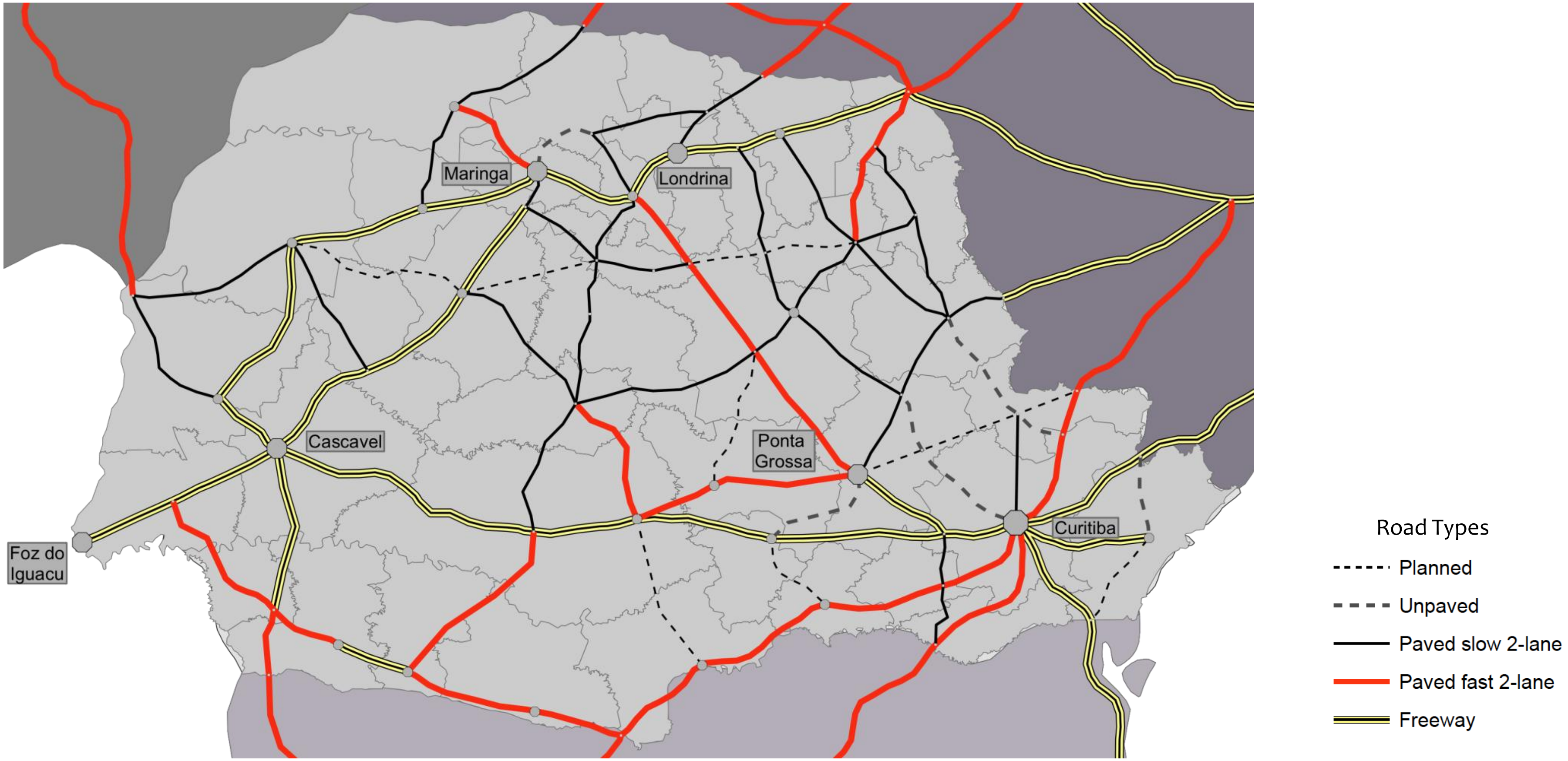
- Solution for demand forecasting assuming current trends



Solution for **accessibility** maximization

Case Study – Paraná (Brazil)

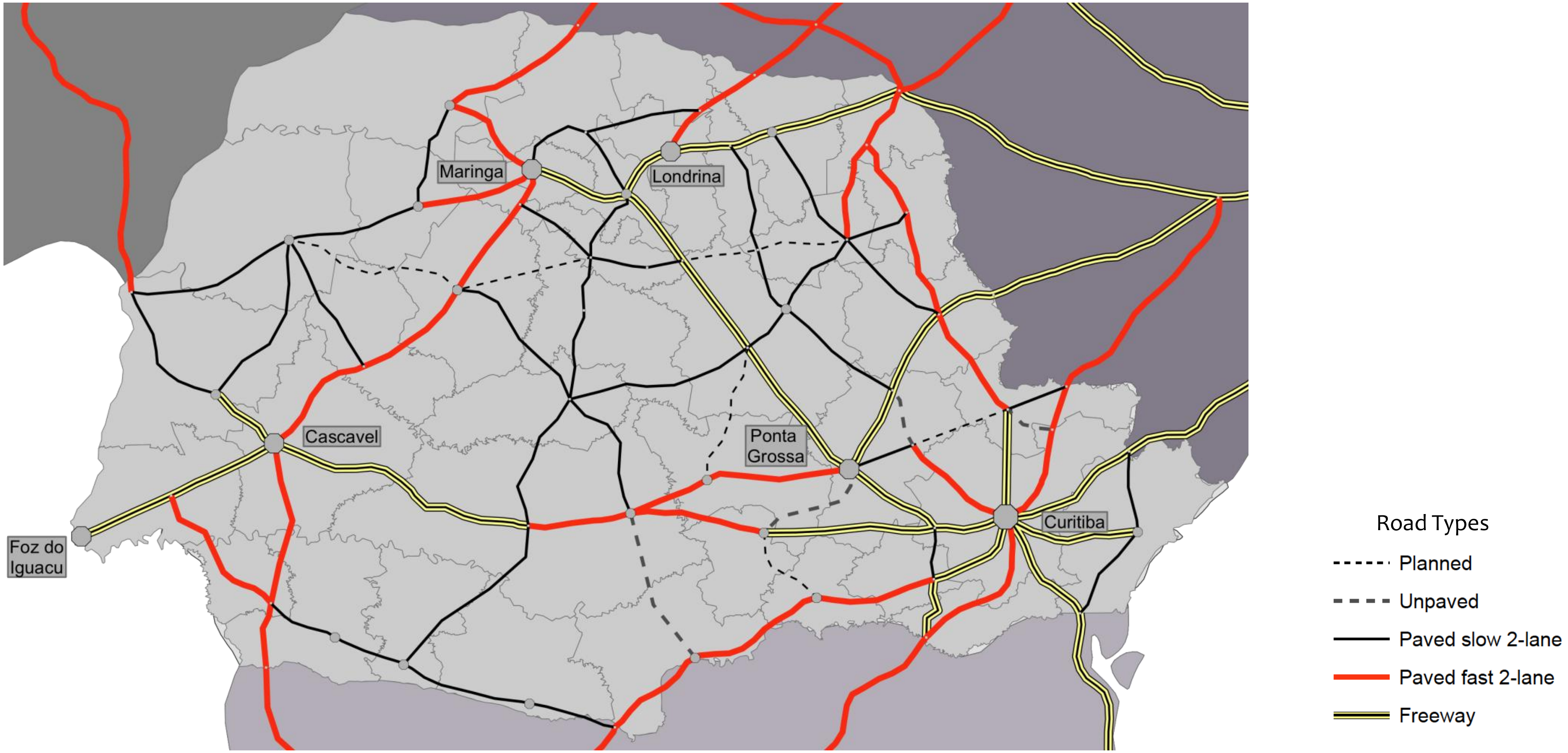
- Solution for demand forecasting assuming current trends



Solution for **accessibility** and **equity** maximization

Case Study – Paraná (Brazil)

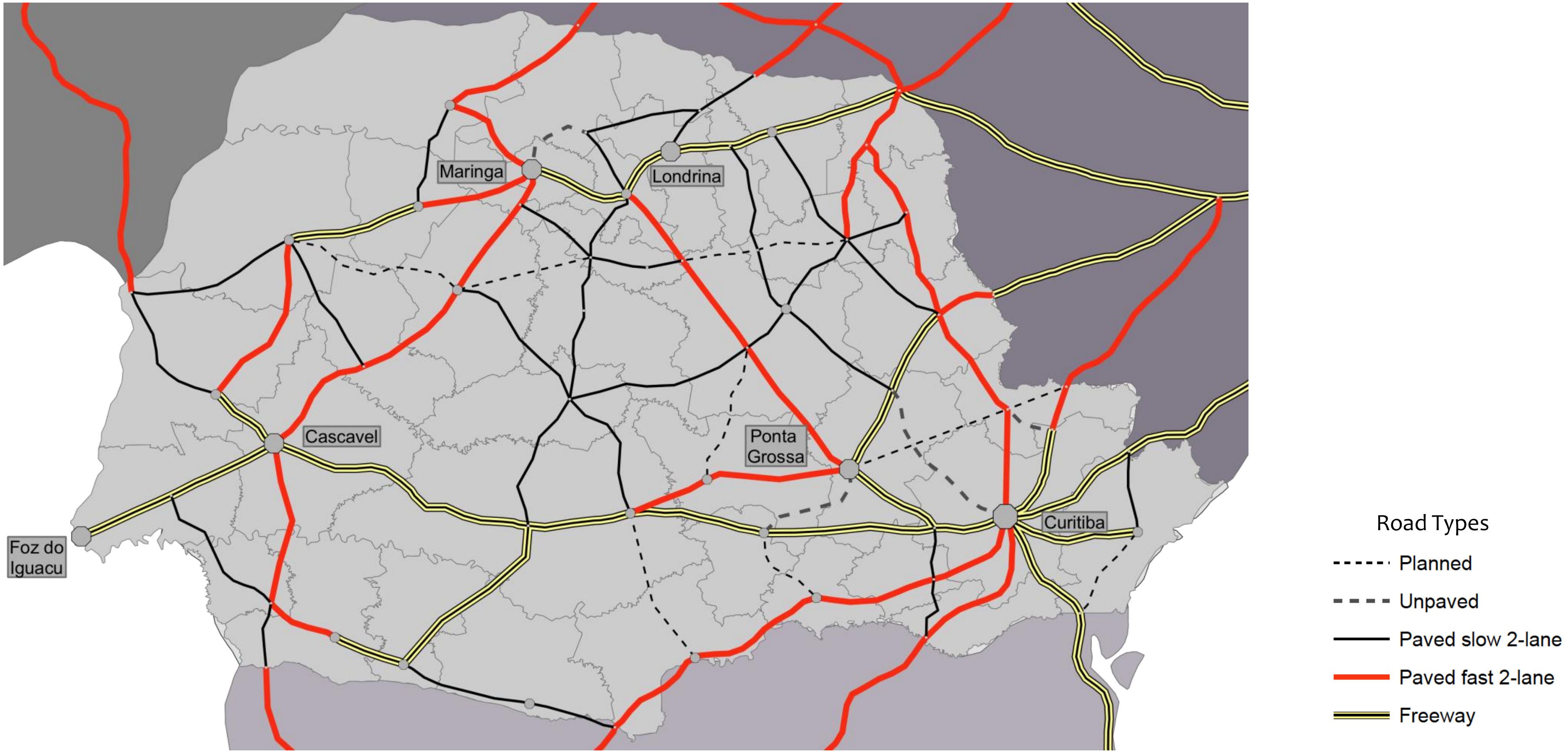
- Solution for demand forecasting assuming current trends



Solution for **accessibility** and **robustness** maximization

Case Study – Paraná (Brazil)

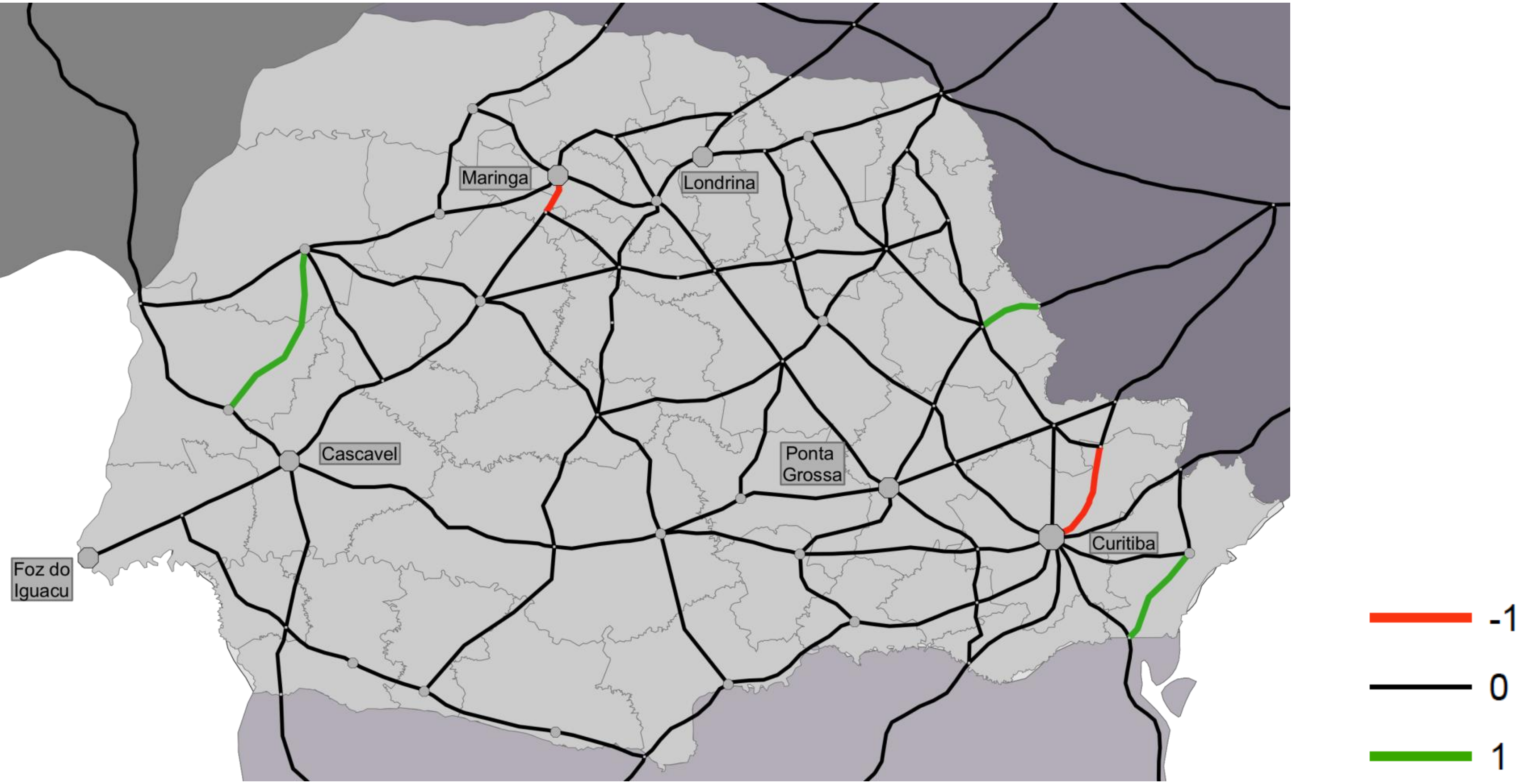
- Solution for demand forecasting assuming current trends



Solution for **accessibility**, **equity**, and **robustness** maximization

Solution Robustness

- Difference in solutions when demand is **reduced in 20%:**



Solution with less 20% of budget – solution with full budget

Solution Robustness

- Difference in solutions when demand is **increased in 20%:**

Solution with more 20% of budget – solution with full budget

Conclusion

— The proposed approach provides a **multi-objective** perspective to the RNDP for the long-term evolution of a **national or regional road network**;

— The approach has some **innovative features** (e.g., multi-level, uses the concept of level of service, demand elastic);

— **Three to four measures** were used to assess each optimization **objective** (efficiency, equity, and robustness);

— **Three heuristic methods** were used and compared (LSA, VNSA, and EGA);

— A user-friendly computer program, ***OptRoad***, was developed.

Conclusion

— The proposed approach is aimed to **help policy-makers in their strategic decisions** regarding the long term (say, 20 years) evolution of their national and regional road networks.

— This approach can be more easily accepted by practitioners because:

- It is compatible with the HCM;
- It assumes a road hierarchy;
- It considers the long-term influence on demand;
- It considers a multi-objective perspective.

— At this stage, the approach **is already useful** in practical applications:

- it can give meaningful results to long-term interurban road network planning problems, and provide a **good starting point for the study of detailed solutions.**

Future research

- Integration of rail transportation (regular and high-speed rail) → a multi-modal network design problem;
- Separation between passenger and freight traffic;
- Inclusion of other traffic assignment approaches (metropolitan networks → parallel user equilibrium traffic assignment);
- Definition of a multi-period investment program;
- Inclusion of (internal) investment financing analysis (build-operate-transfer schemes).

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