A before–after analysis for the design problem on an urban road network

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Abstract

In this paper, a road network design problem at an urban level is reported. After providing a general overview of the problem, a mathematical formulation is provided. In the design model, both the network layout and the signals setting are considered. An application on a real network is performed. In relation to the deign procedure, a comparison between the before and after configurations (generated with a plan or design) is reported. The objective is to increase the safety of road users.
Keywords: heuristic algorithms, genetic algorithm, Tabu Search, network constraints.

1 Introduction

In the literature, the Network Design Problem (NDP), referred to an urban transportation network, is relative to the network layout and to the signals setting optimization. In the network layout the link directions and the lanes allocation are designed; in the signals setting the phases at junctions and the phases order are designed. A network configuration includes both network layout and signals setting. A first method for classifying the NDPs depends on the design variables considering: the network layout; the signals setting; the network layout and the signals setting. In third case: the layout and the signals setting can be optimized jointly or sequentially; the junctions can be considered isolated or interacting. Generally, the variables involved in network layout are discrete, the variables involved in signals setting are continuous. Considering this, the NDPs can be

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classified also in relation to the variables: discrete, continuous, mixed (with discrete and continuous variables) problems.

Figure 1 shows a general approach to apply for solving a NDP (*supply design model*). It is a loop approach, which has as input the supply and the demand starting from external *objectives* and *constraints*. Mono and multi-objective problems can be considered. The considered case assumes that the *demand* is rigid. The *supply* can change at each procedure iteration because it is the control variables (network layout and in signals setting). A *demand-supply interaction model* allows evaluating the *performances* and the *impacts* of actual network configuration. A *test* is performed to evaluate if the objectives are reached.

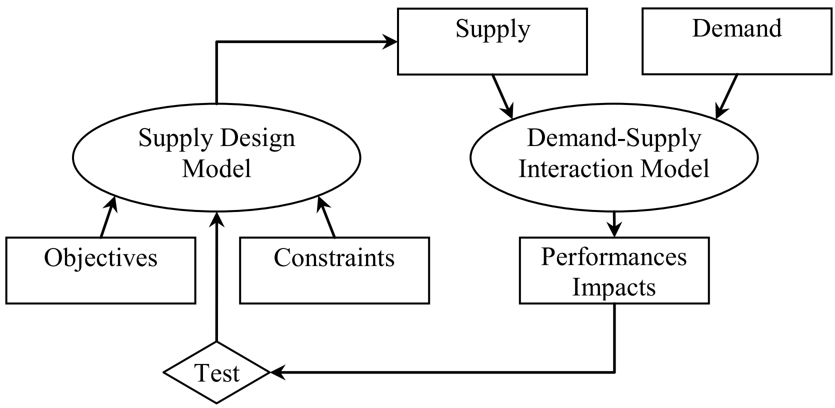

Figure 1: Network Design Problem: a general approach.

Considering the previous classification, Table 1 reports some work present in literature. Some of this work is also briefly commented on in the next paragraphs.

Relating to the network layout Billheimer and Gray [1] propose a heuristic approach to solve the problem in uncongested networks. The problem is extended at congested network (e.g. [2, 3]).

Relating to the signal setting design, two sub-classifications can be made, according to *isolated junctions* or *interacting junctions*. In first case, some of these papers are: Webster [20], Webster and Cobb [21], Allsop [8, 9] and Cantarella *et al*. [12]. In the second case, some of these papers are: Cantarella *et al*. [12], Sun and Mouskos [28], Marcianò and Vitetta [26]. Other distinctions, based on path choice, can be added.

Relating to the network layout and the signals setting design, Cantarella *et al.* [11] propose some heuristic approaches to solve the problem considering rigid supply and demand. Poorzahedy and Rouhani [30] propose several hybrid algorithms considering rigid demand and the construction of new lanes. Russo and Vitetta [29] propose a three-step method for the solution selection (topological similarity, cluster analysis, solution selection). Recently the design procedures are applied in comparison with the transit design [34]. The models and the procedures and for simulation and design system is applied also in evacuation in urban area [35, 36])

Table 1: Network Design Problem: design approach.

Network layout		Billheimer and Gray [1], Chen and Alfa [2], Foulds [3], Poorzahedy and Abulghasemi [4], Solanky *et al*. [5], Xie and Turnquist [6], Xu *et al*. [7]
Signals setting	Isolated junctions	Allsop [8–10], Cantarella *et al*. [11, 12], Cascetta *et al*. [13], Chiou [14], Gartner [15], Meneguzzer [16], Sheffi and Powell [17], Smith [18], Tan and Gershwin [19], Webster [20], Webster and Cobbe [21]
	Interacting junctions	Cantarella *et al*. [12, 22], Ceylan and Bell [23], Gartner [15], Little [24], Little *et al*. [25], Marcianò and Vitetta [26], Marcianò *et al*. [27], Sun and Mouskos [28]
Network layout and signals setting		Cantarella *et al*. [11], Russo and Vitetta [29], Poorzahedy and Rouhani [30], Gallo *et al*. [31], Caggiani and Ottomanelli [32], Polimeni and Vitetta [33]

In this paper, a formulation of the NDP is proposed and some algorithms to solve it are discussed. Moreover, an analysis to compare the previous configuration (before), the after configurations provided by the urban plan and the designed configuration is reported. The comparison is aimed for testing the quality of the proposed model and procedure and cannot be considered as a plan evaluation. Considering the junction design, integrated with the layout design, the objective is to increase the safety of road users.

The paper is structured as follows. In Section 2, the mathematical formulation of the NDP is reported (considering mono-level, bi-level and equivalent formulation). In Section 3, some algorithms to solve the problem are proposed. In Section 4 an analysis before-plan-design, to compare the network configurations, is reported.

2 Network design problem

In this section, a formulation for the NDP is proposed, considering both the network layout and the signals setting. The search for new solutions is influenced by the objectives and the constraints. Some actors, with different objectives, are involved in the problem:

- transport system users, who seek to minimize travel time and monetary costs;
- transport system managers, who seek to maximize the difference between revenues and costs and maximize the safety of the road users;

- community, who seek both to minimize pollution and maximize usable urban areas.

It is worth noting that these objectives are often conflicting. Moreover, the same individuals usually act as both transport system users and community members, so they themselves have conflicting objectives.

The main kinds of constraints are:

- technical (minimum green times, maximum cycle length, maximum speed, maximum flows, …);
- external (limit values for concentrations of air pollutants, maximum noise levels, budget constraint, maximum estimated number of accident, …);
- behavioural (supply-demand interaction, …).

Decision variables can be classified as:

- integer (for lane allocation, signal stages);
- continuous (for signal settings, signal offsets, road pricing, park pricing);
- mixed integer (for any combination of variables from both the first two sets).

To take into account the conflicting objectives related to the NDP, a multi-objective model could be formulated as in (1).

Objective function: $$z(\mathbf{y}, \mathbf{f}) = \{z_1(\mathbf{y}, \mathbf{f}); z_2(\mathbf{y}, \mathbf{f}); \ldots; z_m(\mathbf{y}, \mathbf{f})\} \tag{1}$$

Control variables: $$\mathbf{y} \tag{2}$$

Constraints:

$$\mathbf{y} \in S_y \tag{3}$$

$$\begin{aligned} &\mathbf{f} = \mathbf{f}_{SNL}(\mathbf{c}(\mathbf{f}, \mathbf{y})) \\ &\mathbf{f} \in S_f \end{aligned} \tag{4}$$

where:

- ${}^{T}\mathbf{y} = [{}^{T}\mathbf{y}^{TO}, {}^{T}\mathbf{y}^{SS}]$ is the design variables vector (^{T} stays for transpose), with
  - $\mathbf{y}^{TO}$ the vector of variables related to network topology (note that an entry of this vector can be include any elements related to link configuration);
  - $\mathbf{y}^{SS}$ vector of variables related to signals setting (note that an entry of this vector can be include any elements related to the junction configuration);
- $\mathbf{f}$ is the link vector flow;
- S_y is the set of admissibility of design variables;
- S_f is the set of admissibility of link flow;
- z_i (with i = 1, 2, …, m) is a function representing the ith objective;
- $\mathbf{f}_{SNL}$ stochastic network loading function.

2.1 Mono criteria and mono-level formulation

In mono-criterion and mono-level formulation, the equation (1) is formalized, considering only one objective, as the total travel time spent in the network (5):

$$z(\mathbf{y}, \mathbf{f}) = {}^{T}\mathbf{c}(\mathbf{y}, \mathbf{f}) \cdot \mathbf{f} \tag{5}$$

The objective function can be modified considering the users' safety (i.e. inserting the number of accidents) or a weighed sum of different objectives indicator.
The problem can be formulated as a constrained non-linear mono-level problem.

$$minimize_{\mathbf{y}}\ {}^{T}\mathbf{c}(\mathbf{y}, \mathbf{f}) \cdot \mathbf{f} \tag{6}$$

constraints:

- technical
  - structural

$$y \in S_y \tag{7}$$

  - connection and signals setting

$$w_{rs} < +\infty \qquad \forall\, r, s \in C \tag{8}$$

$$\mathbf{y}^{SS} \in S_g \tag{9}$$

- (behavioural) equilibrium

$$\mathbf{f} = \mathbf{f}_{SNL}(\mathbf{c}(\mathbf{f}, \mathbf{y})) \tag{10}$$

$$\mathbf{f} \in S_f \tag{11}$$

where
- N, the node set;
- $C \subseteq N$, centroid set;
- w_{rs}, path cost;
- S_g is the set of admissibility of signal setting design variables.

In the technical constraints structural, connection and signals setting constraints are considered. The former concerning the physical characteristics of the links (e.g. maximum lanes number), the latter concerning the existence of at least a path between each origin-destination pair and the regulation at junctions (e.g. maximum green value).

2.2 Mono criteria and bi-level formulation

In a bi-level formulation the equilibrium problem is specified as a component of the problem:

First level

$$minimize_{\mathbf{y}}\ {}^{T}\mathbf{c}(\mathbf{y}, \mathbf{f}) \cdot \mathbf{f} \tag{12}$$

Second level

$$\mathbf{f} = \mathbf{f}_{UE}(\mathbf{y}) \tag{13}$$

constraints:

$$y \in S_y \tag{14}$$
$$w_{rs} < +\infty \qquad \forall\ r, s \in \mathbf{C} \tag{15}$$
$$\mathbf{y}^{SS} \in S_g \tag{16}$$
$$\mathbf{f} \in S_f \tag{17}$$

$\mathbf{f}_{UE}$ is a function that, for each network configuration $\mathbf{y}$, gives the user equilibrium flow.

2.3 Mono criteria and equivalent formulation

The problem can be also formulated (the equivalent problem has the same solution of the original problem) as a mono-level problem with linear constraints. Equation (18) formalizes the equivalent problem; the constraints are (14–17).

$$minimize_{\mathbf{y}}\ z(\mathbf{y}, \mathbf{f}_{UE}(\mathbf{y})) \tag{18}$$

3 Algorithms

The procedure proposed to solve the NDP consists of two levels: at the first level considering a problem with integer variables, at the second considering a problem with continuous variables.

The integer design problem requires a high computation effort, this forces us to use heuristic approaches. In [11] some heuristics are proposed to solve the problem: Hill Climbing (HC); Simulated Annealing (SA); Tabu Search (TS); Genetic Algorithms (GA).

Also two hybrid algorithms are proposed (so that the second algorithm start from the result obtained from first algorithm): Tabu Search and Genetic Algorithms (TS+GA); Tabu Search and Path Relinking (TS+PR).

In [11] the best solutions are obtained applying the GA and in the rest of this section will be treated the GA.

The GA [37] is a heuristic based on biological mechanisms related to the survival of species. Three are the main structures in the algorithm: the selection (identify the best elements in the population), the crossover (couple some elements in the population), the mutation (introduce an element of variability in any solutions).

The continuous problems can be solved as in [11], by using a projected gradient algorithm. Known the network layout by the solution of integer variables problem, the objective function is evaluated with an assignment procedure, where the signals at the junction are designed and the network performances are calculated.

4 Analysis before-plan-design

In this section, an application on real network and a comparison among the old configuration (*before*), the present configuration actuated by a plan (*plan*) and the designed configuration (*design*) is reported. The plan is considered as a benchmark regarding the results of the proposed model and procedure.

The town choice for the comparison is Melito di Porto Salvo (Italy). In Table 2 some characteristics of the city are reported. Figure 2 shows the graph of the study area, representing the before configuration of the network.

Table 2: Melito P.S.: some characteristics.

inhabitants	11,594
travel numbers (peak hour) [veic/h]	3893
nodes	96
links	189
network length [km]	23
signalized junctions	37

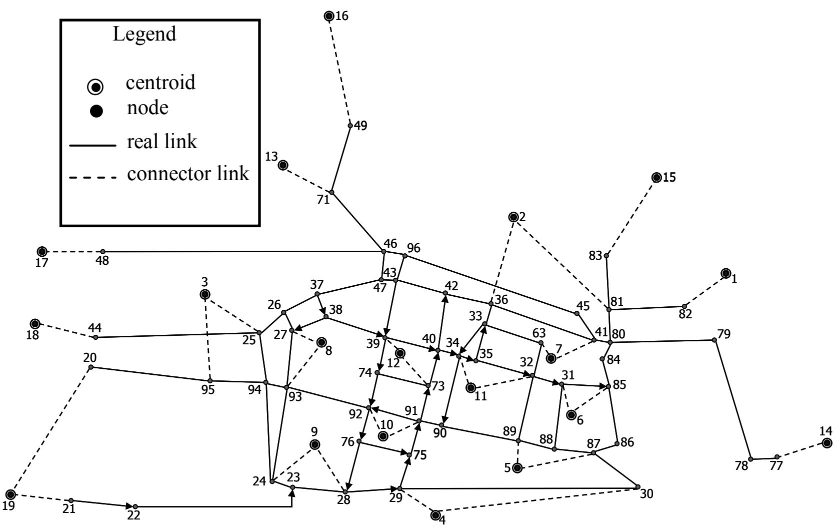

Figure 2: Before network configuration.

The urban traffic plan of Melito P.S. was thinking of encouraging travelling by bus, bicycle and on foot in order to increase safety. This can have to collateral effect the increasing of the total travel time for the car driver. One of the actions of the plan is the reduction of lane width, decreasing the link capacity. One of the proposed topologic configurations is reported in Figure 3.

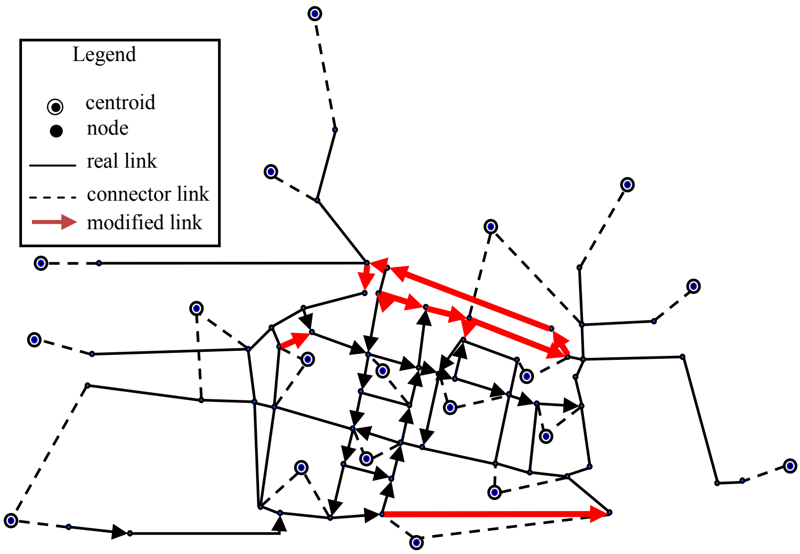

Figure 3: Plan network configuration.

The network design is performed using the formulation reported in Section 2.1. Figure 4 shows the network configuration found with the proposed method.

For comparing the solutions, the Δw indicator is defined (note that Δw is a negative number when the objective function increases, positive otherwise):

$$\Delta w = (w_0 - w^* / w_0)$$

where
w_0, objective function to minimize value for the before configuration;
w^*, objective function to minimize value for the plan or design configuration.

Respecting the before configuration, the plan configuration has as variation in the cost the value Δw = -5.7% (Figure 5). The negative values indicate that the total travel time for car driver increases. It is emphasized that the negative value of Δw is caused by the fact that the main objective of the urban plan is to reduce the use of cars.

Comparing the before configuration and the design configuration, the objective function decreases about of 2.1% (Δw = 2,1%, Figure 5). Comparing design configuration with the plan configuration, both the solutions design the main ring as a mono directional way (clockwise in the plan, anticlockwise in the proposed procedure).

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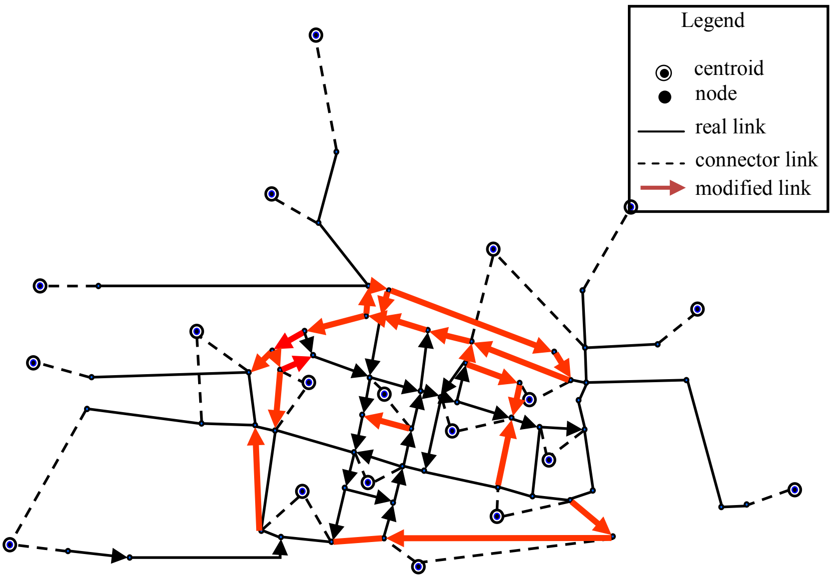

Figure 4: Design network configuration.

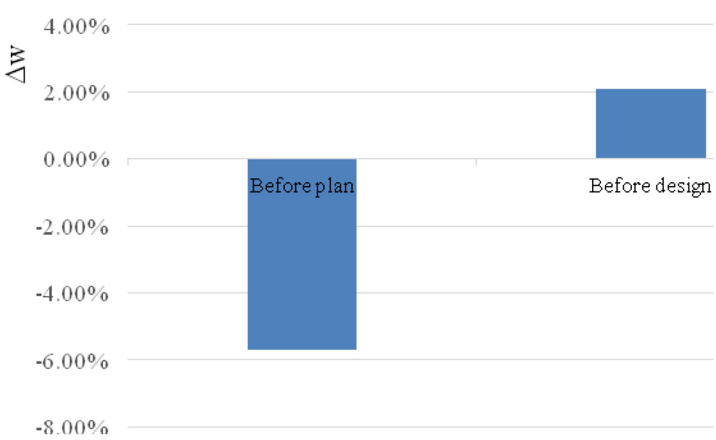

Figure 5: Proposed approach configuration.

5 Conclusions

In this paper, the road network design problem is reported. Two variables type are considered: the network layout and the signals setting. The former is approached as a discrete problem, the second as a continuous problem. The solution procedure proposed is heuristic (genetic algorithm). An application in a real case is provided with the aim to compare the plan with the designed network configuration, performing a before-plan-after analysis. In detail, three possible configurations are compared: a before configuration, the designed configuration proposed by the urban plan, the designed configuration output of the proposed approach. The comparison is developed defining an indicator related to the comparison of the objective function. From the comparison it emerges that the proposed approach improves the network performances (in terms of road user costs), respect to the plan configuration.

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