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Better for everyone: An approach to multimodal network design considering equity

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Abstract

We propose a formulation of the Network Design Problem (NDP) to support transport planners in dealing with multimodal networks in contexts characterised by different (and sometimes conflicting) interests and limited resources in a transparent way. We expect that the implementation of the method can increase the acceptability of transport schemes.
The proposed formulation expands the scope of traditional NDP approaches: firstly, it takes public transit into account alongside private transport. Then, it considers the relevance of equity among other planning goals, enabling the achievement of solutions with a fair distribution of transport impacts (benefits and costs) among the users. Finally, it proposes the conjoint use of fuzzy and rigid goals and constraints to improve the quality of the solutions.
Equity is defined as the mode-specific relative variation of the overall mobility between Origin-Destination (OD) pairs. We propose two specifications of the equitable NDP: one uses a crisp approach, with objective function equal to the overall network cost. The other is a fuzzy maximisation of the level of satisfaction generated by a certain network configuration. The level of satisfaction depends on the extent at which a given solution achieves private and public transport equity and overall network cost targets.
We illustrate the approach in the case of a signal time planning problem in a small network. The evaluation of the performance of crisp and fuzzy optimisation shows that the former approach provides better solutions to private transport and vice versa. We propose that, when using fuzzy optimisation, the decision maker should evaluate a set of nearly-optimal solutions selected on the basis of Pareto optimality.

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Keywords: Equitable transit; Multimodal Network Design problem; Fuzzy optimisation; Multi criteria decision making.

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1. Introduction

Mobility is fundamental in any society. Advances in transportation shape the life of individuals and the organisation of societies, crucially affecting the development of civilizations. The increase of world population and the diffusion of western development models are generating a rise of demand for transportation. National and local governments must take decisions concerning transport networks in a careful way, above all in urban contexts, to grant mobility and, at the same time, reduce and mitigate mobility-related problems such as congestion, air pollution, noise, accidents, and segregation of vulnerable categories.

Planning, design and control issues are traditionally addressed in NDP (Faharani et al., 2013). The objective of NDP is to determine the optimal allocation of (new) resources in a transportation network (Friesz, 1985). In this definition, the facilities may be represented by either nodes or links. In addition, since transportation includes both public and private transport, this problem can involve transit networks in addition to road networks in a multimodal framework (D'Acierno et al., 2011).

One of the biggest challenges for transportation planning is to provide solutions in which some resources and/or impacts are distributed as evenly as possible among users. The difficulty of the task is partly due to the fact that costs and benefits can be quantified in different ways and that the equity of their distribution is subject to interpretation (Karner and Niemeier, 2013).

In recent decades, transportation planners and policymakers have become increasingly concerned with equity and its application to the development of transportation systems (Bertolaccini, 2013). Equity objectives and constraints have already been included in private transportation NDP considering spatial allocation of road improvements, highway investment, intergenerational equity, tolls, congestion pricing, and cordon pricing (Meng and Yang, 2002, Yang and Zhang, 2002, Antunes et al., 2003, Chen and Yang, 2004, Sumalee et al., 2009, Barbati, 2012). On the other hand, often researchers in the field of transit network design do not appear to have explicitly incorporated issues of equity and access, predominantly focusing on the minimization of user and operator costs (Kepaptsoglou and Karlaftis, 2009).

Farahani et al. (2013) note that minimizing the total travel time/cost, the most common form of objective function in NDP, may lead to unbalanced congestion levels throughout a network and hence some OD pairs may benefit more than others in term of travel time reduction. In some case, selected OD may even experience an increase of costs. Hence, it is necessary to introduce equity measures in the NDP formulation, to ensure a more equitable distribution of benefits.

Our literature review shows that multimodality has been largely ignored in road and public transit NDP. In addition, nearly all NDP are framed in a deterministic way. However, actually, both the data available to the analysts and the problem constraints and/or available resources can be affected by uncertainty, and fuzziness (Caggiani and Ottomanelli, 2011 and 2014). In this paper we address all these shortcomings, putting forward an NDP formulation considering multimodal equity goals in a context of uncertain data/constraints.

The remainder of the paper is organized as follows. Firstly we provide a brief discussion of the concept of equity and its implementations in transportation planning. Then multimodal equity indicators are introduced, followed by the general formulation of the proposed model. Subsequently, we compare the performance of crisp and fuzzy approaches in solving our problem by means of a toy network. We show that the fuzzy approach can be used to derive a set of nearly-optimal solutions selected on the basis of Pareto optimality, which should be carefully examined by the decision-maker in search of the most appropriate solution. Conclusions and future research directions are identified in the last section.

2. Equity and Fairness in Transport Planning

2.1. Concept of equity

Equity is a complex and multifaceted subject, whose definition is somehow arbitrary. Essentially it is a form of distributive justice (Rock et al., 2014). Different people have different concepts of equity, but also, which of the aspects of equity that seems important will depend very much on the particular context and circumstances (Langmyhr, 1997). In this paper, equity refers to the fairness and appropriateness of the distribution of impacts (benefits and costs) (Litman, 2014). What might be considered a fair distribution is, again, a complex issue, and it is discussed below in relation to transportation.

In the decision-making field, equity measures are commonly used to assess the economic and social impacts of different development scenarios. Despite the increasing effort to incorporate equity in decision-making models, there is little agreement on the best way to assess equity. A large number of measures can be found in literature, but few attempts have been made to review and compare such metrics, so as to identify the appropriate measure(s) for each type of application. A rare exceptions is the paper Marsh and Shilling (1994) presenting a detailed review of equity measures for public facility planning.

Two general categories of equity can be singled out: horizontal equity and vertical equity (Repetti and McDaniel, 1992). Horizontal equity (fairness or egalitarianism) concerns the provision of equal resources to individuals or groups considered equal in ability. Promoting horizontal equity means to avoid favoring one individual or group over another, and so to offer services regardless of needs or actual ability. Vertical equity (social justice, environmental justice or social inclusion) applies to the distribution of resources among individuals with different abilities and needs. Vertical equity is promoting by supporting groups based on their social class or specific needs in order to make up for overall societal inequalities. These different types of equity often overlap or conflict. Therefore, transport planning involves tradeoffs between different equity objectives (Litman, 2014).

2.2. Transit equity

"Transportation equity is a civil and human rights priority. Access to affordable and reliable transportation widens opportunity and is essential to addressing poverty, unemployment, and other equal opportunity goals such as access to good schools and health care services.[...] Providing equal access to transportation means providing all individuals with an equal opportunity to succeed" (The Leadership Conference on Civil and Human Rights, 2015).

The last decades have witnessed a slow but steady paradigm shift towards the consideration of equity and social inclusion as an integral part of the transit planning process. The need for systematically incorporating spatial, temporal and socioeconomic distributional effects in transport decision-making is discussed in Jones and Lucas, 2012. Equity and social inclusion have been initially discussed with respect to fare policies, concessionary fares, and transit subsidies. Recently the scope of research has been widened to include population groups with mobility limitations (Ferguson et al., 2012).

Also the implementations of the equity concept in public transport planning can be classified in one of the two above mentioned perspectives: the horizontal equity framework has been used in the "mass transit" approach, aiming at maximizing the number of served users it encapsulates (Currie and Stanley, 2007). In the "social transit" perspective, a case of vertical equity, the goal is to provide public transit service to those who need it most, such as people without private transport means or specific low income groups, youth or ethnic minorities (Murray and Davis, 2001, Garrett and Taylor, 1999, Deakin, 2007).

Rising personal incomes, greater availability of cars, lower fuel prices, and substantial public investment in road infrastructure have contributed to reduce the demand for public transit. Still, many people without regular access to cars depend on public transit. For these "transit dependent" (or "captives") the continue availability of public mass transit is vital to access jobs, education, medical care, and other fundamental services (Garrett and Taylor, 1999). Therefore, it is essential to incorporate public transportation in NDP. In the following, we extend the NDP formulation to consider the concept of equity applied to public transit in a quantitative way. We adopt a mass transit perspective, fostering horizontal equity to ensure the best distribution of the service among users.

3. NDP with multimodal equity constraints

3.1. Multimodal equity constraint specification

Meng and Yang (2002) define equity considering the OD travel costs generated by the modification of a network. In particular, they consider the ratio between the equilibrium travel costs after ($z_w(\boldsymbol{x})$) and before ($\bar{z}_w$) changing the network for each OD pair *w* in the network:

$$\alpha_w = \frac{z_w(x)}{\bar{z}_w} \tag{1}$$

Let $\alpha = \max_w \alpha_w$. If $\alpha < 1$ all users benefit from the network design implementation, if $\alpha > 1$ some users experience an increase of travel costs. To improve the equity of the solution, a constraint can be added to the traditional NDP formulation, enforcing that the possible equilibrium OD travel cost increases are below a given threshold α_{max}, set by the decision makers. In other words, α_{max} is the maximum permissible lack of equitability of the benefit distribution.

However, the formulation of Meng and Yang (2002) neglects the level of the demand between the OD pairs. Therefore, the use of an equity constraint based on α in Equation (1) may generate solutions with remarkable benefits (in terms of individual costs) for OD pairs with low demand and smaller negative consequences for busy OD connections. To avoid this problem, let:

$$\delta_w = \frac{d_w}{\sum d_w}(\alpha_w - 1) \tag{2}$$

i.e. the relative variation of OD pair cost brought about by the network modification, weighted by the ratio of the demand d_w associated to that OD to the total demand. δ_w is an indicator of the variation of the overall mobility cost. We propose to account for the equity issue in the NDP by adding a constraint on the value of $\delta = \max_w \delta_w$.

3.2. Network Design Problem (NDP): general formulation

NDP is an allocation problem. In the mainstream approach to NDP resources are deployed so as to minimize the total system cost under a set of constraints and taking into account the user behavior.

$$x^* = \arg\underset{x}{\mathrm{opt}}\, z(x, f^*) \tag{3}$$

s.t.

$$f^* = \Delta(x)P(x, C(f^*, x))d(C(f^*, x)) \tag{3a}$$

$$x, f^* \in E, T \tag{3b}$$

where:

- *z* is the function of the total cost of the network;
- **x** is the vector of the design variables;
- **f** * is the vector of equilibrium assignment link flows;
- **P** is the path choice probability matrix;
- **C** is the vector of path costs;
- **d** is the vector of travel demand.

Equation (3a) represents the consistency constraints among demand, flows and supply parameters. Equations (3b) requires that the set of the design variables and that of the equilibrium flows satisfy external (*E*) and technical (*T*) constraints such as, respectively and for example, available budget and link flows-capacity ratio.

Note that this formulation is suitable to Continuous NDP, that is problems in which the decision variables are continuous as in the case of road capacity expansion, timing traffic light, and determination of tolls for some specific streets.

Nearly all road NDP (RNDP) studies deal with the improvement of existing networks. In contrast, public transit NDP (TNDP) studies mainly deal with the configuration of new transit networks, or the partial reconfiguration of the existing networks. A common characteristic of RNDP and TNDP is that they consider only a single mode. In reality, as explained above, in general multiple modes coexist and interact with each other. Our formulation is a case of a Multi-Modal Network Design Problem (MMNDP) with two modes (private transport and buses). We note that a multimodal problem arises when at least two modes are considered and simulated, even if design decisions are related to only one of the modes (Faharani et al., 2013). In our case, within the general formulation of the proposed model, the interactions between flows of different modes are neglected: networks of different modes are not related to each other, and thus the flows of one mode do not have any effect on the flows of the other mode. Indeed, in our car-bus problem, buses move in dedicated lanes, and therefore public transit flows are physically separated from private transport ones. Consequently, *z* (the function of the total cost of the network) is simply the sum of the costs of private and public transport.

4. Comparison of two specifications of NDP with equity constraints

Here we study two different specifications of the problem in equations (3) to (3b), one based on crisp optimization, the other on fuzzy optimization. We illustrate them by an application to the network of Yang and Zhang (2002). We compare the performance of the two approaches in terms of equity of the suggested solutions.

4.1. Case study

In our test, the supply design variables are signal settings parameters. We adopt a global optimization approach, in which we search for the vector of optimal effective green times (**x***) for all signalized intersections. These values are obtained through the minimization of the network total cost *z* depending on signal settings (**x**), on equilibrium flows (**f***) and on equity constraints. This analysis has been carried out on the test network and data proposed by Yang et al. (2001), to which we added a bus rapid transit lane (Fig. 1).

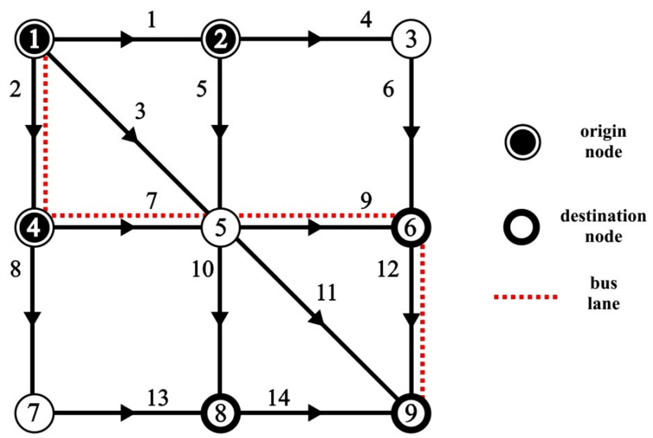

Fig. 1. Test network

The network is made up of 9 nodes (3 origins and 3 destinations), 14 links and 9 O-D pairs. We consider signalized intersections at node 5, with three-phases regulation scheme, and at nodes 6 and 8, with two-phases regulation scheme. Let g_{ph}^{nd} the effective green time for phase *ph* at node *nd*. The vector of the design variables is **x** = $[g_1^5;\ g_2^5;\ g_3^5; g_1^6;\ g_2^6;\ g_1^8;\ g_2^8]$. For all the signalized intersections the effective cycle time is fixed to C_t = 90 seconds.

A single public transport line is operated in the network, as shown in Fig. 1. We assume the presence of a bus lane along the route. Therefore, in this example we neglect the interaction between flows of different modes. . However the formulation presented above is general, and can be applied to fully multimodal situations. The bus stops coincide with the nodes traversed by the bus line (1,4,5,6,9). In our test, we do not have accurate data about the demand assigned to each bus stop, but we know just how many people globally moving from a given origin to a given destination using public transport. We assume a dwell time equal to 10 seconds for all the stops.

The travel demand **d** (Table 1) is assigned to the network using a Deterministic User Equilibrium traffic assignment model; i.e. we suppose that the network travel times are deterministic and dependent on the congestion level, and that all travelers are perfectly aware of the travel times and always able to identify the shortest travel time route. Several algorithms are available to calculate the equilibrium link flow with rigid demand; we use the Frank-Wolfe algorithm (LeBlanc et al., 1975, Nguyen, 1976).

Table 1. O-D vector

O-D	**1-6**	**1-8**	**1-9**	**2-6**	**2-8**	**2-9**	**4-6**	**4-8**	**4-9**
L	1	2	3	4	5	6	7	8	9
D	120	150	100	130	200	90	80	180	110

We assume that 30% of the demand generated by the OD pairs 1-6 and 1-9 is served by public transport.

We specify different link cost function for the two modes of transport. For the private transport system, the link cost c_l is the sum of the link travel time and the waiting time at the signalized intersections. The link travel time tc_l, function of the link flow f_l and of the link capacity ca_l, is calculated using the well-known BPR link cost function (Bureau of Public Roads Traffic Assignment Manual, 1964) (4) where the free flow travel time (*tr*) and capacity (*ca*) depend on the considered link *l*.

$$\mathrm{tc}_l(\mathrm{f}_l) = \mathrm{tr}_l\left[1 + 0.15\left(\frac{\mathrm{f}_l}{\mathrm{ca}_l}\right)^4\right] \qquad l = 1,2,... \tag{4}$$

The waiting time is estimated using the Doherty's delay function (Doherty, 1977) (5):

$$\mathrm{t^l}_{\mathrm{wa}} = 0.5 \cdot \mathrm{C_t}(1-\mu)^2 + \frac{1980}{\mu \cdot \mathrm{s}} \cdot \frac{\mathrm{f_t}}{\mu \cdot \mathrm{s} - \mathrm{f_t}} \qquad \text{if } f_l \le 0.95 \cdot \mu \cdot s$$

$$\mathrm{t^l}_{\mathrm{wa}} = 0.5 \cdot \mathrm{C_t}(1-\mu)^2 + \frac{198.55}{\mu \cdot \mathrm{s}/3600} \cdot \frac{220 \cdot \mathrm{f_t}}{(\mu \cdot \mathrm{s})^2/3600} \qquad \text{if } f_l > 0.95 \cdot \mu \cdot s \tag{5}$$

where:

- t^l_{wa} is the waiting time at intersection on link *l* (s/veh);
- f_l is the traffic flow on link *l* (veh/h);
- *s* is the saturation flow (veh/h);
- *g* is the effective green time;
- μ is the effective green ratio (g/C_t).

In the public transport, the link cost values c_{bus} are the sum of the link travel time, the bus dwell time and the waiting time due to the signalized intersections. Travel time t^l_i at every link i can be calculated by (6):

$$t^l_i = \frac{L_i}{v_i} \qquad i = 1,2,\ldots \qquad (6)$$

where L_i is the length of link i, while v_i is the bus speed at link i (in our test assumed to be 20 km/s).
The model of dwell time t^l_{dw} of buses at a bus stop is represented in (7) (Liu and Sinha, 2007):

$$t^l_{dw} = c_o + \sum_j c_j p_j N \qquad j = 1,2,\ldots \qquad (7)$$

where c_j is the average boarding time of ticket type j passengers, p_j the proportion of type j passengers and N the total number of passengers waiting for the service. Parameter c_o is a constant door opening and closing time and an observed value of 5 seconds (Clark and Pretty, 1992) was used in the model. In this study, only one ticket type was modeled.
The waiting time t^l_{UD} is estimated using the Webster's Uniform Delay Model (8), on the assumptions of stable flow and a simple uniform arrival function:

$$t^l_{UD} = \frac{RV}{2} \qquad (8)$$

where R is the duration of red phase, V is the number of vehicles arriving during the time interval given by the difference between the instant in which they arrive at the traffic light and when the light has turned green. Length of red phase is given as the proportion of the cycle length which is not green.

4.2. Performed optimizations

We solve the optimization problems using genetic algorithm (GA) metaheuristic. The analysis entails two steps: in the first one we generate 600 starting configurations, i.e. vectors of design variables; in the second step, we apply GA using each of these starting configuration as starting point of different runs. Details on the optimization of the fuzzy specification are given by Caggiani and Ottomanelli, 2014, who present a fuzzy non-linear programming to solve an equilibrium NDP.

Table 2. NDP specification

		Equity Crisp Specification (ECS)	**Equity Fuzzy Specification (EFS)**
Objective Functions	Satisfaction	-[(1)]	max $(g_1h_1 + g_2h_2 + g_3h_3)$
	Network total cost	min z (**x**, **f***)	-[(1)]
Problem Constraints	Network total cost	-[(1)]	$z(\mathbf{x}(h_1), \mathbf{f}^*) \le (1 - h_1)$
	Car equity	$\delta^{car}_{ECS} \le \delta^{car}_{max}$	$\delta^{car}_{EFS} \le \delta_{l\_car} + (\delta_{u\_car} - \delta_{l\_car})\cdot(1-h_2)$
	Bus equity	$\delta^{bus}_{ECS} \le \delta^{bus}_{max}$	$\delta^{bus}_{EFS} \le \delta_{l\_bus} + (\delta_{u\_bus} - \delta_{l\_bus})\cdot(1-h_3)$
	Demand – flows Consistency	$\mathbf{f}^* = \Delta(\mathbf{x})\mathbf{P}(\mathbf{x}, \mathbf{C}(\mathbf{f}^*, \mathbf{x}))\mathbf{d}(\mathbf{C}(\mathbf{f}^*, \mathbf{x}))$	
	Cycle time consistency	$\sum_{ph} g^{nd}_{ph} = C_t \ \forall\, nd \in \{5,6,8\}$	

[(1)]= not applicable in the optimization

The crisp and fuzzy specifications of the NDP with equity constraints are shown in Table 2.

The objective in ECS is to minimize the total network costs, sum of the costs of car and public transport users. In EFS we maximize the overall satisfaction *H*, and we add a constraint on the admissible network total cost. The total satisfaction *H* is the weighted sum of three components h_1,h_2 and h_3, concerning total network cost, the equity of the solution to private transport users, and the equity to public transport users respectively. The constraint on the total network cost requires the solution cost to be smaller than the cost corresponding to starting configuration. Each satisfaction index is a measure of how well the solution performs in terms of the related quantity. The weights (g_1,g_2,g_3) are introduced to let the decision makers rank the components of the overall satisfaction. They will be assumed equal to 1 in the following. The equity constraints of the fuzzy specification account for a certain degree with uncertainty in their definition. In the following, δ_{max} and δ_{min} in the ECS are used as the upper and lower bound of the fuzzy set of the equity constraints in EFS, but in general they can be different.

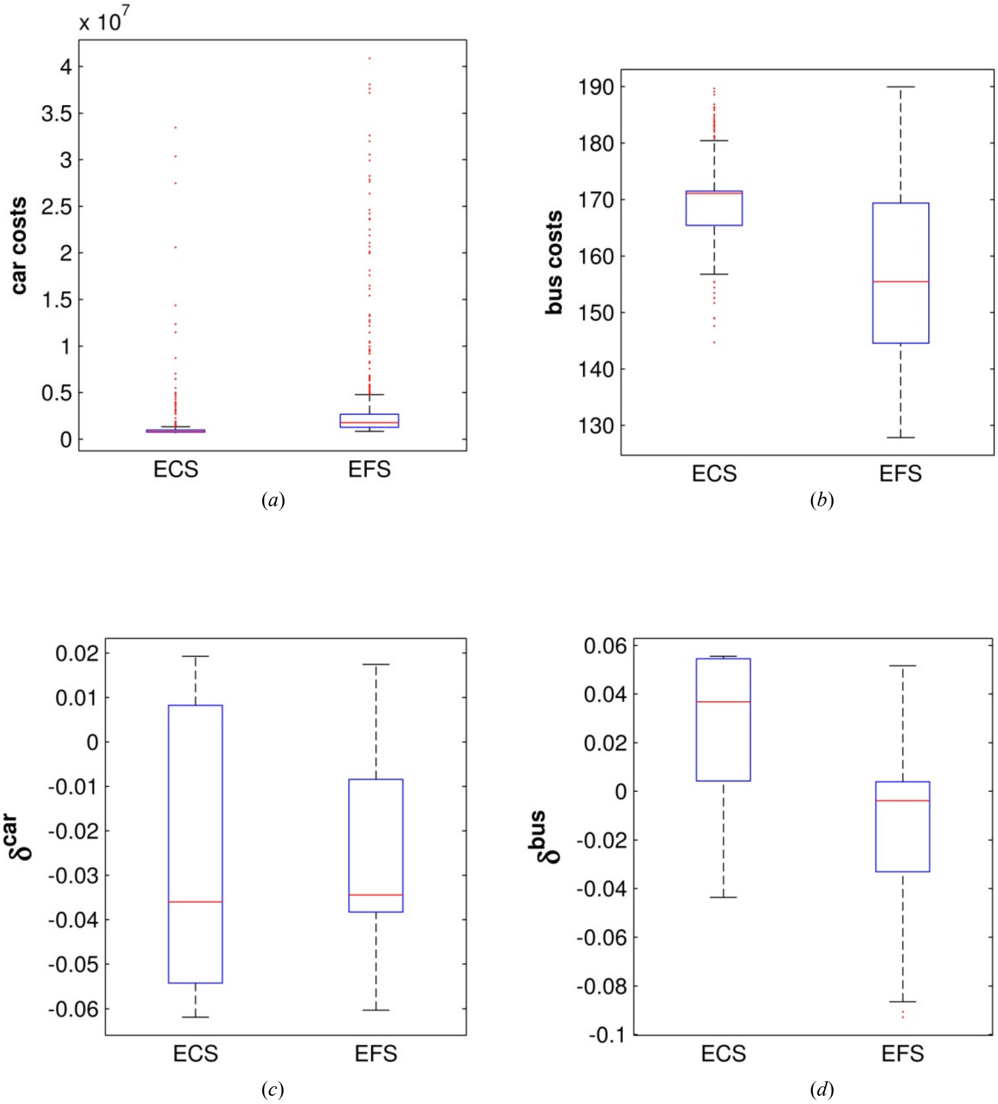

Fig. 2. Optimizations results: (a) Private transport costs; (b) Public transport costs; (c) Private transport equity indicator; (d) Public transport equity indicator.

Using different starting configuration, each GA run (potentially) generates a different solution. The results of our experiments are summarized in Fig. 2 by means of box plots. In each box, the central mark indicates the median value, the edges are the 25th and 75th percentiles, the whiskers extend to the most extreme non-outlier values, and outliers are plotted individually.

Fig. 2(a) and 2(b) show the private and public transport costs respectively. The fuzzy approach seems to work better in case of public transport, although the values are more scattered. Fig. 2(c) and 2(d) show the degree of equity achieved by the two approaches for car and bus users respectively. The values are comparable for private transport, whereas the fuzzy specification gives definitely better results for the public transport service (note that lower values of δ^{bus} correspond to more equitable solutions).

Overall, the test suggests that EFS should be preferred to ECS to promote the use of public transport, because it generates more convenient and equitable solutions for bus users. Clearly, this conclusion has to be confirmed by applications to larger and more complex networks. In the next section, we analyse the solutions of EFS in greater detail, focusing on the three components of the overall satisfaction *H* used as objective function.

4.3. Multi criteria decision in EFS

Our aim is to solve an NDP considering not only the overall network cost but also the equity of the solution for each class of users. That means that our allocation problems has several concurrent (and possibly conflicting) goals. To solve it, we formulate the EFS as a single objective maximization problem, in which the objective function is the sum of the degree at which the solution achieves each of our goals. Note that this presuppose the existence of a single network authority, with the power of imposing a design. Metaheuristic methods like GA are not always able to identify global maxima and, in general, each run finds a different solution (in our test, we have 600 runs, each with a different starting configuration). Therefore, the problem arises of selecting one of the detected local optima as solution to the problem. It is not so obvious to choose the solution with the maximum overall satisfaction, since it is also possible that the authority is confronted with solutions with similar values of the overall satisfaction, deriving from different combinations of satisfaction of the specific goals. In these cases, we propose the analysis of the Pareto front of the local optima in the space of the specific satisfactions.

Pareto optimality is a state of allocation of resources in which it is impossible to make any subject better off without making at least one other subject worse off. A Pareto Optimal Solution (POS) dominates non-optimal solutions and is non-dominated by other POS. A POS is non-better than another POS in at least one objective (Deb, 2001). Therefore, any POS may be attractive to the network authority (especially those with high overall satisfaction). The network design can be selected by choosing a point on the Pareto front (the geometric locus of Pareto optima) according to the authority's priorities.

Fig. 3(*a*), 3(*b*) and 3(*c*) give a 2D representation of the Pareto front of satisfaction. Each point in Fig. 3(*d*) represents the solution found by one run of GA (corresponding to a specific starting condition). The coordinates of the points are the values of the satisfaction of the three goals in our problem, namely overall cost, equity to car users, and equity to public transport users. The Pareto front is made up of the 16 non-dominated solutions in red. The coordinates of the 16 points on front are given in Table 3, where solution are listed for decreasing values of overall satisfaction. It can be seen that the all the POS have a level of satisfaction of the car equity constraint very close to 1. This means that it is easy to keep the fairness of the solution as to car drivers in the desired interval $[\delta^{\text{car}}_{\text{min}}, \delta^{\text{car}}_{\text{max}}]$; indeed, very likely the enhancement of the public transport equity does not affect to a great extent the private transport, as in our case study buses move on a rapid transit (separate) lane.

The satisfaction of the constraint concerning the network cost ranges from 0.5192 to 0.8580, and that of the constraint on the public transport equity takes values between 0.4605 and 0.9006. Note that the difference between the level of the overall satisfaction of S1 and S2 is very small (less than 0.11%). The two solutions have also the same level of satisfaction of the private transport equity constraint, but they clearly differ as to the satisfaction of the two other constraints: S1performs better in terms of overall costs but is dominated by S2 as to the public transport equity.

These 16 solution reach the highest level of satisfaction. This is indicative of how the optimization is able to improve the status of the corresponding starting configuration, namely how much it manages to reduce the overall costs and increase the achieved levels of equity. Nevertheless, objectively there is no clue about the factual level of equity and the actual costs to be incurred. These are displayed in Fig. 3(*e*), 3(*f*), 3(*g*) and 3(*h*). Costs and equity values are normalized in the range between 0 and 1; the lowest overall cost scored at the end of the 600 runs is assumed to be the zero, the uppermost is set equal to 1. Same holds for the private and public transport indicators of equity shown on the two other axes. The Pareto front is made up of the 63 non-dominated solutions in red, the ones able to achieve the lowest overall costs and the greater level of car and bus equity (the closest to 0). Therefore, a network authority concerned with reducing the overall cost should opt for one of these 63 solutions, while taking into account the equity components, choosing according to his priorities (private or public transport).

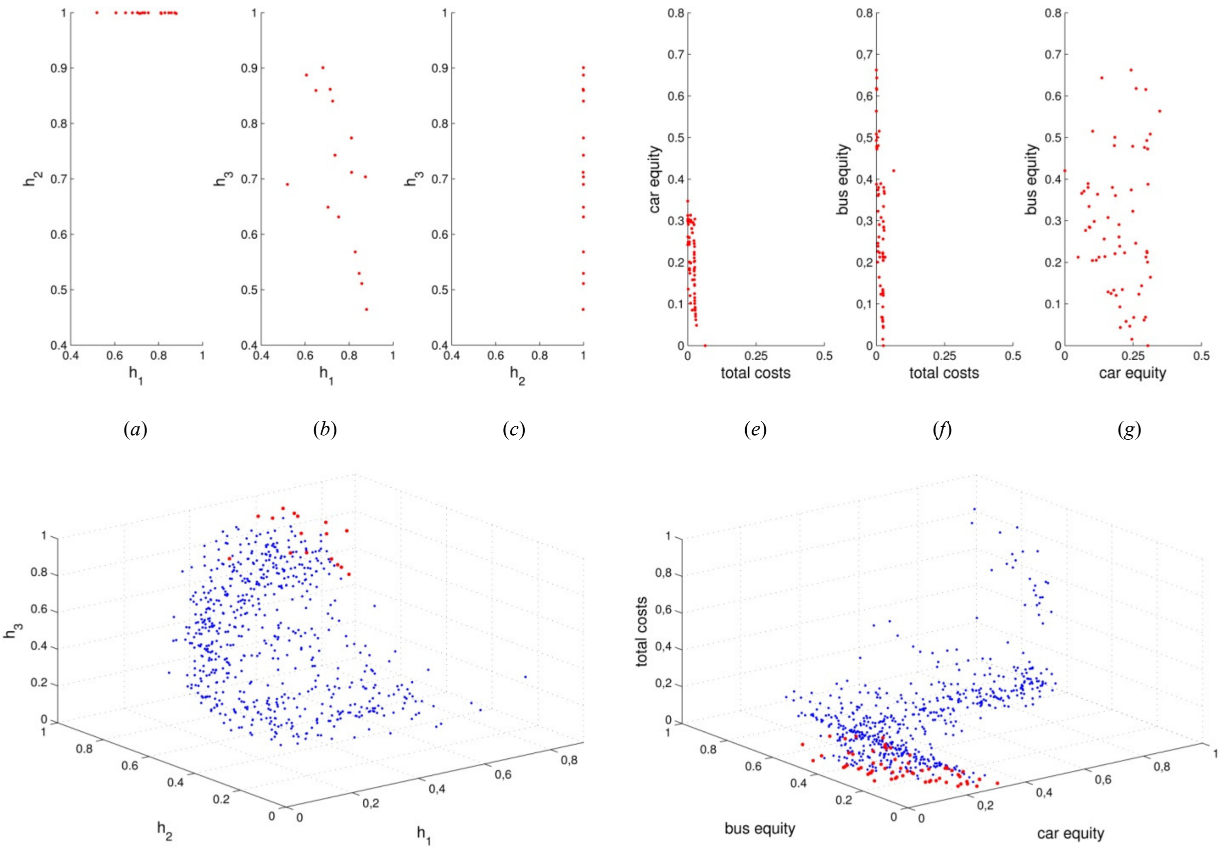

Fig. 3. Graphical representation of Pareto fronts: (a) 2D - h_1 and h_2; (b) 2D - h_1 and h_3; (c) 2D - h_2 and h_3; (d) 3D - h_1,h_2 and h_3; (e) 2D - total costs and car equity; (f) 2D - total costs and bus equity; (g) 2D – car equity and bus equity; (h) 3D – car equity, bus equity and total costs.

Table 3. Optimal Pareto solutions of satisfaction

Solution number	h_1 – Total costs	h_2 – Car equity	h_3 – Bus equity	$H = h_1 + h_2 + h_3$
S1	0.8107	0.9996	0.7738	2.5841
S2	0.6811	0.9996	0.9006	2.5813
S3	0.8742	0.9996	0.7035	2.5773
S4	0.7143	0.9984	0.8615	2.5741
S5	0.7256	0.9997	0.8403	2.5656
S6	0.8118	0.9983	0.7119	2.5219
S7	0.6496	0.9997	0.8596	2.5089
S8	0.6062	0.9997	0.8873	2.4932
S9	0.7363	0.9997	0.7428	2.4787
S10	0.8280	0.9996	0.5682	2.3958
S11	0.7527	0.9997	0.6313	2.3837
S12	0.8462	0.9997	0.5294	2.3753
S13	0.8580	0.9997	0.5112	2.3689
S14	0.7041	0.9999	0.6490	2.3530
S15	0.8800	0.9984	0.4645	2.3428
S16	0.5192	0.9999	0.6901	2.2092

5. Conclusions

In this paper we propose to apply the concept of equity in NDP. Depending on the way in which the concerning NDP constraints are formulated, equity may be horizontal and/or vertical, related to private and/or public transport. Taking into account not only the overall network costs, but pursuing a fair distribution of the costs among different groups of users may increase the acceptability of network designs.

We present two specifications of the equitable NDP, one formulated as crisp minimization problem (ECS), the other as fuzzy maximization problem (EFS). We illustrate the two approaches by an implementation in a network already used in the literature. The test reveals that the two methods can lead to different results. In the case we analyze, EFS is more favorable to public transport. Of course, this result cannot be considered conclusive but requires further confirmation by applications to more complex network. In any case, the fuzzy approach is more suitable and theoretically consistent with contexts with approximate and/or uncertain data.

In EFS, the objective function is a satisfaction index measuring the degree at which the solution overall fulfills the three goals we aim to reach in the design problem: lowering network costs without excessively penalizing any group of car and bus users. This formulation provides solutions which can be implemented in situations where the network is regulated by an authority with a comprehensive responsibility over the transport system. We include weights in the problem specification to allow the possibility for the authority to prioritize some goals over the others.

We solve EFS (and ECS) by GA. The application of GA does not guarantee the identification of the global optimum and different implementations may identify different local optima. Using the Pareto front, we at first test the ability of the optimization to improve the overall satisfaction starting from different initial configurations. All the achieved optima show a value of the satisfaction related to car equity really close to 1. Probably allowing cars and buses to stay in the same lane (neglecting the rapid transit bus lane), there would be more interaction between the two modes, and enhancements on public transport equity would affect more the private transport. Another possibility could be adopting a tolling strategy to have access to certain areas of the transport network.

Secondarily we display the Pareto front related to the final values assumed by costs and equity at the end of each optimization run. This would make the decision-making process more transparent, permitting the decision maker to identify, among all the optimal solutions, that with the set of goal-specific values which suits best his priorities.

Our specifications of the equitable NDP should be validated with applications to real world networks, with stronger interactions between different modes of transport. Future research may include formulations representing situations with competition between actors, for instance between different providers of public transport service.

Specifications of constraints considering vertical as well as horizontal aspects of equity would allow designing transport networks to respond to the needs of disadvantaged population groups.

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