An Origin-Destination Based Parking Pricing Policy for Improving Equity in Urban Transportation

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Abstract In this paper we propose to optimise parking pricing fares in urban areas with the aim to improve transportation equity; the optimisation approach is applied to an origin-destination parking pricing policy that can differentiate the tariffs for each origin-destination pair, considering the difference in accessibility, in particular with public transport services. An optimisation model is implemented, and a solution algorithm is proposed. Model and algorithm are tested on the case study of Naples (Italy), where the quality of transit services is very different between zones and OD pairs; therefore, differentiating parking fares as a function of origin and destination of the trip may be very useful for rebalancing accessibilities among zones, aiming to improve transportation equity.

Keywords Transportation · Parking pricing · Equity · Optimisation Accessibility

1 Introduction

Parking pricing is widely used in almost all middle-large and large European cities. In some cases, it is adopted only for municipality cash reasons since this policy can collect money rapidly without significant monetary investments. A more important reason for its application is the promotion of transit systems use since the parking pricing increases the car use cost and, therefore, tends to move users towards public transport, even without further investments on the transit system.

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The parking pricing, which belongs to the transport pricing policies that also include road pricing, is more diffused in urban areas than the road pricing since it is simpler to be adopted. However, this policy represents only a 'second best' approach to road user charging [1] since not all facilities may be priced.

A review of parking measures and policies can be found in [2, 3]; some case studies of road pricing and parking policies are reported in [4].

Usually, parking pricing policies are destination-based: the fare depends on the parking zone and, often, the more central the zone, the higher the fare. Moreover, in some cities, residents can park freely in their zone or paying a low-cost annual subscription. The destination-based approach can be not equitable if the transit system has significantly different levels of service among city zones; indeed, people who have the availability of good public transport services for their trips and, then, have an actual alternative to personal car, pay the same parking fare of people destined in the same zone who do not have the service or have a low-quality transit service. A more equitable policy should provide different fares on different origin-destination (OD) pairs, reducing parking costs for these disadvantaged people; parking fares, instead, should be higher for OD pairs that are well served by the public transport system. A policy based on OD parking pricing could improve equity of the whole system, acting on the accessibilities among OD pairs, since they depend both on transit service supply and parking pricing fares.

In this paper, we propose an OD parking pricing policy where the fares are optimised so to maximise equity in terms of origin-destination accessibility. An OD parking pricing policy was previously proposed in [5] with a different objective (the minimisation of society's global costs, regardless of equity), while an origin-destination taxi faring was proposed in [6], with the aim to improve equity of the transit systems. Equity in transportation is an important topic that, recently, has been studied by several researchers, such as, for instance, [7, 8].

The paper is organised as follows: Sect. 2 describes the problem and formulates an optimisation model; a solution algorithm is proposed in Sect. 3; numerical results on a real-scale case are summarised in Sect. 4; finally, Sect. 5 concludes.

2 Problem Description and Model Formulation

Our goal is the fare design of on-street public parking areas; moreover, we assume that the transportation demand is known and the multimode transportation supply (mass transit system and road system) is modelled.

Usually, parking fares are defined as a function only of the destination area (destination-based), regardless of the origin of the trip. In this paper, we propose to design parking fares considering both the origin (identified with the residence of the car owner) and the destination. In this case, all cars should be provided with an identification card indicating the residence zone of car owner (the same card usually used as the license for free parking in the residence zone), and the parking signs should show the different fares as a function of the origin zone.

To solve this problem, we propose an optimisation model where the decision variables are the OD parking fares (one for each OD pair), and the objective function should measure the transportation equity. In particular, we propose to use the same objective function proposed in [6], that is the variance of the logsum variables of the mode choice model divided by the car distance, for each OD pair. More in detail, we introduce the following terms:

$$s''_{OD}(\boldsymbol{V}_{OD}) = s'_{OD}(\boldsymbol{V}_{OD})/D^{car}{}_{OD} \qquad \forall\, OD \tag{1}$$

$$s'_{OD}(\boldsymbol{V}_{OD}) = s_{OD}(\boldsymbol{V}_{OD})/\theta \qquad \forall\, OD \tag{2}$$

$$s_{OD}(\boldsymbol{V}_{OD}) = \theta \ln \sum_m \exp(V^m{}_{OD}/\theta) \qquad \forall\, OD \tag{3}$$

where $\boldsymbol{V}_{OD}$ is the vector of systematic utilities referring to different modes m, $V^m{}_{OD}$, $D^{car}{}_{OD}$ is distance by car from zone O to zone D on the minimum path, $s'_{OD}(\boldsymbol{V}_{OD})$ is the logsum variable, θ is the parameter of the Logit model, $s_{OD}(\boldsymbol{V}_{OD})$ is the EMPU (*Expected Maximum Perceived Utility*) variable and Eq. (3) calculates the EMPU variable using a Logit model. Further details on EMPU variable, logsum variable, Logit model and systematic utilities can be found in [9]. The logsum variable is, then, directly proportional to the EMPU variable that is considered a measure of the accessibility [10] between O and D. In our problem, we have to divide it by θ for practical reasons (the parameter θ is not explicitly known since it is included in the coefficients of the Logit model and calibrated with them) and by the distance so to underline the effects of the quality of the connections between zones: two OD pairs with the same quality of connecting services will have the same value of $s''_{OD}(\boldsymbol{V}_{OD})$ independently on the distance.

The objective function is, then, given by $var(s''(\boldsymbol{V}_{OD}(\boldsymbol{y})))$; it is able to represent the transportation (in)equity: the lower the value of the objective function, the higher the equity (theoretically, it is equal to 0 if there is perfect equity). The constraints of the problem refer to minimum and maximum values of parking fares and to the discrete feature of them (indeed, even if theoretically these fares can be continuous variables, the actual applicability of the proposed policy requires a limited number of feasible fares). We consider as decision variable for an OD pair an integer number, y_{OD}, multiplied by a fixed fare value, *ffv*, that can be, for instance, assumed equal to 0.5 €/h or other fractions of the currency. Hence, the optimisation model may be formulated as follows:

$$\boldsymbol{y}^{opt} = \underset{\mathbf{y}}{\operatorname{argmin}}\; var(s''(\boldsymbol{V}_{OD}(\boldsymbol{y}))) \tag{4}$$

subject to

$$y_{OD} \text{ integer} \qquad \forall\, OD \tag{5}$$

$$0 \le y_{OD} \le y_{max} \qquad \forall\, OD \tag{6}$$

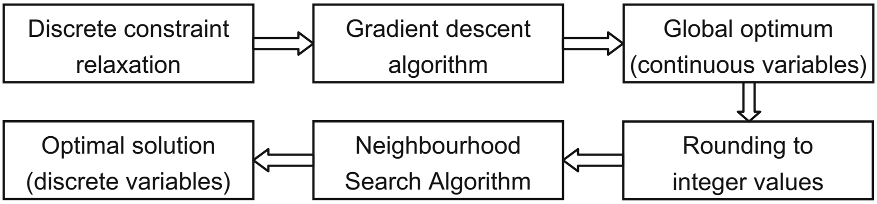

Fig. 1 Solution method

where $\boldsymbol{y}$ [$\boldsymbol{y}^{opt}$] is the [optimal] vector of decision variables, y_{OD}, one for each OD pair, y_{max} is the maximum value of the decision variable.

Analogously to [6], it is possible to state that objective function (4) is convex. Indeed, we can write:

$$var(s''(\boldsymbol{V}_{OD}(\boldsymbol{y}))) = \Sigma_{OD}(s''_{OD}(\boldsymbol{V}_{OD}(\boldsymbol{y})) - s''_{M}(\boldsymbol{V}_{OD}(\boldsymbol{y})))^2/(n_{OD} - 1)$$

which is convex, since the terms $(s''_{OD}(\boldsymbol{V}_{OD}(\boldsymbol{y})) - s''_{M}(\boldsymbol{V}_{OD}(\boldsymbol{y})))$ are strictly decreasing and, therefore, convex with the increase in a value of y_{OD}; the quadratic function of a convex function is convex and a linear combination of convex functions is a convex function as well. Therefore, the optimisation problem has only one local optimum that corresponds to the global one, if we assume continuous variables. Naturally, assuming variables as discrete, theoretically more than one solution may correspond to the optimum.

3 Solution Method

For solving the optimisation model (4)–(6), which is a non-linear discrete model, numerous methods and algorithms can be used; most of them are based on constraint relaxation (such as branch-and-bound, or Lagrangian relaxation) and heuristic rounding. Considering that the problem could be theoretically formulated with continuous variables (the discrete assumption is necessary only for implementing the policy in real-world cases) and that the objective function is convex, continuous and derivable under this assumption, we propose to solve first the continuous problem with a standard gradient algorithm. Successively, we round the solution to the nearest integer one and, finally, use a neighbourhood search (NS) method to identify the local optimal discrete solution that is nearest to the global optimal continuous one. In Fig. 1 the proposed solution method is reported.

The used NS method examines at each iteration the neighbourhood of the current solution and generates the next solution as the best one of all solutions belonging to the neighbourhood. Each neighbourhood contains all solutions obtained by changing the value of a variable, y_{OD}, increasing or decreasing its value (satisfying the constraints), and maintaining unaltered the other values. Therefore, in our case, a neighbourhood may contain at most $2 \cdot n_{OD}$ solutions. The algorithm ends when all solutions in the neighbourhood are worse than the current solution, which can be considered a local optimum.

4 Numerical Results

We tested the proposed approach on a real-scale case, the city of Naples (Italy) that has about one million inhabitants. The choice of this case study was driven by a feature that is necessary for developing the proposed policy: transit system is inequitable; indeed, some OD pairs are well connected by high-frequency metro or funicular lines, other ones are connected only with low-frequency services (rail or bus lines) and other ones are only marginally served or are not served at all by public transport services.

An essential point of the procedure is to identify the parking fare zones, which are zones of the city that will have the same fares; since the objective of the policy is to improve the equity, the fare zones are identified considering their similarity concerning transit supply. We partitioned the study area into 20 zones, as reported in Fig. 2a; these zones were obtained from the union of the 54 traffic zones used for simulating the transportation demand on the territory. Note that, the zone 20 is a suburban zone where currently there are not parking fares. Figure 2b–d report, respectively, the road network, the urban rail network and the bus lines; these elements were implemented in a multimodal transportation supply model with the software Omnitrans 6.0. This software allowed to obtain all data on performances of all transportation modes for each OD pair, that is pedestrian times, transit times (onboard, access/egress, waiting), transit transfers, car travel time and distance. Moreover, for each OD pair also the monetary transit costs were added, according to the current transit fare framework, as well as the car monetary costs as the sum of a travel cost (0.25 €/km) and a parking cost, depending on the parking fares, assuming an average parking duration. Main features of the case study are summarised in Table 1.

The all-mode demand matrix used in the test was the same used in [6] that has given acceptable results for a real-scale application. The mode choice model was adapted from [11] and calibrated for the city of Naples. Since this is a real-scale test and not a real test, we assumed this model to be valid, without performing further specifications and calibrations required in the case of a real application. The specification of the model, whose coefficient values are reported Table 2, is the following:

$$V^{car}{}_{OD} = \beta_b{}^{car} \cdot T^{car}{}_{OD} + \beta_{mc}{}^{car} \cdot C^{car}{}_{OD} + \beta_{park}{}^{car} \cdot C^{park}{}_{OD} + \beta_{ca} \cdot CarAv \quad \forall\, OD$$

$$V^{tran}{}_{OD} = \beta_b{}^{tran} \cdot T^{tran\_b}{}_{OD} + \beta_{ped}{}^{tran} \cdot T^{tran\_ae}{}_{OD} + \beta_w \cdot T^{tran\_w}{}_{OD} + \beta_{tr} \cdot N^{tran\_t}{}_{OD} + \beta_{mc}{}^{tran} \cdot C^{tran}{}_{OD} \quad \forall\, OD$$

$$V^{ped}{}_{OD} = \beta_{ped} \cdot T^{ped}{}_{OD} \quad \forall\, OD$$

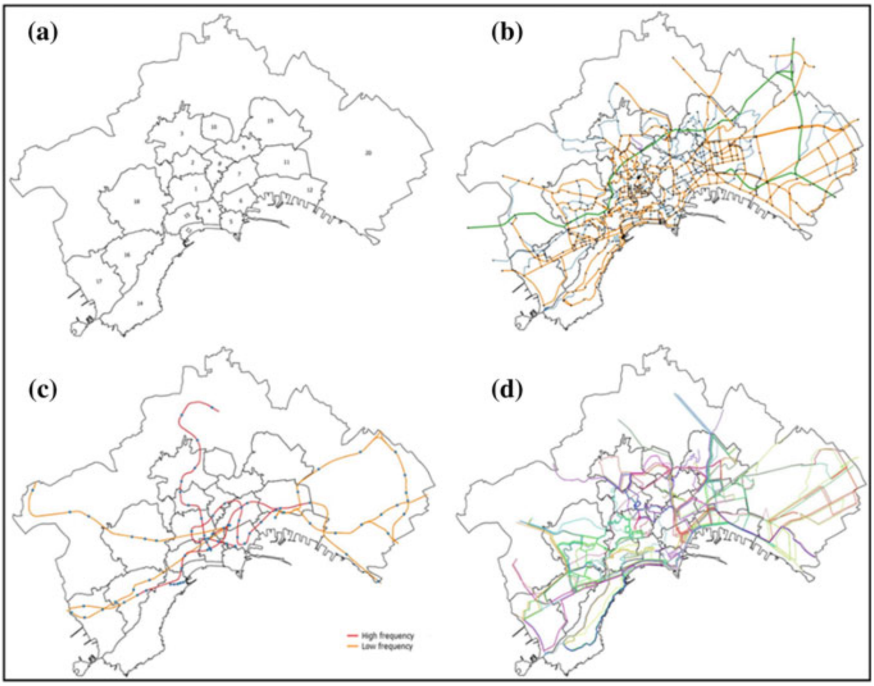

Fig. 2 Case study: **a** fare zones; **b** road network; **c** urban rail network; **d** bus lines

Table 1 Features of the case study

Inhabitants	962,003	Directed rail links	108
Traffic zones (internal centroids)	54	Rail segments	54
External centroids	16	Rail network length (km)	55.2
Fared zones	20	Rail lines (including funiculars)	12
Directed road links	1,774	Rail station (including funiculars)	60
Road segments	887	Bus lines	100
Road nodes	622	Main bus stops	370
Road network length (km)	335.7		

where $V^{car}{}_{OD}\left[V^{tran}{}_{OD}; V^{ped}{}_{OD}\right]$ is the systematic utility of car [(mass) transit; pedestrian] mode from zone O to zone D on the minimum path, $T^{car}{}_{OD}[T^{tran\_b}{}_{OD}; T^{tran\_ae}{}_{OD}; T^{tran\_w}{}_{OD}; N^{tran\_t}{}_{OD}]$ is the expected travel time by car [transit onboard travel time; access/egress transit time; waiting transit time; number

Table 2 Coefficients of the mode choice model

Attribute	Coefficient
$T^{car}{}_{OD}, T^{tran\_b}{}_{OD}$	−1.02
$C^{car}{}_{OD}, C^{tran}{}_{OD}$	−0.20
$C^{park}{}_{OD}$	−0.40
CarAv	2.29
$T^{tran\_ae}{}_{OD}, T^{ped}{}_{OD}$	−1.72
$T^{tran\_w}{}_{OD}$	−2.57
$N^{tran\_t}{}_{OD}$	−0.29

Table 3 Modal split

Mode	Model results (%)	ISTAT data (%)
Private motorised modes	55.6	48.33
Pedestrian	18.4	22.43
Transit modes	26.1	28.53
Other modes	–	0.72

of transfers] from zone O to zone D on the minimum transit path, $C^{car}{}_{OD}\left[C^{tran}{}_{OD}\right]$ is the expected monetary cost by car (only travel costs) [(mass) transit system] from zone O to zone D on the minimum path, $C^{park}{}_{OD}$ is the parking cost on the OD pair, *CarAv* is the average number of cars available per family.

Applying this model, considering a car travel cost of 0.25 €/km, an average parking duration of 4 h and a parking cost of 1.5 €/h on all zones except for zone 20 where the parking is not fared, the model generates the modal split reported in Table 3; the same table reports the modal split in Naples obtained by the ISTAT data [12] for systematic (i.e. home-work and home-school) trips. These results can be accepted for a real-scale test case.

In the application, we have compared results corresponding to three different scenarios: (a) the starting scenario, described before, (b) a scenario without parking fares and (c) the optimised scenario. Scenario (c) is obtained by applying the model (1)–(3) solved with the algorithm described in Sect. 3. The objective function value was equal to 0.375628 in the starting scenario, 0.135585 in the non-fared scenario and 0.096145 in the optimised scenario. Figure 3 reports the values of $s''_{OD}(V_{OD})$ for each internal OD pair for these three scenarios.

5 Conclusions

This paper proposes an origin-destination based parking pricing policy aiming to increase equity in transportation. The principle of the policy is that the OD pairs that are not served with a good quality public transport system should pay less

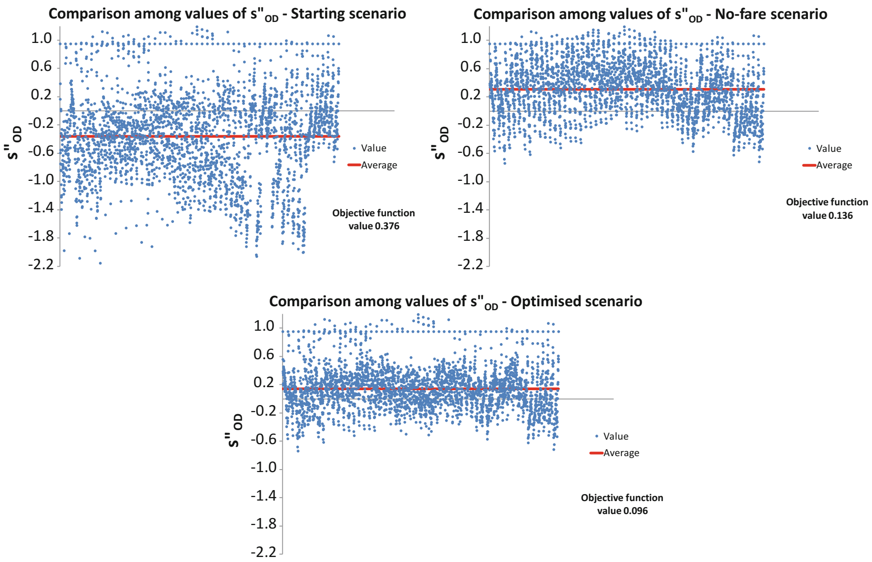

Fig. 3 Values of $s''_{OD}(\boldsymbol{V}_{OD})$ for each internal OD pair

for parking, considering that the whole society finances (mass-)transit systems. We propose an optimisation model and a solution algorithm for implementing the policy; the proposed approach is tested on a real-scale case study giving promising results.

Future research will be addressed to test the proposal considering different mode choice models, focusing on the elasticities of the modal split with car parking costs, to evaluate other impacts of the policy, such as consumption and emissions, and to optimise also the zoning phase besides the fares.

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