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Optimal planning of charging stations and electric vehicles traffic assignment: a bi-level approach

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Abstract: A new bi-level approach is proposed for the location and sizing of charging stations, considering both the transportation and energy demands. The lower level considers the User Equilibrium traffic assignment conditions for Electric Vehicles (EVs) which are derived and inserted as constraints in the overall optimization problem. The higher level presents the formalization of an optimization problem for the optimal planning of locations, sizes and unit prices of a set of new charging stations in a territory characterized by the presence of an already existing set of charging stations. A case study in the Genoa Municipality is considered for the application of the proposed model.

Keywords: Electric vehicles, charging stations, optimization, User Equilibrium, smart grids, traffic assignment, energy demand assessment.

1. INTRODUCTION

The increasing presence of electric vehicles (EVs) is motivated by many reasons, related to the necessity of reducing pollutant emissions and the use of fossil fuels. In this connection, automotive industry, mobility planners and distribution companies are all solicited to urgently solve a number of problems, in order to encourage the progressive shift of the private transportation demand from traditional towards EVs. Among the various objectives, the availability and the accessibility of a sufficient set of charging stations represents one of the most critical issues, since an extensive presence over the territory is a fundamental condition to favor the transition to this new technology (Ferro et al. 2018). The problem related to planning the location (and sizing) of the charging stations (CSs), especially in an urban environment, and the overall mobility planning problem must be coupled and considered as a single one. In the literature, many contributions provide different formalizations and solutions to this planning problem. A survey of spatial localization methodologies for the EV charging infrastructure is presented in (Pagany et al., 2018). Here, financial costs, spatial coverage of a charging station (demand density), and trip length generally represent the main target. According to the availability of data and to the local characteristics, a broad variety of models and approaches are used. Instead, a hybrid approach characterizes the study presented in (Awasthi et al. 2017) about an optimal planning problem regarding the placement of vehicle charging stations. Their approach combines genetic algorithms with particle swarm optimization. The work presented in (Lee and Han, 2017) is relevant to the optimization of the charging station positioning, but with the purpose of maximizing the flow between origin and destination pairs by refueling at the built facilities. The authors of (Wang et al. 2019) aim at designing locations and capacity of charging stations for supporting long-distance travel by EVs. They consider route-choice and charging behaviors to model the behavior of EVs drivers. The individual drivers' choices are not considered in any of the previously mentioned contributions. Nevertheless, the systematic choices of the drivers can determine the distribution of the charging demand.

To this end, some additional contributions in the literature can be considered. Their objective is to extend the traditional User Equilibrium (UE) traffic assignment approach (Sheffi, 1985) to a case where EVs generate a portion of traffic. The authors in (He et al. 2014) introduce a network user equilibrium model which integrates the choices of destination, route and parking facilities in a context where both conventional and EVs are present. Several studies, as in (Lee et al. 2014, Xiang et al. 2016, Hosseini and MirHassani, 2015), consider the solution of a UE traffic assignment problem as an important condition when the planning of the location of charging facilities is investigated. In this case, based on different models regarding the constraints that affect the routes of electric vehicles, a two-level approach is followed that, at the higher level, solves an optimal location problem, and at the lower level determines the traffic assignment (in particular, of electric vehicles) following the UE principle. In particular, in (Lee et al. 2014) the two-level optimization problem is converted into a mono-level one since it is shown that the Karush-Kuhn-Tucker (KKT) conditions of the lower level decision problem can be included as constraints within the statement of the upper-level problem. The possible waste of time that may be incurred by vehicles before receiving the charging service is not mentioned in any of the contributions present in the literature. In fact, even if *en route* charging is considered (thus necessarily referring to fast charging stations) the charging time for EVs is not negligible, with respect to traveling time. Of course, the level of congestion that characterizes the considered service station has an important impact on the waiting time.

In the present paper, a new bi-level approach is proposed for the location and sizing of charging stations in a territory, taking into account both the transportation and energy demands jointly. In particular, at the lower level, the UE traffic assignment conditions for EVs are derived and inserted as constraints in the overall optimization problem. We will then consider the problem of optimal planning the locations, sizes and unit prices of a set of new charging stations in a territory in which a set of charging stations has already been established (and are active) by other companies. The aim is the one of stating the optimization problem that has to be solved by a new competitor.

The rest of the paper is organized as follows. In Section 2, the system model is reported and the UE conditions in presence of EVs derived. The optimization problem for a new competitor in the market is reported in Section 3, while Section 4 shows the application to a case study.

2. USER EQUILIBRIUM CONDITIONS IN PRESENCE OF ELECTRIC VEHICLES

2.1 The traffic network model

A set of traffic sources S and a set of traffic destinations D is a-priori identified over a traffic network, represented as a directed network, made of a set of oriented links A, and a set of nodes N. Within the set N, two (disjoint) subsets are a-priori identified, namely: the set of sources, and the set of destinations. For any origin-destination pair (s,d), being $s \in S$ and $d \in D$, a traffic demand [#veh/h] is specified. Such a demand is characterized by two different terms:

- A traffic demand q_{sd}^1 which represents traditional vehicles or to EVs which do not need of any recharge during the trip;
- A traffic demand q_{sd}^2 corresponding to EVs which require a (single) recharge during the trip.

A subset R of oriented links A is equipped with (one) electrical charging stations. In the formalization of the model, for any link $a \in R \subset A$, an additional link (with the same initial/terminal nodes as a) will be considered, namely $\tilde{a}$, whose inclusion in the path of a vehicle indicates that a recharge takes place (instead, when no recharge takes place, the vehicles choose link a). Let $\tilde{R}$ be the set of "additional" links (with respect to the original set of links A of the network) that are created in such a way. This leads to an "augmented graph", in which the set of links is $A \cup \tilde{R}$. In the following, we will refer to this augmented graph, where any link with a charging station is formally doubled. Besides, for the sake of simplicity the same symbol a will be used to indicate a generic link in the augmented graph only where there will not be any risk of misunderstanding. Similarly to the usual approach in UE assignment theory for traditional vehicles, for any pair (s,d), a set P_{sd}^1 of eligible oriented paths for traditional vehicles (and EVs that do not require a recharge during the trip) is a-priori determined. Likewise, a set P_{sd}^2 of eligible (oriented) paths for EVS that must be recharged during a trip is defined. Since it is assumed that only *one* recharge is required by those EVs, each path belonging to a set P_{sd}^2, for any (s,d) within the set of origin-destination pairs (i.e., the O/D set), includes *one and only one* additional link included in $\tilde{R}$. Note that, when an EV passes through one of such links, the charging cost and an additional time required for that charging process (including waiting time) must be taken into account. The travel time spent by a vehicle when it is in the link $a \in A$ is assumed to be given by the Bureau of Public Road:

$$t_a(x_a) = t_a^0 \left[1 + \alpha_a \left(\frac{x_a}{CAP_a} \right)^4 \right] \qquad a \in A \tag{1}$$

where:

- t_a^0 is the free flow travel time [h] of that link;
- α_a is an a-priori determined adimensional parameter;
- CAP_a [#veh/h] is the capacity (i.e., the maximum flow) of the link;
- x_a [#veh/h] is the flow over the link.

Instead, as regards other links $a \in \tilde{R}$, it is necessary to consider also the service time plus the waiting time at the charging station, namely $c_{serv,a}$; this cost (time) can be evaluated according to the so-called Davidson formula (Davidson, 1966),

$$c_{serv,a}(x_a) = ts_a^0 \left[1 + \beta_a \left(\frac{x_a}{CAPs_a - x_a + \varepsilon} \right) \right] \qquad a \in \tilde{R} \tag{2}$$

where:

- the term ts_a^0 represents the pure service time [h];
- β_a is an adimensional parameter (to be determined a priori) characteristic of the service station;
- $CAPs_a$ is the capacity of the service station in link a, expressed in [#services/h];
- ε is a very small flow value to prevent the zeroing of the denominator in (2).

Thus, for links $a \in \tilde{R}$, the overall generalized cost $c_{tot,a}(x_a)$ can be defined. This cost includes the travel time (like in (1)), the service time plus the waiting time at the charging station (given by (2)), and the cost paid for the charging service as in (Ferro et al. 2020). That is,

$$c_{tot,a}(x_a) = t_a^0 \left[1 + \alpha_a \left(\frac{x_a}{CAP_a} \right)^4 \right] + ts_a^0 \left[1 + \beta_a \left(\frac{x_a}{CAPs_a - x_a + \varepsilon} \right) \right] + \omega pr_a \qquad a \in \tilde{R} \tag{3}$$

where:

- the term ts_a represents the pure service time [h];
- β_a is an adimensional parameter (a-priori determined) distinctive of the service station;
- $CAPs_a$ is the capacity of the service station in link a, expressed in [#services/h];
- pr_a is the price paid by any customer for a charging service;
- ω is a conversion coefficient that allows converting money into time.

Observe that, since the proposed model is capable of representing the average behavior of drivers over a long horizon, we must consider an *average service request* for all drivers, so that the charging service cost depends only on the link and not on the single service.

The term f_k^{sd} represents the flow relevant to vehicles which do not have any recharge during the trip and that go from s to d along the *k-th* path in P_{sd}^1, k=1,…, K_{sd}^1. Clearly, the summation of the flow f_k^{sd} over all paths belonging to P_{sd}^1 must be equal to the transportation demand (for that origin-destination pair) of traditional vehicles and EVs that do not need to recharge. That is

$$q_{sd}^1 = \sum_{k=1}^{K_{sd}^1} f_k^{sd} \qquad \forall (s,d) \in O/D \tag{4}$$

Similarly, we define g_k^{sd} as the flow relevant to vehicles that need a recharge during the trip and that go from s to d along the *k-th* path in P_{sd}^2, k=1,…, K_{sd}^2. Clearly, even in this case, a constraint analogous to (4) must be fulfilled, namely

$$q_{sd}^2 = \sum_{k=1}^{K_{sd}^2} g_k^{sd} \qquad \forall (s,d) \in O/D \tag{5}$$

Let us now introduce the binary coefficients $\delta_{a,k}^{sd}$ defined as

$$\delta_{a,k}^{sd} = \begin{cases} 1 & if \quad link \quad a \in \; the\; k-th\; path\; in\; P_{sd}^1 \\ 0 & otherwise \end{cases}$$

$$a \in A, \quad (s,d) \in O/D, \quad k = 1,...,K_{sd}^1$$

Similarly, we define the binary coefficients $\xi_{a,k}^{sd}$ as

$$\xi_{a,k}^{sd} = \begin{cases} 1 & if \quad link \quad a \in to\; the\; k-th\; path\; in\; P_{sd}^2 \\ 0 & otherwise \end{cases}$$

$$a \in AU\tilde{R}, \quad (s,d) \in O/D, \quad k = 1,...,K_{sd}^2$$

Clearly, the overall traffic flow on a link $a \in A$ is given by the sum of the flows f_k^{sd} corresponding to paths in P_{sd}^1 that include link $a \in A$, plus the sum of the flow g_k^{sd} corresponding to paths in P_{sd}^2 that include link $a \in A$. That is:

$$x_a = \sum_{(s,d)\in O/D} \sum_{k=1}^{K_{sd}^1} f_k^{sd} \delta_{a,k}^{sd} + \sum_{(s,d)\in O/D} \sum_{k=1}^{K_{sd}^2} g_k^{sd} \xi_{a,k}^{sd} \qquad a \in A \tag{6a}$$

Instead, by definition, for a link $a \in \tilde{R}$ there is no flow f_k^{sd} over this link, so that

$$x_a = \sum_{(s,d)\in O/D} \sum_{k=1}^{K_{sd}^2} g_k^{sd} \xi_{a,k}^{sd} \qquad a \in \tilde{R} \tag{6b}$$

The total cost [h] incurred by a vehicle following the *k-th* path from s to d belonging to P_{sd}^1 is given by the sum (over links $a \in A$) of the travel time over the links included in that path. This cost is

$$c_{path,k}^{sd} = \sum_{a\in A} t_a(x_a)\delta_{a,k}^{sd} \qquad k = 1,...,K_{sd}^1 \tag{7}$$

where $t_a(x_a)$ is given by (1).

Instead, the total cost incurred by a vehicle following the *k-th* path, from s to d, belonging to P_{sd}^2 is composed by the sum of two terms: the sum of the travel times over links $a \in A$ that are included in a path; the total cost $c_{tot,a}(x_a)$ incurred by the vehicle in the unique link $a \in \tilde{R}$ where the recharge takes place. That is

$$\tilde{c}_{path,k}^{sd} = \sum_{a\in A} t_a(x_a)\xi_{a,k}^{sd} + \sum_{a\in \tilde{R}} c_{tot,a}(x_a)\xi_{a,k}^{sd} \qquad k = 1,...,K_{sd}^2 \tag{8}$$

where $t_a(x_a)$ is defined in (1), and $c_{tot,a}(x_a)$ is defined in (2).

2.2 The Electrical Vehicles User Equilibrium Assignment (EV-UEA) Problem

In a UE condition, the travel time on all used paths is equal, and (also) less than or equal to the travel time that would be experienced by a single vehicle on any unused paths. This principle, introduced by Wardrop (1952), and extensively used in Sheffi (1985), has now to be applied to both classes of vehicles that are considered in this paper.

The Electrical Vehicles User Equilibrium Assignment Problem (EV-UEA Problem) consists in finding vectors

$$\underline{f} = col\left[f_k^{sd}, k = 1,...,K_{sd}^1, (s,d) \in O/D \right]$$
$$\underline{g} = col\left[g_k^{sd}, k = 1,...,K_{sd}^2, (s,d) \in O/D \right]$$

such that the following implications are satisfied

$$c_{path,k}^{sd} > c_{path,\mathrm{h}}^{sd} \Rightarrow f_k^{sd} = 0$$
$$\forall (h,k) : h \neq k, (h,k) \in \left\{1,...,K_{sd}^1\right\}, \forall (s,d) \in \mathrm{O/\,D} \tag{9a}$$

$$\tilde{c}_{path,k}^{sd} > \tilde{c}_{path,\mathrm{h}}^{sd} \Rightarrow g_k^{sd} = 0 \tag{9b}$$

In particular, the meaning of (9a) and (9b) is that if the cost of a *k-th* path in P_{sd}^1 (P_{sd}^2) is greater than another *h-th* path in P_{sd}^1 (P_{sd}^2), the correspondent flow of vehicles f_k^{sd} (g_k^{sd}) in the *k-th* path should be equal to zero.

The implications in (9a) and (9b) are equivalent to the following

$$f_k^{sd}, f_h^{sd} \neq 0 \Rightarrow c_{path,k}^{sd} = c_{path,\mathrm{h}}^{sd}$$
$$\forall (h,k): h \neq k, (h,k) \in \{1,...,K_{sd}^1\}, \forall (s,d) \in \mathrm{O/D} \tag{9c}$$

$$g_k^{sd}, \mathrm{g}_h^{sd} \neq 0 \Rightarrow \tilde{c}_{path,k}^{sd} = \tilde{c}_{path,\mathrm{h}}^{sd}$$
$$\forall (h,k): h \neq k, (h,k) \in \{1,...,K_{sd}^2\}, \forall (s,d) \in \mathrm{O/D} \tag{9d}$$

The meaning of (9c) and (9d) is that both flows f_k^{sd}, f_h^{sd} (g_k^{sd}, g_h^{sd}) in the *k-th* and the *h-th* path in P_{sd}^1 (P_{sd}^2) are different from zero, then the corresponding costs must be equal.

2.3 The necessary conditions for the Electrical Vehicles User Equilibrium Assignment (EV-UEA)

In classical transportation planning literature (Sheffi, 1985), an auxiliary mathematical programming problem is introduced, whose first order necessary conditions imply the fulfillment of the User Equilibrium conditions. For the case of this paper such conditions are (Ferro et al., 2020):

$$f_k^{sd}(c_{path,\mathrm{k}}^{sd} - \mu_{sd}) = 0 \quad k = 1,...,K_{sd}^1 \quad \forall (s,d) \in O/D \tag{10}$$

$$c_{path,\mathrm{k}}^{sd} - \mu_{sd} \geq 0 \quad k = 1,...,K_{sd}^1 \quad \forall (s,d) \in O/D \tag{11}$$

$$\sum_{k=1}^{K_{sd}^1} f_{\mathrm{k}}^{sd} = q_{sd}^1 \quad \forall (s,d) \in O/D \tag{4}$$

$$f_k^{sd} \geq 0 \quad k = 1,...,K_{sd}^1 \quad \forall (s,d) \in O/D \tag{4bis}$$

$$g_k^{sd}(\tilde{c}_{path,\mathrm{k}}^{sd} - v_{sd}) = 0 \quad k = 1,...,K_{sd}^2 \quad \forall (s,d) \in O/D \tag{12}$$

$$\tilde{c}_{path,\mathrm{k}}^{sd} - v_{sd} \geq 0 \quad k = 1,...,K_{sd}^2 \quad \forall (s,d) \in O/D \tag{13}$$

$$\sum_{k=1}^{K_{sd}^2} g_{\mathrm{k}}^{sd} = q_{sd}^2 \quad \forall (s,d) \in O/D \tag{5}$$

$$g_k^{sd} \geq 0 \quad k = 1,...,K_{sd}^2 \quad \forall (s,d) \in O/D \tag{5bis}$$

where μ_{sd} and v_{sd} are auxiliary variables introduced to model logical statements (9c) and (9d) as constraints.

3. OPTIMAL PLANNING OF CHARGING STATIONS FOR A NEW COMPETITOR IN THE MARKET

3.1. The model with a new competitor

In this section, we will consider the problem of optimal planning the locations, sizes and unit prices of a set of new charging stations in a territory in which a set of charging stations has already been established (and are active) by other companies. In the formalization of this problem, we will make the assumption that User Equilibrium can describe the behaviour of all drivers (including the drivers of conventional vehicles). Besides, it is assumed that all parameters concerning the service offer of the already present competitors is fixed.

Then, within the set of the set $\tilde{R}$ of the links with a charging station, there are two *disjoint* sets, a priori identified:

a) the set $\tilde{R}_1$ including all stations belonging to the previously established competitors;

b) the set $\tilde{R}_2$ including all *potential* charging stations pertaining to the new competitor; let y_i a binary decision variable whose value is 1 if the *i*-th potential charging station is actually selected in the solution of the optimization problem, and 0 otherwise, for any $i \in \tilde{R}_2$.

It is assumed that the maximum number of the possible new charging stations is fixed and equal to *H*. Thus, the following constraint is introduced

$$\sum_{i \in \tilde{R}_2} y_i \leq H \tag{14}$$

The optimization objective of the new competitor is the minimization of its net cost (costs minus profits). That is,

$$\min \sum_{i \in \tilde{R}_2} \left(k_i y_i + h_i CAPs_i - N_{Hours} gain_i y_i x_i \right) \tag{15}$$

where:

- k_i is the fixed cost for the installation of a new charging station in link $i \in \tilde{R}_2$, measured in [€/year]
- h_i is the coefficient of the proportional cost for the installation of a new charging station in link $i \in \tilde{R}_2$; the proportional cost is obviously linearly dependent on the capacity of the new station installed; h_i is measured in [€/year(#veh/h)];
- $gain_i$ is the gain for a unitary service, measured in [€];
- x_i is, as already specified, the flow over link $i \in \tilde{R}_2$, and is measured in [#veh/h]; of course, this number may be measured in [#services/h];
- N_{Hours} is the (fixed) numbers of hours in a year.

Note that, to obtain the prices seen by the customers at the various stations of the new competitor, we must take into account a (fixed) additive constant $const$, which represents the fixed cost of the energy provided to a single customer, so that

$$pr_i = const + gain_i \qquad i \in \tilde{R}_2 \tag{16}$$

3.2. Optimal planning (location, sizing and pricing) of the service stations of the new competitor.

Now it is possible to state the optimization problem that has to be solved by the new competitor. First of all, note that the planning decision variables are $\left\{y_i, CAPs_i, gain_i, i \in \tilde{R}_2\right\}$.

Then, the optimization objective is that defined in (15) under constraints (4), (4bis), (5), (5bis), (10), (11), (12), (13), (6a), (6b), (7), (8), (1), (3), (14), (16), and

$$My_i - CAPs_i \geq 0 \qquad i \in \tilde{R}_2 \qquad (17)$$

$$CAPs^{MIN}{}_i \geq CAPs_i \geq CAPs^{MAX}{}_i \qquad i \in \tilde{R}_2 \qquad (18)$$

$$0 \leq x_a \leq CAP_a \qquad a \in A \qquad (19)$$

$$0 \leq x_a \leq CAPs_a \qquad a \in \tilde{R} \qquad (20)$$

where, of course, $\tilde{R} = \tilde{R}_1 \cup \tilde{R}_2$.

The meaning of these additional constraints is apparent. Constraints (17) are the usual disjunctive constraints that impose the payment of the fixed cost whenever a new service station (with nonzero service capacity) is activated by the new competitor. Constraints (18) are a priori conditions over the size of the new (potential) service stations. Finally, constraints (19) and (20) derive from the concept itself of capacity (maximum admissible flow, or maximum service rate).

4. APPLICATION TO A CASE STUDY

The overall mixed integer nonlinear optimization problem has been solved (on a PC Intel i7, 16 GB RAM) using LINGO as optimization solver (global solver option), the runtime is around 12 seconds. The optimization problem reported in the previous section (i.e., the auxiliary optimization problem) has been applied to a specific case study in the Liguria Region. In particular, one origin (Sampierdarena) and one destination (Recco) are considered. The possible travels are (see Figure 1): through the highway (Sampierdarena-Genoa East-Nervi-Recco) in which no charging stations are supposed to be present, and through the urban roads (Sampierdarena-Boccadasse-Quinto-Recco). Moreover, when in Quinto, it is possible to take the highway at Nervi. The distance between Sampierdarena and Recco, depending on the chosen path is between 25 and 30 km.

In Figure 1, the charging stations already present are in links $(\tilde{d}, \tilde{e}, \tilde{g})$. Possible charging stations can be placed in links $(\tilde{a}, \tilde{b})$, which connect the nodes Sampierdarena, East Genoa and Nervi as duplicates of links (a, b), till a maximum number of H=1. It results that in this optimization problem two binary decision variables are present, while other variables are continuous and for each regular and duplicated link. As regards ω, it is assumed to be equal to 0.1 [hour/€], while $q_{sd}^1 = 1200$ and $q_{sd}^2 = 50$ [#vehicles/hour], and for the objective function, $k_i = [2 \;\; 20]$, $h_i = [1 \;\; 10]$, and $const = 10$.

Other parameters useful for the system's model are reported in Table1.

In the considered case, $A = (a, b, c, d, e, g, l)$, $\tilde{R}_1 = (\tilde{d}, \tilde{e}, \tilde{g})$, and $\tilde{R}_2 = (\tilde{a}, \tilde{b})$. The set P_{sd}^2 (with K_{sd}^2 =7) is

$$P_{sd}^2 = \left\{(\tilde{d}, e, \tilde{g}), (\tilde{d}, e, g), (\tilde{d}, e, l, c), (d, \tilde{e}, g), (d, \tilde{e}, l, c), \left(a, \tilde{b}, c\right), (\tilde{a}, b, c)\right\}$$

Instead, the set P_{sd}^1 (with K_{sd}^1 =3) is given by:

$$P_{sd}^1 = \left\{\left(a, b, c\right), (d, e, g), (d, e, l, c)\right\}$$

The optimal results of the considered case study show that it is convenient to install 1 charging station in link $\tilde{b}$, with a capacity equal to 10.

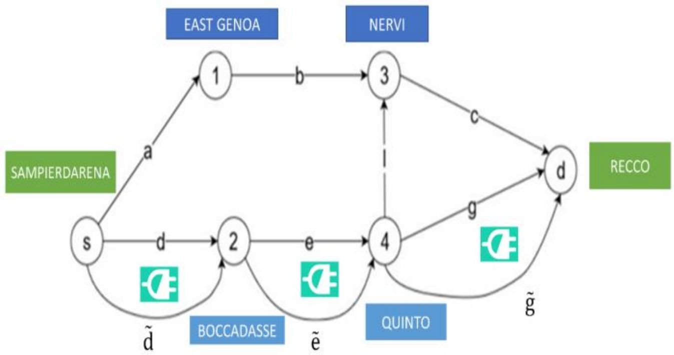

Figure 1. The considered case study.

Table 1. The considered parameters

	t_a^0 [h]	CAP_a [#vehicles/h]	ts_a^0 [h]	$CAPs_a$ [#vehicles/h]	$p_{r,a}$ [€]
a	0,1	1000	0	0	0
b	0,17	1000	0	0	0
c	0,08	1000	0	0	0
d	0,15	750	0	0	0
e	0,25	400	0	0	0
g	0,25	500	0	0	0
l	0,08	500	0	0	0
$\tilde{d}$	0,2	750	0,5	45	15
$\tilde{e}$	0,25	400	0,3	55	15
$\tilde{g}$	0,25	500	0,3	60	15
$\tilde{a}$	0,3	500	0,4		
$\tilde{b}$	0,3	400	0,3		

The detailed results related to the transportation flows and related costs for each path over the network are reported in Table 2, while Table 3 reports the optimal flows over links.

Table 2. Optimal results for the paths in P_{sd}^2 .

$k \in P_{sd}^2$	g_k^{sd}	$\tilde{c}_{path,k}^{sd}$	$k \in P_{sd}^1$	f_k^{sd}	$c_{path,k}^{sd}$
1	0	7	1	859	6,9
2	0	8,6	2	306	6,9
3	0	8,6	3	35	6,9
4	32	6,4			
5	10	6,4			
6	8	6,4			
7	0	6,4			

Table 3. Flows over links in the optimal solution.

Link	x_a	Link	x_a
a	867	$\tilde{d}$	0
b	859	$\tilde{e}$	42
c	912	$\tilde{g}$	0
d	383	$\tilde{a}$	0
e	341	$\tilde{b}$	8
g	338		
l	45		

6. CONCLUSIONS

A new bi-level approach for the jointly sizing of charging stations and traffic assignment is proposed. The innovation is that the model includes the traffic patterns and waiting times in the lower level problem, in addition to a profit function in the upper level. In particular, the lower level is represented by a traffic assignment model to assess energy demands over a transportation network, while the upper level includes decision variables related to the choice of installing a new charging station on a specific link. User Equilibrium traffic assignment conditions are embedded as constraints in the upper level. The proposed approach has been tested over a real test case of the Liguria region (Genoa Municipality). Future developments can be found in the statement of a stochastic optimization problem and in the application to large scale case studies.

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