Fast Charging Stations: Network Planning versus Free Entry*

Valeria Bernardo† Joan-Ramon Borrell‡ Jordi Perdiguero§

22nd April 2013

Abstract

This paper uses a game of strategic interaction for simulating entry of fast charging stations for electric vehicles. The paper compares the equilibria of the game with respect to different models of centrally planning the network of stations. Demand specification considers mobility of consumers. Decisions of consumers and producers are modelled taking into account the expected probability of finding a given facility located in each feasible location. The model is simulated using the the case of the city of Barcelona using the mobility survey, demographic and income data, and the street graph of the city. Planning renders a network of locations that it is out of any equilibria of the entry game. Planning does not satisfy neither the participation nor the incentive compatible constrains.

JEL Classification number: L13, L43, R53
Keywords: Regional Planning, Electric Vehicle; Fast Charging; Games of Strategic Interaction; Entry Models

*We acknowledge unconditional research grants from the Spanish Ministry of Science and Innovation (ECO2009-06946), the Catalan Government (SGR2009-1066) and RecerCaixa (unconditional research grant from the philanthropic arm of La Caixa-CaixaBank)

†Contact author: Dep. Politica Economica - Institut d'Economia Aplicada (IREA) - Grup de Governs i Mercats (GiM), Universitat de Barcelona. E-mail: valeriabernardo@ub.edu.

‡Dep. Politica Economica - Institut d'Economia Aplicada (IREA) - Grup de Governs i Mercats (GiM), Universitat de Barcelona; Public-Private Sector Research Center - IESE Business School, University of Navarra, Spain; Centre en Economia de la Salud (CRES) - Universitat Pompeu Fabra. Email: jrborrell@ub.edu.

§Departament d'Economia Aplicada, Universitat Autonoma de Barcelona; Institut d'Economia Aplicada (IREA) - Grup de Governs i Mercats (GiM), Universitat de Barcelona. E-mail: jordi.perdiguero@uab.cat.

1 Introduction

Reduction of carbon dioxide emissions is one of the main objectives of various United Nations (UN) summits with the intention of moderating or reversing climate change. The road transport industry contributes, above any other industry, to the volume of emissions.

According to the latest statistics published by the European Union, the share of road transport emission out of the total in 2010 was as large as 19.98 percent. The European Commission planned in 2009 to decarbonise road transport in Europe in the following 5 years. There are many measures that can be implemented to decarbonise road transport as improving the efficiency of internal combustion engines, increase fuel taxes to reduce consumption, increase the use of bio-fuels, etc. Among all these feasible policies, the introduction and spread of electric vehicles is one of the policies that can help most to reduce emission levels.

Truly, electric vehicles do not generate global zero emissions, and one should take into account that there are emissions produced in generating the electricity to fed the vehicles. However there are some papers Ahman 2001 or for Nature (WWF) 2008 that show that electric vehicles are more efficient: those vehicles generate less emissions per kilometer. This reduction in emission levels are still higher in those countries with a mix of electricity generation that have a higher share of renewals whether hydro, wind or solar.

While the introduction of electric vehicles can play an important role in reducing emissions of road transport, the introduction and adoption of electric vehicles must overcome a host of barriers. Following the report by Analysis 2009 the four major uncertainties that could limit the introduction of electric vehicles are the following: the high cost of production of electric vehicles due to the high cost of batteries; the shortsighted of consumers that are not willing to pay more for the vehicle in exchange for paying cheaper fuel latter on; the evolution of other technologies such as internal combustion vehicle itself that can make electric vehicles less competitive; and finally, the deployment of a charging network that limits "range anxiety" that users of electric vehicles may suffer.

We define "range anxiety" as the fear that electric vehicle owners may suffer as they may be afraid that they will not find a convenient charging point on the road if needed. The deployment of a network of fast charging stations that reduces "range anxiety" is essential to the adoption en masse of this type of vehicles.

This paper uses a game of strategic interaction for simulating entry of fast charging stations for electric vehicles. The paper compares the equilibria of the game with respect to different models of centrally planning the network of stations. Demand specification considers mobility of consumers. Decisions of consumers and producers are modelled taking into account the expectation of finding a given facility located in each feasible location. The model is applied to the case of the city of Barcelona using the mobility survey, demographic and income data, and the street graph of the city.

As far as we know, this is the first paper that studies free entry and location of fast charging stations using a simulated game of competitive strategic interaction among potential entrants. It is also the first time that results of the entry game will be compared with those obtained by other studies using flow maximization models, which only aim to maximize the number of potential customers that pass through any given node served by a station, but does not take into account whether location is economically feasible for any private operator that competes with the other stations in the city in serving consumers. Doing this comparison, we can see where the locations of stations in planning with respect to the entry game differ significantly.

Preliminary results indicate that entry in the competitive strategic interaction game occurs mostly in the nodes served already by petrol stations. This is because opening any fast charging station in a petrol station has a lower set up cost. Additionally, the amenities of the petrol stations (bar, restaurant, ...) attract demand. Also, the nodes having supermarkets and hypermarkets also attract demand. In the nodes with amenities and super/hypermarkets, users can use the spare time while the batteries of the car are being charged.

Finally, we show that the equilibrium locations in the free entry model which are chosen by firms to maximize their profits in the game of strategic interaction differ significantly from the locations that would be chosen by any planner aiming only to maximize the number of users that pass through the fast charging point. Planning renders a network of locations that it is out of any equilibria of the entry game. Planning does not satisfy neither the participation nor the incentive compatible constrains.

After this introduction, the paper is organized as follows. In Section 2, we present the game of strategic interaction to simulate entry, and then we turn to detail the data and empirical methodology in section 3. Section 4, shows the results obtained in the simulation for the case of Barcelona city, and finally the paper ends discussing the main conclusions that can be drawn from the simulation.

2 The entry game of strategic interaction

Consider a model of entry where the geographical space is divided into a set of finite origin destination zones l ($l = 1, 2, ..., L$) connected through a road network. Consider also that the intersection points of the road network constitute the set of finite feasible locations j ($j = 1, 2, ..., J$) where the firms might decide to enter.

Each location is differentiated regarding two features that are common knowledge for the firms. On the one hand, the locations are differentiated regarding the set up costs of the stations, mostly the costs of grid reinforcement, outlined in the vector z_j^r. On the other hand, each feasible location is considered to be attractive for consumers if it has some amenity around the area such as a coffee shop, supermarket, car wash services, etc. as detailed in the vector x_j^r.

Differently from common entry games and following Houde 2012, we assume that demand is not fixed at a single area but mobility of consumers between origin and destination zones is taken into account. We also take into account that consumers differ with respect to income.

Additionally, consider for any feasible location j $(j = 1, 2, , J)$ an identically and independently distributed ($i.i.d.$) random draw that constitutes profit relevant information on costs over all feasible locations $(s_\varepsilon \epsilon_j)$. Also, consider idiosyncratic tastes of consumers regarding the utility for individual i $(i = 1, 2, I)$ to purchase from a facility located in j $(\varepsilon_i j)$ to be identically and independently distributed ($i.i.d$). Both random shocks are private information: the former is private information for consumers preferences when deciding where to recharge batteries on the go, and the latter is private information of costs for each potential entrant in each location.

Firms take observable information to estimate the expected profits of entering to each feasible location j and simultaneously decided wether to enter $\sigma_k = 1$ or not $\sigma_k = 0$. We assume that there is one and only one potential entrant at each node, and that they are one-shop stations. We plan to check for robustness of the simulation when we allow for networks of stations in the future.

The total quantity of battery recharges sold by each firm entering the market is then given by:

$$N = \sum_{j=1}^{J} \sigma_j \tag{1}$$

2.1 Demand specification

Let the demand for fast charging of electric vehicles be modeled as a discrete choice problem over $j + 1$ possibilities. Consumers are therefore able to choose between consuming at one of the j feasible locations or recharging at home (outsidegood).

Let the commuting paths of individuals between origin-destination zones be called (o_l, d_l)

Let additionally the utility of buying from store j depend on the distance between commuting paths of the individuals and location j, features of the location, characteristics of individuals and unobservable idiosyncratic tastes over each j location.

Then, the deterministic component of the indirect utility of buying from store j to individual i ($\phi_(ij)$) can be expressed as:

$$\phi_{ij} = \lambda D_i[(o_l, d_l), l_j] + \sum_{r=1}^{R} \beta_r x_{jr} + (\overline{\alpha} + \alpha \log Y_i) p_j \tag{2}$$

Being the indirect utility function:

$$u_{ij} = \phi_{ij} + \varepsilon_{ij} \tag{3}$$

where $D_i[(o_l, d_l), l_j]$ represents the distance between path (o_l, d_l) and facility j and λ is a parameter that express the disutility of deviate from commuting path to reach the facility j measured in minutes; x_{jr} is a binary variable that takes the value of 1 whenever at the feasible location j are amenities such as car wash services, supermarkets or coffee stores; $\overline{\alpha} p_j$ measures the desutility of paying posted prices; and $\alpha \log Y_i p_j$ introduce the interaction between income and prices and express the differentiation between individuals that make the same trip.

For the +1 possibility, the utility of recharging at home is normalized to zero.

Thus, the probability for individual i to recharge at facility j, Φ_{ij} is given by a multinomial logit where the individual is allowed to choose between buying at facility j, recharging at home, or buying from any other localization. However, as we are focus in an entry game in which each consumer and potential entrant is taking into account not only existing stations, but also those would be stations that are available if they finally enter, following Bajari and Nekipelov 2010 and Borrell and Casso 2011 we allow consumers to evaluate utility of recharging in each node with respect to the utility of recharging in any other node under the expectation of the probability that finally a station would be available in those other notes. This is why the existence of a facility in any other location apart from j enters in expected terms as the probability for individual i of finding a facility in any other location. This probability of having any entrant at each location is named by the parameter σ_k.

Φ_{ij} is therefore given by:

$$\Phi_{ij} = \frac{\exp[\phi_{ij}]}{1 + \exp[\phi_{ij}] + \sum_{k=1}^{J} \sigma_k \exp[\phi_{ij}]} \tag{4}$$

On the other hand, we assume that individuals demand heterogeneous quantities of energy proportional to the distance travelled per year, which is obtained by adding all the trips between origin destination zones as registered in the survey: $\sum_{l=1}^{L} D(o_l, d_l)$.

Also, we consider that the quantity of energy demanded depends on the share of the electric vehicle (υ). It also depends on the share of consumption of the electric vehicle recharged on the go (τ), and the energy consumption per kilometre (C_0). We assume that all these parameters are common for all individuals. Therefore, individual demand for energy on the go is given by:

$$q_i = \upsilon \tau C_0 \sum_{l=1}^{L} D(o_l, d_l) \tag{5}$$

2.2 The supply

Given the previous set up, expected sales at location j are given by integrating by simulation across consumers the probability of recharging at each location j:

$$s_j = \sum_{i=1}^{I} p_j \Phi_{ij} q_i \tag{6}$$

And expect profits are therefore the following:

$$\pi_j = s_j - \sum_{i=1}^{I} c_j \Phi_{ij} q_i - F_j \tag{7}$$

where c_j are variable costs of providing energy that is common to all locations, and F_j is the fixed cost associated to the location j.

Let the fixed cost F_j have an observable part composed by a common component in equipment for all locations c and a specific component to each location j regarding grid reinforcement and localization z_j^r, and the unobservable ($i.i.d.$) random draw on costs ($s_\varepsilon \epsilon_j$). Therefore, the fixed cost equation is given by:

$$F_j = c + \sum_{r=1}^{R} \mu_j z_j^r + s_\varepsilon \epsilon_j \tag{8}$$

We assume that each entrant compete a la Bertrand in prices with respect to the set of expected entrants that are differentiated by location. From the system of first order conditions, the system of Nash equilibrium pricing is the following:

$$p_j = c_j - \frac{\sum_{i=1}^{I} \Phi_{ij} q_i}{\sum_{i=1}^{I} \frac{\partial \Phi_{ij}}{\partial p_j} q_i} \tag{9}$$

where $\frac{\sum_{i=1}^{I} \Phi_{ij} q_i}{\sum_{i=1}^{I} \frac{\partial \Phi_{ij}}{\partial p_j} q_i}$ is the mark up of the firm that enters at location j.

Finally, given equilibrium pricing p_j and expected profits in each feasible location π_j, each potential firm at each node decides simultaneously whether to enter into the market $\sigma_j = 1$, or not $\sigma_j = 0$. This discrete choice decision is model using a logit as follows:

$$\sigma_j = \frac{\exp[E(\pi_j)]}{1 + \exp[E(\pi_j)]} \tag{10}$$

3 Data and methodology

We use the case of Barcelona as a case-study to test how the model simulates entry and location of fast charging stations in a dense city for which we have mobility survey data, and also demographics and income information. We will also be able to compare simulation results with respect to the results obtained in a companion paper Cruz-Zambrano and Igualada-Gonzalez that uses a Flow Capturing Location-Allocation Model (FCLM) Hodgson 1990 to simulate how a centrally planned network of stations should be designed to capture the mobility flows in the city.

The origin-destination commuting paths were built by using two sources of information: the Mobility Survey from the Metropolitan Transport Authority for the year 2006, and the Catalonia Roads Graph published by the Regional Government. In the survey, the Metropolitan Area of Barcelona is segmented in 304 zones, 63 of which correspond to the city of Barcelona. The shortest paths along the 63 origin destination zones defined within the city were built using the road network graph that presents 940 nodes and 2552 arcs. We take these 940 nodes as the feasible locations of fast recharging stations.

For estimating the commuting path between every origin-destination zone Dijkstra shortest paths algorithm were used Dikstra 1959. We end up having the flows of mobility through the 940 nodes and 2552 arcs across the city of Barcelona.

With all this information, we were able to have an plausible approximation to the flows of mobility in the city for all types of movements: home to work, home to study, home to shopping, home to any other destination, all back to home movements, and pair movements among all these destinations between them across these 940 nodes and 2552 arcs.

The feasible locations. The nodes are differentiated regarding set-up costs and attractiveness for the demand. For that purpose, a map with all fuel stations, hypermarkets and malls of the city was built and the facilities were assigned to the closest node of the net.

Locations were aggregated into four categories according to the following criteria (Figure 1): the nodes in which there is already a petrol station with car wash; the nodes with a petrol station with more than 10 pumps; the nodes with less than 10 pumps; the nodes with malls and supermarkets; and neither of the previous options. Entrants in most of the nodes should pay full upfront set-up costs as there is neither a petrol station, nor a mall or supermarket there. Upfront set-up cost is much lower in all the other cases, particularly in the case of petrol stations with car wash as the grid does not need upgrades. Set up costs range from 90,000 to nil.

The data regarding petrol stations was quoted on−line from the Spanish Ministry of

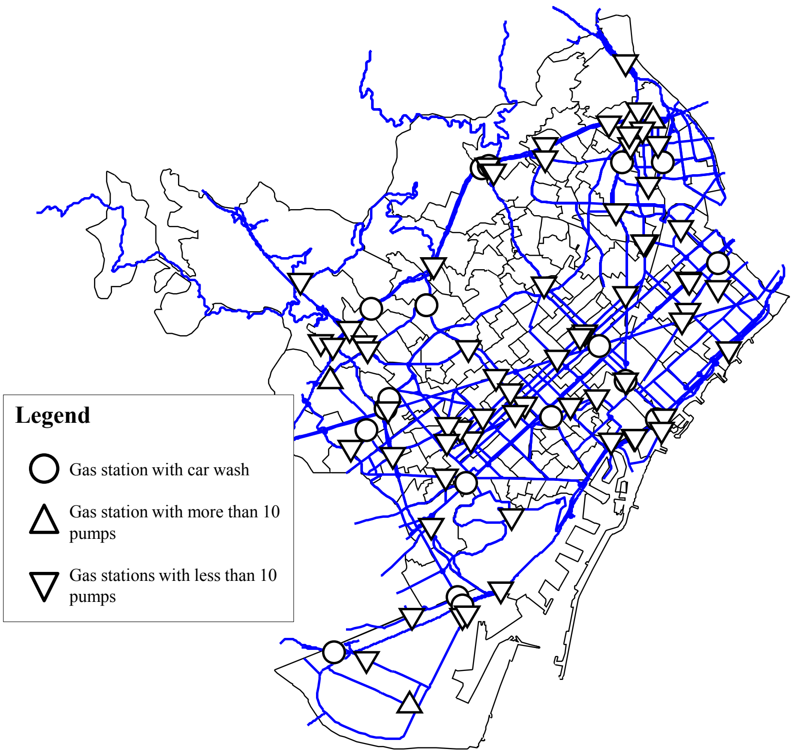

Figure 1: Current location of fuel stations, hypermarkets and malls in Barcelona used for defining fast charging installation costs and demand drivers in the feasible locations j

Industry, Tourism and Commerce; the costs of connection were taken from Schroeder and Traber 2012 the costs of localization in Barcelona were assigned according to current average prices of land, and the parameter μ_j is the same as in Houde 2012.

This same data was used to characterize the feasible locations regarding its attractiveness for the demand. The feature was included by the use of a binary variable that took value 1 whenever at the feasible location amenities such as bar, restaurant, store, and so on were available.

Regarding the marginal cost of providing energy, it was considered for every feasible location equal to 0.15 euros/kwh applied to a standard recharging of 16 kwh.

Assumptions on consumers and mobility. Consumers considered were all making trips in private vehicle between zones within the city and the commuting trips to Barcelona from the other 241 areas [1]. Considering an homogeneous penetration of EVs in each zone of Barcelona, the commuters were assigned to the different areas where the entries to the city are located according to the map of highways of the region.

Income data was taken from a report on income distribution in the city made by the Barcelona City Government and the Catalan Statistics Institute (IDESCAT) for most of the consumers selected for the simulation and some missing values were completed with the information provided in the mobility survey. The average income for the individuals of the sample takes a value of 17455 , with a standard deviation of 5369 , being the maximum income of 30538 and the minimum of 10000 .

The set of parameters $\lambda, \beta, \overline{\alpha}, \alpha$ are the same as in Houde 2012.

The penetration of electric vehicle was considered equal for every individual of the sample.

Methodology. To avoid the curse of dimensionality, we integrate logit demand across a random sample of only 100 representative individuals. They were selected from the mobility survey sample according to the weight of the interviewed sample with respect to the total population.

The probability of entering at each location was obtained through a simulation process including the simultaneous determination of: i) the probability for origin-destination trip i to refuel at facility j ($\Phi_(ij)$); ii) the Bertrand (Nash in prices) equilibrium pricing at each feasible location j (p_j); and, iii) the probability of entry to location j (σ_j).

The probability for origin-destination trip i to refuel at facility j $\Phi_i j$ was introduced as a multinomial logit with random coefficients as in Berry and Pakes 1995. The sources of heterogeneity are two: i) origin-destination path (o_l, d_l); and ii) income Y_i.

[1]The results showed have been obtained by considering only the trips made within the city of Barcelona. New results with commuters trips from and to outside Barcelona city are forthcoming.

The price equation p_j was derived from the first order condition of the firms by considering Bertrand competition (Nash in prices equilibrium). See also Berry and Pakes 1995.

Finally, the probability of entry to location j (σ_j) was introduced as a discrete choice logit model where, following Borrell and Casso 2011, the expected profits of a potential entrant in each location j depends on the probability of having any number of competitors in the others $j-1$ feasible locations.

The simultaneous non-linear problem was solved in Matlab by iteration. Initial conditions were given and convergence took just three iterations.

4 Results

The model has multiple equilibria. In order to compare free entry with respect to planning, we select one free entry equilibrium that has a number of 16 fast charging stations that according to the flow capture model makes sure that 50 percent of the movements in the survey are captured by the stations. We also compute other equilibria of the free entry model for other outcomes of the flow capture model. Results remain very similar.

The results from the simulation of the strategic interaction entry model show how these 16 fast charging stations are located within the city of Barcelona (Figure 2). Cost of entrance and demand attractiveness seem to place an important role in expected profits of the entrants as only one fast charging station would entry into a location with the higher cost of entrance and no amenities. From the others 15, every facility is located in a localization with amenities: two of them are in petrol stations with car wash, two in petrol stations with more then 10 pumps and the rest in hypermarkets, malls and petrol stations with less than 10 pumps. The entrant that pays full entry costs is located in the city centre.

Regarding the differences with the planned solution, in (Figure3) are shown simultaneously the results obtained by Cruz-Zambrano and Igualada-Gonzalez by means of the Flow Location-Allocation Model (FCLM) developed by Hodgson 1990, with the ones obtained in the present simulation of the strategic interaction entry game.

As the figure shows, the results between free market and full planning with flows criteria are really different: only one station coincide. The planning solution allocates the fast charging stations in the main highways around (belt or ring roads) and entering into the city, while in the free entry model most of the stations locate in the city streets. The costs of each location and the attractiveness have a greater influence in determining locations in the free entry game than the amount of pass-by flow of consumers. The station that coincide is located in the city centre and it is of type 3 regarding entrance costs: the entrant has to face full entry costs.

Solving the demand and supply functions for the welfare maximization problem is pending.

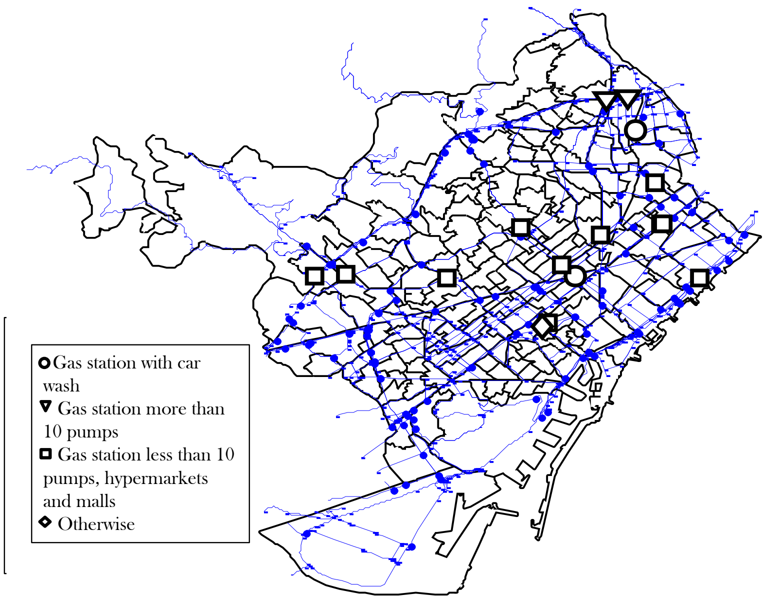

Figure 2: Results from the strategic interaction entry's model: 16 fast charging stations located within Barcelona

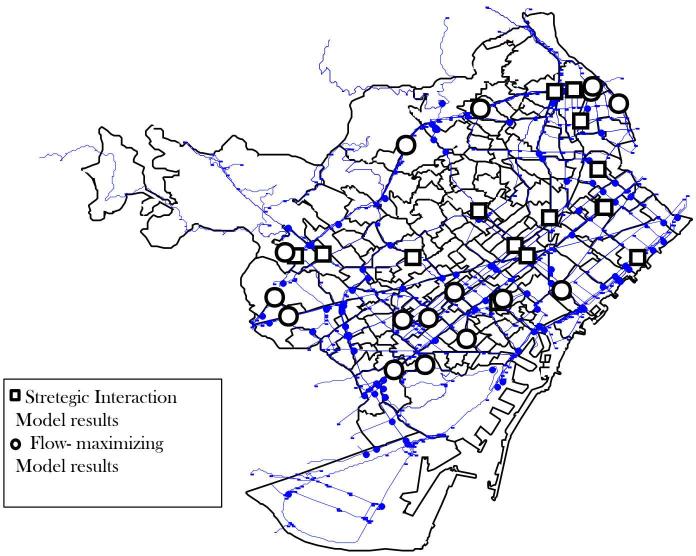

Figure 3: Comparison results from the strategic interaction entry's model and the FCLM

It will allow us to identify the effect of the competitive strategic interaction among entrants with respect to a model of a single-agent network that tries to maximizes entrants profits and consumer surplus.

Robustness checks with respect to different values of the parameters of the model, and also with respect different regulatory scenarios regarding access pricing to electricity is also pending.

5 Concluding remarks

This paper simulates a full game of strategic interaction for modelling entry in the industry of the fast charging stations for electric vehicles. It uses the information of mobility in the city of Barcelona together with income and demographic data, and also the information of the road network and petrol stations, amenities and super/hypermarkets to simulate the equilibria of the game.

One equilibrium of the entry model is compared to a flow capture model used in the planning of networks. As far, the paper shows that planning according only to flow capture by stations renders a network of locations that it is out of any equilibria of the entry game. Planning does not satisfy neither the participation nor the incentive compatible constrains. So, planning renders a network that it is not a sound finance equilibrium project. It seems that a tension between planning objectives such as accessibility and reducing congestion and achieving sound finance of the project. Planning may even be discouraging the deployment of a badly needed network of stations to allow users of the electric vehicle to recharge on the go.

Further research will soon allow us to solve the simulated model as a single agent planing problem aiming to maximize welfare (consumer and producer surplus). The planing using the welfare function from the entry game will also allow to compare free entry with respect to regulated entry. This comparison will be carried for different parameter values and regulatory options. These results will have policy implications, as the paper will show the unintended consequences of planing with respect to free entry.

References

Ahman, M. (2001). Primary energy efficiency of alternative powertrains in vehicles. *Energy 26*, 973–989.

Analysis, C. I. R. . (2009, 23th September). All hail the electric car but where will we plug them in? Technical report, Citi Investment Research & Analysis.

Bajari, P. H. H. J. K. and D. Nekipelov (2010). Estimating static games of strategic interaction. *Journal of Business & Economics Statistics 28 (4)*, 469–89.

Berry, S. J. L. and A. Pakes (1995). Automobile prices in market equilibrium. *Econometrica 63 (4)*, 841–90.

Borrell, J.-R. and C. Casso (2011). Welfare and geographic entry policies.

Cruz-Zambrano, M. V. B. C. C. and L. Igualada-Gonzalez. Optimal location of fast charging stations in barcelona: A flow-refuelling approach.

Dikstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik 1 (1)*, 269–271.

for Nature (WWF), W. W. F. (2008). Plugged in: The end of oil age. Technical report, World Wide Fund for Nature (WWF).

Hodgson, M. J. (1990). A flow capturing location allocation model. *Geographical Analysis 22*, 270 – 79.

Houde, J.-F. (2012). Spatial differentiation and vertical mergers in retail markets for gasoline. *American Economic Review 5*, 2147–82.

Schroeder, A. and T. Traber (2012). The economics of fast charging infrastructure for electric vehicles. *Energy Policy 43*, 136–144.