Optimal Policy and Network Effects for the Deployment of Zero Emission Vehicles *

February 2020

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Abstract

We analyze the impact of indirect network effects in the deployment of zero emission vehicles in a static partial equilibrium model. In most theoretical analyses, direct and indirect effects are conflated, and relatively few authors have explicitly considered indirect network effects. We also introduce the market power of vehicle producers and scale effects in the production function. The model exhibits a multiplicity of local social critical points and market equilibria, suggesting a possibility of lock-in. The optimal two subsidies for vehicles and stations are derived so that the Pareto dominating market equilibrium would coincide with the social optimum. Configurations associated with different values of the parameters are explored to revisit the policy issues at various stages of deployment of hydrogen and battery electric vehicles.

JEL Classification: Q55, Q42, C61

Keywords: network effects; technology deployment; lock-in; optimal policy

*The authors would like to thank for their comments three anonymous reviewers, Mads Greaker, Michel Moreaux, Guillaume de Smedt, Fabien Prieur, Floriane Dieuleveut, Quentin Hoarau and participants to WCERE 2018, Göteburg, the International Conference on Mobility Challenges, Paris, conferences at IPAG, Paris and FAERE, Toulouse. Financial support from the Chair Energy et Prosperity at Fondation du Risque and from ANR/Investissements d'avenir (ANR-11-IDEX-0003-02) is gratefully acknowledged.

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1 Introduction

Emissions from land transport are a major source of greenhouse gas emissions (approximately 24% for the EU28).[1] A large fraction of these emissions is from passenger cars and trucks that heavily rely on fossil fuels. The number of light-duty vehicles may double until 2050 (IEA, 2013). Urban pollution, especially particulate matter (PM2.5) and ground level ozone, is causing 3 million premature deaths annually (OECD, 2014). Battery and fuel cell (hydrogen) electric vehicles (BEVs and FCEVs, respectively, or ZEVs when taken together) are thought to be attractive technologies to ameliorate these challenges, and many cities and countries plan to phase out fossil fuel cars (Burch and Gilchrist, 2018). However, with the exception of BEVs in Norway, the current market shares remain quite low for BEVs and anecdotal for FCEVs, despite the substantial incentives (Lévay et al., 2017; Bjerkan et al., 2016; IEA, 2017).

A major reason advanced to explain such a low rate of penetration of ZEVs is the absence of an adequate infrastructure. A classical chicken-and-egg problem arises: Providers of infrastructure do not invest without a substantial EV market, and consumers do not buy EVs without a consequent infrastructure. The objective of this paper is to formalize this interaction as an indirect network effect. We also introduce two other important features typical of the ZEV market: (i) the limited number of vehicle manufacturers and (ii) a decreasing unit cost in the production of ZEVs. Moreover, we assume that the operators on the fuel retail market are price takers with a convex cost function. Consumers derive utility from transportation and refueling. Consumers pay for the vehicle and the fuel but not for the availability of stations. Indirect network effects, few producers, and cost decreasing with total output are associated in our model to three market failures. We compare the social optimum and the market equilibria, and identify government intervention to mitigate the corresponding market failures.

We prove the existence of both multiple welfare local extrema (Proposition 1) and multiple market equilibria (Proposition 2). The multiplicity is a direct consequence of the indirect network effect. For large markets, its significance decreases. Proposition 3 proves that the

[1] See http://ec.europa.eu/eurostat/statistics-explained/index.php/Climate_change_-_driving_forces

relative welfare loss between the Pareto dominating market equilibrium and the social optimum decreases with the market size. In small or medium sized markets, the indirect network effect plays a significant role; it introduces the possibility of lock-in: remaining stuck at the dominated market equilibrium. Furthermore, even the “best” (Pareto dominating) market equilibrium may be far from efficient. Proposition 4 provides the optimal two first-best subsidies (i.e., car rebates and subsidies for the investment cost of refueling stations) to achieve the social optimum through market forces. For small markets an integrated monopoly, simultaneously providing vehicles and stations may be preferred (Proposition 5). An integrated monopoly internalizes both the indirect network effect and the cost decreasing effect, and only market power needs to be mitigated. We also compare other second-best policies with subsidies either on vehicles or on infrastructure; the result demonstrates that under a limited budget, subsidizing infrastructure induces a larger vehicle park than subsidizing vehicles directly (Propositions 6 and 7).

We discuss how our model can be used for policy guidance. Three archetypal configurations are introduced and calibrated: Takeoff, Powering up, and Cruising, which can be interpreted as the successive phases of the deployment over time. We derive the optimal set of first-best and second-best subsidies for each configuration. We show the relevance of our typology to revisit recent deployments of FCEVs in France, Germany and Japan and more briefly BEVs in Norway and Tesla in the United States (US; Appendix D). Generally, the model is more suited for hydrogen, or BEVs for long-distance trips (e.g., infrastructure deployment along corridors in the deployment of ZEVs in Norway), and the integrated monopoly case nicely fits the situation of Tesla. The model has less relevance when discussing the deployment of small-range BEVs for urban use because these vehicles may be charged at home or at the work-place, even though a charging infrastructure is still necessary for apartments.

More precisely, our proposals demonstrated to comfort the recommendations from empirical studies on the interaction between the demand for vehicles and the infrastructure of refueling stations. Corts (2010) and Shriver (2015) have considered the market for flexible-fuel vehicles and ethanol refueling stations. Corts (2010) investigates the impact of the size of the fleet on the deployment of refueling stations, and Shriver (2015) shows how the density of the network influences the demand for vehicles. Li et al. (2017) analyzes the interaction between the adoption of BEV and entry of refueling stations and establishes that subsidizing charging stations, instead of vehicles, would have led to more vehicle adoptions (see also Springel, 2019; Pavan et al., 2015). Zhou and Li (2018) analyzes the existence of tipping points. We also use our model to highlight a critical feature largely ignored in the empirical literature (except for Figenbaum, 2016): the benefit of combining local and global policies. Although the market for vehicles is global, the market for infrastructure is local; thus, public policy should first encourage deployments in urban areas and then deployments along corridors.

From a conceptual point of view, our model has close connections with Greaker and Heggedal (2010) and Zhou and Li (2018). These authors have developed models of the interaction between vehicle adoption and refueling stations. In these models, as in ours, indirect network effects are introduced, but with different underlying assumptions. This common feature generates multiple equilibria. Although both articles have argued that policy should be designed to surpass the critical mass constraint to reach the Pareto dominating equilibrium, neither have characterized the optimal policy. Compared with these articles, our article introduces the two relevant features of market power and scale effect on the vehicle market and provides a normative analysis: The relationship between market equilibria and welfare critical points is established, and the two optimal subsidies are characterized.

More generally, our paper contributes to the literature on network effects. Network effects describe situations in which the utility of a user is affected by the number of users. Indirect network effects occur through a complementary good (e.g., stations) the supply of which increases with the number of users of the primary good (e.g., vehicles).[2] Shy (2011) provides a brief survey of the literature on network effects. In most analysis direct and indirect effects are conflated, and relatively few authors have explicitly considered indirect network effects (e.g. Chou and Shy, 1990; Clements, 2004; Church et al., 2008). The same situation holds in environmental economics (e.g. Sartzetakis and Tsigaris, 2005; Brécard, 2013; Greaker and

[2] The interaction between hardware and software is a frequent example of a sector with indirect network effects, the analogy with the transportation sector would be that a vehicle corresponds to a hardware and a filing station to a software. A parallel can be made between the taste for variety of software and the consumers benefit from the density of the network of refueling stations.

Midttømme, 2016; Nyborg et al., 2016).

Whereas direct network effects are associated with an externality that justifies a Pigouvian subsidy, whether indirect network effects are associated with a market failure and call for regulation is arguable (Liebowitz and Margolis, 1995); after all, plenty of complementary goods are provided by the market without regulatory supervision. In this respect, our contribution is that the call for regulation may be worthwhile for small and medium sized markets. In our framework refueling stations are under provided because of an unpriced benefit derived by consumers from stations. This induces a reduction of utility from searching and reaching a refueling station which decreases as the market size (and the density of stations) increases.[3] Notably, although Church et al. (2008) claim that "increasing returns to scale in the production of software" (stations in our case) is a necessary condition for indirect network effects, it is not the case in our model.

The paper is organized as follows. In Section 2, the model is introduced and the social optimum studied. In section 3, the market equilibria are derived and compared with the social optimum. In section 4, optimal policies are considered, the optimal subsidy couple is identified. In Section 5, the second-best solutions–integrated monopoly, subsidies either on vehicles or stations only–are considered. The typology elaborated from our model is illustrated numerically in Section 6 and through case studies in appendix D. Section 7 discusses the main limitations of our model and possible extensions. Section 8 concludes. All proofs are in the appendices.

[3] Indirect network effects may be analyzed through the prism of two-sided markets to discuss the potential monopoly power of platforms. We do not consider that, up to now, platforms play a significant role in this market. This may change if sophisticated software allows drivers to optimize their routes based on their position, the remaining level of energy in their battery, the positions and waiting times at surrounding EV charging stations. The "uberization" of transport with the emergence of new modes, such as autonomous vehicles, may encourage the disruption of the whole industry and favor the entry of strong platform players (Shaheen et al., 2017).

2 The model and the social optimum

2.1 Framework

We consider two complementary goods: vehicles and refueling stations. The total quantity of vehicles is X and the number of refueling stations K. The distance traveled per vehicle, and hence the quantity of fuel, are fixed and units are normalized so that the total quantity of fuel consumed is X.

The gross consumer surplus from consuming X vehicles with K refueling stations is $S(X,K) = s(X) - \beta r(K)X$. The term $s(X)$ is the utility from transportation and vehicle ownership, a positive, increasing and strictly concave function with $s(0) = 0$, $s'(X) \geq 0$ and $s''(X) < 0$ for $X \geq 0$. The term $\beta r(K)$ is the utility loss per vehicle associated with refueling, the cost to search and reach a refueling station. It is positive, decreasing and concave with $r(0) = +\infty$ and $r'(0) = -\infty$. For convenience the parameter $\beta \geq 0$ is referred to as the range anxiety factor.

Pollution, either climatic change or local air quality, from fossil fuel vehicles is not explicitly modeled but implicitly perfectly priced (at the Pigouvian level) and embedded into the willingness to pay $s(X)$ for the new clean vehicle.

The total cost to produce X vehicles is $C_V(X)X$. The unit production cost is decreasing with the total quantity produced : $C'_V(X) \leq 0$, $C''_V(X) \geq 0$. This will be simply referred as the scale effect; it integrates several phenomena (scale at such, supply chain effects, learning by doing) which we assume spills over from one firm to the other. We assume that it is relatively small: $s(X) - C_V(X)X$ is concave. Operating a refueling station incurs a fixed cost f, and a convex cost $C_F(x)$, to provide x units of fuel, with $C_F(0) = 0$, $C'_F(x) > 0$ and $C''_F(x) > 0$ for $x \geq 0$. The strict convexity captures the capacity constraint of a refueling station.[4]

[4] In a given context, there is an implicit optimization between the choice of a capacity for a refueling station and the expected size of the market. For instance in Brunet and Ponssard (2017) two scenarios are examined for an FCEV deployment: a low one with a hydrogen retail station of 100 kg/day and a high one with 200 kg/day. Scale effect, as we does not play any significant role in the analysis.

Total welfare is then

$$W(X,K,\beta) = s(X) - \beta r(K)X - C_V(X)X - C_F(X/K)K - fK \tag{1}$$

for $X, K > 0$ and $W(0,0,\beta) = 0$.[5] The minimum efficient scale of a station denoted $\bar{x}$ equalizes average and marginal cost: $(f + C_F(\bar{x}))/\bar{x} = C_F'(\bar{x})$. The associated average cost, which is the long run marginal cost, is denoted $\bar{C}_F$:

$$\bar{C}_F = (f + C_F(\bar{x}))/\bar{x} = C_F'(\bar{x}) \tag{2}$$

To ensure that for a small value of the range anxiety factor there is a positive quantity of vehicles and refueling stations we assume that

Assumption 1

$$s'(0) > C_V(0) + \bar{C}_F \tag{A1}$$

There are two interacting markets: the market for vehicles and the retail market for fuel, or market for "refueling." We do not model upstream fuel production and delivery to refueling stations. The price of a vehicle is p_V and the retail price of refueling is p_F. Capital letters P_V and P_F are used for price functions. Total welfare can then be decomposed as the sum of net consumer surplus, vehicle producers' profit, and the profits of refueling stations operators.

$$W(X,K,\beta) = [S(X,K) - (p_V + p_F)X] + [p_V - C_V(X)]\,X + \left[p_F \frac{X}{K} - C_F\left(\frac{X}{K}\right) - f\right] K \tag{3}$$

Competition works as follows: there are m vehicle producers that compete à la Cournot on the vehicle market taking the price of refueling as given, m is fixed; refueling operators have one station, they are price takers and entry into refueling is free.

The economic reason that explains both multiplicity of equilibria and welfare critical points is that a minimum number of stations is necessary to make individuals buy vehi-

[5] The welfare function given by equation (1) and $W(0,0,\beta) = 0$ is not continuous in $(0,0)$ because of the refueling cost, even for $\beta = 0$, this lack of continuity is not due to range anxiety. It is why we explicitly state that $W(0,0,\beta) = 0$.

cles, below that quantity of stations an electric vehicle is valueless (this threshold K solves $\beta r(K) = s'(0) - C_V(0) - C'_F(0)$). Then there is always a market equilibrium and a local maximum at $(0, 0)$. If there are more than one market equilibrium there are at least two more. Then one is a tipping-point and the other one a stable equilibrium which is always below the standard market equilibrium that would hold without range anxiety ($\beta = 0$). Our model is very stylized and ignores the precise topography of the network of refueling stations, and the multiplicity of usages of vehicles. The importance of the density of the network for users is likely to depend on the heterogeneity of the territory under study, both along the spatial dimension (urban versus rural areas) and the density of the population (number of households and their income), and the available modes of transportation (private and public). More complex models may generate many market equilibria.

2.2 Specification 1

All figures, some results, and the numerical illustrations are obtained with Specification 1. We assume that $s(X)$ is quadratic and $r(K)$ inversely proportional to K. The unitary costs of a vehicle are assumed to be linearly decreasing with respect to the quantity of vehicles, and the refueling cost is assumed to be quadratic:

Specification 1. *Consider the following functional forms*

$$s(X) = (a - \frac{b}{2}X)X \text{ and } r(K) = \frac{1}{K} \tag{4}$$

$$C_V(X) = \max\{c_0 - gX, 0\} \tag{5}$$

$$C_F(x) = c_F x^2/2 \text{ so that } \bar{x} = \sqrt{\frac{2f}{c_F}} \text{ and } \bar{C}_F = \sqrt{2fc_F} \tag{6}$$

in which $a, b, g, c_0, c_F > 0$.

The two parameters a and b generate the demand function. The parameter a referred to as the willingness to pay for zero-emissions vehicles. It increases with the social cost of carbon and the ecological attitude of consumers. The parameter b is related to the elasticity of the demand function and the size of the market. If there are less than β/a stations, even free vehicles cannot generate a positive gross surplus. The cost β/K can be further micro-founded as the cost to reach a station along a line in which the K stations are $1/K$ km apart (Appendix E.2).

The parameter g is the scale factor.[6] To ensure concavity of $s(X) - C_V(X)X$, we assume that $g < b/2$. Additionally, a is assumed to be larger than $c_0 + \bar{C}_F$ (correspond to assumption A1) to ensure that without range anxiety there is a non-negative number of vehicles. Furthermore, g is assumed sufficiently small so that at both the optimum and all market equilibria, scale is not exhausted, that is, $X < c_0/g$. Altogether the parameters satisfy assumption 2:

Assumption 2

$$b > 2g;\ a > c_0 + \bar{C}_F \text{ and } \frac{c_0}{g} > \frac{a - c_0 - \bar{C}_F}{b - 2g} \tag{A2}$$

In our model the three parameters β, m and g generate market failures. The model is static but captures dynamic phenomena (competition and cost change), and even though the dynamics are not directly addressed in the theoretical analysis, it guides our numerical exploration in section 6.1. Therefore, the demand parameters and the market failure parameters are not set independently: in a large, mature market, competition is intense (large m) and the scale effect is low. By contrast, in an emerging market, competition would be low, and an integrated monopoly is likely. Such an extreme case generates two important features: an integrated monopoly internalizes the market failures associated to β (network effect) and g (scale effect).

2.3 Social optimum

First, we examine the social optimum. We denote the optimal quantities of vehicles and stations X^* and K^*.[7] Notably, the welfare function described by equation (1) is not concave if range anxiety is not null for small X and K (cf Appendix A.1).[8]

[6] In a dynamic model, a better formulation would make the unit cost of a competitor depend on its cumulative production and on the cumulative production of the whole industry. The formulation adopted here follows the linear formulation of Fischer (2016), it aims at simplifying the model to obtain explicit formula. In the numerical exercise, we choose g in accordance to the maturity of the market to qualitatively grasp the dynamics.

[7] In case of multiplicity, (X^*, K^*) is the maximizing couple with the largest X.

[8] More precisely, the welfare function $W(X, K)$ is concave with respect to X and with respect to K ($W_{XX} \leq 0$ and $W_{KK} \leq 0$) but not with respect to (X, K) because of the cross derivative W_{XK} which is larger than $\sqrt{W_{XX} \times W_{KK}}$ for small X. This feature is necessary to have a multiplicity of critical points.

If both X^* and K^* are positive they solve the following first order conditions:

$$s'(X) - \beta r(K) = C_V(X) + C_V'(X)X + C_F'(X/K) \tag{7}$$

$$-\beta r'(K)X + \left[C_F'\left(\frac{X}{K}\right)\frac{X}{K} - C_F\left(\frac{X}{K}\right)\right] = f \tag{8}$$

The marginal consumer surplus from an additional vehicle should be equalized with the marginal cost to produce and fill the vehicle. The marginal production cost encompasses the scale effect $C_V'(X)$. The marginal refueling cost, C_F', depends upon the number of stations. To build one additional station costs f but reduces the range anxiety ($-r'(K) > 0$) and the cost of refueling (bracketed term).

As a benchmark, we consider the case without range anxiety: $\beta = 0$.

Lemma 1. *If consumers do not experience range anxiety, that is, $\beta = 0$, the optimal quantity of vehicles is positive (because of assumption A1), and each station operates at the minimum efficient scale:*

$$s'(X^*) = C_V(X^*) + C_V'(X^*)X^* + \bar{C}_F \text{ and } K^* = \frac{X^*}{\bar{x}} \tag{9}$$

With Specification 1:

$$X^* = \frac{a - c_0 - \bar{C}_F}{b - 2g} > 0 \text{ and } K^* = \frac{X^*}{\sqrt{2f/c_F}} \tag{10}$$

In that case, refueling stations operate at the minimum efficient scale. The optimal number of stations is the quantity of vehicles divided by the minimum efficient scale. The corresponding average cost of refueling can be incorporated as a linear function of the number of vehicles. This situation may be seen as a limit situation in which K is sufficiently large so that range anxiety disappears.

For positive range anxiety, we can define two functions $X^0(K)$ and $K^0(X)$ as the optimal quantity of vehicles (resp. stations) for a given number of stations (resp. vehicles). The optimum couple then solves $X^* = X^0(K^*)$ and $K^* = K^0(X^*)$, but there might be several solutions to this couple of equations. For any X, the optimal quantity of stations $K^0(X)$

is positive and solves (8). However, if there are too few stations, the optimal quantity of vehicles is 0. With the general model (Appendix (A.1), if $s'(0) - C_V(0) - \bar{C}_F$ is lower than $\beta r(0)$, as implied by our assumptions, there is either no critical points, in which case $(0, 0)$ is the optimal solution, or there are at least two critical points. In the latter case, these critical points alternate between saddle points and local maxima.

With Specification 1, we can obtain results that are more precise but not explicit expressions. For large β, $(0, 0)$ is the only solution of the system of equations. Otherwise, in cases of interest, there are three solutions to this system of equations $(0, 0)$ and two non-negative critical points (X_-^*, K_-^*) and (X_+^*, K_+^*) with $X_-^* < X_+^*$, the first being a saddle point and the second a local maximum (Appendix A.3). The social optimum is then either $(0, 0)$ or (X_+^*, K_+^*).

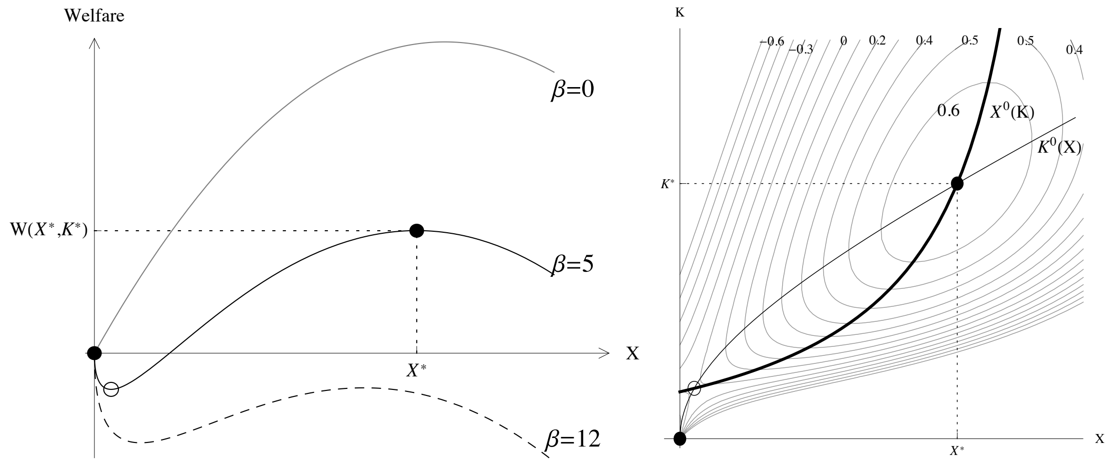
Proposition 1. *With Specification 1, as β increases, the social optimum jumps from (X_+^*, K_+^*) to $(0, 0)$.*

For small β, (X_+^*, K_+^*) is the optimum, and each station operates at a scale lower than the minimum efficient scale, $X^*/K^* < \bar{x}$, and a small increase in the range anxiety factor β induces a decrease in the optimal quantity of vehicles, and an increase in the quantity of stations per vehicle.

Proof in Appendix A.3. This is illustrated in Figure 1. In Figure in 1(a) welfare as a function of X is depicted, with the optimal quantity of refueling stations $K^0(X)$. Different values of β are considered.[9] For $\beta = 0$, welfare is concave, and there is a unique extremum which is a global maximum (Lemma 1). For $\beta = 5$ or 12, there are three local extrema, a minimum at X_-^* (empty circle) and two maxima (full circle): 0 and X_+^*. For $\beta = 5$, the interior maximum is the global optimum, and for $\beta = 12$, the optimum is $(0, 0)$.

In Figure 1(b), the two functions $K^0(X)$ and $X^0(K)$ are plotted together with iso-welfare curves. Figure 1(b) also shows that the intersects of $K^0(X)$ and $X^0(K)$ correspond to the three extrema of the function $W(X, K^0(X))$. Furthermore, the iso-welfare curve shows that the minimum corresponds to a saddle point of $W(X, K)$.

[9] The function depicted is $W(X, K^0(X)) = \max_K W(X, K)$, it is not concave for $\beta > 0$, even though the function $W(X, K)$ is concave with respect to X for any given K.



(a) Welfare with respect to X

(b) Determination of the optimal X and K for $\beta = 5$. The gray lines are iso-welfare curves.

Figure 1: Optimal welfare as a function of the number of vehicles for $a = 3.5$, $c_0 = 1$, $g = 0.1$, $b = 1$, $f = 0.1$, $c_F = 2$ and three values of β: 0 (gray lines), 3 (black plain lines), 12 (dashed lines).

Figure 1 illustrates the discontinuous nature of the optimal solution with respect to parameters, because of the non-concavity of the welfare function. Figure 1 also illustrates the impact of a change of β, but other parameters can also induce a discontinuous shift of the optimum. A continuous increase of the willingness to pay a triggers a jump in the optimal policy. The global optimum cannot be determined through first-order conditions alone and requires the comparison of welfare at the two local maxima.

The multiplicity of extrema and discontinuity of the optimal solution with respect to parameters are both because of range anxiety $\beta X/K$. The following corollary shows that these issues are particularly acute when X is small, and are negligible for large X. The initial development stage of the new technology is when the cost of the complementary network is problematic because the number of stations per vehicle is large. If the willingness to pay for vehicles is large, the costs of refueling become negligible, the situation is similar to a situation with $\beta = 0$.

Corollary 1. *With Specification 1, the range anxiety term $\beta X^*/K^*$ becomes negligible as the willingness to pay "a" increases.*

- *The number of stations per vehicle decreases with respect to a. The size of stations* *increases and converges toward $\bar{x}$, the cost of stations per vehicle converges toward $\bar{C}_F$.*

- *The total utility loss from refueling is bounded and converges toward $\beta\bar{x}$, the range anxiety per vehicle (β/K^*) decreases toward zero.*
- *The welfare loss compared with a situation with $\beta = 0$ converges toward 0:*

$$\frac{(a-\bar{C}_F)^2/2b - W(X^*,K^*)}{(a-\bar{C}_F)^2/2b} \underset{a\to+\infty}{\longrightarrow} 0 \tag{11}$$

Proof in Appendix A.4. When the parameter a is increased toward infinity, assumption A2 is no longer satisfied and scale effects are exhausted: the situation corresponds to $c_0 = g = 0$. A similar result can be obtained with respect to the market size $1/b$, with the slight technical difficulty that for $b < g$, welfare is no longer concave with respect to X for X below c_0/g; however X^* would be larger than this threshold for a sufficiently large market.

3 Market equilibrium

Vehicle producers, referred to as firms, compete à la Cournot, with a fixed number of competitors. Refueling stations, referred to as operators, are price takers, and entry is free. A market equilibrium is then a couple of quantities of vehicles X and stations K, at the intersect of two reaction functions $X^r(K)$ and $K^r(X)$. The reaction function $X^r(K)$ is the aggregate production in which each firm maximizes its profit for a given K, assuming that each other firm plays its equilibrium quantity. The reaction function $K^r(X)$ is the total number of stations for a given X, assuming that the demand for fuel is equally divided among operators and that the total number of operators is such that the profit of an operator is null.

3.1 Refueling station

The market for refueling works as a "textbook" perfectly competitive market. For a given refueling price p_F, a station supplies the quantity x that equalizes price and marginal cost. Its profit is then $p_F x - C_F(x) - f$, and entry is profitable as long as $p_F > \bar{C}_F$.

For a given quantity of vehicles and stations, the refueling price ensures that a quantity X is supplied: $p_F = C_F'(X/K)$. At the free-entry equilibrium, the refueling price is equal to the average cost $\bar{C}_F$, and each station operates at the minimun efficient scale:

$$K^r(X) = \frac{X}{\bar{x}}, \text{ i.e. } C_F'(\frac{X}{K})\frac{X}{K} - C_F(\frac{X}{K}) = f \tag{12}$$

Compared with $K^0(X)$, which solves equation (8), there are fewer stations per vehicle because operators do not internalize the effect of stations on range anxiety.

3.2 Vehicle production

Vehicle producers compete à la Cournot, taking as fixed both the quantity of stations K and the refueling price p_F.[10] Their anticipation of the fuel retail price is fulfilled at the equilibrium so that $p_F = C_F'(X^r(K)/K)$.

The inverse demand function facing these Cournot firms is

$$P_V(X, K, p_F) = \frac{\partial S}{\partial X}(X, K) - p_F = s'(X) - \beta r(K) - p_F \tag{13}$$

The profit of a firm producing X_i and facing a production $X_{-i} = X - X_i$ by the others is

$$\pi_V(X_i, X_{-i}, K, p_F) = [P_V(X_i + X_{-i}, K, p_F) - C_V(X_i + X_{-i})]X_i \tag{14}$$

There are m symmetric Cournot competitors, and under standard assumptions on the price and cost functions there is a unique equilibrium for a given K, which is null for small K.

Lemma 2. *For any quantity of stations K there is a unique equilibrium quantity of vehicles $X^r(K)$, if*

$$[s''(X) - C_V'(X)] + [s'''(X) - C_V''(X)]X < 0 \tag{15}$$

Furthermore,

- *If $K < r^{-1}\Big((s'(0) - C_V(0) - C_F'(0))/\beta\Big)$, no vehicles are produced: $X^r(K) = 0$;*

[10] Another possibility is to assume that vehicle producers anticipate the influence of the number of vehicles on the equilibrium refueling price $p_F = C_F'(X/K)$, exercising their market power as an oligopsony on the refueling market. It would slightly complicate the analysis without adding any relevant insights.

- *If* $K > r^{-1}\Big((s'(0) - C_V(0) - C'_F(0))/\beta\Big)$, X^r *is the unique solution of*

$$s'(X) - \beta r(K) + \left[\frac{s''(X)}{m} + \frac{m-1}{m}C'_V(X)\right]X = C_V(X) + C'_V(X)X + C'_F(X/K) \quad (16)$$

Proof in Appendix B.1. Inequality (15) ensures that each firm reaction function is decreasing with respect to the production it faces, and it is a slight extension of a standard assumption on the price function (see Vives, 2001, chapter 4) to our case with scale effect. It is stronger than the assumption necessary to ensure concavity of profit, because since it requires $P_V(X) - C_V(X)$ to be not too convex. It is satisfied with Specification 1 for which it boils down to $b > g$ which is satisfied from Assumption A2 (in Appendix B.1 Lemma 2 is stated with Specification 1).

Comparing the first-order condition (7) and the Cournot equilibrium equation (16) shows that for any K, the oligopoly production of vehicles is suboptimal because of market power and scale effects. The associated inefficiencies are related to the number of firms and the scale effect, and are null if $C'_V = 0$ and $m = +\infty$. The explicit expression of the solution with Specification 1 is given in the Appendix B1.

3.3 The market equilibria

Combining both reaction functions, $(0, 0)$ is always an equilibrium and at any other equilibrium, the quantity of vehicles solves equation (16) with $K = X/\bar{x}$. Condition (15) is no longer sufficient to ensure uniqueness of a solution to (16) once K is replaced by $K = X/\bar{x}$. Because K increases with X, the marginal revenue of a firm can actually be increasing with respect to its production or the production of its competitor because of the range anxiety term. The vehicle price function P_V can actually be increasing with respect to X, for small X, because of range anxiety.

With Specification 1, a complete characterization is feasible.

Proposition 2. *With Specification 1; there is a unique equilibrium at* $X = 0$ *and* $K = 0$ *if and only if*

$$\beta > \frac{1}{4}\frac{m}{m+1}\frac{(a - c_0 - \bar{C_F})^2}{\bar{x}(b-g)} \quad (17)$$

Otherwise, there are three equilibria each characterized by a quantity of vehicles $X \in \{0, X_-^E, X_+^E\}$*. There is one stable equilibrium at* $X = 0$ *and* $K = 0$ *and another stable equilibrium with* $X = X_+^E > 0$ *and* $K = K_+^E > 0$*, and one unstable equilibrium in between the two stable ones:* $0 < X_-^E < X_+^E$ *and* $0 < K_-^E < K_+^E$*.*

$$X_\pm^E = \frac{m}{m+1}\frac{a - c_0 - \bar{C}_F}{b-g}\left\{\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 4\beta\frac{m+1}{m}\frac{(b-g)\bar{x}}{(a-c_0-\bar{C}_F)^2}}\right\} \text{ and } K_\pm^E = \frac{X_\pm^E}{\bar{x}} \quad (18)$$

Proof in Appendix B.2. Stability is defined with respect to the aggregate reaction functions $X^r(K)$ and $K^r(X)$ so that any tâtonnement process starting close to the equilibrium would converge to the equilibrium, formally it is so if the slope of $K^r(X)$ is lower than the inverse of the slope of $X^r(K)$.

Proposition 2 is illustrated in Figure 2. The two reaction functions are depicted, and the equilibria are at their intersects. The empty circle corresponds to the unstable low equilibrium, and the filled circles to the two stable equilibria. The instability of the X_-^E equilibrium is illustrated by the arrows: a few more refueling stations would trigger a tâtonnement toward the stable large X_+^E equilibrium, and with fewer stations, it would trigger a tâtonnement toward the equilibrium with no vehicle and no station. The unstable X_-^E equilibrium can be interpreted as a "tipping point". The dotted lines described the social optimum, and we observe that both the optimal quantity of vehicles and stations are larger than the equilibrium ones.

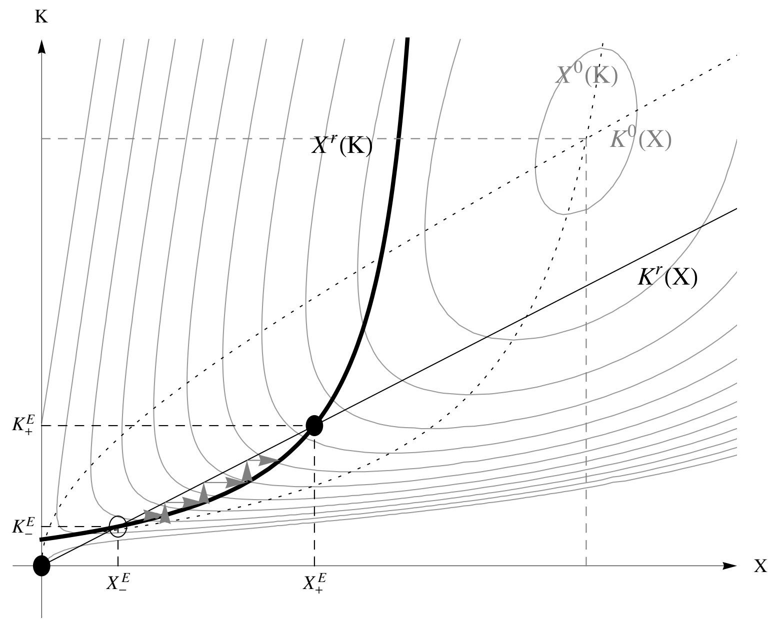


Figure 2: Market reaction functions, equilibria and iso-welfare for the Powering up calibration in Table 6.1

The differences between the market reaction functions and the optimal functions are linked to the three market failures at play: market power, scale effects, and network effects. The adopted modeling approach ensures that all these inefficiencies could be "switched-off" by setting $m = +\infty$, and $c'_V = \beta = 0$, so that a competitive benchmark exists. This competitive benchmark decentralizes the corresponding optimum and no regulation is necessary in that case.

Corollary 2. *For $\beta = 0$, $C'_V = 0$, and $m = +\infty$, there is a unique stable market equilibrium that corresponds to the optimum allocation (X^*, K^*).*

4 Optimal policy

The regulator faces two issues: a possible lock-in at a Pareto dominated equilibrium, and the sub-optimality of vehicle and station quantities even at the Pareto equilibrium. Policies to address these issues are discussed successively.

4.1 Lock-in

A lock-in situation may occur if there are several market equilibria, and the prevailing equilibrium is not the best one. Because the intermediary equilibrium is unstable, it is an unlikely candidate for lock-in, but the market can be locked at the stable $(0, 0)$ equilibrium.

In the present model, it is straightforward to compare market equilibria when several co-exist: The equilibrium with the largest quantities of stations and vehicles Pareto dominates the others. Both consumer surplus and vehicle producer profits are increasing with respect to the quantity of stations, and the profit of refueling stations being null, the following corollary holds.

Corollary 3. *If there are several market equilibria, welfare, consumer surplus, and vehicle producers' profit are larger at the market equilibrium with the largest quantity of vehicles.*

Therefore, we recommend pusking the market toward the large stable equilibrium. To do so, the regulator can invest (directly or indirectly) in $K_-^E + \epsilon$ stations. This would ensure that only the large (X_+^E, K_+^E), Pareto dominating, equilibrium prevails.

More precisely, the optimal policy could be decomposed in two steps: First, cross the tipping point, so that $(0, 0)$ is no longer a stable equilibrium and a unique equilibrium exists. Second, the regulator should set subsidies to realign this market equilibrium with the optimum. Formally, optimal welfare could then be written as

$$W(X^*, K^*) = \underbrace{\left[W(X_+^E, K_+^E) - W(0,0)\right]}_{\text{First step gains}} + \underbrace{\left[W(X^*, K^*) - W(X_+^E, K_+^E)\right]}_{\text{Second step gains}}$$

A worthwhile analysis would be that of the welfare gains associated with each of these two steps. This is not feasible to do so analytically, but a comparative static exercise on consumer willingness to pay could be performed.[11] As the demand for vehicles increases, two of the three sources of inefficiencies vanish: scale effects are fully exploited and range anxiety becomes negligible. The situation is then comparable with a standard Cournot oligopoly in which the relative loss is inversely proportional to the number of competitors (cf Corchón, 2008, for a generalization).

[11] See section 6 for a numerical quantification.

Proposition 3. *With Specification (1); the relative welfare loss between the equilibrium (X_+^E, K_+^E) and the optimum is eventually decreasing with respect to consumers willingness-to-pay "a" and converges toward*

$$\frac{W(X^*,K^*) - W(X_+^E,K_+^E)}{W(X^*,K^*)} \underset{a\to+\infty}{\longrightarrow} \frac{1}{(m+1)^2} \tag{19}$$

4.2 Combined subsidies for infrastructure and vehicles

Suppose the regulator wants to align the market reaction functions to implement the social optimum through combined subsidies on refueling stations (as a subsidy on the capex f) and vehicles (as a rebate on the consumer price). We denote them as s_K and s_V, respectively. The quantity of refueling stations is such that

$$C_F'(\frac{X}{K})\frac{X}{K} - C_F(\frac{X}{K}) = f - s_K \tag{20}$$

the free-entry equilibrium refueling price is lower, and stations operate at a lower scale than without subsidy. The profit of a vehicle producer is

$$\pi_V = [P_V(X_i + X_{-i}, K, p_F) + s_V - C_V(X_i + X_{-i})]X_i$$

in which $P_V(X, K, p_F)$ is given by (13). The oligopoly reaction function $X^r(K, s_V)$ is either null or solves

$$s'(X) - \beta r(K) + \left[\frac{s''}{m} + C_V'\frac{m-1}{m}\right]X + s_V - C_V(X) - C_F'(X/K) = 0 \tag{21}$$

The regulator can select both subsidies to realign the incentives of firms and station operators to achieve the social optimum through market forces.

Proposition 4. *The optimum can be decentralized with a subsidy couple (with first the* *general model and second Specification 1):*

$$s_K^* = -\beta r'(K^*)X^* \qquad\qquad = \frac{\beta X^*}{K^{*2}} \tag{22}$$

$$s_V^* = -s''(X^*)\frac{X^*}{m} - C_V'(X^*)X^*\frac{m-1}{m} \qquad\qquad = (b-g)\frac{X^*}{m} + gX^* \tag{23}$$

Proof. With the two defined subsidies, the optimal quantities X^* and K^* solve the two market equilibrium equations (20) and (21); thus they constitute an equilibrium. □

The three market failures at work justify subsidizing both vehicles and stations. The subsidy on vehicles involves both market power and scale effects. The subsidy on stations only involves range anxiety.

5 Second-Best policies

5.1 Integrated monopoly

We consider an integrated monopoly that both produces vehicles and invests in refueling stations. The monopoly jointly sets the prices of vehicle and refueling, and its total profit is

$$\pi_M(X, K) = [P_V(X, K) + s_V - C_V(X)]X + p_F X + s_K K - (C_F(X/K) + f)K \tag{24}$$

$$= \left[(a - bX) - \frac{\beta}{K} + s_V - C_V(X)\right] X + s_K K - (C_F(\frac{X}{K}) + f)K \tag{25}$$

The firm internalizes the range anxiety cost and optimally chooses the quantity of refueling stations for a given X and without subsidy ($s_K = 0$).[12] The profit-maximizing quantity of vehicles, if positive, solves the equation (21) for $m = 1$.

With an integrated monopoly, only a subsidy on vehicles is necessary to implement the optimum. The derivation of the optimal subsidy follows the same route as in the preceding

[12] The optimality of the choice of K by an integrated monopolist is not general but due to our specifications of $S(X, K)$ in which the marginal surplus from K is linear in X:

$$\frac{\partial S}{\partial K} = X\frac{\partial^2 S}{\partial K \partial X}(= X\frac{\partial P_V}{\partial K})$$

under a more general specification $S(X, K) = s(X) - \beta r(K, X)X$ an integrated monopolist would still under-invest in K under the plausible case of a positive cross derivative of r, and over-invest otherwise.

section.

Proposition 5. *With an integrated monopoly, only a subsidy on vehicles is necessary to implement the optimum,* $s_K = 0$ *and*

$$s_V = -s''(X^*)X^* = bX^* \tag{26}$$

An integrated monopoly is certainly less efficient than an oligopoly with many competitors: ordinarily, the increased market power does not balance the internalization of the network effect. However, an integrated monopoly does outperform a non-integrated monopoly. First, there may be no market equilibrium with a non-integrated monopoly, whereas there may be with an integrated monopoly. Second, in the presence of multiple market equilibria, the integrated monopoly overcomes the lock-in issue. Third, the integrated monopoly outcome outperforms the best market equilibrium.

5.2 Subsidies on either vehicles or infrastructure

We now consider situations in which a subsidy is only available either on vehicles or on refueling stations. The analysis of these incomplete policies has a dual objective: First, these are realistic situations that have been empirically compared in several recent papers; Second, the analysis of a vehicle-only subsidy will clarify the role of indirect network effects.

Consider the implementation of a subsidy on vehicles. The regulator maximizes $W(X, K^r(X))$ with respect to X. An indirect network effect argument appears because

$$\begin{aligned} \frac{\partial W}{\partial X} + \frac{\partial W}{\partial K}\frac{\partial K^r}{\partial X} &= \Big[\frac{\partial S}{\partial X} - C_V - C_V'X - C_F'\Big] + \Big[-\beta r'(K)X + \Big(C_F'\frac{X}{K} - C_F\Big) - f\Big]\frac{1}{\bar{x}} \\ &= \Big[s'(X) - \beta r(\frac{X}{\bar{x}}) - C_V - C_V'X - \bar{C_F}\Big] - \beta r'(\frac{X}{\bar{x}})\frac{X}{\bar{x}} \end{aligned} \tag{27}$$

Indirect network effects are encompassed in the last term. An additional vehicle induces an increase of the quantity of stations inversely proportional to the minimum efficient scale (factor $1/\bar{x}$), and welfare is enhanced because of the unpriced reduction of range anxiety.

Proposition 6. *If the regulator can only subsidize vehicles, the optimal subsidy is*

$$s_V^{SB} = -s''(X^{SB})\frac{X^{SB}}{m} - \frac{m-1}{m}C_V'(X^{SB})X^{SB} - \beta r'(\frac{X^{SB}}{\bar{x}})\frac{X^{SB}}{\bar{x}} \tag{28}$$

$$= (b-g)\frac{X^{SB}}{m} + gX^{SB} + \beta\frac{\bar{x}}{X^{SB}} \qquad \textit{with Specification 1} \tag{29}$$

in which X^{SB} *solves*

$$s'(X) - \beta r(\frac{X}{\bar{x}}) - \beta r'(\frac{X}{\bar{x}})\frac{X}{\bar{x}} = C_V(X) + C_V'(X)X + \bar{C_F}. \tag{30}$$

Proof in Appendix C.1. The optimal subsidy encompasses an additional term compared with the situation in which both subsidies are available (cf equation (23)). This additional term is the unpriced benefit from additional stations triggered by an increase of the fleet. The other terms in equations (28) are similar to the optimal first-best subsidy except that the quantity of vehicles differs. .

The optimal quantity of vehicles in that second-best scenario can be compared with the first-best scenario. . With Specification 1, X^{SB} is equal to the optimal quantity of vehicles when $\beta = 0$, as given in Lemma 1, which is higher than X^*. With $r(K) = 1/K$, range anxiety is proportional to the scale of stations, and this scale is fixed at $\bar{x}$ when stations are not subsidized. Therefore, the total utility loss $\beta X/K$ is fixed and does not influence the optimal choice of X. With a general $r(K)$, the comparison is less straightforward because of two conflicting effects: the indirect network argument pushes for more vehicles, but, the lower quantity of stations per vehicle pushes in the other direction (lower marginal utility from vehicles $W_{XK} \leq 0$). The first effect dominates and X^{SB} is larger than X^* if

$$r''(K)K > -2r'(K)$$

which means that the indirect network benefit $(-r'(K)K)$ decreases at a lower pace than the direct effect of the network on the marginal utility from vehicle $-r(K)$.

Finally, the total subsidy in the two cases–with the two subsidies or only a vehicle subsidy–

can be easily compared with Specification 1. There are two forces that work in the same direction: Because there are more vehicles when only a vehicle subsidy is available, the two first terms in s_V^{SB} are larger than s_V^*, and the additional third term, attributable to network effect, implies a total larger subsidy than the total subsidy for stations in the first-best case:

$$\beta \frac{\bar{x}}{X^{SB}} \times X^{SB} = \beta \bar{x} > \beta \frac{X^*}{K^*} = s_K^* K^*$$

Corollary 4. *With Specification 1; the total subsidy when only a vehicle subsidy is available is larger than the total subsidy when two subsidies are available:*

$$s^{SB} X^{SB} \geq s^* X^* + s_K^* K^*$$

We now suppose that the regulator can only subsidize stations, the optimal second-best subsidy encompasses a term that reflects the benefits of increasing the quantity of vehicles. The influence of stations on the equilibrium quantity of vehicles occurs through two channels: refueling price and range anxiety. Only an implicit equation can be found for the optimal subsidy, and the precise expression and the comparison with the first-best quantity of stations or vehicles are not possible. .

Lemma 3. *With Specification 1, if the regulator can only subsidize refueling stations, the optimal subsidy satisfies the equation:*

$$s_K^{SB} = -\beta r'(K) X + \left[\frac{-s''}{m} - C_V' \frac{m-1}{m} \right] X^r(K) \frac{\partial X^r}{\partial K} \tag{31}$$

$$= \beta \frac{X}{K^2} + \left(\frac{b}{m} + g \frac{m-1}{m} \right) \frac{X}{K^2} \frac{\beta + c_F X}{\frac{m+1}{m}(b-g) + c_F / K} \tag{32}$$

Proof in Appendix C.1.

We observe that with these second-best approaches, the welfare obtained is lower than the optimal welfare. Consequently, there is a range of values of β such that there are no vehicles and stations with a second-best approach whereas there are in the first-best situation.

The last notable result, is a comparison of the impact on the total quantity of vehicles of one euro spent subsidizing stations or vehicles. Such a comparison paves the way for a full-fledged analysis of an optimal policy with costly public funds, and that is a topic for further research.

Proposition 7. *If the inequality (15) is satisfied (it is with Specification 1), one euro spent subsidizing refueling stations has a larger impact on the quantity of vehicles than one euro spent subsidizing vehicles directly.*

Proof in Appendix C.3. The result, which holds with the general model (the inequality (15) is very standard), is proved for small initial subsidy but might not be true for large initial subsidy. A subsidy on vehicles directly affects the supply of vehicles, and a subsidy on stations operates indirectly through both the refueling price and the range anxiety. For a small subsidy, the reduction of the retail price of fuel is equivalent to a subsidy on vehicles, and the reduction of range anxiety explains the larger effect of a subsidy on refueling stations. Interestingly, this result is in line with the empirical analysis of Pavan et al. (2015); Li et al. (2017); Springel (2019).

6 A typology of configurations, its calibration, and policy recommendations

6.1 A typology of configurations and its calibration

Our static model features exogenous parameters related to demand, cost, and market structure. We use the model to explore public policy that is the most suited to a number of configurations. Based on detailed case studies summarized in Appendix D we propose to formalize the deployment of ZEVs through a typology that represents three successive stages of deployment: Takeoff, Powering up, and Cruising. Schematically, the Takeoff stage typically takes place in delimited geographical clusters through demonstration projects supported by local public-private partnerships and joint ventures between manufacturers and energy providers. Then, the coordination among clusters is critical to move to the Powering up stage to cash-in the benefit of learning by doing. Competition should be encouraged, and exclusive deals eliminated, and joint subsidies for infrastructure and vehicles remain necessary. Eventually, subsidies are eliminated, and the carbon tax is sufficient to drive the market forces to allocate the available technologies to the relevant segments, which is what we call the Cruising stage.

Takeoff is characterized by low demand, a high marginal cost of vehicle production with a high scale factor, and a high market concentration. For Powering up, demand is increased, the marginal cost and the scale factor are decreased, and the market concentration increased. At the Cruising stage, demand is high, the marginal cost is again decreased and the scale factor becomes negligible, market concentration is low, and the range anxiety issue is eliminated because of the existence of a large infrastructure. The proposed typology is summarized in Table 1.

Phase	Takeoff	Powering up	Cruising
Structural characteristics	Major risks & high costs Low demand Limited entry	Local clusters Declining costs Private demand emerges Multiple entry	Many competitors and technologies (BEV, PHEV, FCEV, etc.) and modes of transport (public and private transport, car sharing, etc.)
Support policies	Support integration in local clusters with car manufacturer and energy providers Raise social awareness: transport plans in cities direct and indirect incintives (subsidy, carbon tax, traffic restrictions)	Encourage coordination between clusters Active support for infrastructure along corridors Opening up of integrated firms to stimulate entry	Progressive roll-out of financial support policies Introduction of regulation of transport for use of essential facilities and data exploitation

Table 1: A typology of configurations

Ideally, we should elaborate a dynamic model in which the parameters of the model would be endogenized, the players would be forward looking, and the deployment would progress along the three stages. We limit ourselves in this paper to a "structural" static comparative exercise. The three configurations are characterized by different values of the parameters. The calibration aims to capture the qualitative features of each configuration. The corresponding values presented in Table 2. For each configuration, we derive the social optimum, the market equilibria, and the optimal first-best and second-best subsidies. We focus on combining local and global policies for the Powering up stage, to discuss the potential benefit of coordination between clusters.

Parameter	Unit	Takeoff	Powering up	Cruising
a - c_0	€/yr*FCEV	1 500	2 000	5 000
b	€/yr*FCEV^2	0.4	0.2	0.1
g	€/yr*FCEV^2	0.1	0.01	0.005
m		1	2	10
β	€/yr	5 000	5 000	5 000
f	€/yr	50 000	50 000	50 000
c_F	€*S/yr*FCEV^2	0.8	0.8	0.8

Table 2: Calibration of the three configurations

Our model depends on seven parameters. The first five are specific to each configuration and the last four are not. The demand characteristics involve two parameters (a and b). Form Takeoff to Cruising, the willingness to pay a is increased, reflecting a larger acceptability of consumers for ZEVs and a higher price of carbon, and the unit manufacturing cost c_0 can be expected to decline. Because the parameters a and c_0 are substitutes in the model they are considered jointly in the calibration. The parameter b is related to the total size of the vehicle market, and it decreases as this size expands. The production cost of vehicles also depends on the scale factor g, and decreases as the ZEV production increases. The parameter m provides the number of firms in our Cournot model and evolves from a monopoly for Takeoff to intense competition for Cruising. We conduct a sensitivity analysis with respect to market power in each configuration.

Next, we present the parameters which are independent of the configuration. The cost of infrastructure involves the capital expenses of refueling stations (f) and the operational cost (c_F) that induces the capacity constraint. We consider that these costs are not significantly affected by the configuration at hand.[13]

The range anxiety parameter β can be interpreted as the value of time for refueling: it depends on the time to go to the station, eventually on queuing time, and the refueling time as such. This value of time is independent of the configuration.[14]

[13]The standard capacity of a hydrogen retail station is 200 kg/day; assuming that one FCEV needs 1 kg of hydrogen per 100 km and runs 15 000 km per year, such an HRS could deliver H2 to 400 vehicles through 300 operating days per year; the minimum efficient scale corresponding to our numerical values is 353 vehicles. For Cruising, one may consider a higher capacity such as 400 kg/day and adjust the parameters f and c_F accordingly. This would not significantly affect our results because in that case, the size of the market is high; the simulation is available upon request.

[14]For instance, assuming again that a FCEV needs 1 kg of hydrogen per 100 km, has a tank capacity of 8 kg which is refilled when empty at 25%, there would be 25 refills per year; with $K = 20$ and $\beta = 5\ 000$ this

6.2 Social optimum and market equilibria

From the numerical values in Table 2, we derive the social optimum and the market equilibria. The results are reported in Table 3. There is a positive social optimum for each configuration. The situation differs compared with the market equilibria.

For Takeoff, the only market equilibrium is $(0,0)$, whatever the value of m (the threshold value for the existence of a positive equilibirium is $a - c_0 = 3\ 196$, see inequality (17)). Nevertheless, there is a positive integrated monopoly equilibrium (the corresponding threshold value is $a - c_0 = 1\ 311$). The reason to adopt a support policy for an integrated monopoly is that, without it, the relative welfare loss would be 62.8%.

For Powering up, there are two other market equilibria, (X_-^E, K_-^E) and (X_+^E, K_+^E). The equilibria $(0,0)$ and $(X_+^E), K_+^E)$ are stable, and (X_-^E, K_-^E) is not. The equilibrium (X_-^E, K_-^E) is the tipping point. If the tipping point is passed, presumably through some temporary public support, the market will be self sustainable. Nevertheless, it may be worthwhile to continue to support the market because the relative welfare loss of 36.4% remains substantial.

We now consider the Cruising configuration. In this configuration market competition is intense. There are two remaining externalities: the scale effect, but at a low rate because g has been reduced from .01 to .005, and the impact of range anxiety, which is again reduced because we expect a large number of stations (cf footnote 12). We observe that the two market equilibria $((0,0))$ and (X_-^E, K_-^E) are very close to each other. This suggests that there is no need for a support policy to pass the tipping point; moreover, the optimal support policy would only increase the welfare by 2.2%.

6.3 Optimal subsidies and induced transfers

The optimal subsidies and the corresponding transfers are depicted in Tables 4 and 5 respectively. For convenience, the total subsidies are presented in both tables. They correspond to the public support to achieve the social optimum. In Table 4, the total support is decomposed in terms of supports for infrastructure (s_K in €/ station and in % of the fixed cost of a station f) and vehicles (s_V in €/ vehicle and in % of the vehicle price before the

amounts to €10 for each refill, a cost which drops to €2 for $K = 100$.

Scenario	Takeoff	Powering up	Cruising
Social optimum			
X*	5848	9 397	52 395
K*	29	41	165
Welfare (M€/yr)	2.4	6.8	121.9
Oligopoly equilibrium			
m (exogenous)	-	2	10
X_+^E	-	4 707	44 762
K_+^E	-	13	127
Welfare loss (%)	100 %	36.4 %	2.2 %
X_-^E	-	1 318	378
K_-^E	-	4	1
Welfare loss (%)	100 %	45.1 %	99.1 %
Integrated monopoly			
X^m	1 744	4 341	24 796
K^m	14	24	86
Welfare loss (%)	62.8 %	32.7 %	28.1 %

Table 3: Social optimum and market equilibria

rebate).The relative % of support for infrastructure and vehicles are provided.[15] In Table 5, it is decomposed in terms of transfers. In this partial equilibrium analysis, we use the following identity (the industry profit for infrastructure is null):

$$\Delta(\mathbf{W}) = \Delta(\textbf{Consumer Surplus}) + \Delta(\textbf{Industry Profit for Cars}) - (\textbf{Total Subsidies})$$

For each configuration and either for an oligopoly or an integrated monopoly, the total support (from tax payers) is equal to the increased profit for vehicle manufacturers plus the increased consumer surplus accruing to the limited segment of adopters of ZEVs minus the increased welfare. Table 5 presents this decomposition, and the relative changes for each item, when moving from the market equilibrium to the social optimum.

For Takeoff, we compare a policy targeting the social optimum either through an integrated or non-integrated monopoly. Notably, the the absolute price rebates on vehicles, s_V, are identical by construction, namely, 2 339 €/ vehicle, and the difference in % (35% versus 34%) is from the following: With a non-integrated monopoly, the refueling cost is not

[15]Tietge et al. (2016) provides orders of magnitude for the incentive for vehicle in a number of European markets: ranging from 30 to 50 % which is higher than the values reported here for the combined optimal subsidies.

internalized, but the total costs of ownership are identical. The total public support is lower for the integrated monopoly because the firm internalizes the range anxiety and there is no need to subsidize infrastructure, and it amounts to 68% of the fixed cost of a station in the case of a non-integrated monopoly. There is an indirect benefit of subsidizing an integrated monopoly. If public support disappears, the integrated monopoly is sustainable. Once the configuration reaches Powering up, the integration could be dismantled, the tipping point is passed, and the market converges to the Pareto optimum equilibrium.

We now consider Powering up. On the one hand, clearly, subsidizing an integrated monopoly becomes costly (17.7 versus 10.4 M€/yr); thus, such a policy should only be encouraged for Takeoff. On the other hand, subsidizing infrastructure remains essential to achieve the social optimum (57% of the fixed cost of a station f), even if it represents a small percentage of total subsidies (11%). For Cruising, the budget increases to 41.4 M€/yr, an amount not justified by the increased utility (only 15%). Subsidizing vehicles as the market expands becomes prohibitive.

For all configurations, the tax payers' money is mostly allocated to increases in profit and consumer surplus for adopters, rather than to the utility. The figures in % emphasizes this remark. This highlights the regressive feature of such policies. If the tax payers' money is from a carbon tax, essentially from low and middle-income rural and peri-urban populations that cannot adopt the new technology, the regressivity may become a sensitive political concern.

The results of this section (Table 4 and 5) and the preceding section (Table 3) allow us to discuss the relative benefits of a two-step policy, as detailed in section 4.1. In Powering up, we start at the $(0, 0)$ market equilibrium. The first step, cross the tipping point ($X_-^E = 1318, K_-^E = 4$), comprises subsidizing $4 + 1 = 5$ stations, which means a budget of $5 * f =$ 236 340 €/yr. The market would then spontaneously move to the stable equilibrium ($X_+^E = 4707, K_+^E = 13$), climbing the welfare mountain 100-36.4=63.6% up to its summit. In a second step, the regulator sets the optimal subsidies to realign this market equilibrium with the optimum, and climbs the remaining 36.4% for an additional budget, which we estimate to be approximately 5.4 M€/yr (assuming that the second step financing may be limited to extensions from the existing market equilibrium). In view of the respective budgets,

Scenario	Takeoff	Powering up	Cruising
Combined subsidies			
s_K (€/ station)	34 063	28 453	9631
in % of f	68 %	57 %	19 %
in % of total subsidies	7 %	11 %	4 %
s_V (€/ vehicle)	2 339	987	760
in % of vehicle price	35 %	16 %	23 %
in % of total subsidies	93 %	89 %	96 %
Total subsidies (M€/yr)	14.7	10.4	41.4
Integrated monopoly subsidies			
s_V (€/ vehicle)	2 339	1 879	5 239
in % of vehicle price	34 %	27 %	66 %
Total subsidies (M€/yr)	13.7	17.7	274.5

Table 4: Optimal subsidies

this suggests that a two-step policy is efficient (approximately 5.4 versus 10.4 M€/yr). This provides a notable argument for the involvement of the regulator into demonstration projects through financing infrastructure. Such a two-step policy could not be implemented for Takeoff because in such a configuration, no positive market equilibrium prevails.

Scenario	Takeoff	Powering up	Cruising
Combined subsidies			
Tax payers (M€/yr)	- 14.7	- 10.4	- 41.4
Increase in profit (M€/yr)	10.3	6.3	7.0
(in %)	-	298 %	37 %
Increase for adopters (M€/yr)	6.8	6.6	37.1
(in %)	-	298 %	37 %
Increase of welfare (M€/yr)	2.42	2.47	2.73
(in %)	-	57 %	15 %
Integrated monopoly			
Tax payers (M€/yr)	-13.7	-17.7	-274.5
Increase in profit (M€/yr)	8.97	12.9	202.2
(in %)	3 053 %	482%	355 %
Increase for adopters (M€/yr)	6.2	7.0	106.5
(in %)	1 025 %	369 %	346 %
Increase of welfare (M€/yr)	1.52	2.2	34.2
(in %)	169 %	49 %	39 %

Table 5: Analysis of transfers

6.4 Relative benefit of subsidies on infrastructure or on vehicles

Our model can be used to compare the relative benefit of subsidies either on infrastructure or on vehicles, depending on the configuration under study. We leave aside Cruising as irrelevant because as shown in the previous section, subsidies should be eliminated per se.

Our discussion is based on the numerical results detailed in Table 6. From section ,5 we may derive the optimal second-best subsidies (columns 1 and 3). For Takeoff and Powering up, unilateral subsidies are sufficient to generate a market equilibrium, but in either case, there remains a substantial welfare loss relative to combined subsidies (which achieve the social optimum). The welfare loss is higher with subsidies for infrastructure than for vehicles, but the budgets for infrastructure are much lower than for vehicles. Table 6 also shows that the percentage increase in units of vehicles relative to the market equilibrium (if strictly positive) is higher for vehicles than infrastructure subsidies (column 3).

Columns 2 and 4 of Table 6 take a perspective more in line with empirical studies, and illustrate Proposition 7. On the one hand, we suppose the regulator wants to generate a market equilibrium at the minimal cost for Takeoff. Column 2 presents the minimal budgets (5.1 M€/yr and .4 M€/yr) with vehicle and infrastructure subsidies, respectively. On the other hand, we suppose the regulator considers spending the same budget either through vehicles or infrastructure for Powering up. Column 4 gives the achieved market sizes (29% and 37% respectively) with an identical budget (2.9 M€/yr). From these points of view, infrastructure subsidies appear more appealing.

6.5 Benefit of combining local and global policies

Thus far, we have implicitly considered a cluster in isolation. However, the two phenomena of range anxiety and scale effects occur within different spatial scales. Consumers travel within local areas, towns, or regions. vehicle manufacturers are international companies that supply vehicles worldwide.[16] Range anxiety is a local phenomenon, and scale effect is a global phenomenon. In this section, a simple extension of the model is used to explicitly explore this important empirical issue.

[16] Figenbaum (2016) describes the role of foreign vehicle manufacturers at the different stages of the deployment of BEVs in Norway.

Scenario	Takeoff Second best	Takeoff with budget min	Powering up Second best	Powering up with equal budget
vehicles only				
X_+^E	6 086	1 740	9 540	6 053
K_+^E	17	5	27	17
s_V (€/ vehicle)	2 725	843	1 187	300
in % of vehicle price	41%	14%	20%	5%
Total subsidies (M€/yr)	16.6	5.1	11.3	2.9
Welfare loss (%)	20.1%	98%	5.4%	22%
Increase in X (%)	NC	NC	103%	29%
Infrastructure only				
X_+^E	1 942	1 419	6 062	6 448
K_+^E	20	9	13	63
s_K (€/ station)	46 064	41 000	38 766	45 750
in % of f	92%	82%	78%	92%
Total subsidies (M€/yr)	.9	.4	1.4	2.9
Welfare loss (%)	59.4%	82%	15.1%	23%
Increase in X (%)	NC	NC	29%	37%

Table 6: Comparison of subsidies on vehicles or infrastructure

We consider two identical clusters in the Powering up configuration, and two extreme cases: Autarky and Global. Autarky corresponds to the analysis conducted thus far, and each cluster is in isolation with $m = 2$ local vehicle manufacturers and local scale effects. In Global, the $2 \times m = 4$ vehicle manufacturers sell in the two clusters, and scale effects are global. The quantity of vehicles in an individual cluster is denoted as X, and the quantity of stations as K.

The scenario Global is obtained with a simple change of parameter values. For the social optimum, the two countries coordinate and maximize joint welfare. The optimal quantities of X and K are equal to the optimal quantities with a single cluster and a scale parameter $2g$. For the market equilibrium, four manufacturers are competing on each cluster, and the equilibrium quantity of vehicles on each cluster is provided by equation (18), replacing g by $2g$ and m by $2m$. The subsidies are derived accordingly.[17] Altogether, we obtain Table 7.

The benefit of going from Autarky to Global is spectacular. First, we consider how the market equilibrium is affected: the market size increases from 4 707 to 6 405 units: increased

[17]An equivalent means to obtain Global is to consider total quantities X_G and K_G instead of local ones. The global quantities are equal to the single cluster ones with a double market size (b is replaced by $2b$), a doubled range anxiety (β replaced by 2β) and twice as many competitors (m replaced by $2m$).

competition generates more volume, which decreases unit cost through the scale effect; the welfare loss relative to the first-best is reduced from 36% to 24%. We now consider the impact on the optimal policy: the welfare for each country increases by 14.6% (from 6.4 to 7.8 M€/yr), and the total subsidies is reduced by 21% (from 10.4 to 8.3 M€/yr) which means a decrease in the subsidy by car of 29%! The benefits of increased competition reduce the subsidy cost to achieve a higher social optimum.

This analysis provides notable guidelines for public policy. For instance, we consider the context of the European Union (EU). Each EU country may design its support policy based on its national suppliers, or a global EU policy could encourage competition among national suppliers combined with a support policy directly designed at the EU level. Meunier et al. (2019) evaluate the Joint Initiative for hydrogen Vehicles across Europe (JIVE) for the case of fuel cell electric buses.

Another analysis worth pursuing is formal, in a setting with non-identical clusters. The gains from coordination might then be unequally distributed. If asymmetry with respect to production costs was introduced, the impact of coordination on the survival of inefficient firms would introduce industrial policy considerations among clusters.

Scenario Powering up	Autarky	Global
Social optimum		
X^*	9 397	10 441
K^*	41	44
Welfare (M€/yr)	6.4	7.8
Market equilibrium		
m (exogenous)	2	4
X^r	4 707	6 405
K^r	13	18
Welfare loss	36 %	24 %
Optimal policy		
s_K (€/ station)	28 543	27 244
s_V (€/ car)	987	679
Total subsidies per country (M€/yr)	10.4	8.3

Table 7: Benefit of going from Autarky to Global

7 Discussion, caveats, and extensions

Several important features of the transportation sector and electric mobility have not been considered in our model.

7.1 Environmental externality

We do not explicitly model environmental benefits from electric mobility, which amounts to implicitly assuming that the corresponding externalities are priced at the Pigouvian level and influence the demand for ZEVs. However, in many countries negative externalities from fossil fuel vehicles are unpriced (e.g., CO_2 emissions, local air pollution), which can justify to subsidies for electric mobility. A simple extension of our model would add an external benefit function, increasing and concave with the number of electric vehicles; then, the optimal subsidy would have an additional component equal to the marginal external benefit.

In our numerical exercise, the environmental benefits from electric vehicles are encompassed in the demand function, and in the configurations considered, the increase in the demand for electric mobility is partly caused by the increase in the social cost of carbon along a decarbonization trajectory. Making explicit a discrepancy between private and social benefits would lead to a smaller private demand and a larger subsidy, a transfer from the parameter a to the optimal subsidy.

The social benefits from electric vehicles have been questioned along two lines: First, several studies have stressed that the pollution associated with battery and power production reduces, or even cancels, its environmental benefits (Tessum et al., 2014; Archsmith et al., 2015; Bento et al., 2014). Holland et al. (2016) estimate the optimal local electric vehicle subsidy in US states considering these upstream externalities.[18] Second, an electric vehicle is not a perfect substitute for an average fossil fuel vehicle (Davis, 2019; Xing et al., 2019).

A more demanding extension would then explicitly model the interaction between fossil fuel and electric vehicles, and consider the possibility to tax polluting emissions from gasoline vehicles. Such an extension would naturally raise the issue of the strategy of vehicle producers

[18]Bento et al. (2014) analyze the consequences of an indirect subsidy: allowing electric vehicles preferential access to high-occupancy lanes in California. They estimate the negative impact of this measure due to increased congestion in these lanes.

typically engaged in multiproduct competition. Notably, Holland et al. (2016) implicitly assume perfect competition in the vehicle market when computing the optimal subsidy for electric vehicles.

7.2 Competition in the vehicle market

We model imperfect competition in the electric vehicle market as Cournot with an exogenously fixed number of competitors. We consider this model as a stylized representation of market power, and the number of competitors is a proxy for the intensity of competition. The optimal subsidy encompasses a term to correct for the underprovision of vehicles because of market power exercise. Several extensions are discussed: First, other model of imperfect competition are worth considering. Second, the decision to enter the market could be modeled to have an endogenous market structure. And third, in line with the empirical literature on the transportation sector, the vehicle sector would be best modeled as an oligopoly of multiproduct firms with endogenous product characteristics.

First, concerning the robustness of our results with respect to the mode of competition, the case of Bertrand competition among firms with each offering one variety is sketched in Appendix E.1. The optimal subsidy satisfies a formula analogous to (23), with additional factors representing the mode of competition and substitution patterns. The market power correcting component, $-S''(X^*)X^*/m$, is reduced with price competition (the residual demand being more elastic). The scale effect component, $-gC'(X^*)X^*(m-1)/m$ is increased because each firm considers the reduction of rival production with respect to its own production.

Second, with a homogeneous good and Cournot competition, the free entry equilibrium number of firms is larger than the welfare-maximizing number (Mankiw and Whinston, 1986; Suzumura and Kiyono, 1987; Suzumura, 2012). This result persist with endogenous (cost reducing) sunk costs. Therefore, if we simply add a fixed entry cost and endogenize the number of vehicle producers m (still assuming price taking behavior on the refueling station level), the optimal policy should be augmented with an entry tax, which could be implemented through licenses (to market an electric vehicle). With imperfect substitution among varieties (one firm corresponds to one variety), entry can be insufficient because firms do not consider the benefit for consumers of increased variety.[19]

Third, several empirical papers have estimated models of the automobile market based on product characteristics and differentiation (Berry et al., 1995; Petrin, 2002). Wollmann (2018) extends the empirical analysis by considering an endogenous set of vehicles offered by a fixed number of competitors. Wollmann (2018) does not analyze the optimal regulation of such a sector, and some simplification would be necessary to allow for a tractable analysis.[20] For the problem we examine, it would be particularly notable to introduce heterogeneity with respect to the valuation of network density ($\beta r(K)$ in our model).[21]

7.3 Competition on the retail market

In the retail market, we assume perfect competition (price-taking behavior) and decreasing returns to scale. This is one of the key differences between our model and the models of Greaker and Heggedal (2010) and Zhou and Li (2018), which both consider imperfect competition and a constant marginal cost of refueling (they also consider perfect competition on the vehicle market while we assume imperfect competition).[22]

Neither Greaker and Heggedal (2010) nor Zhou and Li (2018) analyze the optimal policy as we do, and the assumption of imperfect competition on the refueling market does not modify the issue of lock-in and the need to overcome the tipping-point, but it modifies the optimal subsidy scheme. In theory, entry is excessive in many common models of differentiated goods (footnote 19), and notably, the model used by Greaker and Heggedal (2010). In Appendix E.2, we reproduce the model of refueling of Greaker and Heggedal (2010) with

[19] Insufficient entry can arise if the elasticity of substitution is not constant. With a Constant Elasticity of Substitution utility function, both Cournot and Bertrand competition leads to excessive entry, and monopolistic competition leads to the optimal number of firms (Etro, 2014). Monopolistic competition has received a lot of scrutiny since the seminal work of Spence (1976) and Dixit and Stiglitz (1977), and Zhelobodko et al. (2012) is a recent contribution.

[20] The few articles, that we are aware of, that analyze endogenous market structure with multiproduct firms (Anderson and De Palma, 2006; Ottaviano and Thisse, 2011; Caminal and Granero, 2012) have not considered the choice of product characteristics.

[21] Heterogeneity with respect to the range effect β could account for the difference between short-distance urban trips and long-distance inter-city trips. For the former (e.g. commuters, taxis), the density of the network of refueling stations is less problematic than for the latter.

[22] Greaker and Heggedal (2010) consider price competition along a Salop's Circle, while Zhou and Li (2018) consider a general specification, inspired by Gandal et al. (2000), in which the price-cost margin is a function of the number of stations.

the convex refueling cost in our framework. With that model, there is an excessive entry of stations for a given quantity of vehicles, and a too-high refueling price, which would further reduce the equilibrium quantity of vehicles.[23] The policy consequences would be to subsidize fuel and control the entry of stations, once the lock-in issue is managed; or set a price cap on fuel and subsidize stations.

We think that it is methodologically sound to first model competition in the retail market as pure and perfect with capacity constraints. We consider that our model is better suited for a normative analysis for two reasons: First, in their models there are two intertwined market failures on the refueling market (market power and scale economies) that mask the specific market failure associated with the refueling network. Second, the capacity constraint of refueling stations is a realistic and important feature of the design of a network of refueling stations.[24]

However, there is empirical evidence of market power in retail gasoline markets (see Remer, 2019, for a recent contribution), and this may also be the case for refueling stations. Several issues despite location are likely to play a role such as ability to park, charging technology, and affiliation to retail stores, energy comparnies or car producers. Extensions of our model would be worth exploring in these directions.

7.4 Dynamic issues

As a starting point for this discussion, our model is worth comparing with Zhou and Li (2018). Zhou and Li (2018) elaborate a dynamic model, but their discussion focuses on the steady states, which could be compared with our market equilibria. There are three possible cases: (i) no positive equilibrium, (ii) a critical mass case with three equilibria of which two are stable, and (iii) a case with only one stable equilibrium. Their dynamic model is actually close to our static model with a tâtonnement process because they do not model the evolution of the demand (social cost of carbon), costs, or competition in the vehicle market.

[23]Ghosh and Morita (2007) shows that entry could be insufficient in an upstream industry if the downstream industry is uncompetitive.

[24]A google search of "Charge rage" should convince the reader. For instance *'Charge Rage'– electric car owners get angry after having vehicles unplugged* (The Telegraph 23 Jan 2014) https://www.telegraph.co.uk/news/worldnews/northamerica/usa/10592660/Charge-Rage-electric-car-owners-get-angry-after-having-vehicles-unplugged.html .

A more satisfying and demanding dynamic model would incorporate the evolution of demand and cost and forward-looking players. A notable ingredient would be to consider multiple local markets, for instance, several cities or market segments (households, taxis, trucks), to analyze the progressive diffusion of ZEVs from one market to the other. Further research could explore the optimal design of a dynamic public policy contingent on the characteristics of each spatial area, inducing coordination among the largest ones to achieve a high volume to reduce the cost and then encouraging smaller ones. Such analysis would extend and nicely complement the empirical findings of Zhou and Li (2018), who argue that a uniform policy (identical s_v for all cities) is dominated by a discriminatory subsidy targeting cities constrained by a critical-mass. The analysis would also extend the theoretical analysis of Bramoullé and Olson (2005) on the optimal allocation of abatement among two options subject to learning-by-doing, by considering interactions between options (cities in our case).

Several other features could be incorporated in a more complete dynamic model: early movers versus mainstream consumers, differentiated products, endogenous choice of vehicle characteristics by strategic producers, and a more precise description of the structure of the refueling network (urban vs inter-city). Particular attention should be given to the competition between battery and hydrogen technologies and their respective competitive advantages on the different market segments (commuting, long-distance, light and heavy-duty vehicles, collective transport through taxis, and buses). Such a large dynamic model can only be properly managed through simulations. In this respect our model is a useful complement to such complex models as developed by Harrison (2014). Our static model, despite its limitations, allows an evaluation of the relative importance of the market failures at the various stages of deployment, which may be of interest in designing a more exhaustive model.

8 Conclusion

In this paper, we formalize the interaction between three important features in the deployment of zero emission vehicles: indirect network effects; scale effects, which incorporate learning by doing and spillovers; and imperfect competition among vehicle producers. Indirect network effects are from the deployment of refueling stations and are associated with a market failure because of an unpriced benefit for consumers from refueling stations. The more stations there are, the lower the cost to search for and reach a station.

Ordinarily, there are three critical points (two maxima and a saddle point) and three market equilibria; thus, there is a possibility of lock-in and a tipping point. Next, we focus on the Pareto dominating equilibrium and derive the optimal subsidies to achieve the social optimum through market forces. We also examine two other schemes: one in which an integrated monopoly jointly operates the infrastructure and the manufacturing of vehicles, and another in which only vehicle rebates or infrastructure subsidies would be used. This analysis points out the superiority of jointly subsidizing stations and vehicles. Allowing for an integrated monopoly can only be justified at the very early phase of deployment because competition in the vehicle market is a key factor for the expansion phase of the deployment.

We calibrate our model and perform a numerical analysis of three archetypal configurations–Takeoff, Powering up and Cruising–which correspond to the successive phases of deployment. For example, we find that a subsidy of approximately 68% of the fixed capital cost of a station and a rebate of approximately 35% on the listed price of vehicles in the Takeoff stage would be necessary to induce the social optimum through market forces. The level of the infrastructure subsidy would gradually decline as the market develops to a Powering up configuration. The vehicle rebates depend on two factors: degree of competition and scale effect. All subsidies disappear in Cruising. Empirical observations are revisited in the context of our model and provide ground for justifying second best policies focused on favoring subsidies for infrastructure. They also highlight the observed empirical benefit of integration at the Takeoff stage, as observed by the joint venture between fuel providers and vehicle manufacturers for FECV, in Paris for taxis. Similarly, the integration of manufacturing and operation of electric chargers, such as exemplified by Tesla, appeared a key factor at the early stage of deployment of BEV, and is now followed by other vehicle manufacturers.

A simple extension of the model is provided to enhance the benefit of coordinating policies across regions: Although network effects are mostly regional, scale effect and market structure are better analyzed at more global levels. This idea is worth exploring further in parallel with the multiplication of regional clusters for the deployment of hydrogen mobility.

This model attempts to bridge the gap between conceptual analysis and discussions of scenarios elaborated from complex numerical models. We posit that this approach could be applied to other forms of green transportation, for example, buses, trucks, and autonomous vehicle, and possibly to startups' deployments (startups incubators) or rehabilitation of town centers, all of which benefit of pooling resources, to highlight the interaction between indirect local network effect and more global scale effect.

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Appendix

A Optimum

A.1 General model

Partial derivatives are denoted with indices for functions with multiple arguments. In order to ease the presentation some additional notations should be introduced to isolate both range anxiety and the refueling cost, let us define

$$\phi(X) =_{def} s(X) - C_V(X)X \tag{33}$$

so that $W(X, K, \beta) = \phi(X) - [f + c_F(X/K)]K - \beta r(K)X$. We assume that $\phi''(X) < 0$, and $\phi'(X) = 0$ for some positive X.

Result: The welfare function is not concave for $\beta > 0$ if

$$\lim_{X->0} s''(X) - C'_V(X)X - C''_V(X)X > -\infty. \tag{34}$$

The condition (34) means that $\phi''(0) > -\infty$. Some calculations gives the following relationships between second order derivatives:

$$W_{XX} = \phi'' - C''_F \frac{1}{K} \tag{35}$$

$$W_{KK} = -C''_F . \frac{X^2}{K^3} - \beta r''(K)X \tag{36}$$

$$W_{XK} = C''_F . \frac{X}{K^2} - \beta r'(K) \tag{37}$$

then both $W_{XX} < 0$ and $W_{KK} < 0$ and the Hessian is

$$H(X,K,\beta) = W_{XX}W_{KK} - W_{XK}^2 = -\phi'' C_F'' \frac{X^2}{K^4} - \beta \left[\beta r'^2 + \phi'' r'' X - C_F'' \frac{X}{K^2} \big(2r' + r'' K \big) \right] \tag{38}$$

For $\beta = 0$ the Hessian is negative for all $X, K > 0$. However, for all $K > 0$, thanks to Condition (34) $\lim_{X->0} H(X,K,\beta) = -\beta^2 r'(K)^2 < 0$. Note that if $\phi''(0) = -\infty$ it is possible that the Hessian stay positive for all β.

Result: There are zero or more than two critical points if $\phi'(0) - \bar{C_F} < \beta r(0)$ (which is true if Condition (34) holds).

We proceed in several steps.

i) For all $X > 0$ there is a unique positive solution of equation (8): The left-hand side is strictly decreasing with respect to K, it is larger than f for $K = X/\bar{x}$ and lower than f for large K. Therefore, since $W_{KK} < 0$, $K^0(X)$ is this unique positive solution (it is not null).

ii) $K^0(X)$ is larger than $X/\bar{x}$ because $C_F'(\bar{x})\bar{x} - C_F(\bar{x}) = f$

iii) $\lim_{X->0} K^0(X) = 0$: by contradiction otherwise there is a $\underline{K}$ such that $K^0(X) \geq \underline{K}$ for all X. Then, for all X

$$f = -\beta r'(K^0)X + \left[C_F' \left(\frac{X}{K} \right) \frac{X}{K^0} - C_F \left(\frac{X}{K^0} \right) \right] < -\beta r'(\underline{K})X + \left[C_F' \left(\frac{X}{K} \right) \frac{X}{\underline{K}} - C_F \left(\frac{X}{\underline{K}} \right) \right]$$

the right-hand side converges toward zero when X converges toward zero. A contradiction.

After those preliminaries, we can analyze $W(X, K^0(X), \beta)$. We already know that the second order derivative of this function with respect to X is not negative everywhere, it is positive for small X (since H is negative). To establish the multiplicity of critical points we need a stronger result, we would like to show that this function is decreasing for small X.

Its derivative with respect to X is :

$$W_X(X, K^0(X), \beta) = \phi'(X) - C_F'(\frac{X}{K^0(X)}) - \beta r(K^0(X))$$

And from ii) $K > X/\bar{x}$, so that

$$W_X(X, K^0(X), \beta) < \phi'(X) - C_F'(\bar{x}) - \beta r(K^0)$$

and for small X it is negative if $\phi'(0) - \bar{C_F} < \beta r(0)$.

A.2 Specification

With Specification (1), the derivatives of welfare are:

$$W_X = a - bX - \frac{\beta}{K} - (c_0 - 2gX) - c_F \frac{X}{K} = \left[a - c_0 - \frac{\beta}{K}\right] - \left[b - 2g + \frac{c_F}{K}\right] X \tag{39}$$

$$W_K = \frac{\beta X}{K^2} + \frac{c_F}{2} \frac{X^2}{K^2} - f = \frac{1}{K^2}\left[\beta X + \frac{c_F}{2} X^2\right] - f \tag{40}$$

Second order derivatives and the hessian are:

$$W_{XX} = -\left(b - 2g + \frac{c_F}{K}\right);\ W_{KK} = -\frac{2}{K^3}\left[\beta X + \frac{c_F}{2} X^2\right];\ W_{XK} = \frac{1}{K^2}(\beta + c_F X) \tag{41}$$

$$H = W_{XX} W_{KK} - W_{XK}^2 = (b - 2g) c_F \frac{X^2}{K^3} - \beta\left[\frac{\beta}{K^4} - 2(b - 2g)\frac{X}{K^3}\right]. \tag{42}$$

A.3 Proof Proposition 1

Proof of Lemma 1

For $\beta = 0$, welfare is concave for $X, K > 0$. There is a unique local maximum that solves the two equations (7) and (8). The optimal K as a function of X solves (8) that is $X/K = \bar{x}$ then plugging it into equation (7) completes the proof. It is as if the refueling cost was linear with respect to the quantity of fuel $\bar{C}_F.X$.

Proof of Proposition 1

All calcualtions are done with the Specification (1).

Result 1: For small β the optimum is positive: $(X^*, K^*) \in \mathbb{R}^2_{>0}$.

Proof. By continuity: $W(X^*(\beta = 0), K^*(\beta = 0), \beta = 0) > 0$ so that for small β, $W(X^*(\beta = 0), K^*(\beta = 0), \beta) > 0 = W(0, 0, \beta)$. □

Equation (8) gives the optimal quantity of stations for a given quantity of vehicles:

$$K^0(X) = X\left[\frac{1}{f}\left(\frac{\beta}{X} + \frac{c_F}{2}\right)\right]^{1/2} = \frac{X}{\bar{x}}\left[1 + \frac{2\beta}{c_F X}\right]^{1/2}. \tag{43}$$

And for small enough K, X^0 is lower than c_0/g and given by :

$$X^0(K) = \max\left\{\frac{a - c_0 - \beta/K}{b - 2g + c_F/K}, 0\right\}. \tag{44}$$

Define $K^1(X)$ the inverse of $X^0(K)$ given by eq. 44:

$$K^1(X) = \frac{\beta + c_F X}{(a - c_0) - (b - 2g)X} \tag{45}$$

It is well defined for $X < (a - c_0)/(b - 2g) =_{def} \bar{X}$. These functions are such that $W_X(X, K^1(X)) = 0$ and $W_K(X, K^0(K)) = 0$.

Result 2: Two situations can arise: either for all $X \in (0, \bar{X})$ $K^1(X) > K^0(X)$ or there are two solutions $X_- < X_+$ to the equation $K^1(X) = K^0(X)$.

Proof. • $K^1(0) > K^0(0)$ and $K^1(X) > K^0(X)$ for X sufficiently close to $\bar{X}$.

• The derivatives of K^1 and K^0 are:

$$K^{0\prime} = \frac{1}{2\sqrt{f}} \frac{\beta + c_F X}{\sqrt{\beta X + c_F X^2/2}} \text{ and } K^{1\prime} = \frac{c_F(a - c_0) + (b - 2g)\beta}{[(a - c_0) - (b - 2g)X]^2}$$
$$K^{0\prime\prime} = -\frac{\beta^2}{4\sqrt{f}} \left[\beta X + \frac{c_F}{2} X^2\right]^{-3/2} \text{ and } K^{1\prime\prime} = 2(b - 2g)\frac{c_F(a - c_0) + (b - 2g)\beta}{[(a - c_0) - (b - 2g)X]^3}$$

The difference $K^1(X) - K^0(X)$ is convex. Its derivative is increasing, first negative (since $K^{0\prime}(0) = +\infty$) and eventually positive (since $K^{1\prime}(\bar{X}) = +\infty$). Therefore, either $K^1 - K^0 > 0\ \forall X \in (0, \bar{X})$, or there are two roots X_- and X_+ to the equation $K^1 = K^0$ with $0 < X_- \leq X_+ < \bar{X}$. □

Each root $X_\pm$ cancels the derivative of the function $W(X, K^0(X))$ and is a local extremum and associated with a singular point of $W(X, K)$. At the lowest root, $K^1 - K^0$ is decreasing so that $W_{XX}W_{KK} < W_{XK}^2$ and X_- is a local minimum of $W(X, K^0(X))$, and $(X_-, K_0(X_-))$ a saddle point of $W(X, K)$. At X_+, the function is increasing $W_{XX}W_{KK} > W_{XK}^2$ and X_+ is a local maximum.

Combine Results 1 and 2 to get that for small β there are two local maxima (one at $(0, 0)$ the other positive) and a local minimum. For large β there is a unique maximum at $(0, 0)$.

When there are two local maxima, the positive local maximum is the global maximum if and only if β is sufficiently small, otherwise the maximum is at $(0,0)$.

Impact of β:

In matrix form:

$$\begin{bmatrix} W_{XX} & W_{XK} \\ W_{XK} & W_{KK} \end{bmatrix} \begin{bmatrix} X_\beta \\ K_\beta \end{bmatrix} = \begin{bmatrix} -W_{X\beta} \\ -W_{K\beta} \end{bmatrix} \tag{46}$$

therefore, with H define by eq. (42):

$$\begin{bmatrix} X_\beta \\ K_\beta \end{bmatrix} = \frac{1}{H} \begin{bmatrix} -W_{KK}W_{X\beta} + W_{XK}W_{K\beta} \\ -W_{XX}W_{K\beta} + W_{XK}W_{X\beta} \end{bmatrix} = \frac{1}{H} \begin{bmatrix} -\beta X^*/K^{*4} \\ \left(X^*(b-2g) - \beta/K^*\right)/K^{*2} \end{bmatrix} \tag{47}$$

So X is strictly decreasing with respect to β. And the quantity of stations per vehicle is

$$\frac{K^*}{X^*} = \left[\frac{1}{f}\left(\frac{c_F}{2} + \frac{\beta}{X^*}\right)\right]^{1/2}$$

which is strictly increasing with respect to β since $X^*(\beta)$ is decreasing.

A.4 Proof of Corollary 1

Impact of a

Welfare at the positive local maximum is increasing with respect to a, so the positive local maximum is the global maximum for large a.

Again, using the matrix form, the derivatives of optimum quantities with respect to a are:

$$\begin{bmatrix} X_a^* \\ K_a^* \end{bmatrix} = \frac{1}{H} \begin{bmatrix} -W_{KK} \\ W_{XK} \end{bmatrix} = \frac{1}{H} \begin{bmatrix} 2\left(\beta X^* + \frac{c_F}{2}X^{*2}\right)/K^{*3} \\ \left(\beta + c_F X^*\right)/K^{*2} \end{bmatrix} = \frac{1}{H} \begin{bmatrix} 2f/K^* \\ \left(\beta + c_F X^*\right)/K^{*2} \end{bmatrix}$$

And at the optimum the Hessian is:

$$H = \frac{1}{K^{*3}}\left[2(b-2g)\left(\beta X^* + \frac{c_F}{2}X^{*2}\right) - \frac{\beta^2}{K^*}\right] = \frac{1}{K^{*3}}\left[2(b-2g)fK^2 - \frac{\beta^2}{K^*}\right]$$

so that

$$X_a^* = \frac{1}{b-2g}\frac{2fK^{*2}}{2fK^{*2}-\beta^2/K^*} > \frac{1}{b-2g}$$

Remark: the denominator is positive because the Hessian is at a maximum.

Both quantities are strictly increasing with respect to a at a bounded rate, they converge toward $+\infty$. For sufficiently large "a" $X^* > c_0/g$, assumption A2 is no longer satisfied, and the situation is then equivalent to $c_0 = g = 0$ (thanks to learning by doing production cost are null).

Remark: there is a range of a at which $X^* = c_0/g$ but we do not analyze these peculiar situations in detail.

Let us consider that $c_0 = g = 0$ (the same formula hold for the derivative with respect to a). Both K^* and X^* converge towards $+\infty$, and X^*/K^* increases and converges towards $\bar{x}$ (from equation (43)).

And for the convergence of welfare ratio, note first that from the first order condition $W_X = 0$, the ratio $bX^*/(a-\bar{C}_F)$ converges toward 1, and then write:

$$W(X, K^0(X)) = (a - \bar{C}_F - \frac{b}{2}X)X + X\left[\bar{C}_F - \frac{\beta}{K} - \frac{c_F}{2}\frac{X}{K} - f\frac{K}{X}\right] \tag{48}$$

$$\frac{W(X, K^0(X))}{(a-\bar{C}_F)^2/(2b)} = 1 - \left(\frac{bX}{a-\bar{C}_F} - 1\right)^2 + \frac{2bX}{(a-\bar{C}_F)^2}\left[\bar{C}_F - \frac{\beta}{K} - \frac{c_F}{2}\frac{X}{K} - f\frac{K}{X}\right] \tag{49}$$

the last two terms converge towards zero when a increases.

B Equilibrium

B.1 Proof of Lemma 2

There are m symmetric Cournot producers. The price function is given by (13), and the unitary cost is a function of total production. The best response of a firm is a function of the aggregate production of its competitors (and not its precise allocation among them). The derivative of the price function is $\partial P_V/\partial X = s''(X)$, and under assumption (15), the best response of a firm is decreasing and there is a unique Cournot equilibrium for any p_F, which is then equal to $c_F'(X/K)$ at the vehicle market equilibrium. The interested reader is referred to Vives (2001, Chapter 4) for an extended discussion on conditions ensuring existence and unicity of Cournot equilibrium.

The equilibrium quantity is zero if $P_V(0, K, p_F) - C_V(0) < 0$ and injecting that $p_F = C'_F(X/F) = C'_F(0)$ gives that the equilibrium is zero if $s'(0) - \beta r(K) - C_V(0) - c'_F(0) < 0$, which is equivalent to $K < r^{-1}\big((s'(0) - C_V(0) - C'_F(0))/\beta\big)$.

Otherwise, $X^r(K)$ is positive and solves

$$P_V - C_V(X) + [\frac{\partial P_V}{\partial X} - C'_V]\frac{X}{m} = 0.$$

Injecting the price function (13), and replacing $p_F = C'_F$, gives Equation (16).

With Specification 1, condition 15 is satisfied (the second bracketed term is null and the first is $-(b-g) < 0$ from Assumption A2). And the Lemma 2 becomes

Lemma 4. *With Specification 1; For a given quantity of stations K, there is a unique equilibrium total quantity of vehicles $X^r(K)$.*

- *If $K < \beta/(a - c_0)$, no vehicles are produced: $X^r(K) = 0$;*
- *If $K > \beta/(a - c_0)$ then*

$$X^r(K) = \frac{m}{m+1}\frac{1}{b-g}\left[a - c_0 - \frac{\beta}{K} - p_F\right] = \frac{a - c_0 - \beta/K}{\frac{m+1}{m}(b-g) + c_F/K} \tag{50}$$

B.2 Proof of Proposition 2

There is always an equilibrium at $X = 0, K = 0$.

If an equilibrium with positive quantities exists it is such that

$$X = \frac{m}{m+1}\frac{1}{b-g}\big[a - c_0 - \frac{\beta}{K} - p_F\big] \text{ and } p_F = c_F\frac{X}{K},\ K = \frac{X}{\bar{x}}$$

so that X^E is the solution of a second order equation:

$$\frac{m+1}{m}(b-g)X^2 - (a - c_0 - \bar{C}_F)X - \beta\bar{x} = 0$$

the analysis of which gives the result of Proposition: there is no real solution if condition (17) is satisfied and otherwise the two solutions are given by equation (18).

C Optimal policies

Let us write K^r and X^r as functions of the subsidies: $K^r(X, s_K)$ and $X^r(K, s_V)$. Note that each function has only one subsidy as argument. The influence of s_K on X only occurs indirectly. The two reaction functions are given by:

- $K^r(X, s_K)$ solves (20), with Specification 1 it is $K^r(X, s_K) = X/\sqrt{2(f - s_K)/c_F}$
- $X^r(K, s_V)$ solves equation (21), with specification 1 it is

  that is

$$X^r = \frac{m}{(m+1)(b-g)}\left[a + s_V - c_0 - \frac{\beta}{K} - p_F\right] = \frac{a + s_V - c_0 - \frac{\beta}{K}}{\frac{m+1}{m}(b-g) + c_F/K} \tag{51}$$

Equilibrium quantities, at the largest non-null equilibrium, are denoted $K^E(s_K, s_V)$ and $X^E(s_K, s_V)$, and depends on both subsidies.

C.1 Proof of Proposition

To find the optimal subsidy s_V one can either take the derivative of $W(X^E(0, s_V), K^E(0, s_V))$ with respect to s_V or the derivative of $W(X, K^r(X, 0))$ with respect to X since s_V influences K^E only indirectly.

Taking the derivative of welfare gives eq. (27), X^{SB} cancels that equation, and combining equation (21) together with the expression of the subsidy in Proposition 6 implies that X^{SB} is an equilibrium with that subsidy.

Comparison of X^{SB} and X^*:

X^{SB} satisfies, using the notation $\phi(X) = s(X) - C_V(X)X$ and that with $K = X/\bar{x}$:

$$\phi'(X) = \beta[r(K) + r'(K).K] + \bar{C}_F.$$

. Injecting equation (8) into equation (7), X^* satisfies

$$\phi'(X) = \beta[r(K) + r'(K).K] + [f + C_F(\frac{X}{K})]\frac{K}{X} \text{ with } K = K^0(X) > X/\bar{x}$$

In the right-hand side: the second bracketed term is the average cost of refueling which is larger than $\bar{C}_F$, and the first bracketed terms is increasing with respect to K if $r'' > -2r'$. It implies that $X^{SB} > X^*$. Furthermore, if $r(K) = 1/K$ then $r(K)+r'(K).K = 0$ and X^SB is the unique solution of $\phi'(X) = \bar{C}_F$ which coincides with X^* for $\beta = 0$.

C.2 proof of Lemma 3

The optimal subsidy s_K is found by looking at the derivatives of $W(X^r(K,0), K)$.

$$\begin{aligned}
\frac{dW}{dK} &= \left[\frac{-s''}{m} - C_V'\frac{m-1}{m}\right] X^r(K)\frac{\partial X^r}{\partial K} + [\beta r'(K)X - s_K] \text{ from (20) and (21)} \\
&= \left[\frac{b}{m} + g\frac{m-1}{m}\right] X^r(K)\frac{\beta + c_F X^r}{\frac{m+1}{m}(b-g) + c_F/K} + \frac{\beta X}{K^2} - s_K \text{with Specification 1.}
\end{aligned}$$

C.3 Proof of Proposition 7

Let us consider that the regulator has ϵ euros.

- If a subsidy on stations is used it is such that $s_K K^E(s_K, 0) = \epsilon$ and for a small ϵ, s_K is approximately equal to $\epsilon/K^E(0,0)$, we look at the impact of the introduction of such a subsidy:

  At the equilibrium $X^E(s_K, 0) = X^r(K^E, 0)$ and $K^E(s_K, 0) = K^r(X^E, s_K)$ so that

  $$dX^E = s_K\frac{\partial X^E}{\partial s_K}(0,0) = \frac{1}{K^E}\left(1 - \frac{\partial X^r}{\partial K}\frac{\partial K^r}{\partial X}\right)^{-1}\frac{\partial K^r}{\partial s_K}$$

- Similarly, for a subsidy on vehicles such that $s_V X^E = \epsilon$ the change of X is:

  $$dX^E = \left(1 - \frac{\partial X^r}{\partial K}\frac{\partial K^r}{\partial X}\right)^{-1}\frac{\partial X^r}{\partial s_V}\frac{1}{X^E}$$

- Then the difference on the total quantity of vehicles if ϵ is spent to subsidize stations or to subsidize vehicles is:

$$\left[\frac{\partial X^r}{\partial K}\frac{\partial K^r}{\partial s_k}\frac{1}{K^E} - \frac{\partial X^r}{\partial s_V}\frac{1}{X^E}\right]\left[1 - \frac{\partial X^r}{\partial K}\frac{\partial K^r}{\partial X}\right]^{-1} \tag{52}$$

the second factor is positive at the largest equilibrium, next denoting D the opposite of the derivative with respect to X of the left-hand side of equation (21) satisfied by X^r (it is positive thanks to assumption 15), the partial derivatives of X^r are:

$$\frac{\partial X^r}{\partial s_V} = \frac{1}{D} \text{ and } \frac{\partial X^r}{\partial K} = \frac{1}{D}[c''_F\frac{X}{K^2} - \beta r'(K)]$$

and from equation (20)

$$\frac{\partial K^r}{\partial s_K} = \frac{1}{C''_F X^2/K^3} \tag{53}$$

Therefore, the first bracketed factor of the comparison (52) is equal to,

$$\frac{1}{D}\underbrace{\left[C''_F\frac{X}{K^2} - \beta r'(K)\right]}_{\partial X^r/\partial K}\underbrace{\left[\frac{1}{C''_F}\frac{K^3}{X^2}\right]}_{\partial K^r/\partial s_k}\frac{1}{K} - \frac{1}{D}\frac{1}{X} = \frac{-\beta r'(K)}{D}\frac{K^2}{C''_F X^2} > 0$$

D Empirical relevance

In this appendix we show the relevance of our typology to discuss deployments of Fuel Cell Electric Vehicles (FCEV). We also revisit more briefly deployments of Battery Electric Vehicles (BEV). The emphasis will be on the interaction between vehicle manufacturers and infrastructure providers.

In 2018 in France there were three pilot projects for FCEV that are worth discussing: EasHymob, Zero Emission Valley and Hype.[25] They illustrate three different ways to address the tipping point issue in a Takeoff configuration: an unsuccessful attempt due to low demand and two potentially successful ones.

[25]For a general discussion of these projects see http://www.chair-energy-prosperity.org/en/publications-2/politique-encourager-deploiement-vehicules-a-hydrogene-france/

The EasHymob project stems from a call for projects from the European Union (European Innovation and Networks Executive Agency) dating back to 2014 for a Takeoff in January 2016.[26] The 2016 plan targeted 15 stations and 250 vehicles by the end of 2018. The subsidy amounted to 50 % of a €5 million budget intended to finance the deployment of stations. As well as this European subsidy, there was in addition a regional and national subsidy of 20 % on the infrastructure and €13,000 on hydrogen vehicles (40 % of the list price).

The cost-benefit analysis of this plan revealed two major weaknesses. First, deployment focuses on light commercial vehicles, mainly the electric Kangoo with hydrogen range extender. This hybrid technology increases the range from 180 to 300 km, which is well suited to captive fleets. On the other hand, without deployment of other FCEV vehicles, the volume of hydrogen demanded is low and the distribution network is very expensive. Second, the subsidy is for a public or predominantly public entity, which poses several problems: the difficult financial situation of municipalities, their administrative slowness and the fact that their long-term business vision is more limited than that of a company. Thus the objective has been to reduce the price of the deployed infrastructure as much as possible and to move towards low capacity stations (20-50 kg/day) at 350 bar. These stations, while enabling an initial extended distribution network to be installed, will not be profitable because of their small size and their inability to refuel passenger vehicles, for which the standard pressure is 700 bar. This project is not expected to pass the tipping point and achieve sustainability through market forces.

The Zero Emission Valley project was launched in 2017. Like the EasHyMob project, it also places the emphasis on the deployment of captive fleets in order to ensure its Takeoff. Three distinctive features are notable which suggest that the tipping point will be passed. It benefits from the direct support of manufacturers such as Engie and Michelin, which will cover investment in and operation of the stations. The refueling stations concerned are double-pressure (350 and 700 bar) and compatible with heavy vehicles such as buses or trucks. It is thus possible that high consumption of hydrogen will quickly result in a return on investment compatible with the financial sector. To minimize the risk taken by manufacturers that invest on the stations, subsidies through repayable advances by a state

[26] For a detailed analysis of this case see (Brunet and Ponssard, 2017)

agency (ADEME) will be put in place. Such public support makes it possible to call on significant industrial financing while presenting balanced risk sharing.

The Hype project was launched in December 2015 by the Paris Electric Taxi Company (STEP). This company exclusively uses hydrogen vehicles. The technology has a competitive advantage over BEV for this market segment with a refuelling time of a few minutes and a substantial range of about 500-600 km, which is essential for heavy use vehicles such as taxis. In 2017 the operator had 70 vehicles supplied from two stations operated by Air Liquide (a H2 producer), located in the center of Paris (at Pont de l'Alma) and near Orly airport. In 2018 there are a 100 vehicles (Hyundai and Toyota) and four stations (Pont de l'Alma, Orly, Roissy and Versailles). Caisse des Dépôts et Consignations, a French public bank, has taken a stake in Hype's equity, as has Air Liquide. The project benefits from European subsidies. In 2019 a joint venture was formed involving STEP, Air Liquide and Toyota aiming to expand the fleet to 700 vehicles by 2020.[27] This further development is expected to be self sustainable without any public support.

The Hype project highligths that (i) the integrated monopoly solution provides substantial synergies between cars and stations; the latter being calibrated to face a predictable demand, (ii) the initial public support was enough to pass the tipping point, (iii) private companies have enough expectations outside this cluster to take the risk (i.e. one may reseanably expect that large cities will strongly encourage zero emission vehicles, taxis and VTC being prominent targets).

Interestingly the deployments of FCEB in Germany and Japan also illustrate the need for close coordination between vehicle manufacturers and infrastructure poviders. In Germany a national deployment plan known as H2 mobility had been elaborated. To foster its achievement a national consortium was set up to provide funds with expectations to achieve as much as 400 stations in 2023.[28] The consortium involves the German state along with vehicle manufacturers and fuel providers, i.e. hydrogen but also fossil fuels and electricity providers.[29] However, German vehicle manufacturers have been slow to market FCEVs, pos-

[27]See Toyota news room 2019 https://newsroom.toyota.eu/air-liquide-idex-step-and-toyota-create-hysetco-to-promote-the-development-of-hydrogen-mobility/

[28]See for instance http://www.eenewseurope.com/news/germany-plans-promoting-hydrogen-drives-0.

[29]See Fuel Cells Bulletin 2013 (10) https://doi.org/10.1016/S1464-2859(13)70350-X

sibly because of a lack of direct financial stake in the consortium. In 2018 there are stations but not many cars.[30]

In Japan a consortium had also been set up. In 2017, there were about a hundred stations and 3 000 FCEV. The objective of the consortium is to launch 80 additional stations for an expected car park of 40 000 vehicles in 2021. A key ingredient of this success lies in the fact that the Japanese car manufacturers do have financial stakes in the consortium.[31]

Compared to FCEV the deployment of BEV appear much more advanced. We briefly review the coordination between car manufacturers and infrastructure providers along two cases: the Tesla approach and the overall deployment of EV in Norway.

From its early stage of deployment Tesla adopted an integrated strategy in which Tesla owners obtained exclusive access to a network of EV chargers.[32] According to a recent survey, in 2018, there are 1,344 supercharger exclusive stations worldwide, around 580 of which are in the US. The Tesla internal navigating system provides the driver with detailed information on where to make stops for a given trip; this information is updated depending on the actual energy consumption of the car and the waiting times at stations along the way. Now that competition is increasing in this market segment with the entry of high profile companies such as Porsche, the integrated strategy of Tesla appears as a significant barrier due to the expensive, capital-intensive effort to build out a network of superchargers. It may be time for a change of regulation about this exlusivity. Note also that rebates for the acquisition of such luxury cars have been eliminated.

The deployment of EV in Norway provides a broad perspective on the interaction between car manufacturers and infrastructure providers. Norway has the highest rate of deployment (Tietge et al., 2016). This situation is the result of a long story which started as early as the late 90'. Based on the multilevel perspective proposed by Geels (2012) the detailed case study of Figenbaum (2016) highlights the different phases of this story. A number of comments are directly relevant for our discussion: (i) the surge in BEV only started in 2010 while the deployment had started in the early 80's, (ii) prior to 2010 large subsidies were

[30]Based on a private conversation with industry analysts

[31]See https://www.airliquide.com/fr/media/air-liquide-10-entreprises-japonaises-unissent-accelerer-deploiement-energie-hydrogene-japon

[32]See https://www.theverge.com/2018/10/3/17933134/ev-charging-station-network-infrastrcuture-tesla

provided to cars such as exemptions for registration and value added taxes, exemptions of charges for toll and parking, free access to bus lanes... enough to initiate a low private demand in cities and surroundings, (iii) in 2008-2009, a six million euros package for the establishment of charging stations as part of a national recovery plan (Figenbaum, 2016, page 23) was launched followed in 2011 by a further ambitious financial support program for fast charge stations (Figenbaum, 2016, Table 1, page16) allowing for a recharging station every 50 km on all major inter-city roads, (iv) in 2010 the car manufacturers launched a large variety of BEVs providing models with size and quality equivalent to traditional fossil fuel vehicles.

In 2016, BEVs and Plug-in Hybrid Electric Vehicles (PHEVs) made more than half of new car sales in Norway.[33] A gradual phasing out of incentives was contemplated (Figenbaum, 2016, page 25). Altogether we interpret this deployment as (i) unsuccessful attempts to pass the tipping point during the Takeoff phase prior 2010, (ii) success during the powering up phase between 2010 and 2018 due to close a coordination between a large portfolio of subsidies for cars and infrastructure, which coïncided with the entry of many car manufacturers in the EV market, and (iii) while the country is now facing the cruising phase and the corresponding change in its support policies.

E Extensions

E.1 Mode of competition among vehicle producers

Here, we briefly sketch an extension of our model with price competition among firms producing imperfectly substitutable varieties (one variety per firm) within a market segment (e.g. class A,B,C,...).

There are m vehicle producers, each firm $i \in \{1, .., m\}$ produces a quantity x_i, consumers surplus is $s(x_1, .., x_m) - \beta r(K) \sum x_i$ with $s(.)$ symmetric, positive, increasing and strictly concave. Welfare is

[33]See https://www.weforum.org/agenda/2017/03/norway-is-leading-the-charge-towards-electric-vehicles-and-just-hit-another-milestone-along-the-way-d69a8170-cbdc-4d8a-95cd-f9bdf3c8e3ae/

$$W(X,K) = s(\frac{X}{m},...,\frac{X}{m}) - \beta r(K)X - C_V(X)X - C_F(\frac{X}{K})K - fK$$

To alleviate notations, partial derivatives are denoted with indices ($s_i = \partial s/\partial x_i$), s_{11} and s_{12} are the second order derivatives of gross surplus. For all i, j with $i \neq j$, by symmetry of s, $s_1(x,..,x) = s_i(x,..,x)$ and $s_{12}(x,...,x) = s_{ij}(x,...,x)$. Welfare maximization first order conditions are similar to equations (7) and (8), with s' replaced by $s_1(X^*/m,...,X^*/m)$ in eq. (7).

With Cournot competition, imperfect substitution has a modest impact on our results. The optimal subsidy would be characterized by a formula identical to (23) with s'' replaced by s_{11}.

With Bertrand competition, imperfect substitution has a more profound impact. For a given K, fuel price p_F and subsidy s_V, let us look at the choice of firm 1 when all other firms chooses a price p. For a price q, firm 1 produces $x(q,p)$ and each other firm $y(q,p)$ such that

$$s_1(x,y,...,y) - \beta r(K) - p_F = q \text{ and } s_2(x,y,...,y) - \beta r(K) - p_F = p \tag{54}$$

Firm 1 maximizes $\pi_1(q,p) = \big[q + s_V - C_V\big(x(q,p) + (m-1)y(q,p)\big)\big]x(q,p)$, the first order condition is (with $x_1 = \partial x/\partial q$ and $y_1 = \partial y/\partial q$)

$$[q + s_V - C_V - C_V'.x] + \frac{x}{x_1} - C_V'.(m-1)y_1\frac{x}{x_1} = 0.$$

The optimal couple of subsidies are chosen so that market equilibrium equations coincide with welfare maximization first order conditions. The latter are similar to equations (7) and (8). The optimal subsidy of stations is unchanged. For the optimal subsidy of vehicle it satisfies:

$$s_V^* = \frac{1}{-x_1}\frac{X^*}{m} - C_V'(X^*)X^*\frac{m-1}{m}\left(1 - \frac{y_1}{x_1}\right).$$

Then, the derivatives of productions with respect to the price q, x_1 and y_1, are found by taking the derivative of equations (54). Denoting $\sigma = s_{12}/s_{11}(> 0)$ the degree of substitutability, the optimal subsidy of vehicles then satisfies

$$\begin{aligned} s_V^* &= \frac{X^*}{m}\left[-s_{11} - \frac{(m-1)s_{12}^2}{-s_{11}-(m-2)s_{12}}\right] - C_V'(X^*)X^*\frac{m-1}{m}\left[1+\frac{s_{12}}{s_{22}+(m-2)s_{12}}\right] \\ &= -s_{11}\frac{X^*}{m}\left[1-\frac{(m-1)\sigma^2}{1+(m-2)\sigma}\right] - C_V'(X^*)X^*\frac{m-1}{m}\left[1+\frac{\sigma}{1+(m-2)\sigma}\right] \end{aligned}$$

compared to the formula (23) the two bracketed factors encompasses the effect of price competition and imperfect substitution. With price competition there is less need to correct for market power but scale effect are less internalized. Furthermore, the first factor is decreasing with respect to σ while the last one is increasing: closer substitutes are associated with more intense competition. With perfect substitute, $\sigma = 1$, the first term vanishes and the second one becomes $c_V'(X^*)X^*$, the price is equal to the marginal cost and the subsidy only corrects for scale effect.

E.2 Refueling along a Salop's circle

We reproduce the analysis of Greaker and Heggedal (2010): There are X owners of electric vehicle homogenously distributed over a circle (size normalized to 1), the transportation cost is t ($ per km), and the K refueling stations are equidistributed. Each station is a local monopoly with a cost $C_F(x)$ that maximizes its profit considering the price of other stations fixed.

First, let us show that $\beta = t/4$ for the two models to correspond: at an equilibrium (with full market coverage) every station charges a price p_F and every consumers goes to the nearest station so that total refueling cost is

$$-p_F X - X \times K \times 2\int_0^{1/2K} tudu = p_F X + tX/(4K)$$

which correspond to our specification 1 with $\beta = t/4$.

Second, consider a station, the two neighbouring stations fixing a price p_F, for a price p the quantity of consumers that goes to the station is $x(p, p_F) = 1/K + (p_F - p)/t$, the profit maximizing price satisfies $p - C_F'(x) = x_p/x_p' = t/K + (p_F - p)$ and, at equilibrium $p = p_F$ so $p_F - C_F'(X/K) = \frac{4\beta}{K}$.

Finally, at the free entry equilibrium the price is equal to the average cost: $p_F = [C_F(X/K) + f]\, K/X$. And, for a given X, entry is excessive since the derivative of welfare with respect to K, at the free entry equilibrium is negative:

$$-\beta r'(K)X + C_F'\left(\frac{X}{K}\right)\frac{X}{K} - C_F\left(\frac{X}{K}\right) - f = \beta\frac{X}{K^2} - 4\beta\frac{X}{K^2} < 0.$$

There are two issues associated with imperfect competition on the refueling market: the price of fuel departs from marginal refueling cost, and, entry is excessive.