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

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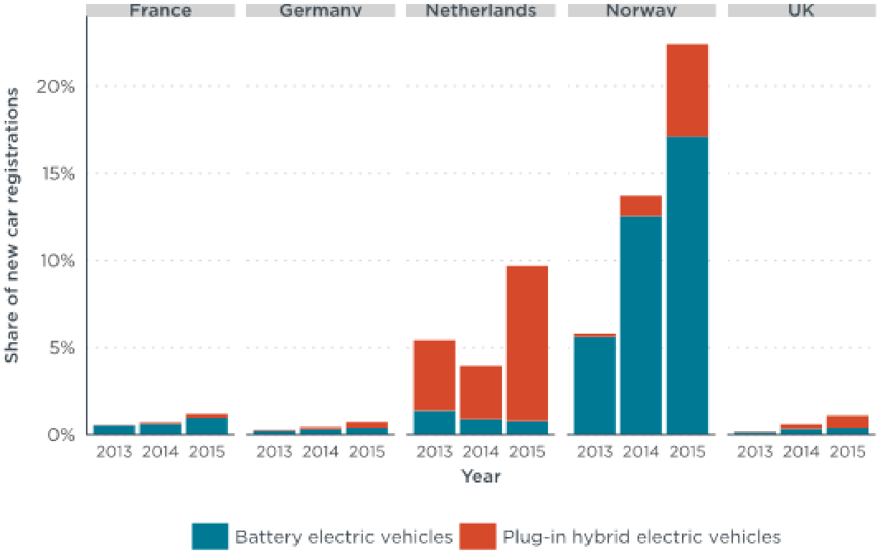
Introduction

- Externalities from traditional (gasoline) cars:
  - GHG emissions (World 14%, France 28%, US 27%)
  - Local pollution: particulate matter and noise
    France: 48000 premature death, 9 to 15 months lost
- Electric vehicles should be deployed
  - Two technologies: Battery and Fuel Cell (hydrogen)
- The current low rate of penetration is explained by:
  - Cost of a car
  - Lack of filling infrastructure
  - Limited range

Introduction



Comparison of BEV deployment in Europe (Tietge, 2016)

INCENTIVE CATEGORY	EXAMPLES
Direct consumer incentives	• Vehicle purchase subsidy or tax incentives • Vehicle registration fee exemptions
Indirect consumer incentives	• Preferential access (access to bus lanes, free or preferential parking, access to low-emission zones, etc.)
Infrastructure support	• Funding for charging infrastructure • Funding for home chargers
Complementary policies	• Public procurement preference for electric vehicles • Consumer outreach and education • Research & development support

Overview of incentives (Tietge, 2016)

France: Innovative business models for clean mobility

HYPE Taxi Fleet Project - Paris

hype The «taxi of tomorrow»

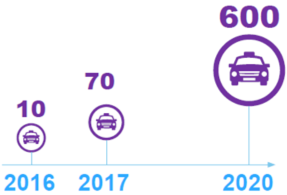
An emission-free Paris

Air Liquide

Key Enabler of the project

Launched in Dec. 2015, during COP 21

FCEV taxi fleet



Objective

- Analysis of the early stage of deployment of a technology that requires an infrastructure (critical complementary good)
  - Clarification of the "chicken-and-egg" debate, and the role of indirect network effects
- Model (partial equilibrium) with
  - Imperfect competition (Cournot) on the car market
  - "Scale effect" (learning-by-doing, supply base development) on the car market
  - "network effect": filling stations are critical, competitively supplied, with limited capacity (no economies of scale issue)
- Analysis of the social optimum, the market equilibrium, the optimal (first and second best) policies

\+ Numerical illustration based on FCEV deployment in Germany

Results

- Multiple welfare extrema and market equilibria
  - both related to critical network
  - possible lock-in
- The “best” market equilibrium is still sub-optimal because of the three market failures
- Couple of subsidies on both cars and stations are required to implement the optimum
  - or integrated monopoly and car subsidy only
- Anlysis of second-best policies in which only cars or stations are subsidize
- Numerical illustration with FCEV in Germany

Related Literature (I)

Network effects:

- The utility of a user is increasing with the number of users: positive externality
  Rohlfs (1974), Katz and Shapiro (1985) Farrel and Saloner (1986)
- Indirect network effect:

More hardware users $\rightarrow$ more softwares $\rightarrow$ increase WTP for hardware
More EV users $\rightarrow$ more filling stations $\rightarrow$ increase WTP for EV

- Direct and indirect network effects are often conflated (Shy, 2011)
  - Explicit modeling: Clements (2004), Church et al. (2008), Chou and Shy (2004)
  - Debate: Is there a market failure? (Liebowitz and Margolis, 1995)

Related Literature (II)

- **Environmental economics**:
  - Empirical evaluations of policies (rebates, free parking etc), Bjerkan et al. (2016), Pavan et al. (2015)
  - Numerical simulations with infrastructure: Meyer and Winebrake (2009), Harrison and Thiel (2017)
  - Direct Network effects: Sartzetakis and Tsigaris (2005), Brecard (2013), Greaker and Midttome (2016)

- Greaker and Heggedal (2010) theoretical analysis of the possibility of lock-in with infrastructure
  - Filling stations: Scale economies (no capacity constraints) and price competition à la Salop (1979)
  - No Welfare and policy analysis

Outline of the presentation

- The model
- Social optimum
- Market equilibrium
- Optimal policy
- Numerical Illustration (FCEV in Germany)

The model

- Two goods: cars and fuel
  - prices p_V and p_F
  - quantity of fuel per car is fixed, X is the quantity of cars and of fuel
  - fuel is distributed by K filling stations
- **Consumers** gross surplus:

$$S(X,K) = s(X) - r(K)X$$

  - $r(K)$ is “range anxiety”, cost to search and reach a station, $r'(K) < 0$
- Specification:

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

- Consumers net surplus: $S(X,K) - p_V X - p_F X$

The model

- **Production**
- Cars:
  - Production cost $C_V(X)X$ with $C_V'(X) < 0$
  - "scale effects": learning-by-doing, eco-system development
  - m Cournot competitors:

$$\pi_V(X_i, X_{-i}) = P_V(X_i + X_{-i})X_i - C_V(X_i + X_{-i})X_i$$

  - Specification:

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

The model

- Fuel:
  - $C_F(x)$ cost to provide x by a filling station
  - f is the cost of a filling station
  - Total filling cost:

$$C_F(\frac{X}{K})K + fK$$

  - Specification:

$$C_F = \frac{c_F}{2}x^2$$

- The minimum efficient scale x_m: $C_F'(x_m) = (C_F(x_m) + f)/x_m$

$$x_m = \sqrt{\frac{2f}{c_F}}, \ \bar{C}_F = \sqrt{2fc_F}$$

- Competition is pure and perfect: price taking and free entry.

Optimum

- Welfare is:

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

- It is not concave because of range anxiety:

$$W_{XX} < 0, \ W_{KK} < 0 \text{ but } W_{XK} = (\beta - c_F X)/K^2$$

  - multiplicity of critical points
  - and First Order Conditions are not sufficient for optimality

Optimum

- First Order Conditions:

$$s'(X) - r(K) = C_V(X) + C_V'(X)X + C_F'(X/K) \tag{2}$$

$$-r'(K)X + \left[C_F'\left(\frac{X}{K}\right)\frac{X}{K} - C_F\left(\frac{X}{K}\right)\right] = f \tag{3}$$

gives

- Optimal quantity of stations for a given X:

$$K^0(X) = X\left[\frac{1}{f}\left(\frac{\beta}{X} + \frac{c_F}{2}\right)\right]^{1/2} = \frac{X}{x_m}\left[1 + \frac{2\beta}{c_F X}\right]^{1/2}. \tag{4}$$

- Optimal quantity of cars for a given K:

$$X^0(K) = \max\left\{\frac{a - c_0 - \beta/K}{b - 2g + c_F/K}, 0\right\}. \tag{5}$$

it is null if K below $(a - c_0)/\beta$.

Optimum

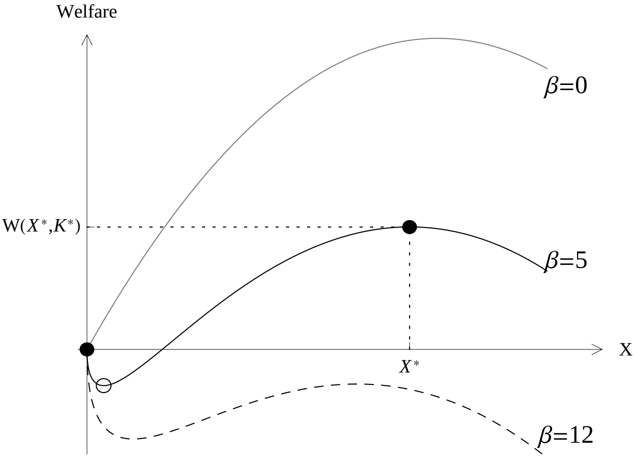
- The optimum (X^*, K^*) solves the couple of FOCs
- Multiple solutions :
  - $(0, 0)$ is a local maximum
  - (X^*_-, K^*_-) is a saddle point
  - (X^*_+, K^*_+) is a local maximum

Proposition

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: $X^*/K^* < x_m$,*
- *an increase of β induces a reduction of the optimal quantity of vehicles, and an increase of the quantity of stations per vehicle.*

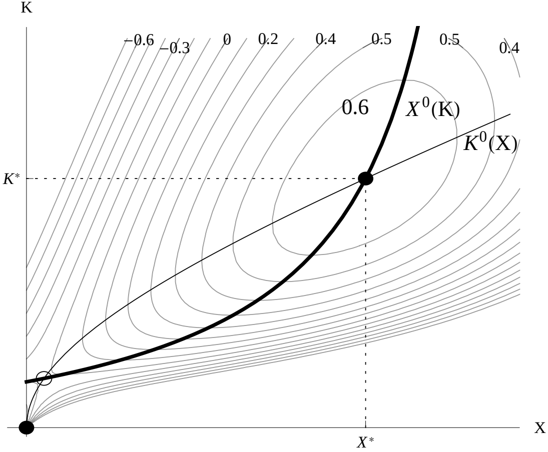
Welfare $W(X, K^0(X))$ as a function of X (K is optimal)



$a = 3.5,\ c_0 = 1,\ g = 0.1,\ b = 1,\ f = 0.1,\ c_F = 2,\ \beta = 5$

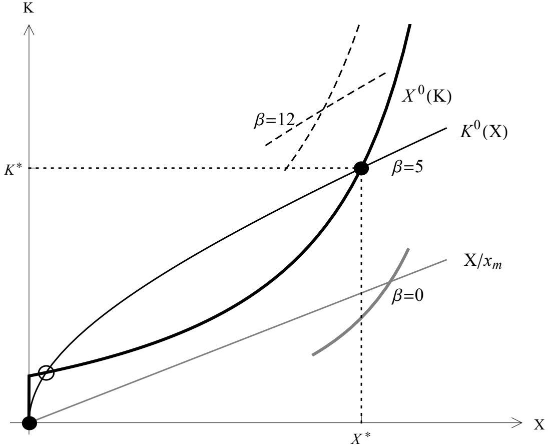
Optimum

In (X, K) space with iso-welfare, minimum is the saddle point



$a = 3.5,\ c_0 = 1,\ g = 0.1,\ b = 1,\ f = 0.1,\ c_F = 2,\ \beta = 5$

In (X, K) space, change of β:



$a = 3.5,\ c_0 = 1,\ g = 0.1,\ b = 1,\ f = 0.1,\ c_F = 2,\ \beta = 5$

Market Equilibrium

- Two interacting markets: cars and fuel, gives two reaction function $K^r(X)$ and $X^r(K)$
  - Fuel is Textbook: price competition

$p_F = C_F'(X/K)$

Market Equilibrium

- Two interacting markets: cars and fuel, gives two reaction function $K^r(X)$ and $X^r(K)$
  - Fuel is Textbook: price competition and free-entry

$p_F = C_F'(X/K) = [C_F(X/K) + f]/(X/K)$, so $K^r(X) = \frac{X}{x_m}$

Market Equilibrium

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  - Fuel is Textbook: price competition and free-entry

$$p_F = C_F'(X/K) = [C_F(X/K) + f]/(X/K), \text{ so } K^r(X) = \frac{X}{x_m}$$

  - Car producers compete à la Cournot with:

$$P_V(X, K) = \frac{\partial S}{\partial X} - p_F = a - \frac{\beta}{K} - bX - p_F$$

Market Equilibrium

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  - Car producers compete à la Cournot with:

$$P_V(X,K) = \frac{\partial S}{\partial X} - p_F = a - \frac{\beta}{K} - bX - p_F$$

so

$$P_V + P_V' \frac{X^r}{m} - C_V - C_V' \frac{X^r}{m} = 0$$

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

Market Equilibrium

Proposition

There is a unique equilibrium at $X = 0$ and $K = 0$ if and only if

$$\beta > \frac{1}{4}\frac{m}{m+1}\frac{(a - c_0 - \bar{C}_F)^2}{x_m(b-g)} \tag{6}$$

Otherwise, there are three equilibria with $X \in \{0, X_-^E, X_+^E\}$ and $K = X/x_m$

- $(0,0)$ *and* (X_+^E, K_+^E) *are stable*
- (X_-^E, K_-^E) *is unstable*
- *with* $0 < X_-^E < X_+^E$.

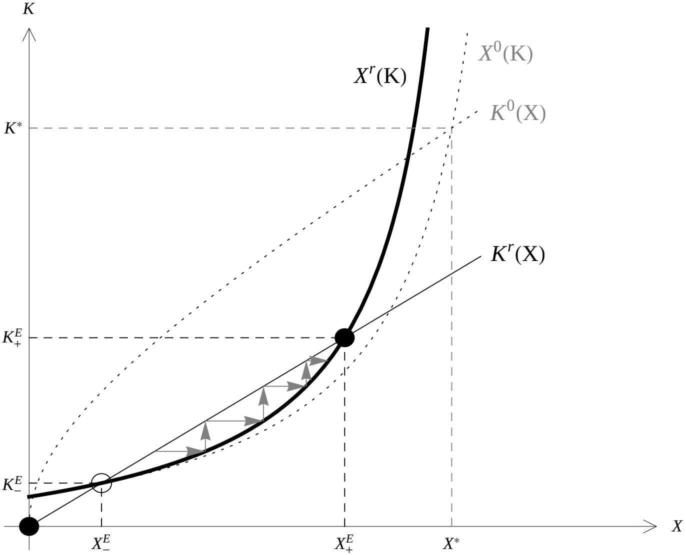


Figure: Market reaction functions and equilibria, for $a = 5$, $b = 1$, $c = 1$, $g = 0.01$, $m = 10$, $\beta = 5$, $f = 0.1$, $c_F = 2$

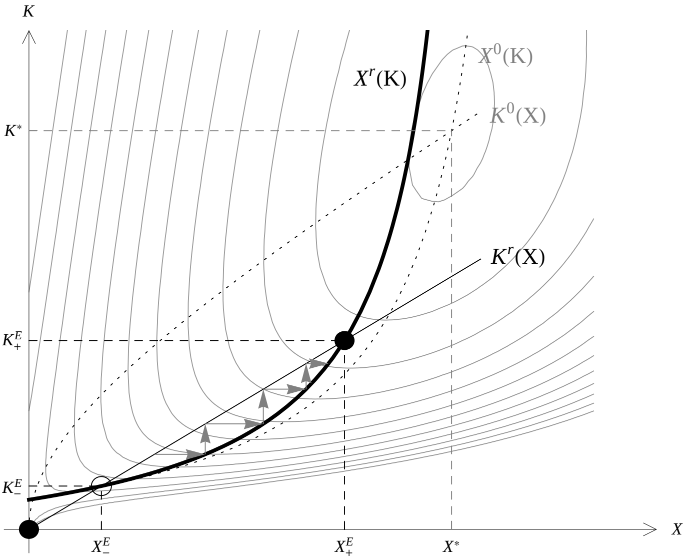


Figure: Market reaction functions and equilibria, for $a = 5$, $b = 1$, $c = 1$, $g = 0.01$, $m = 10$, $\beta = 5$, $f = 0.1$, $c_F = 2$

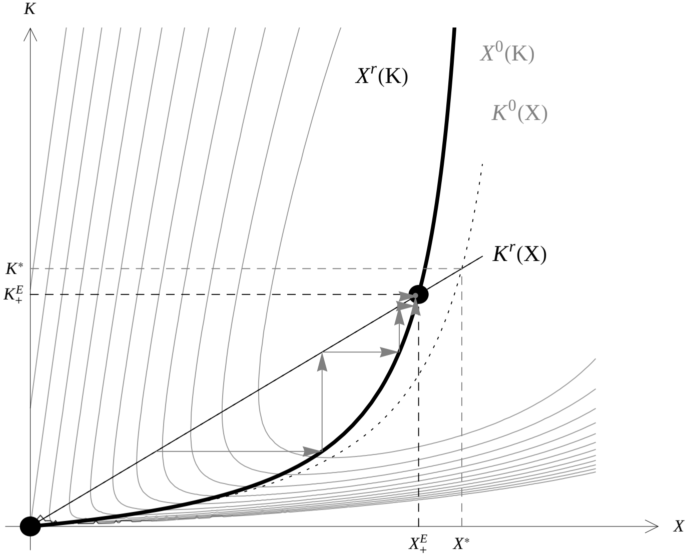


Figure: Market reaction functions and equilibria, for $a = 5$, $b = 1$, $c = 1$, $g = 0.01$, $m = 10$, $\beta = 0$, $f = 0.1$, $c_F = 2$

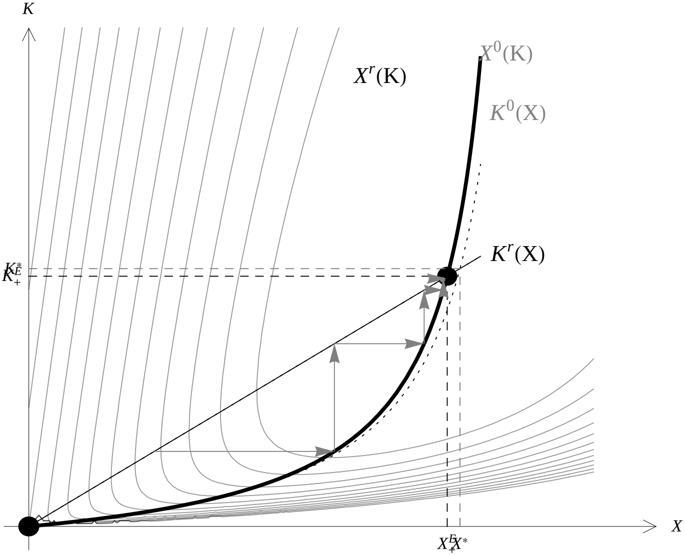


Figure: Market reaction functions and equilibria, for $a = 5$, $b = 1$, $c = 1$, $g = 0.01$, $m = 50$, $\beta = 0$, $f = 0.1$, $c_F = 2$

Optimal Policy

- Two issues:
  - lock-in at a Pareto dominated equilibrium
  - sub-optimality of the Pareto dominating equilibrium

Lemma: If several equilibria co-exist (X_+^E, K_+^E) Pareto dominates

- Policy should cross the tipping point K_-^E and ensure that $(X_+^E, K_+^E) = (X^*, K^*)$
- Three Market Failures:
  - Imperfect competition (decreases with m)
  - Scale effects (decreases with g, increases with m)
  - "Indirect network effect" or range anxiety effect: unpriced benefits $\beta X/K$ (decreases with β)

Optimal Policy

Proposition

The optimum can be decentralized with a subsidy couple:

$$s_K = \frac{\beta X^*}{K^{*2}} \tag{7}$$

$$s_V = b\frac{X^*}{m} + g\frac{m-1}{m}X^* \tag{8}$$

- With an integrated Monopoly the optimum can be obtained setting

$$s_K = 0 \text{ and } s_V = bX^*$$

Optimal Policy- 2nd Best

Proposition

If the regulator can only subsidize cars, the optimal subsidy on cars is

$$s_V^{SB} = \beta \frac{x_m}{X^{SB}} + b\frac{X^{SB}}{m} + g\frac{m-1}{m}X^{SB}$$

in which X^{SB} *is larger than* X^* *and equals to* $X^{SB} = \frac{1}{b-2g}\left[a - c_0 - \bar{C}_F\right]$ *which is the optimal quantity of vehicles without range anxiety* $\beta = 0$.

- First term corrects for underprovision of stations $\simeq$ indirect network effects

Lemma

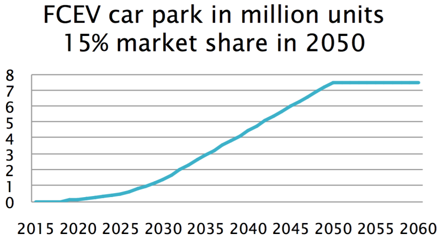
If the regulator can only subsidize filling stations,

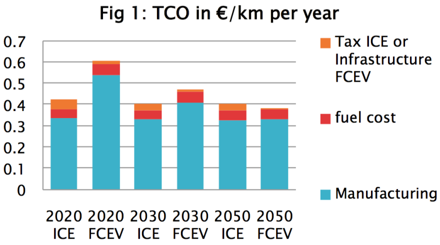
$$s_K^{SB} = \beta\frac{X}{K^2} + \left(\frac{b}{m} + g\frac{m-1}{m}\right)\frac{X}{K^2}\frac{\beta + c_F X}{\frac{m+1}{m}(b-g) + c_F/K}$$

Illustration - FCEV

Deployment of FCEV (hydrogen car) in Germany:

- From a scenario by Mc Kinsey (2010) and Creti et al. (2017)
- We get β and c_F to ensure consistency of the trajectory
- and cost figures are given.
- WTP a varies to reflect growth of the CO2 price and the market





Scenario	Take-off	Building-up	Expansion	Stationary
Social optimum				
X*	3 293	8 892	24 796	26 059
K*	20	39	86	90
Welfare (M€/yr)	.2	6.4	57.0	66.5
Oligopoly equilibrium				
m (exogenous)	1	2	10	10 000
X^r	-	4 539	21 610	25 740
K^r	-	13	61	73
Welfare loss (%)	100 %	36.1 %	2.0 %	.3 %
Integrated monopoly				
X^m	-	4 224	12 049	13 002
K^m	-	24	49	49
Welfare loss (%)	100 %	31.3 %	27.0 %	25.6 %

Table: The social optimum and the market equilibria

Scenario	Take-off	Building-up	Expansion	Stationary
Combined subsidies				
s_K (€/ station)	39 574	29 217	16 758	16 209
s_V (€/ car)	659	911	608	1
of which market power	642	867	484	1
Integrated monopoly				
s_V (€/ car)	659	1 778	4 959	5 212
Cars only				
s_V (€/ car)	-	1 122	679	68
X^{SB}	(3 775)	9 038	24 827	26 086
K^{SB}	(11)	26	70	74
Welfare loss wrt FB	100 %	6.0 %	.3 %	.3 %
Welfare return of sub	-	19.0 %	5.8 %	.7 %
Infrastructure only				
s_K (€/ car)	-	38 791	22 934	16 216
X^{SB}	-	5 894	22 065	26 056
K^{SB}	-	35	85	90
Welfare loss wrt FB	100 %	13.7 %	1.3 %	.0 %
Welfare return of sub	-	104 %	22 %	13 %

Table: The optimal subsidies

Illustration - FCEV

- Infrastructure is critical but does not require much subsidies
- Cars are heavily subsidized both in FB and SB
  - massive transferts to firms (and adopters)
  - notably with an integrated monopoly
  - due to scale effects that should eventually disappear
- To subsidize only infrastructure is not very effective
  - but return per subsidy is important (consistent with empirical results of Pavan et al., 2015)
  - range anxiety factor β likely to be under-calibrated
  - sensitivity analysis to be done

Conclusion

- Critical role of infrastructure explains both multiplicity of extrema and equilibria
- The market failure associated is a positive externality of stations on consumers
  - micro-foundation of indirect network effects
- Optimal policy should both cross the tipping point and correct the equilibrium
- Both infrastructure and vehicles should be subsidized
- The model allow to assess the contribution of each market failure
- Extensions: costly public funds, dynamic, entry in car manufacturing