Electric vs. Conventional Vehicles: Environmental Externalities and Urban Spatial Policies

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Motivation

Local air pollution in cities

- WHO (2016): More than 1 billion people exposed to urban air pollution ⇒ 1 million premature deaths and 1 million pre-native deaths each year
- In economic terms: Urban air pollution costs appr. 2% of GDP in developed countries and 5% in developing countries (UNEP, 2017)
- 90% of urban air pollution can be attributed to emissions from conventional vehicles with internal combustion engines (henceforth CVs) (UNEP, 2017)
- Electric vehicles (henceforth EVs) could largely reduce these emissions
- EVs are still (much) more expensive than CVs ⇒ *policies to promote EV adoption in many countries* (one-off subsidies, free parking in city centers, use of bus lanes and ride-sharing lanes)

Motivation

Framing the problem in a spatial context

- In a city, most local air pollution comes from commuting (with CVs)
- Households face a trade-off: they can locate to less polluted areas but then need to make longer commuting trips to work
- Longer commutes (with CVs) create more local pollution

- Our research questions:
  - Where will/should commuters with EVs/CVs locate?
  - What would optimal (first- and second-best) spatial policies look like?
  - Is there a rationale for a subsidy on EVs?
  - What is the effect on urban sprawl?

Related Literature

- Pollution externalities in urban models:
  - Pollution from stationary sources (industry): Henderson (1977); Arnott et al. (2008); Kyriakopoulou and Xepapadeas (2013, 2017)
  - Pollution from non-stationary sources (commuting): Verhoef and Nijkamp, (2003), Schindler et al. (2017)
  - Pollution from commuting and housing (and production): Borck and Brueckner (2016), Borck (2016)
- Optimal policies for adoption of EVs in urban model: Hirte and Tscharaktschiew (2013) $\Rightarrow$ optimal electric power subsidy is negative (due to negative tax-interaction effects)
- Methodologically: van den Berg and Verhoef (2016) $\Rightarrow$ commuting and different types of cars (self-driven vs. self-driving cars)

The Model

Setup and assumptions

- Linear monocentric city (Alonso, 1964)
  - Central Business District (CBD) at $r = 0$
  - residential area from $r = 0$ to $r = S$ where S is the endogenous city boundary
- N workers:
  - identical ex ante except for their choice of vehicle
  - all commute to the CBD
  - either own an EV or a CV with an internal combustion engine
- workers derive utility from housing space h and a composite numéraire good z but are negatively affected by local air pollution P from CV emissions:

$$U(r) = h(r)^{\alpha} z(r)^{1-\alpha} P(r)^{-\beta}, \quad 0 < \beta < 1$$

- All workers earn the same wage w and pay a lump-sum tax T
- They pay a residential land rent $R(r)$ at the spatial point r for housing h
- Depending on which car they drive, their budget constraints are:

$$
\begin{aligned}
R(r)h(r) + z(r) &= w - T - (\tau_C + t)r - F_C && \text{if CV} \\
R(r)h(r) + z(r) &= w - T - \tau_E r - F_E && \text{if EV}
\end{aligned}
$$

- Per trip, the costs of driving a CV are τ_C (fuel cost) plus t (environmental tax or eco-tax).
- Per trip, the cost of driving an EV is τ_E.
- Fixed cost of CV (EV): F_C (F_E).

- We assume that $\tau_E < \tau_C$ (and $\tau_E < \tau_C + t$) , but $F_E > F_C$.
- fraction of people buying an EV: δ_E
- $\delta_C = 1 - \delta_E$: no other mode choices
- public budget is balanced:

$$NT + t \int_0^S [1 - \delta_E(r)]\, n(r)\, dr = \bar{G}$$

  where $\bar{G}$ is exogenously given public expenditure.
- t is chosen by the government and T adjusts to satisfy the budget constraint

The Model

Pollution

- Commuting with CVs causes local pollution:

$$P(r) = 1 + \varepsilon \int_r^S \left[1 - \delta_E(r)\right] n(r)\ dr$$

- $n(r)$ is the density of workers at spatial point r
- ε is emissions per unit of distance driven

- In equilibrium, all workers enjoy the same level of utility $\bar{u}$
- CV and EV users have the following demand functions:

$$z_C^*(r) = (1-\alpha)\left[w - T - (\tau_C + t)r - F_C\right]$$

$$h_C^*(r) = \frac{\bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}}}{(1-\alpha)^{\frac{1-\alpha}{\alpha}} \left(w - T - (\tau_c + t)r - F_C\right)^{\frac{1-\alpha}{\alpha}}}$$

$$z_E^*(r) = (1-\alpha)(w - T - \tau_E r - F_E)$$

$$h_E^*(r) = \frac{\bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}}}{(1-\alpha)^{\frac{1-\alpha}{\alpha}} \left(w - T - \tau_E r - F_E\right)^{\frac{1-\alpha}{\alpha}}}$$

- The residential bid-rent functions for CV and EV users are:

$$R_C^*(r) = \frac{\alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} (w - T - (\tau_c + t)r - F_C)^{\frac{1}{\alpha}}}{\bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}}}$$

$$R_E^*(r) = \frac{\alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} (w - T - \tau_E r - F_E)^{\frac{1}{\alpha}}}{\bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}}}$$

$\Rightarrow$ increase with disposable income but decrease with ecotax t, higher fixed cost of vehicles and pollution $P(r)$

Equilibrium City Size / Structure

- Assume $t = 0$.
- If the boundary of the city is occupied by CV users:

$$S_C = \frac{1}{\tau_C}\left[w - T - \frac{r_A^{\alpha}\bar{u}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}} - F_C\right]$$

where r_A is the value of agricultural land (exogenous)

- while if it is occupied by EV users:

$$S_E = \frac{1}{\tau_E}\left[w - T - \frac{r_A^{\alpha}\bar{u}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}} - F_E\right]$$

Equilibrium City Size / Structure

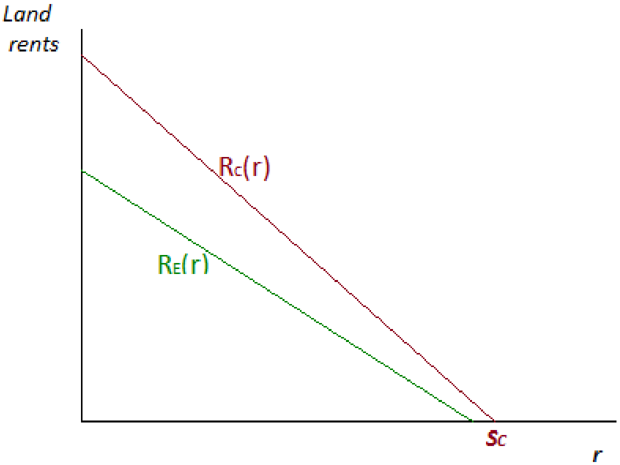
1. $$S_C > S_E \quad \text{if} \quad F_E > \frac{(\tau_C - \tau_E)W + \tau_E F_C}{\tau_C}$$

   where $W = w - T - \frac{r_A^{\alpha}\bar{u}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}$.
   If the price of EVs is very high, then the city will be fully occupied by CV users.

2. $$S_C < S_E \quad \text{if} \quad F_E < \frac{(\tau_C - \tau_E)W + \tau_E F_C}{\tau_C}$$

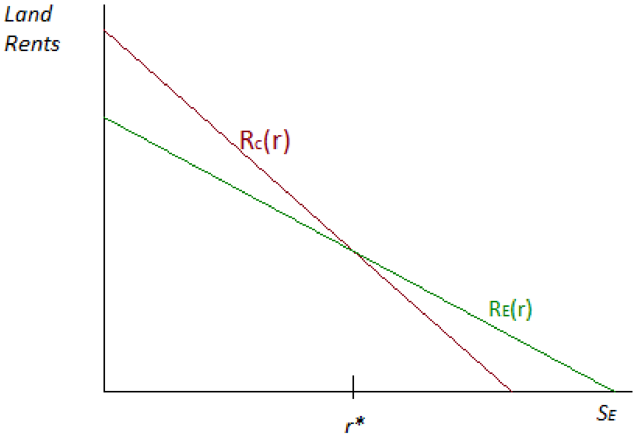
   then both types of drivers locate in the city.

Equilibrium City Size / Structure



City fully occupied by CV users

Equilibrium City Size / Structure



CV users locate in $(0, r^*)$ and EV users locate in (r^*, S_E)

Market Allocations

Population Density

- Land density at each point r equal to unity:

$$n(r)h(r) = 1 \Rightarrow n(r) = \frac{1}{h(r)}$$

- When everyone drives a CV:

$$n_C^*(r) = \frac{(1-\alpha)^{\frac{1-\alpha}{\alpha}} (w - T - \tau_c r - F_C)^{\frac{1-\alpha}{\alpha}}}{\bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}}}$$

- When everyone drives an EV:

$$n_E^*(r) = \frac{(1-\alpha)^{\frac{1-\alpha}{\alpha}} (w - T - \tau_E r - F_E)^{\frac{1-\alpha}{\alpha}}}{\bar{u}^{\frac{1}{\alpha}}}$$

$\Rightarrow$ Not clear where population density is higher

- Pollution at each spatial point is given by:

$$P(r) = \tau_c^{\frac{\beta}{\alpha+\beta}} \left[\left(\frac{\bar{u}^{\frac{1}{a}}}{\varepsilon(1-\delta_E)\beta} \right)^{\frac{\beta}{\alpha+\beta}} + \left(\frac{\varepsilon(1-\delta_E)\beta}{\bar{u}^{\frac{1}{a}}} \right)^{\frac{a}{\alpha+\beta}} \int_r^S (w - T - \tau_c r - F_C)^{\frac{1-\alpha}{\alpha}} \, dr \right]$$

⇒ Pollution is higher closer to the city center (# number of CV users who pass by rises)
⇒ Pollution is lower the higher # of EV users and the more EV users locate to the right of the spatial point under study

First-best policy

- Environmental externality exclusively stems from commuting by CV users
  $\Rightarrow$ first-best policy needs to be a site-specific tax on CV users
- Social planner maximizes value of land in the city:

$$\max_{h(\cdot),z(\cdot),n(\cdot),P(\cdot),S} \int_0^S \{[w - T - \tau_c r - F_C - z_C(r)]\,[1 - \delta_E(r)]\,n(r)$$
$$+[w - T - \tau_E r - F_E - z_E(r)]\delta_E(r)n(r) - r_A\}\; dr$$

$$s.t. \qquad P(r) = 1 + \varepsilon \int_r^S [1 - \delta_E(r)]\,n(r)\; dr$$
$$n(r) \leq \frac{1}{h(r)}$$
$$\bar{u} \leq U(z_i(r), h_i(r), P(r)), \qquad i = C, E$$

First-best policy and optimal allocations

- $\mu(r)$: costate variable which measures the marginal impact of a CV driver on the remaining residents when locating at the spatial point r.
- From the necessary conditions for the optimum, we obtain:

$$\tilde{h}_C(r) = \left(\frac{1}{1-\alpha}\right)^{\frac{1-\alpha}{\alpha}} \bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}} (w - T - \tau_c r - F_C - \mu(r)\varepsilon)^{-\frac{1-\alpha}{\alpha}}$$

$$\tilde{h}_E(r) = \left(\frac{1}{1-\alpha}\right)^{\frac{1-\alpha}{\alpha}} \bar{u}^{\frac{1}{\alpha}} P(r)^{\frac{\beta}{\alpha}} (w - T - \tau_E r - F_E)^{-\frac{1-\alpha}{\alpha}}$$

$$\tilde{z}_C(r) = (1-\alpha)(w - T - \tau_c r - F_C - \mu(r)\varepsilon)$$

$$\tilde{z}_E(r) = (1-\alpha)(w - T - \tau_E r - F_E)$$

$\Rightarrow$ allocations are the same for EV drivers but different for CV drivers
$\Rightarrow$ at the optimum, CV users should internalize the marginal damage they are causing, $\mu(r)\varepsilon$

First-best policy and optimal allocations

- From the co-state condition, we get:

$$\dot{\mu} = \frac{\beta}{1-\alpha} P(r)^{\frac{\alpha+\beta-1}{1-\alpha}} \bar{u}^{\frac{1}{1-\alpha}} \left(\frac{1-\delta_E(r)}{h_C(r)^{\frac{1}{1-\alpha}}} + \frac{\delta_E(r)}{h_E(r)^{\frac{1}{1-\alpha}}} \right)$$

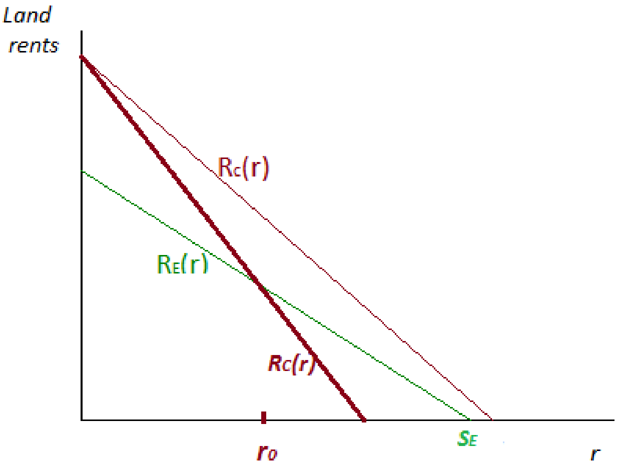
- The solution to this differential equation is given by:

$$\mu(r) = \frac{\beta}{1-\alpha} \bar{u}^{\frac{1}{1-\alpha}} \int_0^r \left(\frac{(1-\delta_E(x))}{h_C(x)^{\frac{1}{1-\alpha}}} + \frac{\delta_E(x)}{h_E(x)^{\frac{1}{1-\alpha}}} \right) P(x)^{\frac{\alpha+\beta-1}{1-\alpha}} dx$$

$\Rightarrow$ Shadow cost increases with distance to the city center: The more CV users locate in spatial points farther away from the city center, the higher the costs they impose on residents locating between the city center and those spatial points

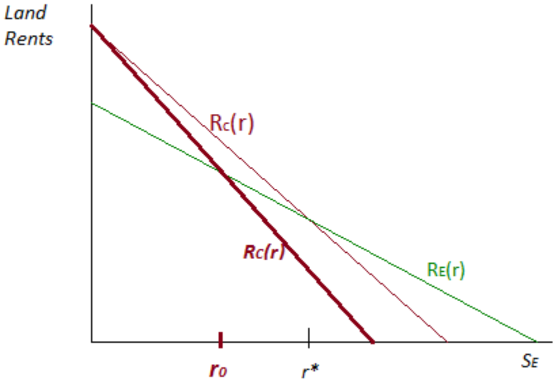
First-best policy and optimal allocations

- The optimal policy will be a lump-sum, site-specific tax, $t^*(r) = \mu(r)\varepsilon$, imposed on CV drivers.
- Since $\mu(r)$ increases with distance, the CV drivers who locate far from the city center will pay a higher tax which will decrease their bid-rent.
- At the optimum, when $r > r_0 : R_C(r) < R_E(r)$,
- and when $r < r_0 : R_C(r) > R_E(r)$.
- CV users should locate closer to the city center and EV users should locate at the city fringe!
- The size of these two areas, as well as the number of people who will buy EV, depends on the parameter ε.
- The higher ε, the higher is the site-specific tax, the more costly it is for CV drivers to locate closer to the boundary of the city.



Optimal Allocation: CV users locate in $(0, r_0)$ and EV users locate in (r_0, S_E)

Optimal City Size / Structure



Optimal Allocation: CV users locate in $(0,r_0)$ and EV users locate in (r_0, S_E)

Conclusion

- In a no-policy equilibrium, the city is:

1. Populated by CV users only if the difference between the fixed cost of EVs and the fixed cost of CVs is much higher than the cost savings from using an EV vs. a CV.
2. Populated by both CV and EV users, where the latter will always locate close to the boundary (longer-distance commuters) if there are significant cost savings from using an EV.

- First-best policy:
  - CV users pay for the externalities they impose on all residents and the cost is proportional to the damage / distance.
  - This makes the use of CV more expensive especially for long-distance commuters.
  - This results in a higher number of EV users who should locate at the city boundary.

Further work

- Derive second-best policies (uniform fuel tax, subsidy to EV purchases, subsidy to charging stations etc.)
- Optimal location of charging stations $\longrightarrow$ how can this change the location and the number of users?
- Network effects (peer-effect or signaling?)
- Introduce other characteristics:
    - Longer leisure trips: recharging infrastructure matters
    - Wage heterogeneity
    - Global pollution
- Political economy: What policies would commuters vote for? How would they use the tax system for redistributive purposes?