

Equilibrium Trade in Automobiles

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Dynamic Programming and Structural Econometrics #9

Equilibrium Trade in Automobiles

(JPE, 2022)

The Doubly Nested Fixed Point Algorithm (DNFXP)

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How much is a Volvo in Denmark?



About \$200,000!

Menu



MODELLER > VARIANT > MOTOR & GEAR > DESIGN > EKSTRAUDSTYR & PAKKER > SAMMENDRAG



STANDARD:

20" letmetalffælge 10-sp
Tinted Silver Diamond Cut
(173)



VOLVO XC90

Inscription
T6 8-trins automat AWD, 7
sæder

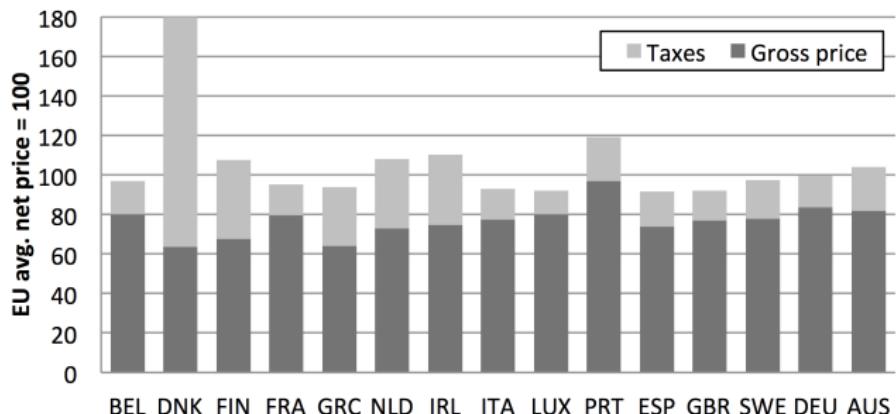
Grundpris

DKK 1 348 091

MSRP in US: \$62,350

Danish car registration tax: 180%! (plus 25% VAT)

Toyota Avensis



Car taxes in Denmark

- ▶ **Annual Revenue:** 30–50 billion DKK
- ▶ \cong 2–3 pct. of GDP
- ▶ \cong 4–7 pct. of total tax revenue
- ▶ Most revenue originates from taxation of ownership and registration of new cars.
- ▶ Car *usage* tax (fuel tax) is not unusually high

Policy question: What are the effects of switching car taxes from purchase to usage?

Our main finding: The Danish new car tax is “over the top” of the Laffer curve. We identify welfare improving tax policies that reduce the new car tax and raise the gas tax, generating higher consumer welfare, government tax revenue, and reducing CO₂ emissions.

The Laffer Curve is a graphical representation of the relationship between tax rates and tax revenue

The Laffer Curve suggests that at some point, increasing tax rates beyond a certain level will actually result in a decrease in government revenue. This occurs because the disincentive effects of high tax rates outweigh the revenue gains from the increased tax rate.

Part I: Stationary equilibrium with transaction costs and consumer heterogeneity: theory

Part II: Modeling the Danish secondary market for automobiles

Model: Zurcher on Steroids

- ▶ **Consumers:** Unit mass, infinitely lived, discrete types τ
 - ▶ *Ownership decisions:* keep, trade, purge + scrap or sell if applies
 - ▶ *Driving decision:* how much to drive
- ▶ **Cars:** $j \in \{1, \dots, J\}$ types of ages $a \in \{1, \dots, \bar{a}\}$
Ophugning
- ▶ **Scrapage:** Forced (accidents & end of life) or by choice
 - ▶ Stochastic: due to accident with probability α_j
 - ▶ End of life: at scrappage at age \bar{a}
 - ▶ Endogenous: when getting rid of a car voluntarily
- ▶ **Idiosyncratic heterogeneity:** IID EV/GEV terms (non-degeneracy of choice probabilities \Rightarrow existence of equilibrium)
- ▶ **Key simplification:** all dynamic effects through age of car and ownership states (driving has no dynamic implications)

DNFXP algorithm (roadmap)

- ▶ **Outer optimization:** Maximum likelihood search over θ
- ▶ **Inner equilibrium solver:** Find prices, P^* , so $ED(P^*, q(P^*)) = 0$
- ▶ **Excess demand:** Each trial value of P requires
 1. Solve single agent DP/fixed point given P
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Utility of car ownership and consumer heterogeneity

$$\text{Utility} = u(i, a) - \mu [\text{operating costs} + \text{trade and transaction costs}] + \epsilon$$

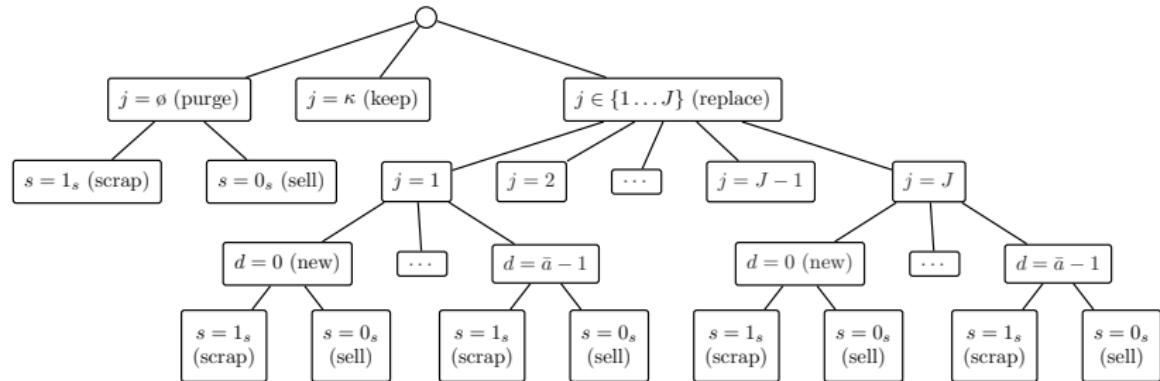
- ▶ Car utility $u(i, a)$ is a decreasing function of car age a that reflects
 - ▶ decreasing utility of car services
 - ▶ increasing cost of maintenance
- ▶ Marginal utility of money μ

Idiosyncratically heterogeneous consumers

- ▶ Extreme value consumer types (taste shifters)
- ▶ GEV specification for $\epsilon \rightarrow$ nested choices to allow correlation between alternatives
- ▶ Logit choice probabilities and analytic expectations

Idiosyncratically heterogeneous consumers have individualized and distinct characteristics that make them different from each other, despite belonging to the same market segment.

Consumer choice tree



Car owners' trading problem

$$V(i, a, \epsilon) = \max \left\{ \begin{array}{l} v(i, a, \kappa) + \epsilon(\kappa); \\ \max_{s \in \{0_s, 1_s\}} [v(i, a, \emptyset, s) + \epsilon(\emptyset, s)]; \\ \max_{\substack{j \in \{1, \dots, J\}, \\ d \in \{0, 1, \dots, \bar{a}-1\}, \\ s \in \{0_s, 1_s\}}} [v(i, a, j, d, s) + \epsilon(j, d, s)] \end{array} \right\}$$

States Choices

- ▶ Existing car (i, a) , traded car (j, d)
- ▶ When existing car (i, a) is replaced, there is additional scrappage choice $s \in \{0_s, 1_s\}$: to sell or to scrap the replaced car.
- ▶ Similar recursive maximization problems for consumers with no car and owner of car of terminal age \bar{a}

Choice specific value functions

$$v(i, a, \emptyset, 1_s) = u(\emptyset) + \mu \underline{P}_i + \beta EV(\emptyset)$$

$$v(i, a, \emptyset, 0_s) = u(\emptyset) + \mu [P_{ia} - T_s(P, i, a)] + \beta EV(\emptyset)$$

$$v(i, a, \kappa) = u(i, a) + \beta(1 - \alpha) EV(i, a + 1) + \beta\alpha EV(i, \bar{a})$$

$$\begin{aligned} v(i, a, j, d, 1_s) = & u(j, d) - \mu [P_{jd} - \underline{P}_i + T_b(P, j, d)] + \\ & + \beta(1 - \alpha) EV(j, d + 1) + \beta\alpha EV(j, \bar{a}) \\ v(i, a, j, d, 0_s) = & u(j, d) - \mu [P_{jd} - P_{ia} + T_s(P, i, a) + T_b(P, j, d)] + \\ & + \beta(1 - \alpha) EV(j, d + 1) + \beta\alpha EV(j, \bar{a}) \end{aligned}$$

States Choices → Current period utility Future value

- Similar expressions for consumers with no car and owner of car of terminal age \bar{a}

Solving the consumers' problem

$$EV(i, a) = \sigma \log \left\{ \sum_{j,d,s} \exp \left[\frac{v(i, a, j, d, s)}{\sigma} \right] \right\}$$

- ▶ **Fixed point of Bellman operator in EV space**

$$EV(P) = \Gamma(EV(P), P)$$

- ▶ Conditional choice probabilities are then analytical, similar to

$$\Pi(j, d, s | i, a) = \frac{\exp [v(i, a, j, d, s)/\sigma]}{\sum_{j'} \exp [v(i, a, j', d', s')/\sigma]}.$$

- ▶ Note: CCPs implicitly depend on car prices, P
- ▶ The sell/scrap decision s is separable (see paper for details)
- ▶ Fixed point solved using gradient-based Newton method with very precise starting values

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Stationary flow market equilibrium framework

Assumptions

1. Infinitely inelastic supply of new cars \bar{P}_j
2. Infinitely elastic demand for scrapped cars \underline{P}_j
3. $J(\bar{a} - 1)$ endogenously determined used car prices P_{jd}

Definition: Ownership Distribution

$$q = \left(\underbrace{(q_{11}, \dots, q_{1\bar{a}})}_{\text{car 1}}, \dots, \underbrace{(q_{J1}, \dots, q_{J\bar{a}})}_{\text{car } J}, \underbrace{q_\emptyset}_{\text{no car}} \right) \in \mathbb{R}^{J\bar{a}+1}$$

- ▶ q_{ia} is the fraction of consumers holding car i of age a
- ▶ By our timing assumption new cars purchased in any time period are accounted for as one-years-old cars in the next time period (so q_{j0} is undefined)

Equilibrium

Definition: Stationary Equilibrium

A pair $q^* \in \mathbb{R}^{J\bar{a}+1}$ and $P^* \in \mathbb{R}^{J(\bar{a}-1)}$ such that

1. Consumers maximize expected discounted utility,
2. Secondary market clears for all tradeable cars,
3. Ownership distribution is time-invariant.

The dynamics of the ownership distribution q are described by

- ▶ *Trade* transition probability matrix $\Omega(P)$ composed of conditional choice probabilities of trading decisions
- ▶ *Physical* transition probability matrix Q : ageing of cars + stochastic transitions to terminal age \bar{a} (involuntary scrappage)

In the paper we also prove the *flow property* of this stationary equilibrium: all cars scrapped in each period are replenished by the exact amount of new cars bought in the same period

Trade transition probability matrix

$$\Omega(P) =$$

$J\bar{a} + 1 \times J\bar{a} + 1$ matrix

$$\begin{bmatrix} \Delta_{11}(P) + \Lambda_1(P) & \Delta_{12}(P) & \dots & \Delta_{1J}(P) & \Delta_{1\emptyset}(P) \\ \Delta_{21}(P) & \Delta_{22}(P) + \Lambda_2(P) & \dots & \Delta_{2J}(P) & \Delta_{2\emptyset}(P) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \Delta_{J1}(P) & \Delta_{J2}(P) & \dots & \Delta_{JJ}(P) + \Lambda_J(P) & \Delta_{J\emptyset}(P) \\ \Delta_{\emptyset 1}(P) & \Delta_{\emptyset 2}(P) & \dots & \Delta_{\emptyset J}(P) & \Pi(\emptyset|\emptyset, P) \end{bmatrix}$$

Then $q \cdot \Omega(P)$ is distribution of cars after the trading phase

- ▶ $\Delta_{ij}(P)$ composed of choice probabilities of trading car i to car j
- ▶ $\Lambda_i(P)$ composed of keeping probabilities for car i
- ▶ $\Pi(\emptyset|\emptyset, P)$ is probability to remain in the no car state

Physical transition probability matrix

$Q =$

$J\bar{a} + 1 \times J\bar{a} + 1$ matrix

$$\begin{bmatrix} Q_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & Q_2 & 0 & \cdots & 0 & 0 \\ 0 & 0 & Q_3 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & Q_J & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix}$$

$$Q_j = \begin{bmatrix} 0 & 1 - \alpha_j & \cdots & 0 & \alpha_j \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 - \alpha_j & \alpha_j \\ 0 & 0 & \cdots & 0 & 1 \\ 1 - \alpha_j & 0 & \cdots & 0 & \alpha_j \end{bmatrix}$$

- ▶ Aging of cars with probability $1 - \alpha_j$
- ▶ Total loss accidents with probability α_j
- ▶ Last row in each Q_j block is applies to the purchased new cars

$q \cdot \Omega(P)Q$ is ownership distribution in the next period

The stationary holdings distribution

$$\underbrace{q_t}_{t} \rightarrow \underbrace{q\Omega(P)}_{\text{after trading}} \rightarrow \underbrace{q\Omega(P)Q}_{t+1}$$

Condition for time invariance of the ownership distribution:

$$q = q\Omega(P)Q$$

Theorem (Uniqueness of stationary ownership distribution)

If scale of GEV shocks distribution is positive then stationary ownership distribution is unique.

DNFXP algorithm (roadmap)

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Excess demand functions

- **Demand:** Fraction of consumers buying a given car (j, d):

$$D_{jd}(P, q) = \Pi(j, d | \emptyset, P) q_\emptyset + \sum_{i=1}^J \sum_{a=1}^{\bar{a}} \Pi(j, d | i, a, P) q_{ia}$$

- **Supply:** Fraction of owners that sell (not scrap) their car (j, d)

$$S_{jd}(P, q) = (1 - \Pi(\kappa | j, d, P)) (1 - \Pi(1_s | j, d, P)) q_{jd}$$

- **Market clearing condition** is the non-linear system of equations in ownership shares q and prices P

$$ED(P, q) \equiv D(P, q) - S(P, q) = 0$$

- Given the stationarity condition $q = q(P)$
- $J(\bar{a} - 1)$ equations with $J(\bar{a} - 1)$ unknowns

Existence of stationary equilibrium

Theorem (Equilibrium existence)

The stationary equilibrium for the automobile economy with the idiosyncratically heterogeneous consumers (q^, P^*) exists, and in equilibrium it holds:*

$$q^* = q^* \Omega(P^*) Q,$$
$$0 = ED(P^*, q^*).$$

- ▶ Only existence: q^* is unique, but unclear about P^*
- ▶ However, have not seen any signs of multiplicity in computations

DNFXP algorithm (roadmap)

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How to compute stationary flow equilibrium quickly?

Solving non-linear system of equations:

- ▶ **Gradient-based solver!** (in a series of lemmas show that all major objects in the model are smooth functions of prices, see paper)
- ▶ **Analytical derivatives**
- ▶ **Precise starting values** from the solution of the similar problem without transaction costs (linear system of equations, see appendix)

Newton method is therefore applied:

1. When solving the DP problem (Newton-Kantorovich)
 2. When solving for equilibrium prices
 3. When maximizing likelihood
- ▶ Chain rule of calculus used everywhere to build up gradients from already computed parts
 - ▶ Run time in seconds for reasonable size problems on a laptop using simple Matlab implementation

Adding persistent consumer heterogeneity

We extend the model to allow for several types of consumer heterogeneity:

- time-invariant
- time-variant
- combination of the two

- ▶ Existence theorems
- ▶ Computational algorithm is linear in the number of types
- ▶ Allows for sorting of consumers into the ages and types of cars
 - ▶ Rich hold newer better cars, poor hold older worse cars
 - ▶ Gains from trade and longer surviving cars
- ▶ The equilibrium conditions change only slightly

$$\text{Stationarity by type: } \forall \tau \quad q_\tau^* = q_\tau^* \Omega_\tau(P^*) Q$$

$$\text{Market clearing in a sum: } 0 = \sum_{\tau=1}^N f_\tau ED(P^*, q_\tau^*).$$

- ▶ Market clearing condition integrated over types

Gains from trade between rich and poor consumers

Rich mans Volvo

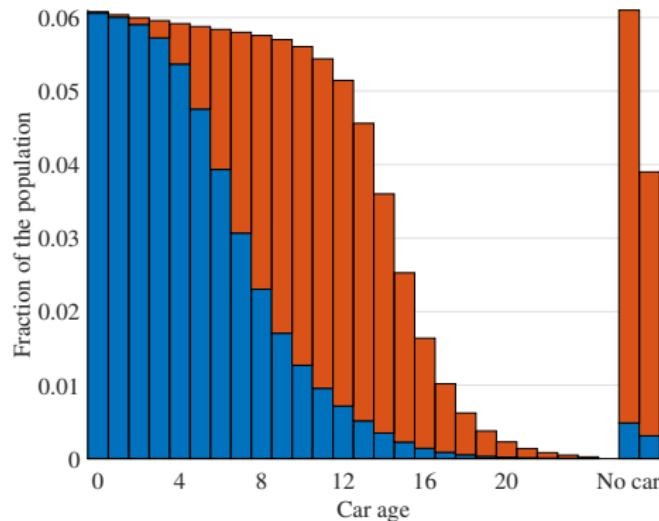


Poor mans Volvo

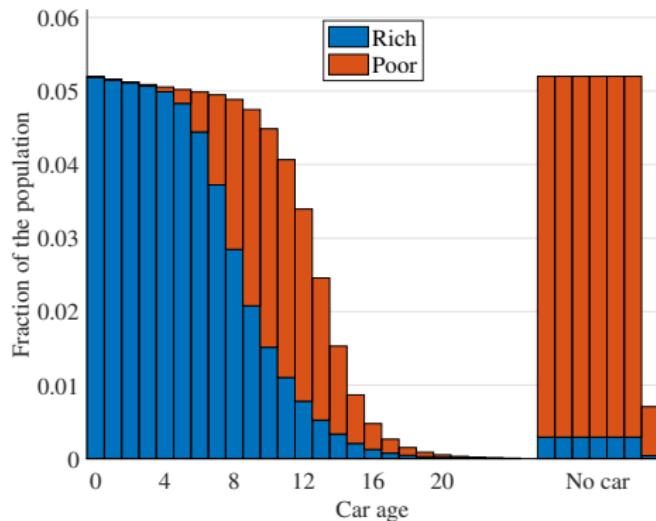


Illustrative example: ownership by two consumer types

Normal transactions costs



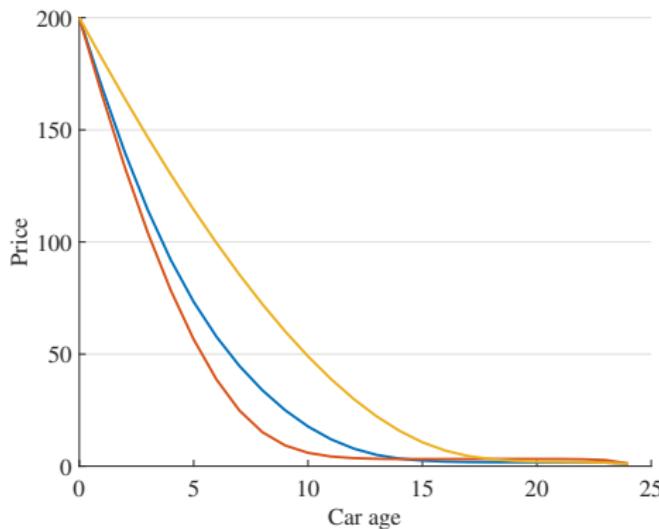
High transactions costs



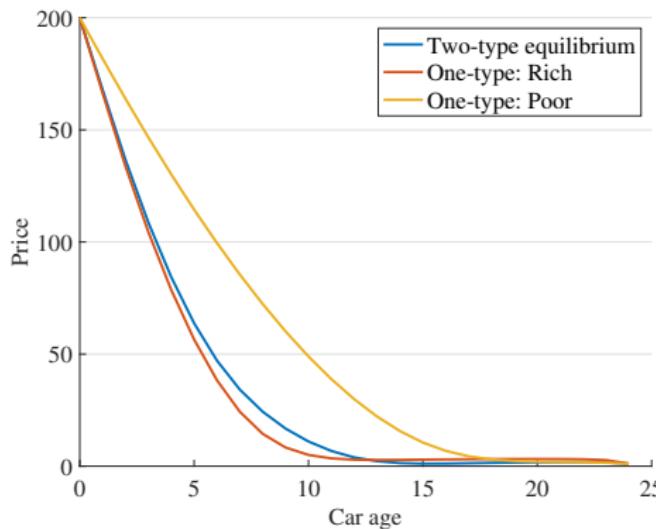
- ▶ Sorting of consumers in each regime
- ▶ Heterogeneous effects of transaction costs

Illustrative example: equilibrium prices - two consumer types

Normal transactions costs



High transactions costs



High transactions costs:

- ▶ Equilibrium prices similar to economy where all consumers are rich (many poor consumers are now driven out of the market)
- ▶ Transactions costs limits gains from trade
→ partially "kills off" the market for used cars.
(cars are scrapped earlier)

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Doubly Nested Fixed Point MLE estimator

- ▶ **Data:** counts $N_{x'x\tau}$ of transitions of household from state x (combining ownership and observable characteristics) to x' by the observed types τ
- ▶ Let θ denote the **vector of structural parameters**
- ▶ Transition probability $\Pi(x'|x, \tau, \theta)$ of the observed household state x composed of choice and transition probabilities at θ (see paper for details)
- ▶ Likelihood function

$$L(\theta) = \sum_{\tau} \sum_{x'} \sum_x N_{x'x\tau} \log \Pi(x'|x, \tau, \theta)$$

- ▶ Analytic gradient of the likelihood function again relies on using chain rule of calculus and already computed derivatives
- ▶ BHHH algorithm for approximation of Hessian

Part II: Modeling the Danish secondary market for automobiles

Simulating the effects of a hypothetical tax reform

Proposed Danish IRUC reform:

- ▶ lowers registration taxes, and
- ▶ raises usage taxes (road charging or gas tax).

Outcomes of interest:

- ▶ Equilibrium dynamics of car ownership and type choice:
 - ▶ new car sales and trade in secondary markets
 - ▶ fleet age and scrappage
 - ▶ value of the car stock
- ▶ Driving, fuel demand, and emissions
- ▶ Redistribution and welfare
- ▶ Need to capture these effects simultaneously

To implement the counterfactual simulation:

1. Estimate the model using Danish register data
2. Cut the registration tax rates for new vehicles by half
3. Increase the fuel tax rate such that revenue is unchanged
4. Compute economic/welfare/environmental implications

Utility specification with driving

Consider a utility function (indexes i and τ dropped)

$$u(a, x) = u_{\text{car}}(a) + u_{\text{drive}}(a, x) + \mu[\text{trade} + \text{transaction cost}]$$

Ownership utility: $u_{\text{car}}(a) = \alpha_0 + \alpha_1 a + \alpha_2 a^2$

Utility from driving: $u_{\text{drive}}(a, x) = (\gamma_0 + \gamma_1 a)x - \mu p x + \frac{\phi}{2} x^2$

- ▶ x is kilometers driven, p is cost per kilometer inclusive of tax
- ▶ **parameters** may be specific to car type i and consumer type τ
- ▶ See paper and online appendix for the estimated values of parameters

Assumption

The probability of an accident and other physical deterioration in an automobile is independent of the amount of driving x .

⇒ **driving is a static subproblem** of the overall DP problem that can be solved independently

Optimal amount of driving

Structural driving equation implied by the F.O.C.

$$x^*(p, a) = -\frac{1}{\phi} [\gamma_0 + \gamma_1 a - \mu p] = d_0 + d_1 a + d_2 p$$

Plugging optimal driving back into $u(a, x)$

$$\begin{aligned} u(a, x^*(p, a)) - \mu[\text{trade} + \text{transaction cost}] &= \\ \alpha_0 + \alpha_1 a + \alpha_2 a^2 - \frac{1}{2\phi} [\gamma_0 + \gamma_1 a - \mu p]^2 &= u_0 + u_1 a + u_2 a^2 \end{aligned}$$

- ▶ (d_0, d_1, d_2) are reduced form parameters that can be estimated separately from data on driving
- ▶ (u_0, u_1, u_2) are indirect utility parameters that can be identified from the dynamic model model together with μ
- ▶ Then structural parameters $(\alpha_0, \alpha_1, \alpha_2, \gamma_0, \gamma_1, \mu, \phi)$ are identified

Coefficient specification and estimations stages

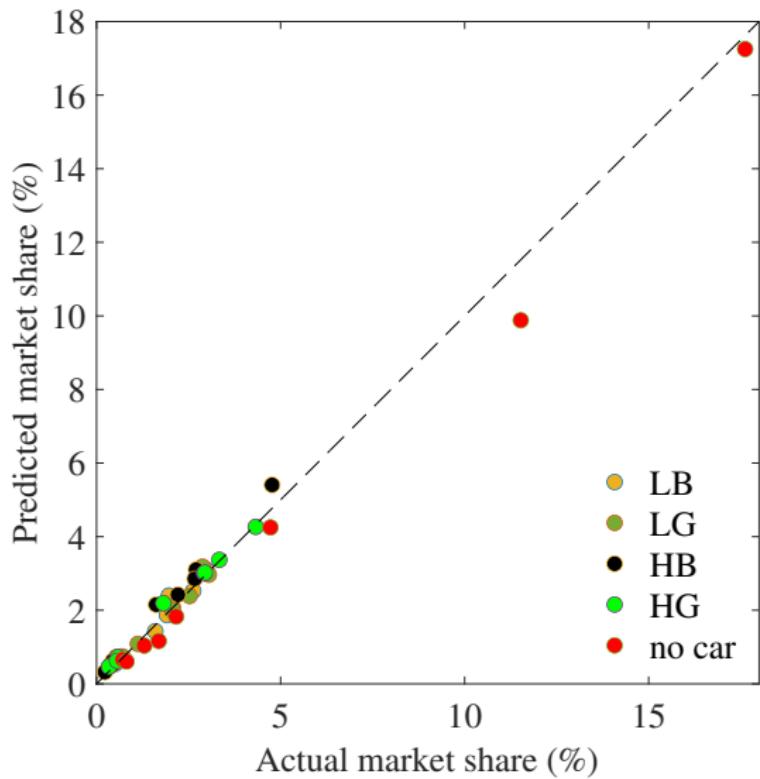
1. Least squares estimation of reduced form parameters of driving equation (d_0, d_1, d_2)
 - ▶ intercept $d_0 = d_0^\tau + d_0^i$ with car and consumer fixed effects
 - ▶ common coefficient with age d_1
 - ▶ coefficient with driving cost $d_2 = d_2^\tau$ by consumer types
2. DNFXP MLE estimation of indirect utility coefficients (u_0, u_1, u_2) and the remaining parameters (μ, ϕ), transaction costs and accident probabilities
 - ▶ intercept u_0^τ and age coefficient u_1^τ by consumer type
 - ▶ marginal utility of money μ_τ by consumer type
 - ▶ Accident probabilities by car type i
 - ▶ Buyer and seller transaction costs (see paper for details)
3. Back out structural parameters in order to run counterfactual simulations

See paper and online appendix for the estimated values of parameters

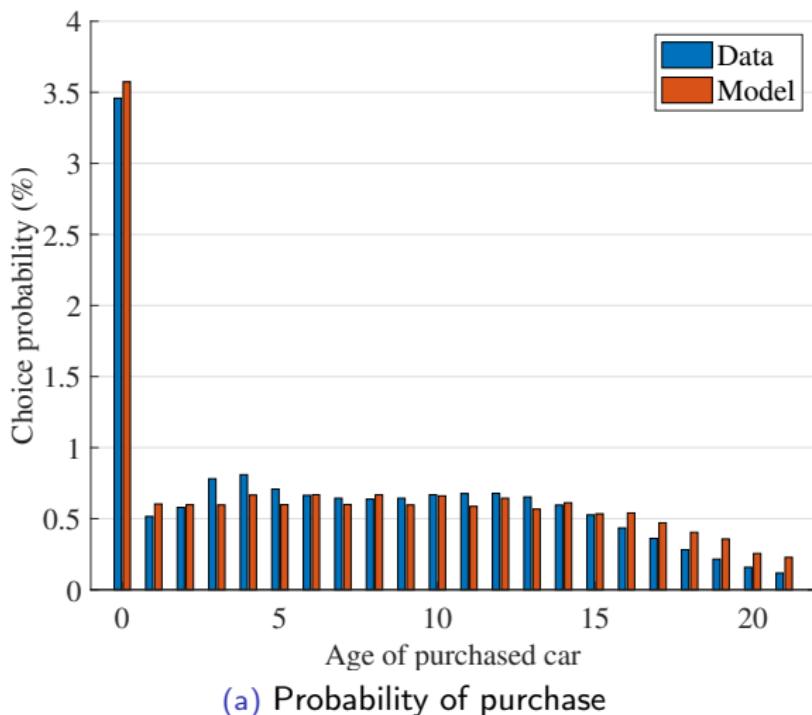
Model captures key features of Danish households

- ▶ Poor households are significantly more likely not to own a car than rich ones which are also willing to pay more for any type of car
- ▶ Couples are more likely to own cars and generally have higher willingness to pay for cars than singles
- ▶ High work distance households are relatively more likely to own cars and have higher willingness to pay for cars than those with low work distance
- ▶ All households preferred the heavy cars to the light ones and brown cars to green ones:
 $\text{heavy brown} \succ \text{heavy green} \succ \text{light brown} \succ \text{light green}$
- ▶ Households with high work distance drive much more than those with low, and more so for the rich
- ▶ Model implies fuel price elasticities between -0.10 and -0.60 across households, similar to Gillingham and Munk-Nielsen (2015)

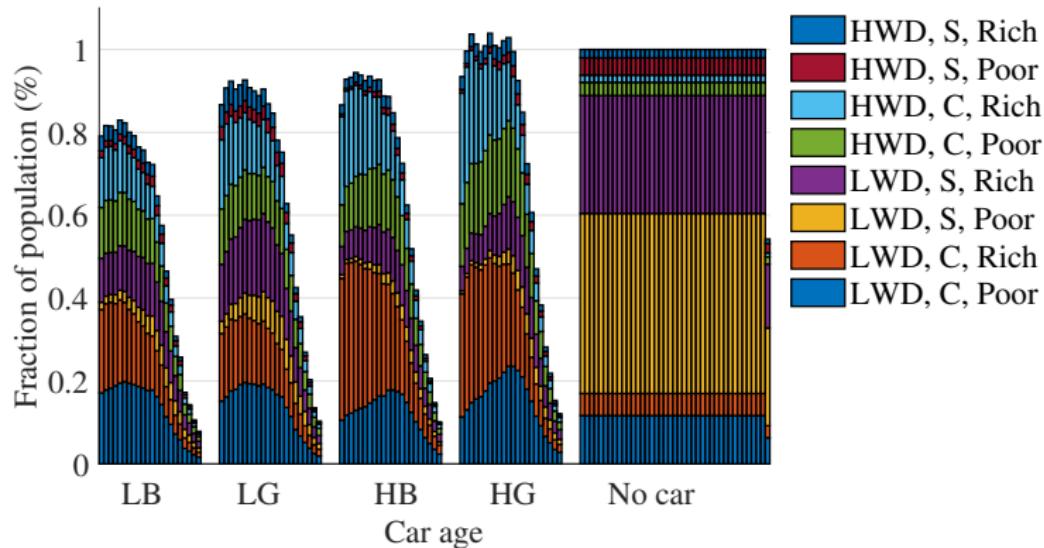
Model fit: Household-specific market shares



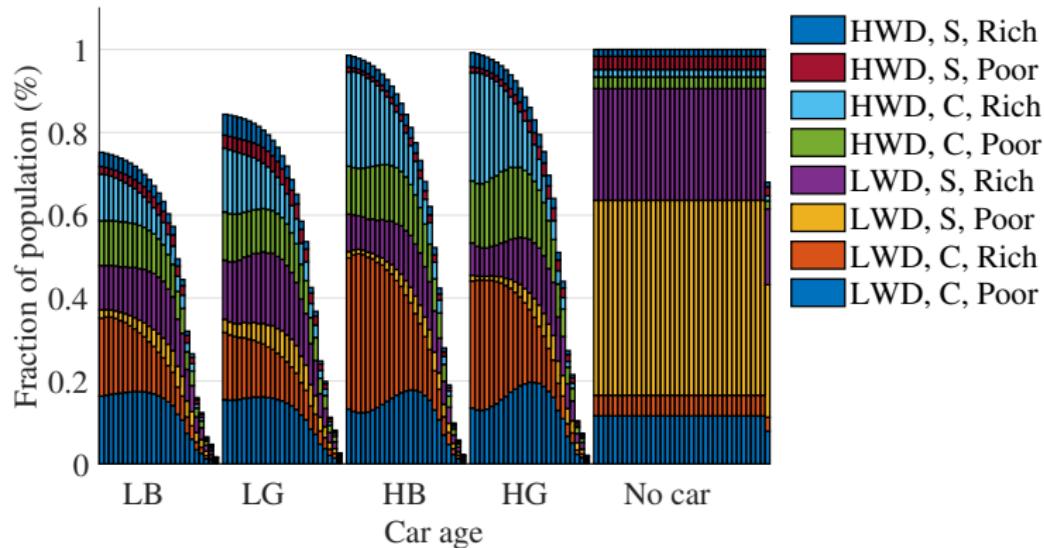
Model fit: Actual and predicted probability purchase



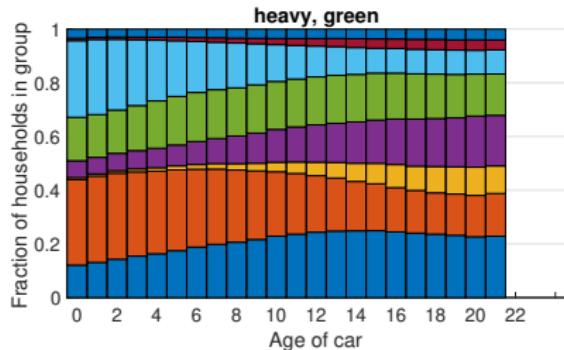
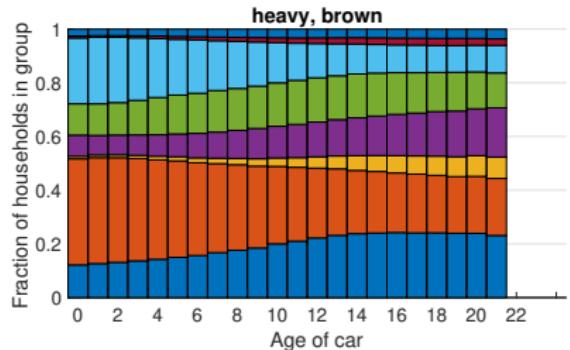
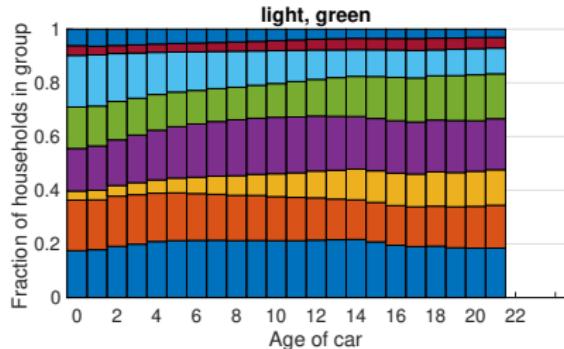
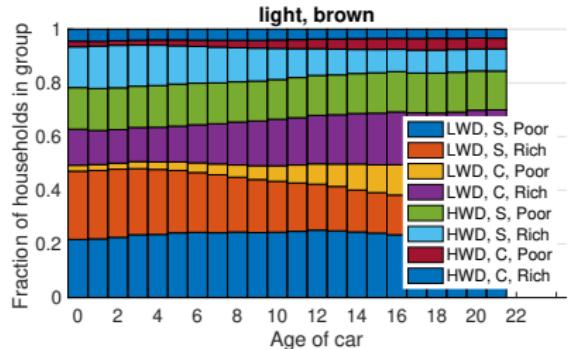
Model fit: Observed ownership distribution



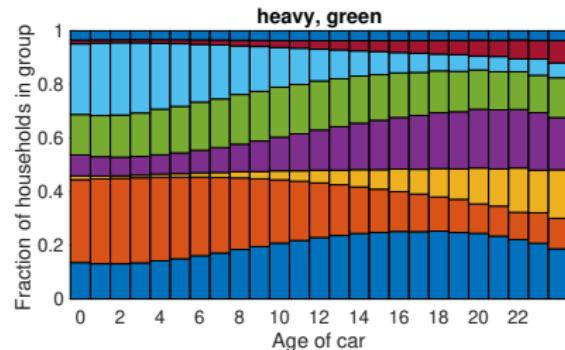
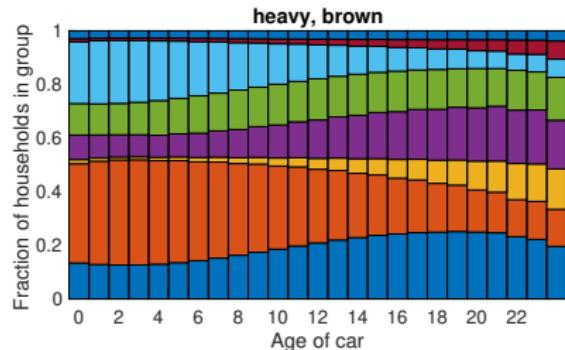
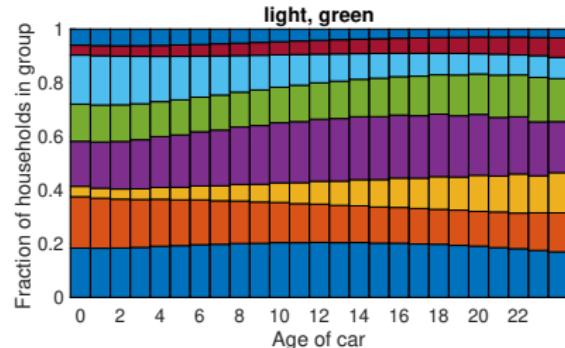
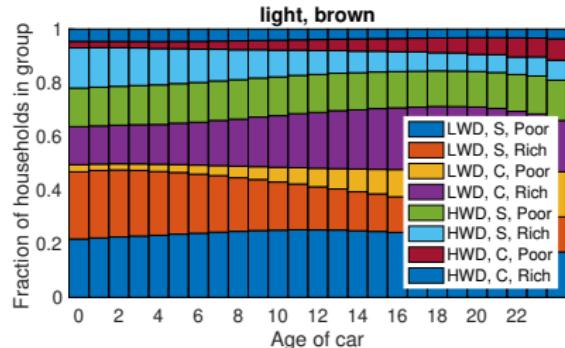
Model fit: Predicted ownership distribution



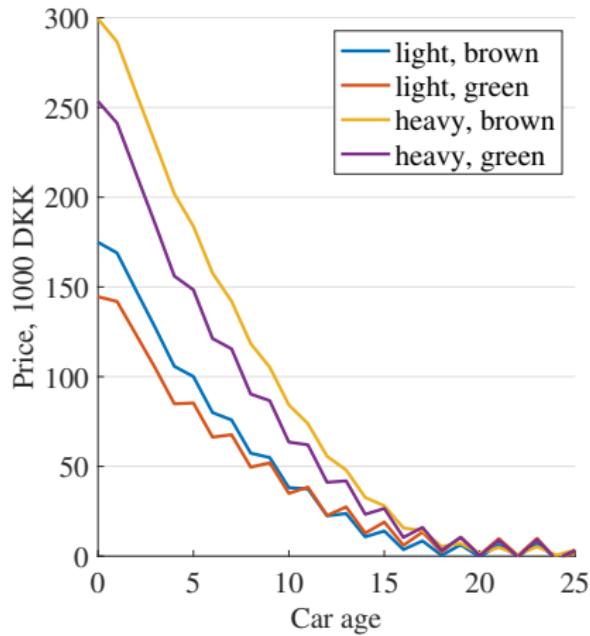
Model fit: Observed sorting



Model fit: Predicted sorting



Predicted equilibrium prices at secondary market



- ▶ Predicted prices similar to used car prices recommended by DAF.

Counterfactual simulation

Halving registration tax: Reduction in new car price between 25.6% (cheapest car), 28.6% (most expensive car)

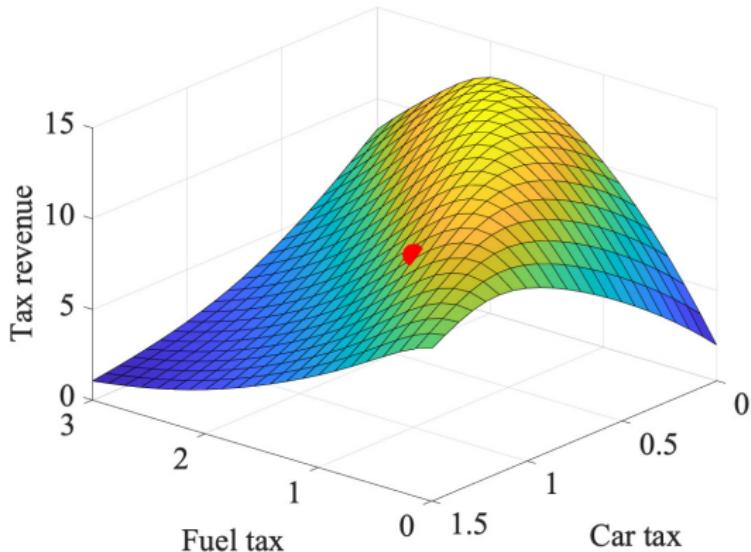
We consider the following four scenarios:

1. **Baseline:** Calibration under Danish tax rates from 2008.
2. **Naive, expected:** Non-equilibrium simulation:
 - ▶ Assume new and used car prices drops proportionally
 - ▶ Increase fuel taxes to keep total tax revenue neutral
(Fuel price increase from 56% to 76% of the price at the pump)
3. **Naive, realized:** Equilibrium simulation:
 - ▶ Policy as above + market equilibrium imposed
 - ▶ Not revenue neutral in equilibrium
(20% lower revenue than expected!)
4. **Sophisticated policy maker:**
 - ▶ Policy revenue-neutral in equilibrium
 - ▶ Fuel tax is lower, but leads to higher total tax revenue
(compared to realized tax revenue for naive policymaker)

Policy Simulation Results

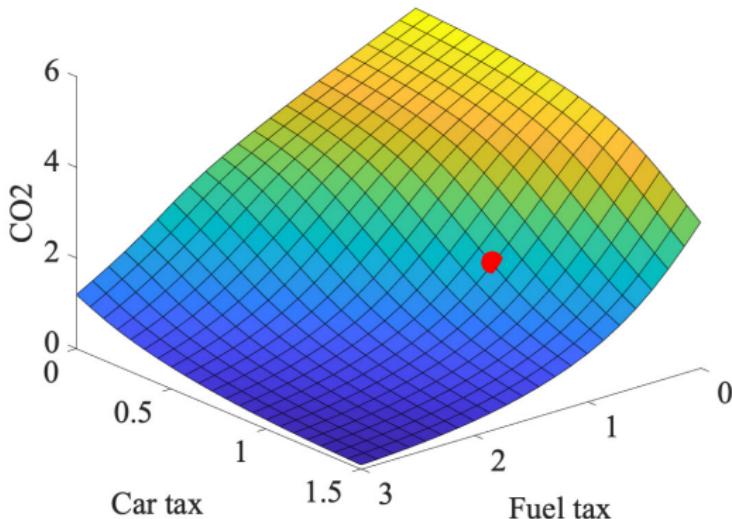
	Baseline	Naive, expected	Naive, realized	Sophisticated
<u>Policy choice variables</u>				
Registration tax (bottom rate)	1.050	0.525	0.525	0.525
Registration tax (top rate)	1.800	0.900	0.900	0.900
Fuel tax (share of pump price)	0.573	0.761	0.761	0.732
<u>Prices</u>				
Price, light, brown (1000 DKK)	174.902	129.532	129.532	129.532
Price, light, green (1000 DKK)	144.551	107.532	107.532	107.532
Price, heavy, brown (1000 DKK)	299.452	214.048	214.048	214.048
Price, heavy, green (1000 DKK)	253.397	182.796	182.796	182.796
Fuel price (DKK/l)	8.322	14.885	14.885	13.243
<u>Outcomes</u>				
Social surplus (1000 DKK)	9.382	11.281	8.439	10.203
Total tax revenue (1000 DKK)	9.391	9.391	7.452	9.391
Fuel tax revenue (1000 DKK)	4.282	5.184	4.983	6.224
Car tax revenue (1000 DKK)	5.110	4.207	2.468	3.167
Non-CO ₂ externalities (1000 DKK)	6.751	3.385	3.281	4.711
Externalities (1000 DKK)	7.374	3.702	3.586	5.157
Consumer surplus (1000 DKK)	7.364	5.592	4.573	5.969
CO ₂ (ton)	2.148	1.094	1.052	1.537
Driving (1000 km)	10.861	5.446	5.279	7.580
E(car age)	6.507	3.080	4.336	5.417
Pr(no car)	0.367	0.535	0.534	0.418

Laffer curves for new car registration tax and fuel tax



New car registration and the fuel tax relative to the baseline level of 1.
Tax revenue from new car sales tax and fuel tax.

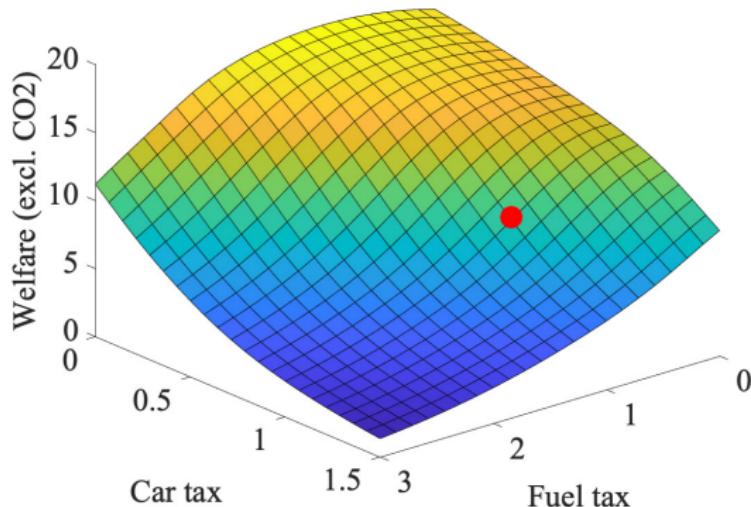
CO₂ emissions vs. new car registration and fuel taxes



New car registration and the fuel tax relative to the baseline level of 1.

Tax revenue from new car sales tax and fuel tax.

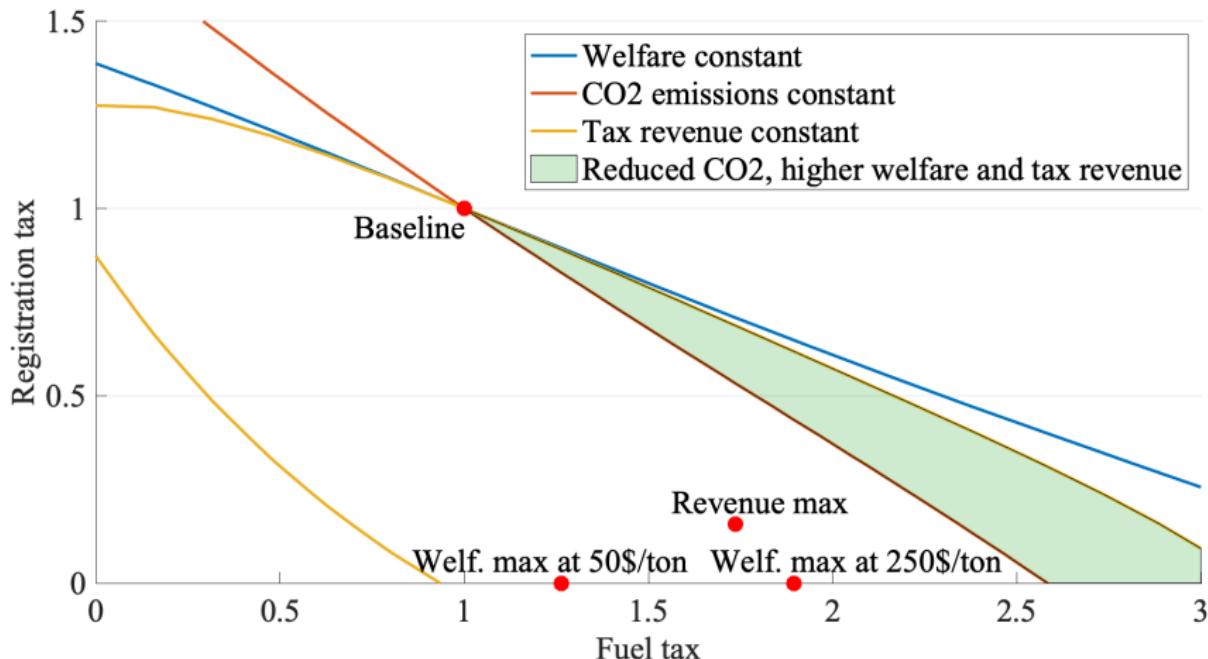
Social welfare (ex CO₂) vs. registration and fuel taxes



New car registration and the fuel tax relative to the baseline level of 1.

Tax revenue from new car sales tax and fuel tax.

Trade-off between CO₂ emissions and social welfare



Conclusion

- ▶ **Theory contribution:** characterize and prove existence of equilibrium in a tractable model of primary and secondary markets.
- ▶ **Applied contribution:** tractable model with
 - ▶ Transactions, scrappage, consumer/car heterogeneity,
 - ▶ Flexible utility: estimating 131 parameters with $39 \cdot 10^6$ observations in under 30 min on a laptop
- ▶ **Conclusion:** High Danish taxes above the Laffer curve's top point
 - ▶ "naive" model overestimates the strength of this effect,
 - ▶ possibly leading to detrimental policies for tax revenues and the environment
 - ▶ Opportunity to reduce CO₂, and increase tax revenues and social welfare