ACCOUNTING FOR EXPECTATIONS ABOUT THE FUTURE

A DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL (DDCCM) OF CAR OWNERSHIP, USAGE AND FUEL TYPE

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OUTLINE

- Introduction
- Background and data
- The dynamic discrete-continuous choice modeling framework
- Illustration of model application
- Conclusion and future works

INTRODUCTION

Aim of the research:

- Model dynamics of car transactions, usage and choice of fuel type in the Swedish car fleet

- Motivations
  - Governmental policies to reduce carbon emissions / car usage:
    - Stockholm congestion tax
    - Independence of fossil fuels
  - Technology changes:
    - Increase of alternative-fuel vehicles
  - Economical features:
    - Financial crisis
    - Fuel price changes

⇨ Car ownership and usage vary importantly over time.
⇨ Model needed to analyze and predict impact of policies on ownership

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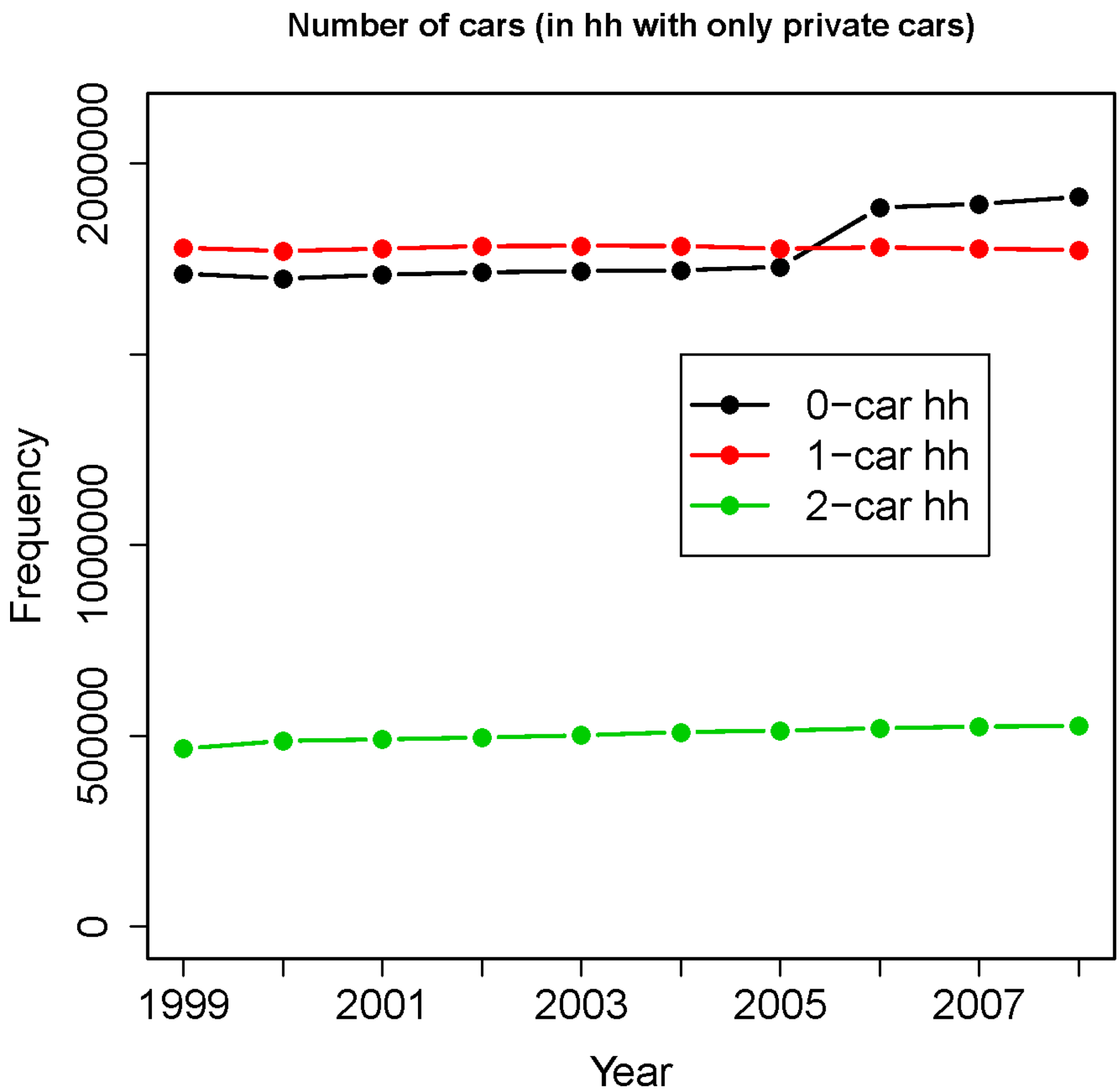
BACKGROUND AND DATA

Register data of Swedish population and car fleet:

- Data from 1998 to 2008
- All individuals
  - **Individual information**: socio-economic information on car holder (age, gender, income, home/work location, employment status/sector, etc.)
  - **Household information**: composition (families with children and married couples)
- All vehicles
  - Privately-owned cars, cars from privately-owned company and **company** cars
  - Vehicle **characteristics** (make, model, fuel consumption, fuel type, age)
  - **Annual mileage** from odometer readings
  - Car bought **new or second-hand**

BACKGROUND AND DATA

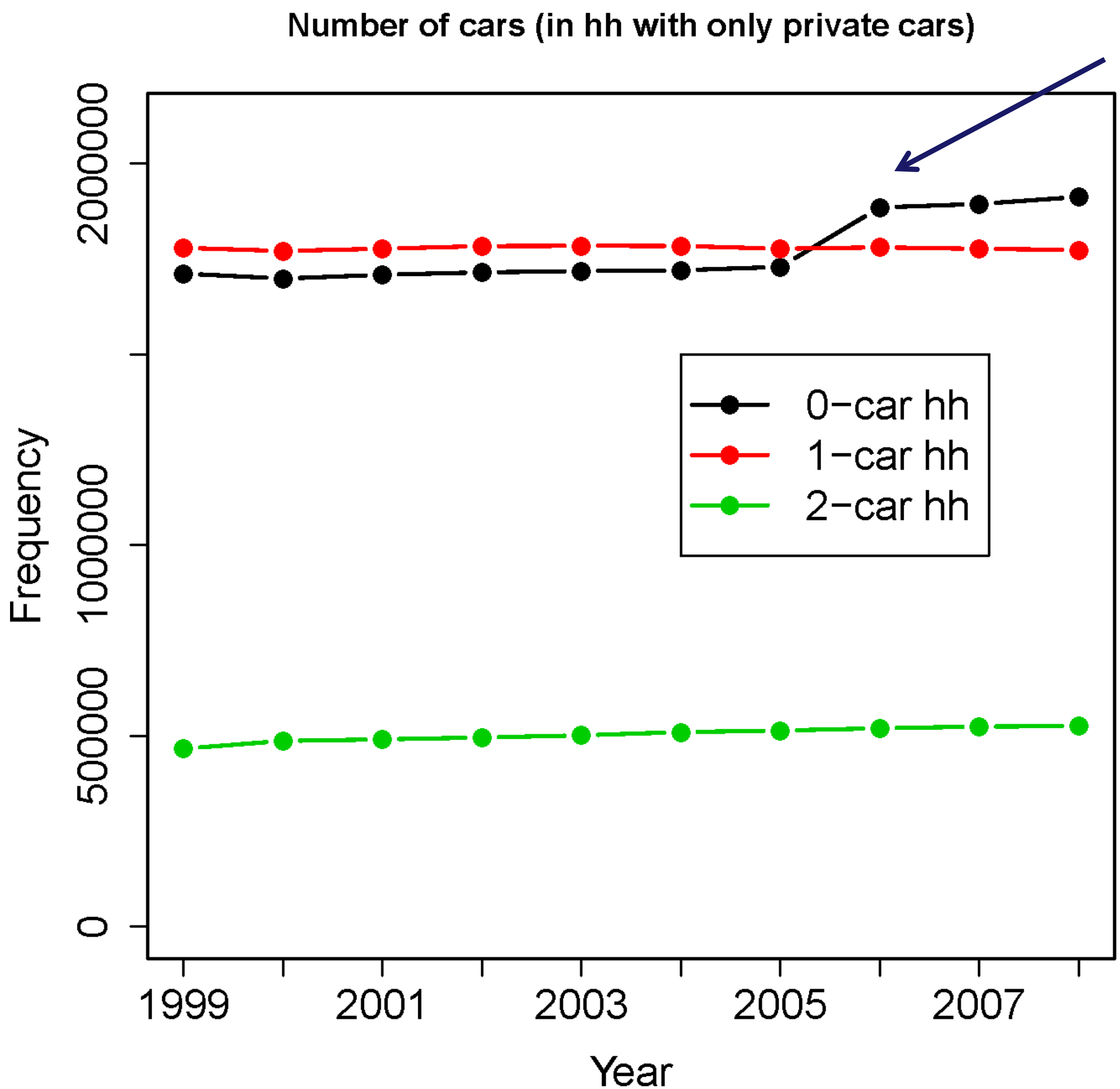
OWNERSHIP



BACKGROUND AND DATA

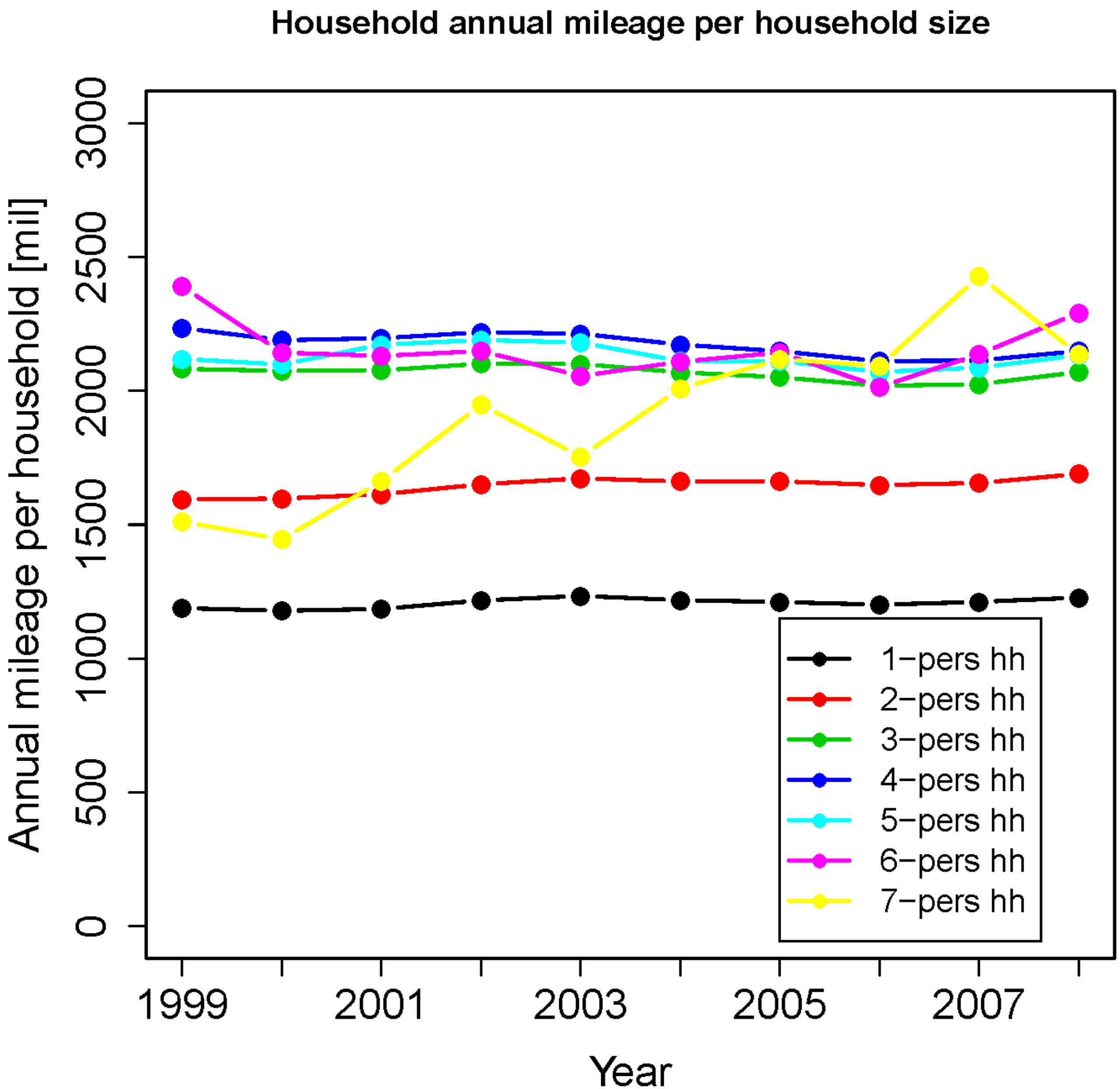
OWNERSHIP

Congestion tax Stockholm



BACKGROUND AND DATA

USAGE



BACKGROUND AND DATA

LITERATURE

- Car ownership models in transportation literature:
  - Discrete choice models (DCM) widely used, but mostly **static models**.
    - Main drawback: do not account for forward-looking behavior
    - Important aspect to account for since car is a durable good
  - **Econometric literature**: **dynamic programming (DP)** models + DCM
  - Recently, **dynamic discrete choice models (DDCM)** starting to be applied in transportation field (Cirillo and Xu, 2011; Schiraldi, 2011)

- Joint models of car ownership and usage:
  - **Duration models** and regression techniques for car holding duration and usage (De Jong, 1996)
  - Vehicle type, usage and replacement decisions using **dynamic programming**, **discrete-continuous**, mixed logit (Schjerning, 2008, and Munk-Nielsen, 2012)
  - **Discrete-continuous model** of vehicle choice and usage based on register data (Gillingham, 2012)

- Wide literature on car ownership and usage models

BACKGROUND AND DATA

RESEARCH ISSUES

- Car are durable goods $\Longrightarrow$ Need to account for **forward-looking behavior** of agents
- Difficulty of modeling a **discrete-continuous choice** when jointly modeling car ownership and usage
- Many models focus on individual decisions, but choices regarding car ownership and usage made at **household level**

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BACKGROUND AND DATA

- Car are durable goods ⟹ Need to account for **forward-looking behavior** of agents
- Difficulty of modeling a **discrete-continuous choice** when jointly modeling car ownership and usage
- Many models focus on individual decisions, but choices regarding car ownership and usage made at **household level**

Proposed methodology:

- Attempt to address these issues by applying **dynamic discrete-continuous choice model (DDCCM)**

Large **register data** of all **individuals** and **cars** in Sweden

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BACKGROUND AND DATA

MAIN FEATURES

- In the area of **dynamic choice modeling**
  - Choices modeled at **household level**
  - **Up to two cars** allowed
- **Constant elasticity of substitution (CES) utility** to model annual driving distance for 2-car households
- Several **choices modeled simultaneously**

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DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

THE CHOICE VARIABLE IN DETAILS

Objective

Model simultaneously car ownership, usage and fuel type.
In details: model simultaneous choice of

$$\text{Transaction type} \times \left[\text{Annual milage – car } c \times \text{Private/company car – car } c \times \text{Fuel type – car } c \times \text{New/2}^{\text{nd}}\text{ hand – car } c \right]^{\#\text{ cars}}$$

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Discrete variables

THE CHOICE VARIABLE IN DETAILS

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Continuous variables

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

ASSUMPTIONS

1. **Choice** at **household level**: up to 2 cars in household

2. **Strategic choice** of:
   - Transaction
   - Type(s) of ownership (company vs private car)
   - Fuel type(s)
   - Car state(s) (new vs 2nd-hand)

⟹ Account for forward-looking behavior of households

3. **Myopic choice** of:
   - Annual mileage(s)

4. **Choice** of **mileage conditional** on choice of discrete variables

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

Myopic choice (static case)

$$P(\text{action}) = \frac{\exp\{\text{instantaneous utility}\}}{\sum_{\text{all poss. actions}} \exp\{\text{instantaneous utilities}\}}$$

Strategic choice (dynamic case)

$$P(\text{action}) = \frac{\exp\{\text{instantaneous utility} + \text{expected discounted utility of future choices}\}}{\sum_{\text{all poss. actions}} \exp\{\text{instantaneous utilities} + \text{expected discounted utilities of future choices}\}}$$

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Embeds a **choice model** into a **dynamic programming framework**

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DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

Components of the DDCCM:

- Agent
- Time step
- State space
- Action space
- Transition rule
- Instantaneous utility function

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Agent: household
- Time step *t*: year
- State space *S*

$$s_t = (\underbrace{y_{1,t}}_{\text{Age – 1st car}}, \underbrace{I_{1,t}}_{\text{Private/ company car – 1st car}}, \underbrace{f_{1,t}}_{\text{Fuel type – 1st car}}, \underbrace{y_{2,t}}_{\text{Age – 2nd car}}, \underbrace{I_{2,t}}_{\text{Private/ company car – 2nd car}}, \underbrace{f_{2,t}}_{\text{Fuel type – 2nd car}})$$

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Action space *A*

$$a_t = (h_t, \tilde{m}_{1,t}, \tilde{I}_{1,t}, \tilde{f}_{1,t}, \tilde{r}_{1,t}, \tilde{m}_{2,t}, \tilde{I}_{2,t}, \tilde{f}_{2,t}, \tilde{r}_{2,t})$$

Transaction type

Mileage – 1st car

Private/ company car – 1st car

Fuel type – 1st car

New/ 2nd hand – 1st car

Mileage - 2nd car

Private/ company car – 2nd car

Fuel type – 2nd car

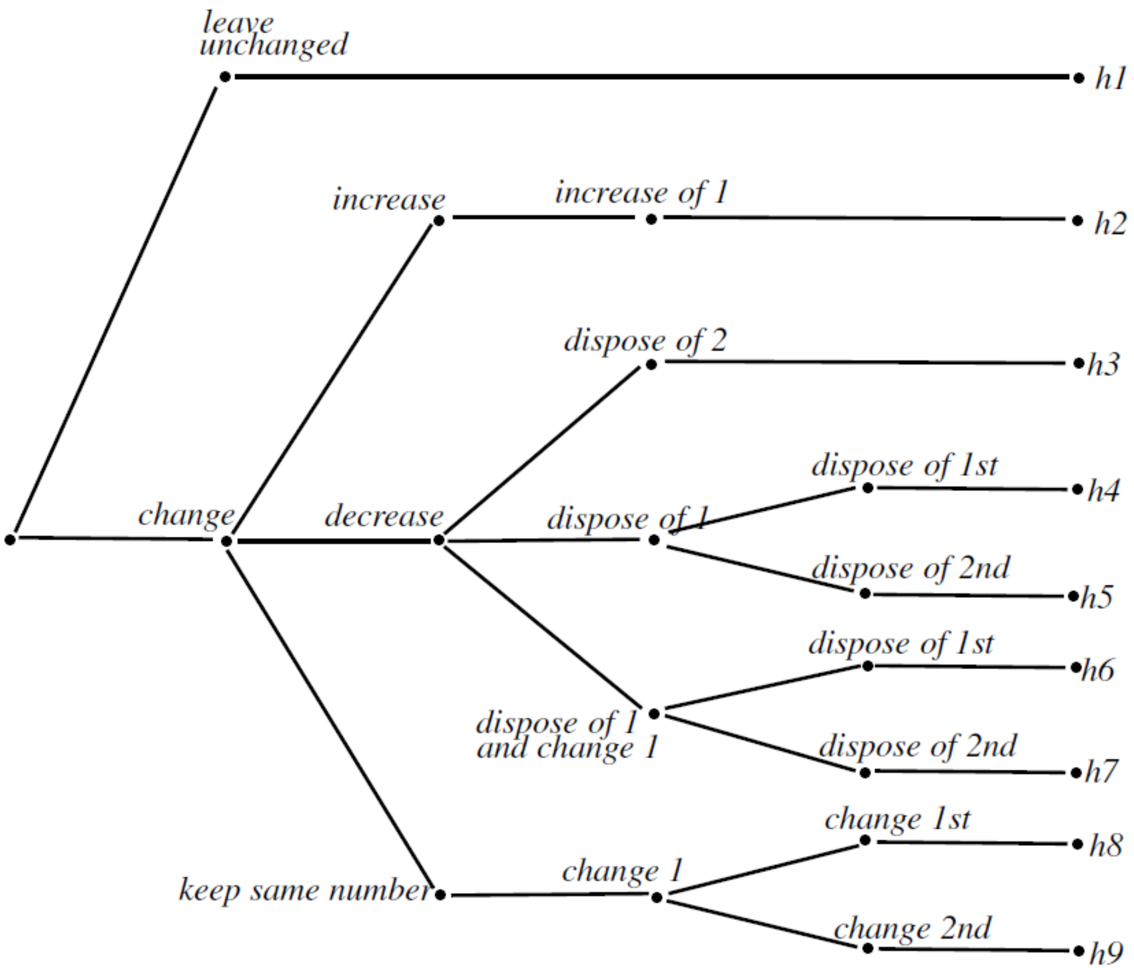
New/ 2nd hand – 2nd car

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Action space *A*

Transaction types



DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Transition rule: deterministic rule: each state s_{t+1} can be inferred exactly once s_t and a_t are known.

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Transition rule: deterministic rule: each state s_{t+1} can be inferred exactly once s_t and a_t are known.

- Instantaneous utility function:

$$u(s_t, a_t^C, a_t^D, x_t, \theta) = \underbrace{v(s_t, a_t^C, a_t^D, x_t, \theta)}_{\text{Deterministic term}} + \underbrace{\varepsilon_D(a_t^D)}_{\text{Random term for discrete choices}}$$

Assume additive **deterministic utility** for simplicity (see also Munk-Nielsen, 2012):

$$v(s_t, a_t^C, a_t^D, x_t, \theta) = \underbrace{v_t^D(s_t, a_t^D, x_t, \theta)}_{\text{Utility for discrete actions}} + \underbrace{v_t^C(s_t, a_t^D, a_t^C, x_t, \theta)}_{\text{Utility for continuous actions}}$$

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

DEFINITION OF THE COMPONENTS

- Instantaneous utility function
  - Utility for continuous actions:
    Constant elasticity of substitution (CES) utility function (e.g. Zabalza, 1983):

$$v_t^C(s_t, a_t^D, a_t^C, x_t, \theta) = (m_{1,t}^{-\rho} + \alpha \cdot m_{2,t}^{-\rho})^{-1/\rho}$$

    - Captures substitution patterns between the choice of both annual driving distances
    - ρ = elasticity of substitution
    - α = share parameter
  - Formulation could be extended to introduce randomness in α.

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

SOLVING THE DYNAMIC PROGRAMMING PROBLEM

1. Finding the optimal value(s) of annual mileage conditional on the discrete choices

2. Solving the Bellman equation to find expected utility of future choices (value function)

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

SOLVING THE DYNAMIC PROGRAMMING PROBLEM

Finding the optimal value(s) of mileage

- Maximization of the continuous utility: $\max_{m_{1,t},m_{2,t}} v_t^C$

  s.t. $p_{1,t}m_{1,t} + p_{2,t}m_{2,t} = \text{Inc}_t$

- Find analytical solutions: $m_{1,t}^*$ and $m_{2,t}^*$

$$m_{2,t}^* = \frac{\text{Inc}_t \cdot p_{2,t}^{(-1/(\rho+1))}}{p_{2,t}^{(\rho/(\rho+1))} + p_{1,t}^{(\rho/(1+\rho))}\alpha^{(-1/(\rho+1))}}$$

$$m_{1,t}^* = \frac{\text{Inc}_t}{p_{1,t}} - \frac{p_{2,t}}{p_{1,t}} m_{2,t}^*$$

- Optimal continuous utility $v_t^{C*}(s_t, a_t^D, a_t^{C*}, x_t, \theta)$

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Solving the Bellman equation

- Logsum formula used in the completely discrete case (DDCM) (Aguirregabiria and Mira, 2010; Cirillo and Xu, 2011)
- Logsum can be applied here given the key assumptions:
  - Choice of mileage(s) is conditional on discrete actions
  - Choice of mileage(s) is myopic

$$\bar{V}(s_t, x_t, \theta) = \log \sum_{a_t^D} \left\{ \exp\{v_t^D(s_t, a_t^D, x_t, \theta) + v_t^{C*}(s_t, a_t^D, a_t^{C*}, x_t, \theta)\} + \beta \sum_{s_{t+1} \in S} \bar{V}(s_{t+1}, x_{t+1}, \theta) f(s_{t+1} | s_t, a_t) \right\}$$

- Iterate on Bellman equation to find integrated value function $\overline{\boldsymbol{V}}$

DYNAMIC DISCRETE-CONTINUOUS CHOICE MODEL

- Parameters obtained by maximizing likelihood:

$$\mathcal{L} = \prod_{n=1}^{N} \prod_{t=1}^{T_n} P(a_{n,t}^{D} | s_{n,t}, x_{n,t}, \theta)$$

- Optimization algorithm is Rust's **nested fixed point algorithm (NFXP)** (Rust, 1987):
    - **Outer optimization algorithm:** search algorithm to obtain parameters maximizing likelihood
    - **Inner value iteration algorithm:** solves the DP problem for each parameter trial
- Plan to investigate variants of NFXP to speed up computational time (e.g. swapped algorithm from Aguirregabiria and Mira, 2002)

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ILLUSTRATIVE EXAMPLE

Assumptions for the example:

- Deterministic utility function

$$v_t^D(s_t, a_t^D, x_t, \theta) = \mathrm{C}(s_t) + \tau(a_t^D) + \beta_{\mathrm{Age}}(a_t^D, s_t) \cdot \max(\mathrm{Age1}_t, \mathrm{Age2}_t)$$

Constant for households with at least one car

Transaction costs

Transaction-dependant parameters relative to age of oldest car

- Chose arbitrary values for parameters

ILLUSTRATIVE EXAMPLE

		β_{Age}			τ
Transaction name	Case	0 car	1 car	2 cars	all households
h_1: leave unchanged		0	-1	-1	0
h_2: increase 1		0	0	-	-3
h_3: dispose 2		-	-	1	0
h_4: dispose 1st	1st car is oldest	-	1.5	1.5	0
	2nd car is oldest	-	-	0	0
h_5: dispose 2nd	1st car is oldest	-	-	0	0
	2nd car is oldest	-	-	1.5	0
h_6: dispose 1st and change 2nd		-	-	0	-4
h_7: dispose 2nd and change 1st		-	-	0	-4
h_8: change 1st	1st car is oldest	-	1.5	1.5	-4
	2nd car is oldest	-	-	0	-4
h_9: change 2nd	1st car is oldest	-	-	0	-4
	2nd car is oldest	-	-	1.5	-4

ILLUSTRATIVE EXAMPLE

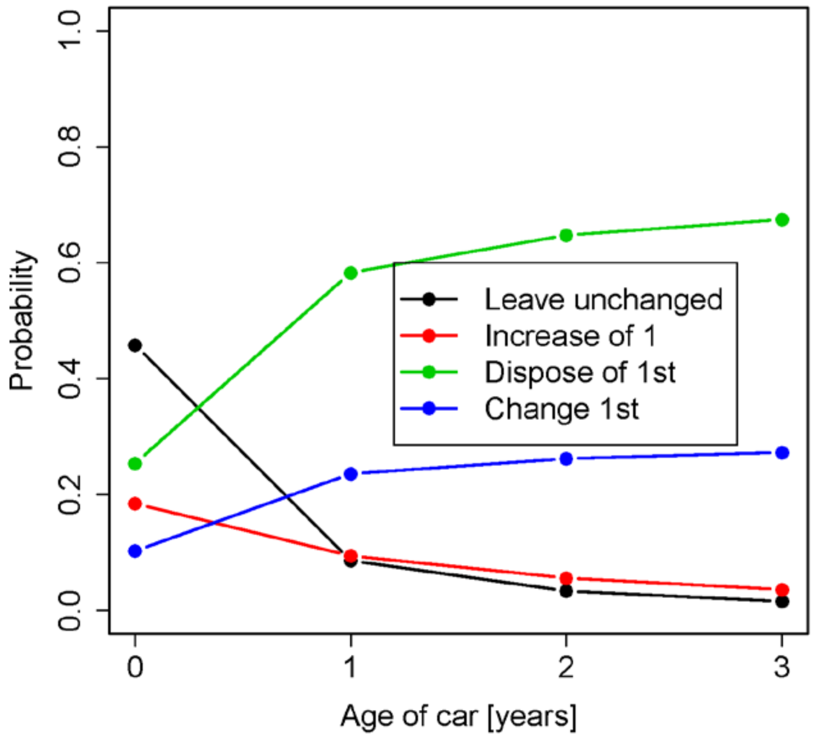
Assumptions for the example:

- Visualize choice probabilities for one observation:
  - 1-car household
  - Annual income = 530’000 SEK (≈ 58300 €; 84800 AUD)
  - 8% expenses on fuel

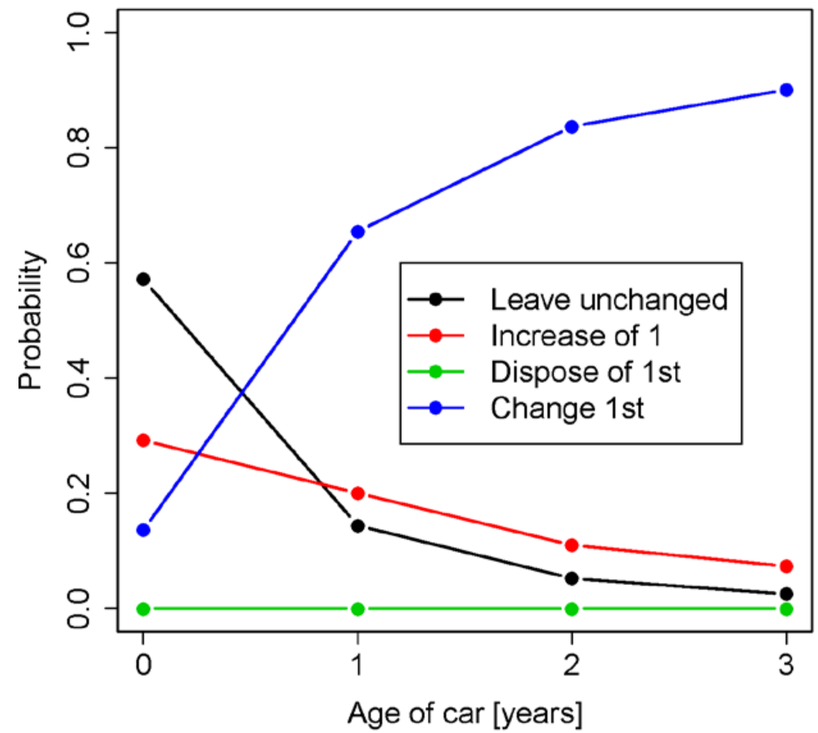
ILLUSTRATIVE EXAMPLE

FROM MODEL APPLICATION

Static



Dynamic



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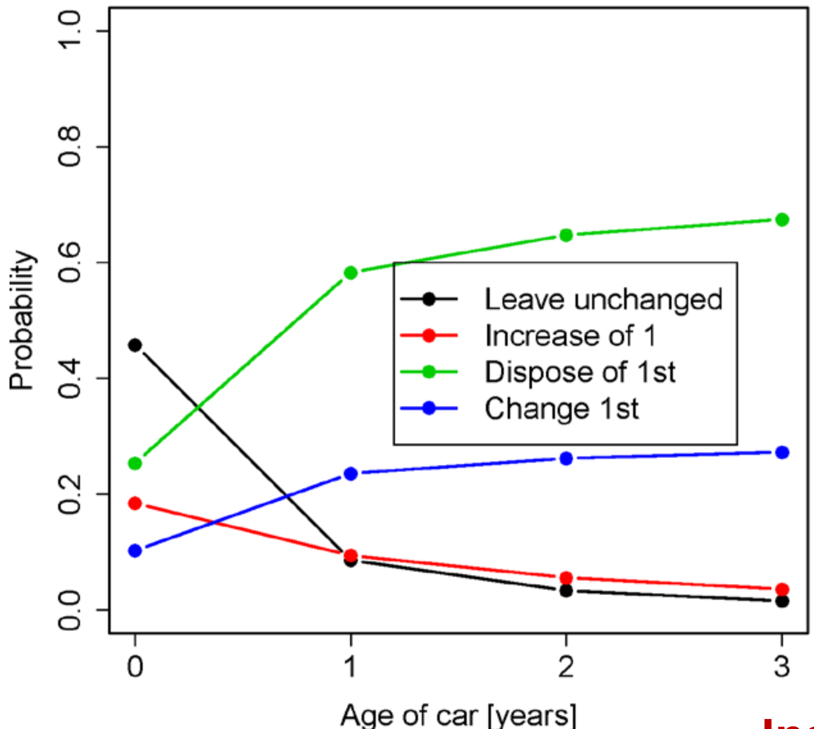

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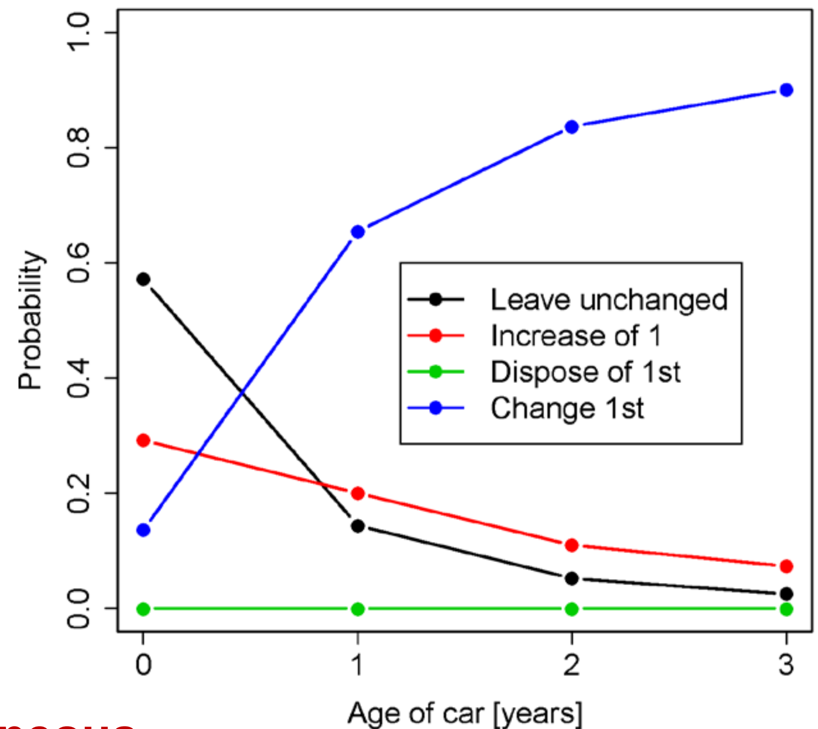

Instantaneous utility

$$P(a^D_{n,t} | s_{n,t}, x_{n,t}, \theta) = \frac{\boxed{v^D_{n,t} + v^{C*}_{n,t}} + \beta \sum_{s_{n,t+1} \in S} \bar{V} f}{\sum_{\tilde{a}^D_{n,t}} \left\{ v^D_{n,t} + v^{C*}_{n,t} + \beta \sum_{s_{n,t+1} \in S} \bar{V} f \right\}}$$

ILLUSTRATIVE EXAMPLE

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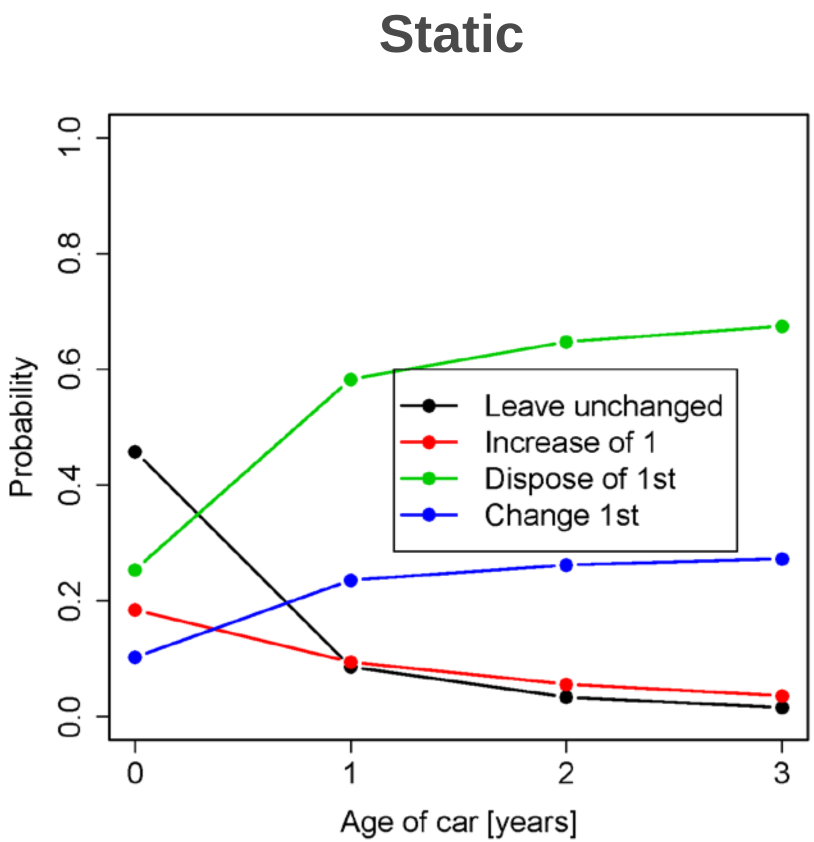

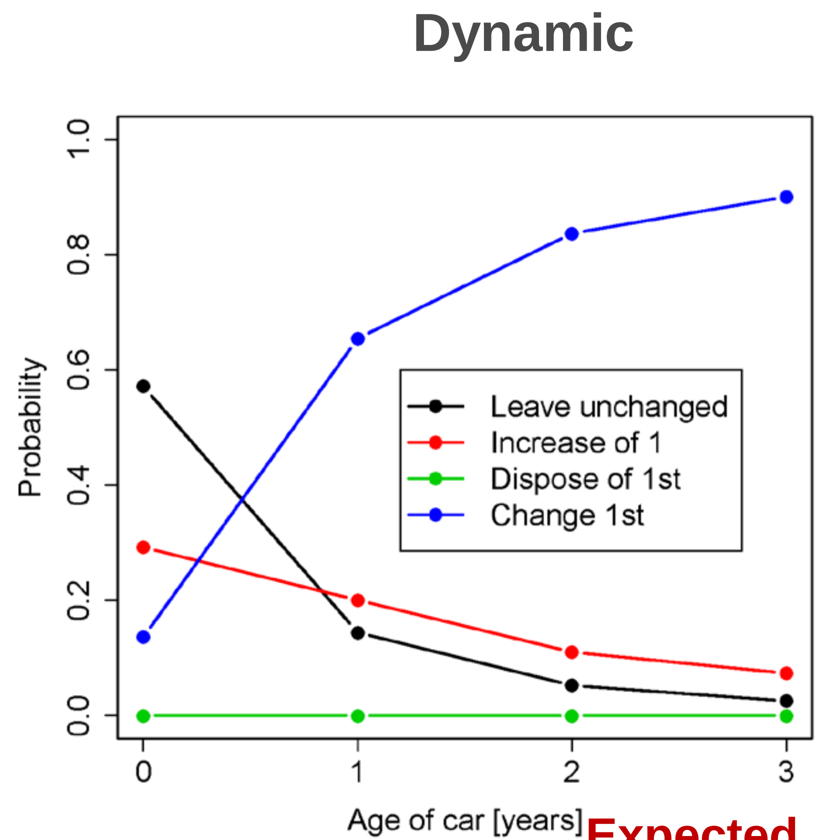

Expected discounted utility

$$P(a^D_{n,t} | s_{n,t}, x_{n,t}, \theta) = \frac{v^D_{n,t} + v^{C*}_{n,t} + \boxed{\beta \sum_{s_{n,t+1} \in S} \bar{V} f}}{\sum_{\tilde{a}^D_{n,t}} \left\{ v^D_{n,t} + v^{C*}_{n,t} + \beta \sum_{s_{n,t+1} \in S} \bar{V} f \right\}}$$

ILLUSTRATIVE EXAMPLE

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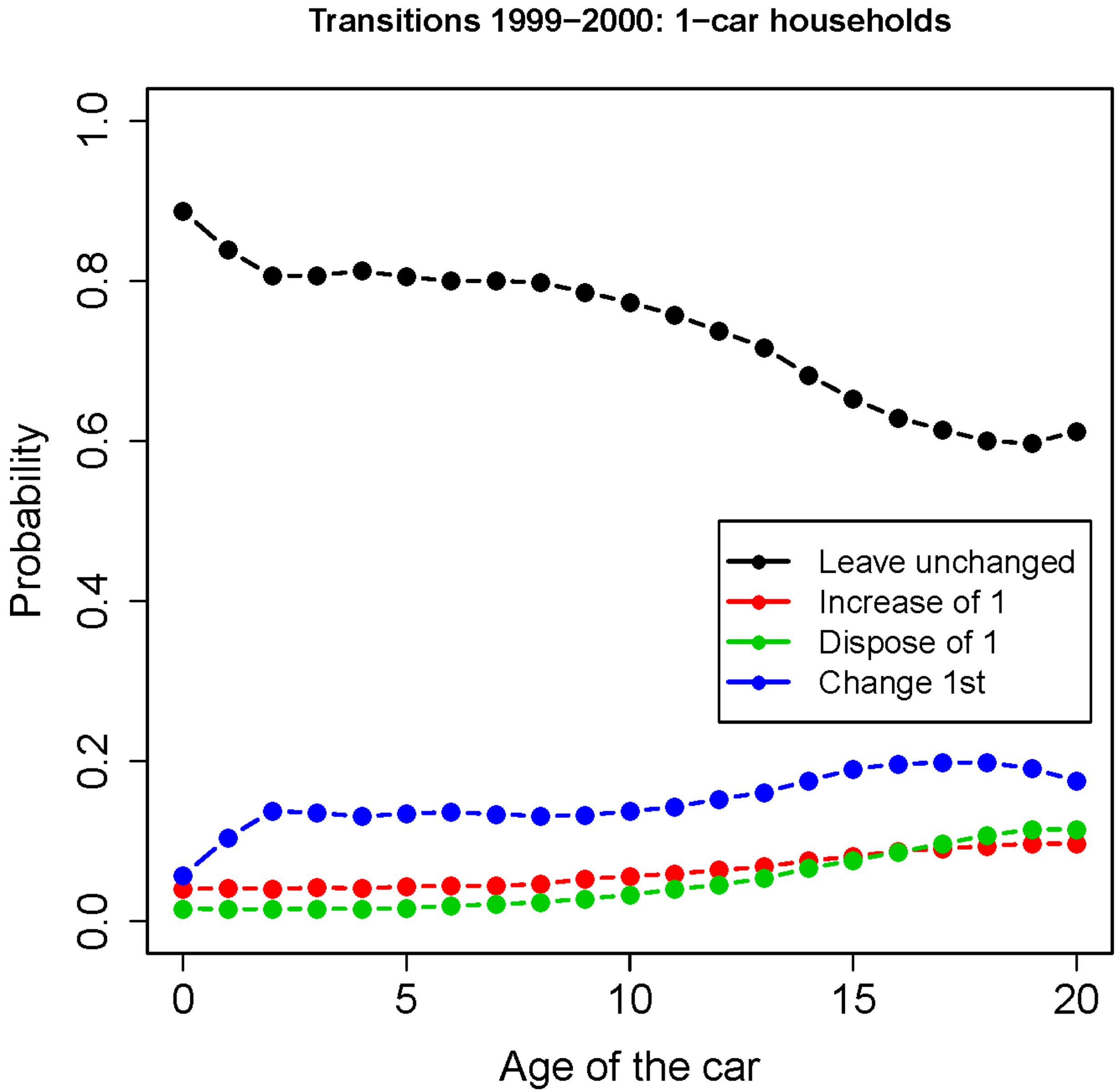

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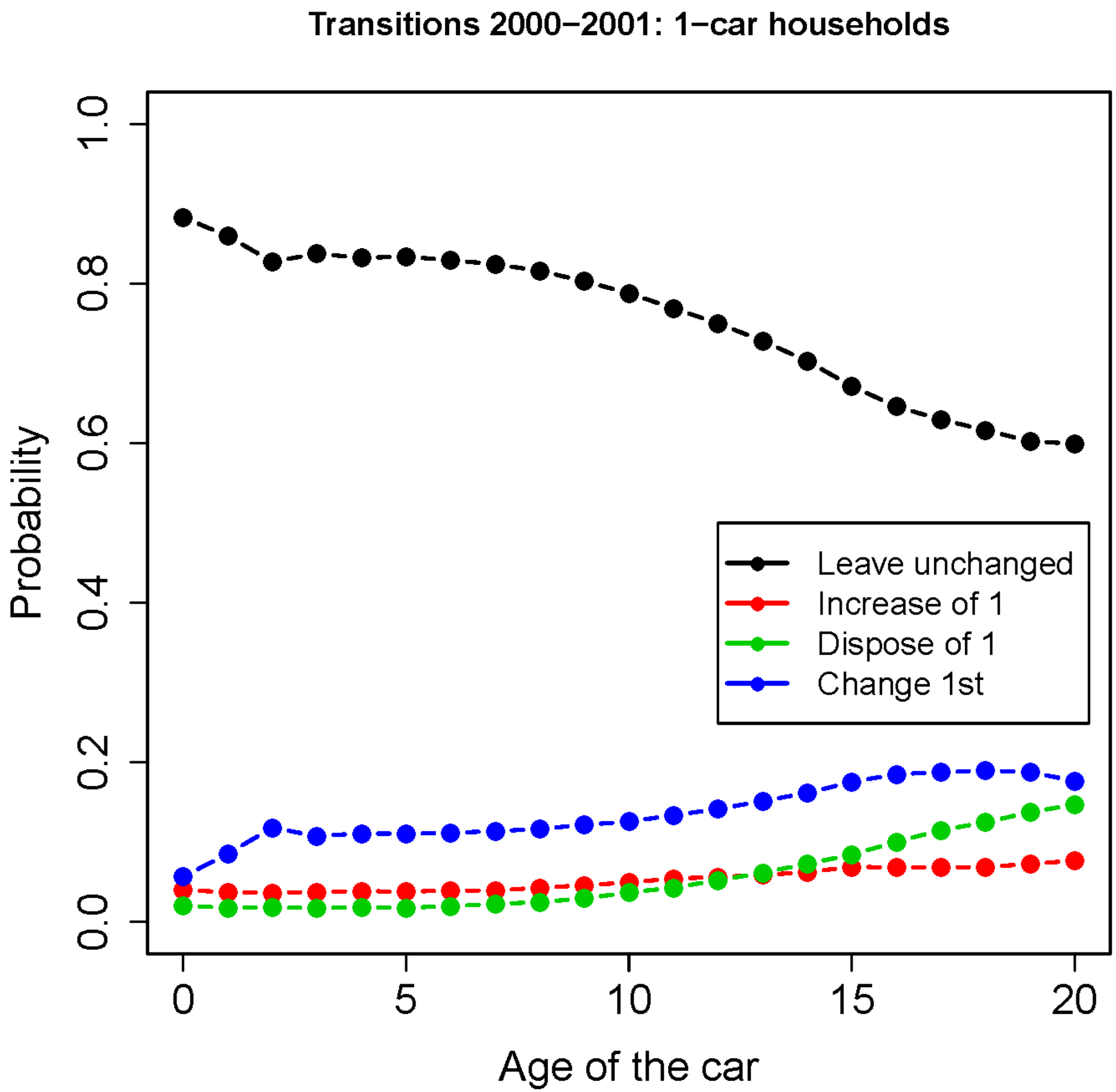

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ILLUSTRATIVE EXAMPLE

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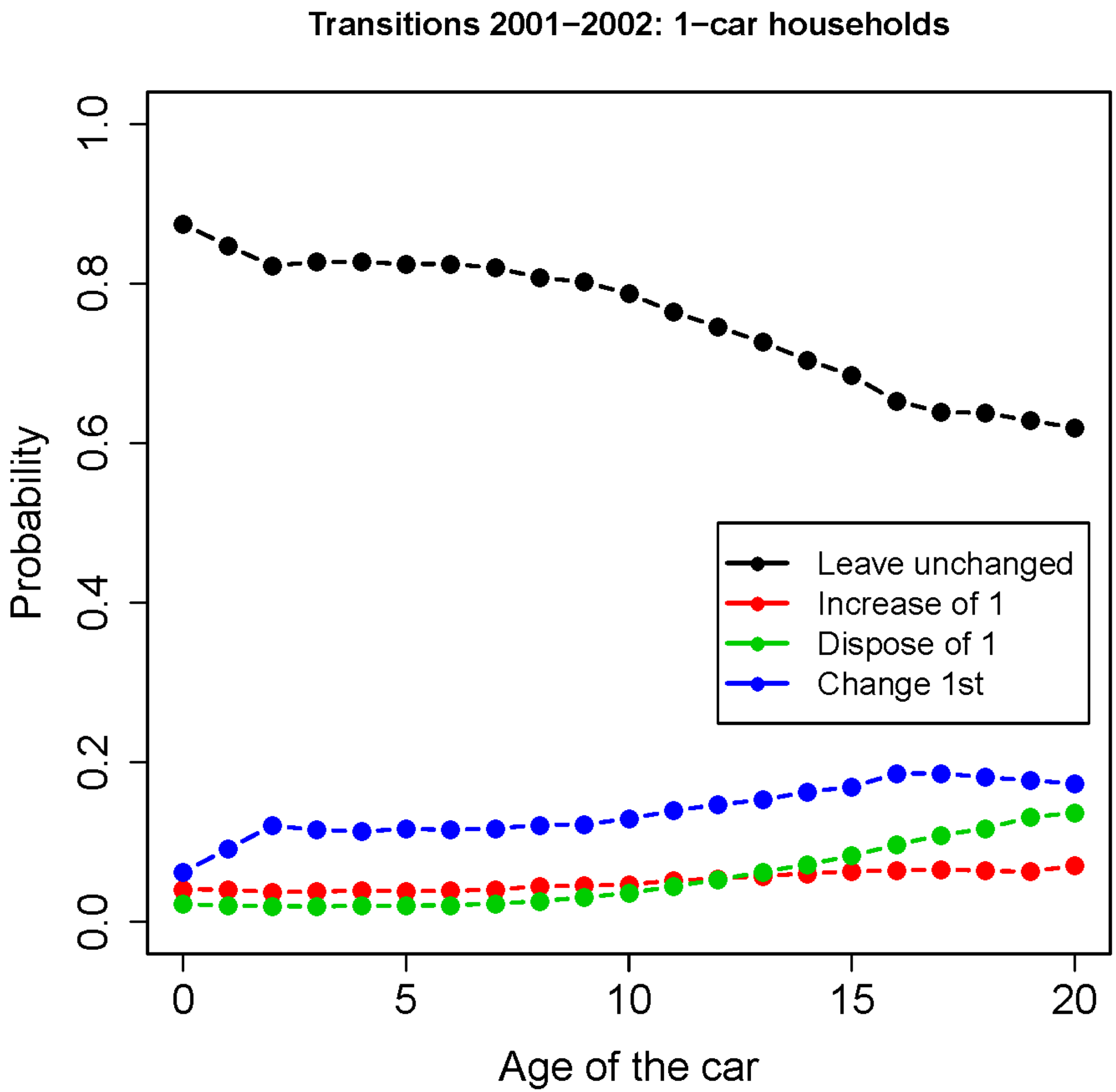

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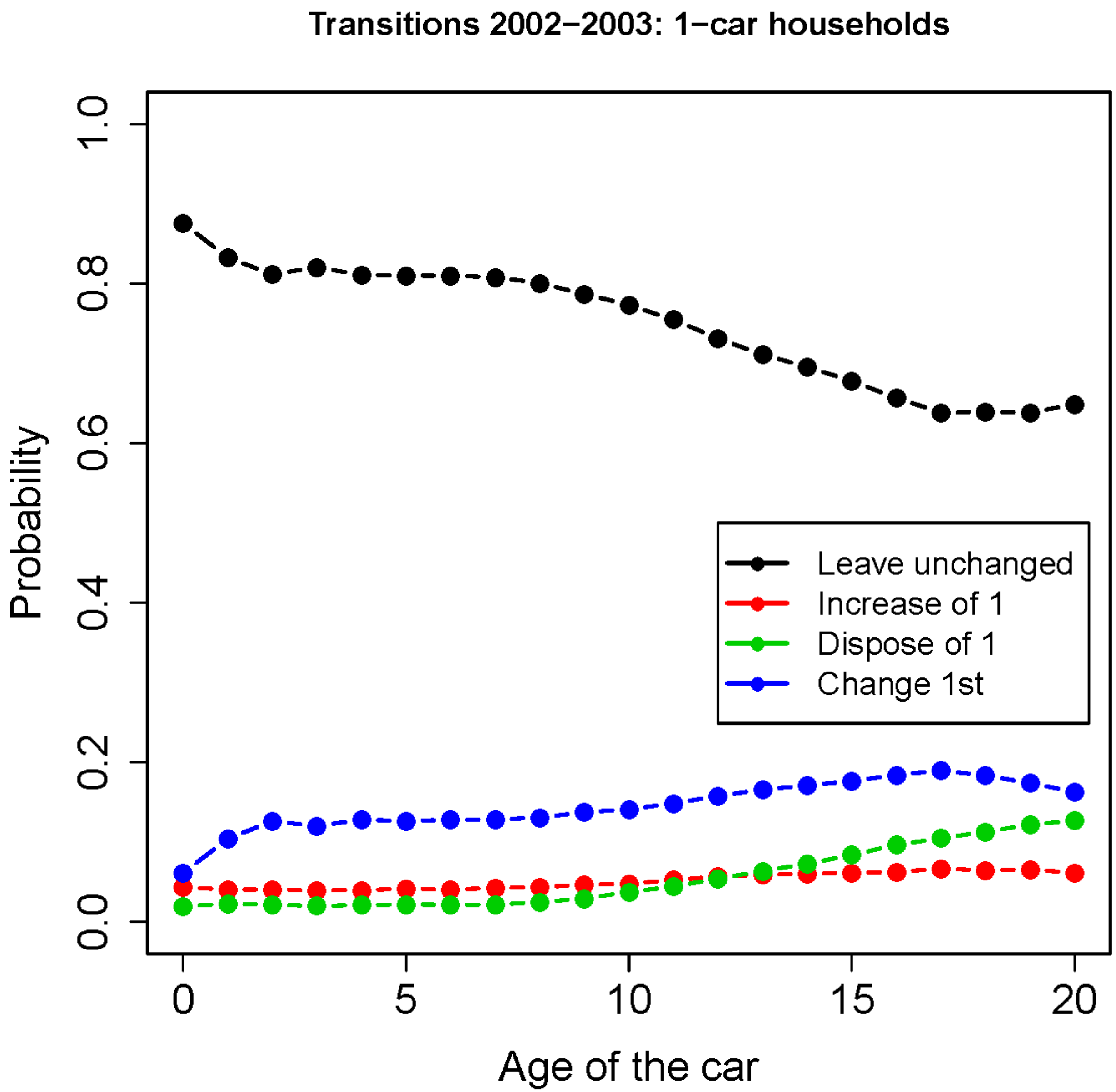

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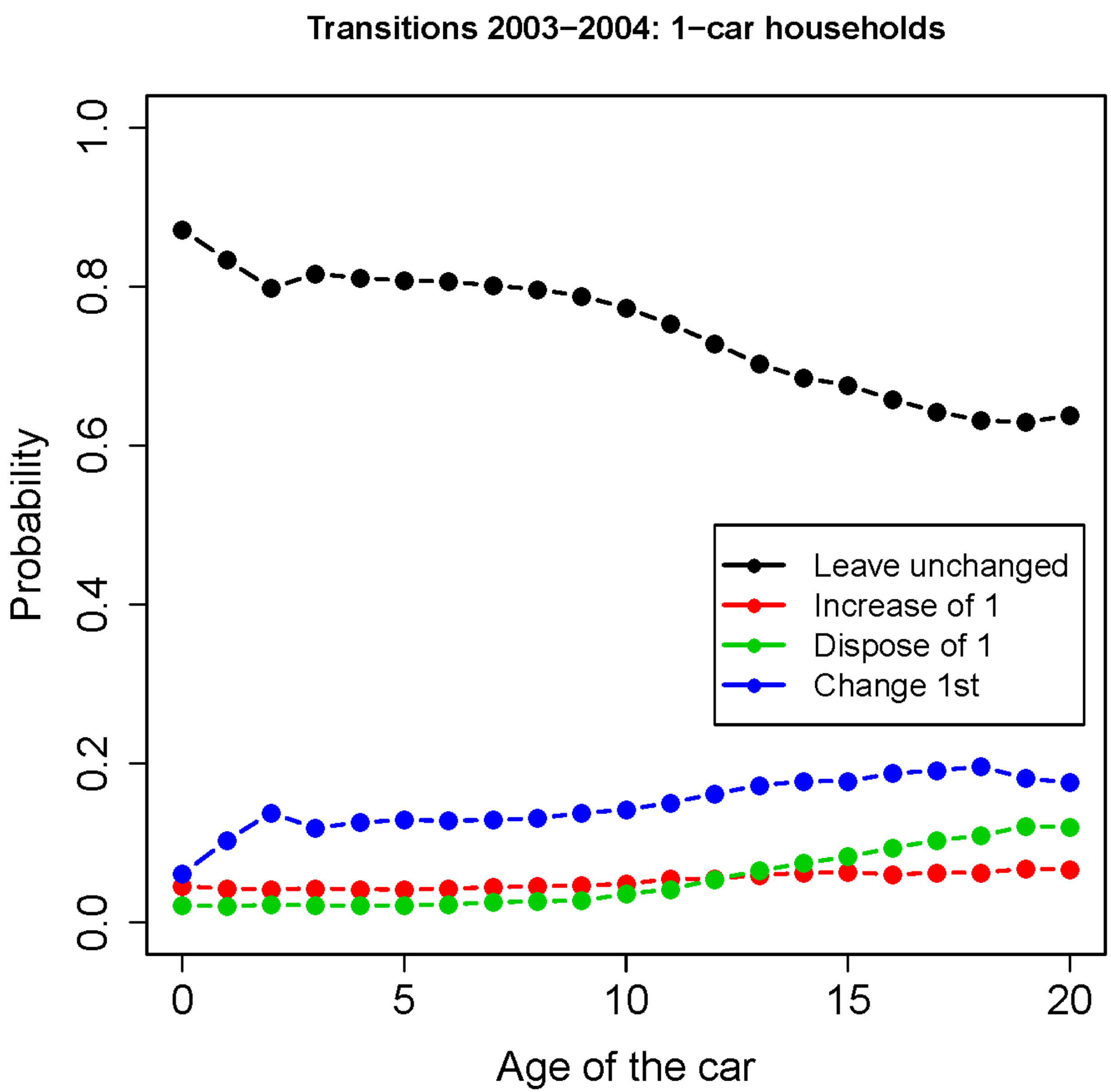

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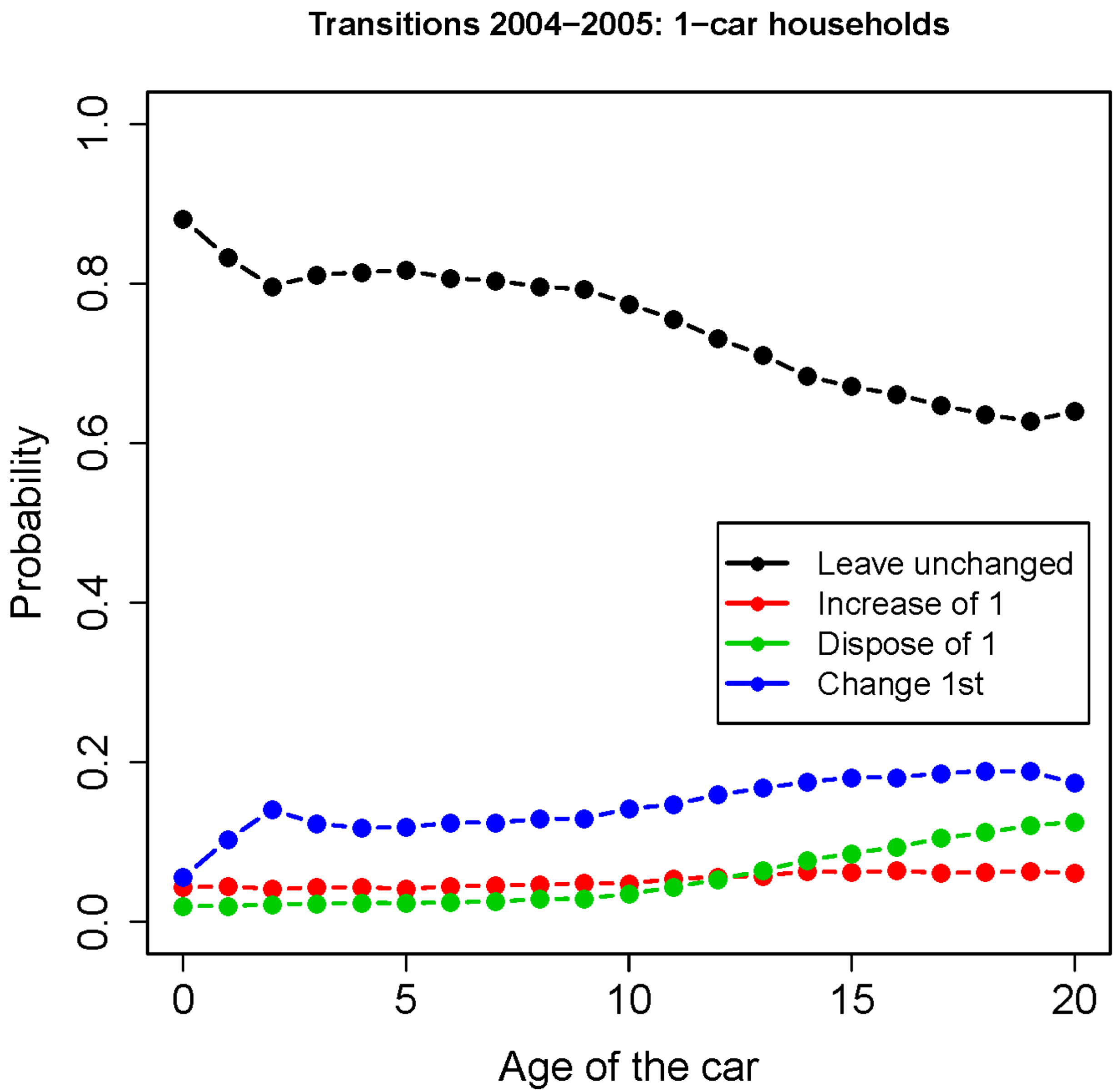

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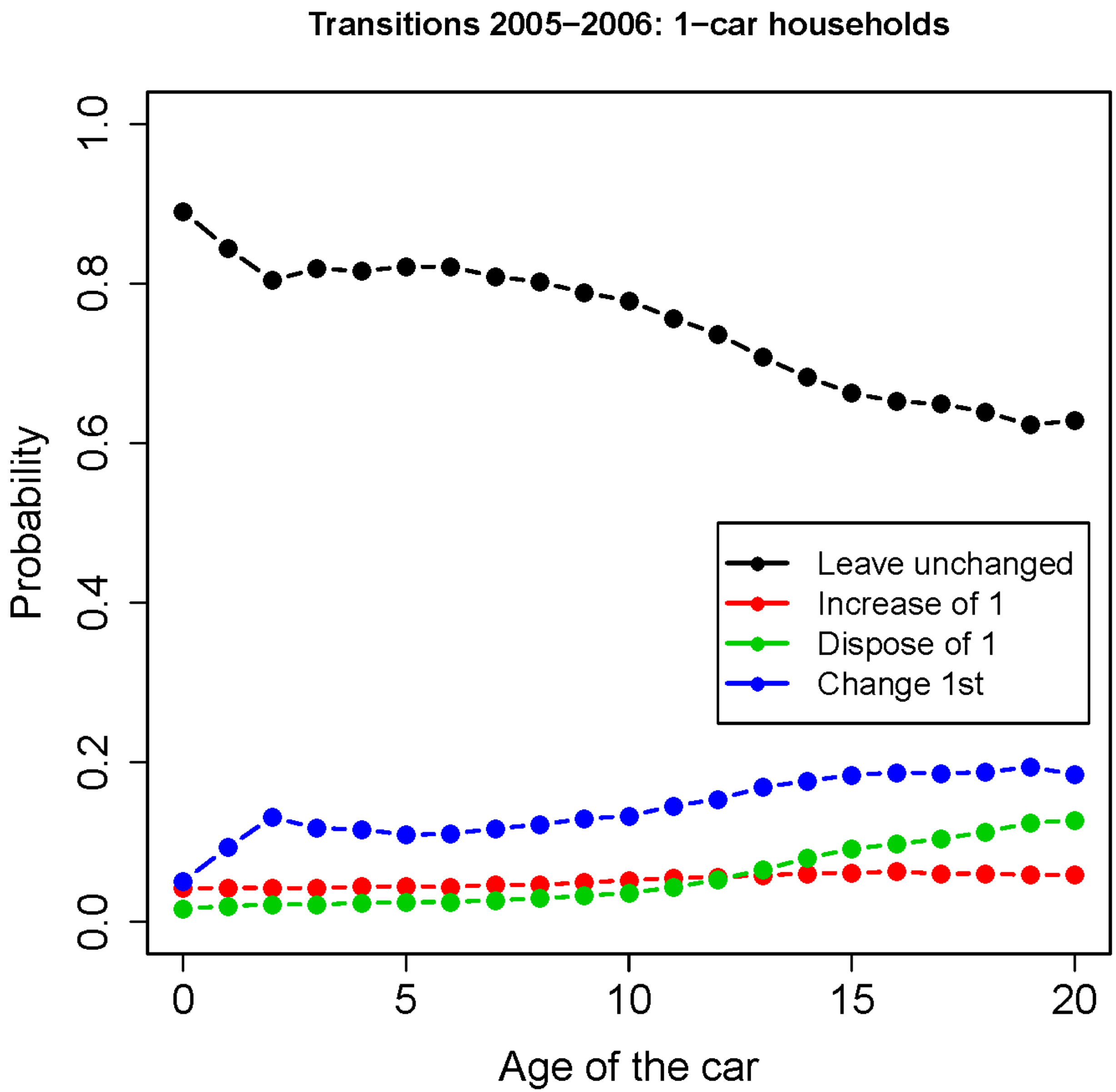

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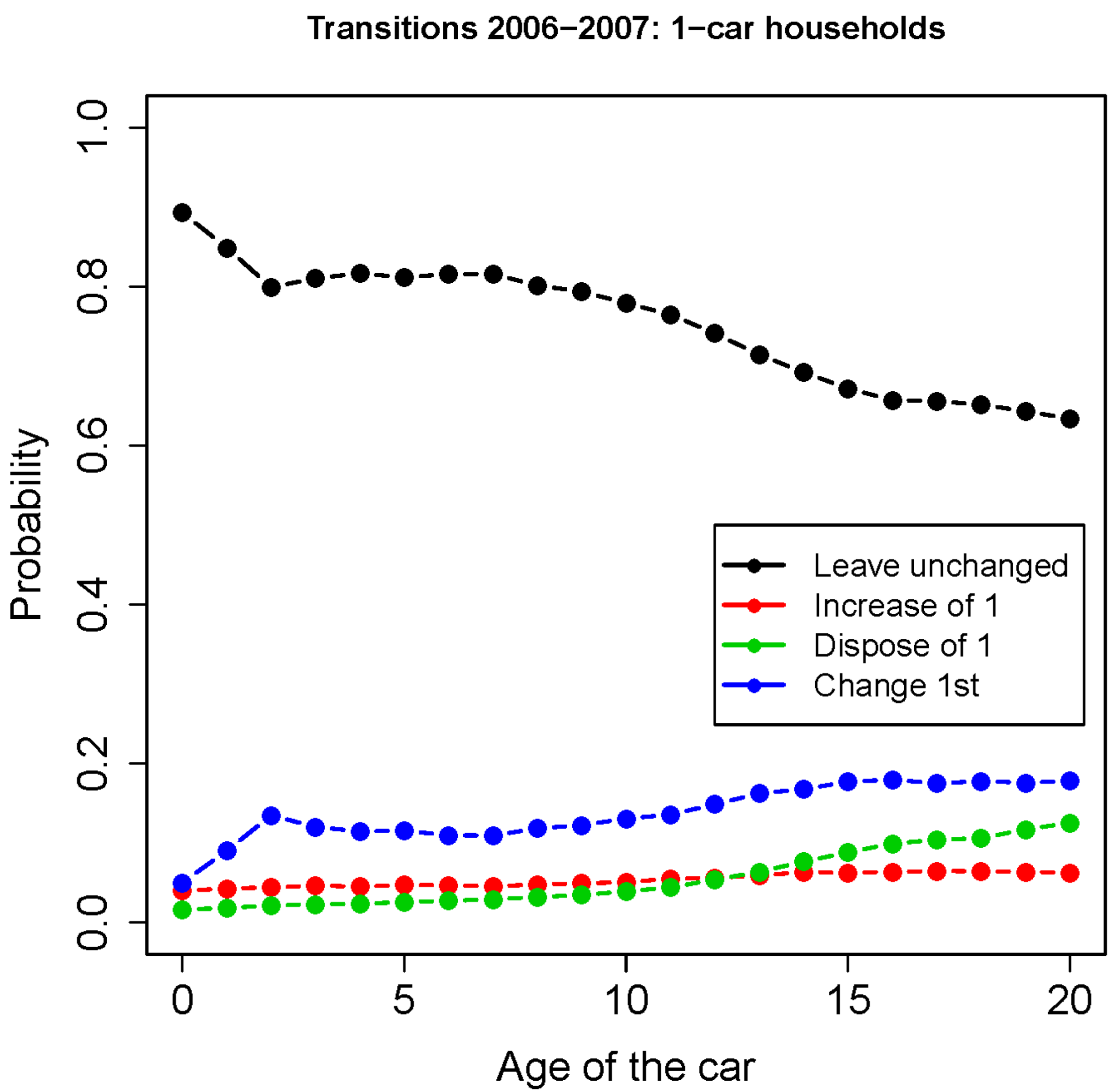

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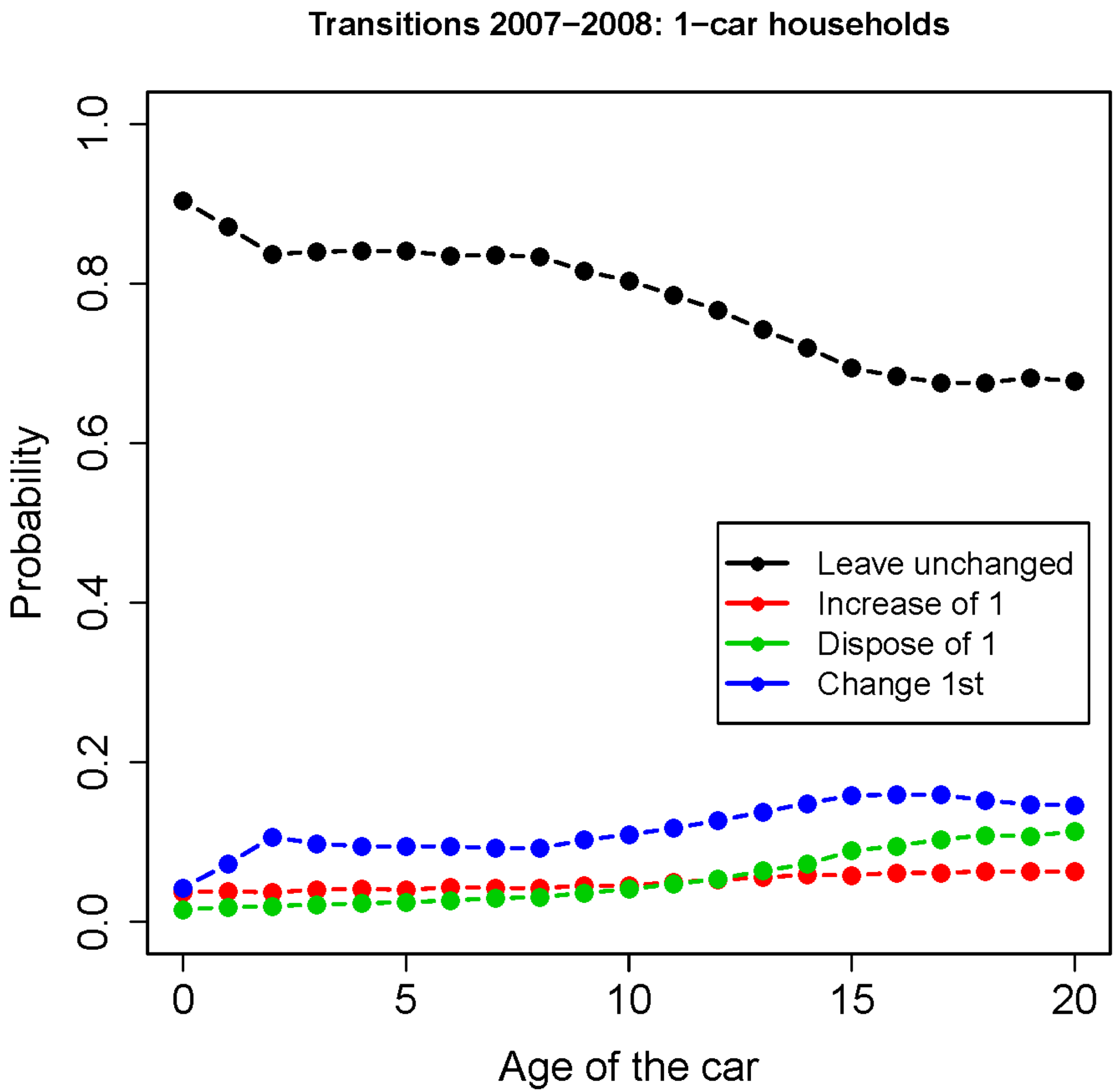

CONCLUSION AND FUTURE WORKS

Conclusion:

- Methodology to model choice of car ownership and usage dynamically
- Example of application shows feasibility of approach

Next steps:

- Model estimation on small sample of synthetic data
- Model estimation on register data
- Scenario testing:
  - Validation of policy measures taken during the years available in the data
  - Test policy measures that are planned to be applied in future years

Thanks!