# Knowing brown and inventing green? Incremental and radical innovative activities in the automotive sector

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# Motivations and research questions

# What kind of knowledge is required for green leadership?

- Firms are characterized by **organizational routines and embedded knowledge** that lead to idiosyncratic innovative behaviours (Simon, 1991; Winter, 1998; Dosi and Nelson, 2010)
- Firms direct innovative search to the neighborhood of established technologies, generating **core-rigidities and inertial procedures** (Dosi, 1988)
- The **eco-innovation literature** has focused on the role of environmental policies, neglecting how firms under similar institutional stimuli form their green technological portfolios
- Green technologies strongly **rely on advances in other green and non-green technological domains** and represent novel **recombination of established knowledge** (Quatraro and Scandura, 2019; Nicolò Barbieri et al., 2020; Nicola Barbieri et al., 2021)

# Eco-innovation in the automotive sector

- The transport sector is responsible for a relevant share of overall global annual $CO_2$ emissions (up to 20%)
- The development of low emission vehicles (LEVs) stands out in the literature as a typical case of technological competition between a dominant design and a set of alternative green technologies
- While competition between LEVs is high, the Internal Combustion Engine (ICE) still represents the dominant design, with firms subject to a *sailing ship effect*

  Dijk and Yarime (2010); Oltra and Saint Jean (2009); Rizzi et al. (2014); Sick et al. (2016); Faria and Andersen (2017); Borgstedt et al. (2017); Yuan and Cai (2021)
- Firms more exposed to clean (dirty) innovation are more likely to direct their research energies to clean (dirty) innovation in the future Aghion et al. (2016)

# Research questions

1. Can we identify different innovation strategies among firms in emerging green trajectories in the automotive sector?
    - data-driven clustering analysis of firms in each trajectory, in terms of their relative patent share and degree of specialization
2. To what extent organizational capabilities and related knowledge explain firm's leadership in each trajectory?
    - Does a broader scope of knowledge favour firm's leadership in emerging green trajectories?
    - Does the degree of coherence with established brown technologies prove to be valuable for green leadership?

# Technological trajectories identification

# Identifying green inventions using patent data

- classification for Climate Change Mitigation Technologies (CCMTs) developed by Veefkind et al. (2012)
- **green invention**: patent with at least one CPC code starting with “Y02”

| Symbol | Classification and description |
|---|---|
| Y | GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS; GENERAL TAGGING OF CROSS-SECTIONAL TECHNOLOGIES SPANNING OVER SEVERAL SECTIONS OF THE IPC; TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS |
| Y02 | TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE |
| Y04 | INFORMATION OR COMMUNICATION TECHNOLOGIES HAVING AN IMPACT ON OTHER TECHNOLOGY AREAS |
| Y10 | TECHNICAL SUBJECTS COVERED BY FORMER USPC |

- we directly observe whether the patent is **assigned to “Y02” by the patent examiner**, thus including patents that would otherwise be ignored by keyword-based searches

# Incremental and radical trajectories using patent data

- **Internal Combustion Engine Green (ICEG)**: technologies aimed at reducing emissions (e.g. enhanced filters) and/or improve efficiency of the ICE powertrain, also using alternative fuels (e.g. bio-fuels).
- **Hybrid-Electric-Fuel cell vehicles (HEF)**: inventions related to pure electric, hybrid-electric and fuel cell vehicles and technologies in battery electric production

| | |
|---|---|
| Y02 | TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE |
| Y02T | CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION |
| Y02T 10/00 | Road transport of goods or passengers |
| Y02T 10/10 | • Internal combustion engine [ICE] based vehicles |
| Y02T 10/12 | • • Improving ICE efficiencies |
| Y02T 10/30 | • • Use of alternative fuels, e.g. biofuels |
| Y02T 10/40 | • • Engine management systems |
| Y02T 10/60 | • Other road transportation technologies with climate change mitigation effect |
| Y02T 10/62 | • • Hybrid vehicles |
| Y02T 10/64 | • • Electric machine technologies in electromobility |
| Y02T 10/70 | • • Energy storage systems for electromobility, e.g. batteries |
| Y02T 10/7072 | • • Electromobility specific charging systems or methods for batteries, ultracapacitors, supercapacitors or double-layer capacitors |

# Dataset creation and exploration

# Dataset

## ORBIS-IP

- Universe of patent applied for by **firms in the automotive sector** (NACE code 29) in the **period 2001-2018**
- Focus on the United States Patent and Trademark Office (**USPTO**), in order to avoid double counting issues and heterogeneity bias of multiple patent offices
- We **impute each firm to its Global Ultimate Owner** (GUO) aggregating subsidiaries to their relative holding firms
- Focus on firms patenting in at least one of the two trajectories: **746** firms

# Firm's specialization in each green trajectory

## Specialisation Index (SI)

Based on Soete (1987), we compute a Balassa Index of Revealed Comparative Advantage:

$$SI_{i,t} = \frac{\frac{p^j_{i,t}}{\sum_j p^j_{i,t}}}{\frac{\sum_i p^j_{i,t}}{\sum_j \sum_i p^j_{i,t}}}$$

where $p^j_{i,t}$ represents the number of patents applied by firm $i$ in trajectory $j$ at time $t$.

- numerator: relative specialization between the two trajectories for each single firm
- denominator: relative specialization for the all set of firms

# Firm's patent share in each green trajectory

## Patent share (PS)

Firm's $i$ share of patenting in each trajectory $j$ at time $t$.

$$PS_{i,t} = \frac{p^j_{i,t}}{\sum_i p^j_{i,t}}$$

- it represents a firm's size indicator in terms of patents

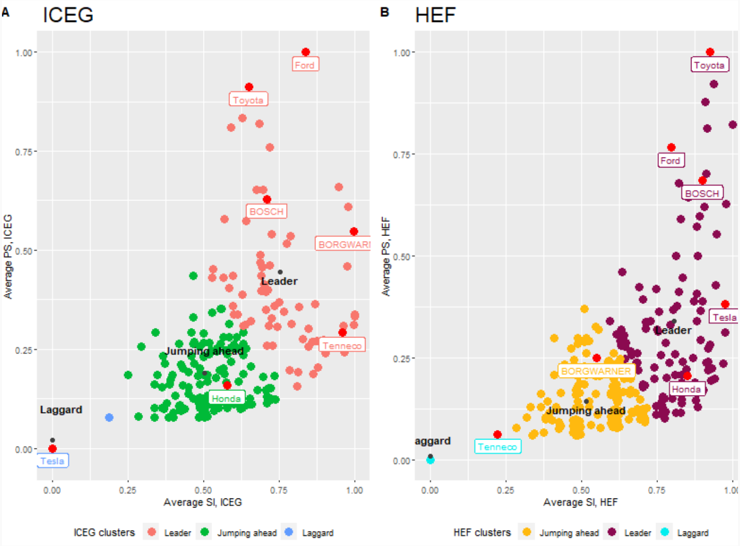
## Normalisation procedure

**For both indicators** (SI and PS) , we:

- compute the **weighted average over two periods:** 2001-2009 and 2010-2018
- apply a **cubic transformation** to reduce the degree of skewness
- **normalization** between 0 and 1 (min-max algorithm)

# Clustering analysis using k-means algorithm

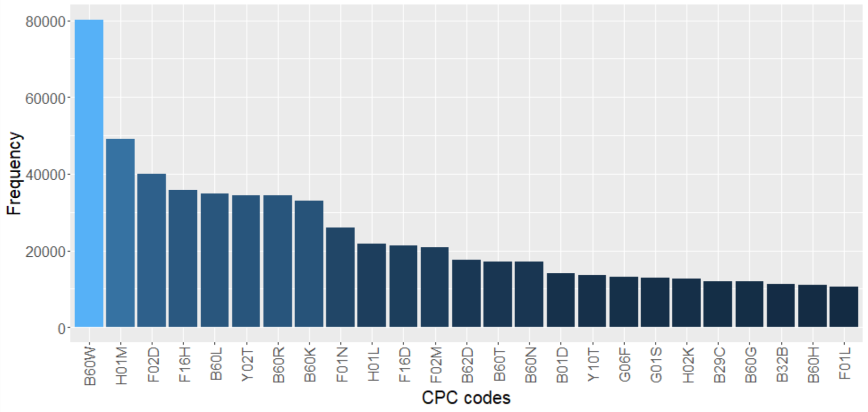
## Technological landscape in terms of Patent Share (PS) and Specialization Index (SI)




K-means clustering. Incremental ICEG trajectory (left panel) and radical HEF trajectory (right panel)

# Breadth of knowledge domain in the automotive industry

## Frequency of the most diffused 4-digit CPC codes



# Co-occurences of CPC codes with patents in the two trajectories

## Top 5 CPC codes by co-occurences' value in each trajectory

ICEG trajectory

| CPC code | description |
| --- | --- |
| F02D | CONTROLLING COMBUSTION ENGINES |
| F01N | SILENCERS/EXHAUST APPARATUS FOR MACHINES OR INTERNAL COMBUSTION ENGINES |
| F02B | INTERNAL COMBUSTION PISTON ENGINES |
| Y02A | TECH. FOR ADAPTATION TO CC |
| F02P | IGNITION FOR INTERNAL COMBUSTION ENGINES |

HEF trajectory

| CPC code | description |
| --- | --- |
| B60L | PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES |
| Y02T | CCMT RELATED TO TRANSPORTATION |
| B60M | POWER SUPPLY LINES FOR ELECTRICALLY-PROPELLED VEHICLES |
| Y04S | INTEGRATING TECH. - IMPROVING ELECTRICAL POWER GENERATION |
| H02J | CIRCUIT SYSTEMS FOR ELECTRIC POWER; STORING ELECTRIC ENERGY |

# Empirical strategy

# Main firm-level variables

## 2 dimensions of knowledge: brown coherence and technological diversification

- **Brown-coherence $TRJ_{t1}$**: average relatedness between firm's brown-technologies in its portfolio at $t1$ and innovation in each trajectory (TRJ). Cosine similarity applied to the matrix of co-occurrences of CPC codes assigned to patents (Breschi et al., 2003)
- **Tech. diversification$_{t1}$**: number of distinct 4-digit CPC codes in which the firm is patenting at $t_1$. Proxy for the breadth of knowledge of the firm

# Additional firm-level controls

- **Green propensity$_{t1}$**: firm's share of green patents on overall applications at $t_1$. Green patents identified by the broader tag *Y02*.
- **Patent portfolio$_{t1}$**: firm's number of patent applications at $t_1$
- **Firm's core business**: a categorical variables for the core business of firms, in particular:
  - **Car maker:** firms in NACE 2910
  - **Supplier**: firms in NACE 2920/2930
  - **Outside automotive**: holding firm (GUO) outside the automotive
- **Periods:** period 1 (2001-2009) and period 2 (2010-2018), following the time aggregation of the clustering analysis.
- **Continents:** dummies for the continent of the firm

# Multinomial logistic regression

## Explaining firm's probability to fall in each cluster

$$ln \left( \frac{P(Y_{i=m,t})}{P(Y_{i=baseline,t})} \right)_{TRJ} = \beta_1 \, tech.diversification_{i,t1} + \beta_2 \, brown\,coherence\,TRJ_{i,t1} +$$
$$\beta_3 \, green\,propensity_{i,t1} + \beta_4 \, patent\,portfolio_{i,t1} + \beta_5 X_i + \lambda_t + \epsilon_{i,t}$$

- **baseline**: Laggard firms
- **m=2,3**: Jumping ahead and Leader respectively
- $X_i$: firm-level controls that do not vary over time
- $\lambda_t$: period fixed effect
- **TRJ** is either the ICEG or HEF trajectory

# Results

# Probability to be Leader in the ICEG trajectory

| Cluster | Variables | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Leader** | brown-coherence ICEG | 14.39*** | 16.86*** | 17.00*** | 14.73*** | 14.93*** |
| | | (1.373) | (1.556) | (1.576) | (2.149) | (1.658) |
| | green propensity | | -2.557*** | -2.734*** | -2.715*** | -1.723*** |
| | | | (0.492) | (0.507) | (0.526) | (0.536) |
| | tech.diversification | | | 0.118*** | 0.0539 | 0.147*** |
| | | | | (0.042) | (0.053) | (0.042) |
| | tech.diversification* brown-coherence ICEG | | | | 0.581 | |
| | | | | | (0.375) | |
| | brown-coherence HEF | | | | | -6.291*** |
| | | | | | | (1.955) |
| | patent portfolio | 0.0958*** | 0.0753*** | -0.0101 | 0.000949 | -0.0266 |
| | | (0.018) | (0.016) | (0.032) | (0.037) | (0.030) |
| | car maker | 2.916*** | 2.865*** | 2.564*** | 2.523*** | 2.962*** |
| | | (0.530) | (0.555) | (0.576) | (0.595) | (0.611) |
| | supplier | 1.718*** | 1.451*** | 1.270*** | 1.412*** | 1.072** |
| | | (0.437) | (0.448) | (0.459) | (0.462) | (0.470) |
| | Observations | 853 | 853 | 853 | 853 | 853 |
| | LogLikelihood | -457.979 | -420.306 | -416.364 | -409.947 | -395.189 |
| | DoF | 22 | 24 | 26 | 28 | 28 |
| | Chi2 | 390.873 | 357.141 | 353.620 | 346.988 | 331.939 |
| | Continent dummies | YES | YES | YES | YES | YES |
| | Period dummies | YES | YES | YES | YES | YES |

# Probability to be Jumping ahead in the ICEG trajectory

| Cluster | Variables | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Jumping ahead** | brown-coherence ICEG | 13.48*** | 15.45*** | 15.31*** | 14.54*** | 13.60*** |
| | | (1.245) | (1.382) | (1.383) | (1.965) | (1.451) |
| | green propensity | | -2.075*** | -2.123*** | -2.116*** | -1.274*** |
| | | | (0.273) | (0.276) | (0.276) | (0.297) |
| | tech.diversification | | | 0.0434 | 0.0438 | 0.0697* |
| | | | | (0.036) | (0.043) | (0.037) |
| | tech.diversification* brown-coherence ICEG | | | | 0.160 | |
| | | | | | (0.363) | |
| | brown-coherence HEF | | | | | -4.198*** |
| | | | | | | (0.762) |
| | patent portfolio | 0.0450*** | 0.0239 | -0.00790 | -0.00906 | -0.0237 |
| | | (0.017) | (0.015) | (0.029) | (0.029) | (0.028) |
| | car maker | 0.920** | 0.860** | 0.778* | 0.821* | 1.039** |
| | | (0.407) | (0.434) | (0.441) | (0.438) | (0.459) |
| | supplier | 0.653** | 0.387 | 0.308 | 0.301 | 0.151 |
| | | (0.275) | (0.285) | (0.292) | (0.294) | (0.304) |
| | Observations | 853 | 853 | 853 | 853 | 853 |
| | LogLikelihood | -457.979 | -420.306 | -416.364 | -409.947 | -395.189 |
| | DoF | 22 | 24 | 26 | 28 | 28 |
| | Chi2 | 390.873 | 357.141 | 353.620 | 346.988 | 331.939 |
| | Continent dummies | YES | YES | YES | YES | YES |
| | Period dummies | YES | YES | YES | YES | YES |

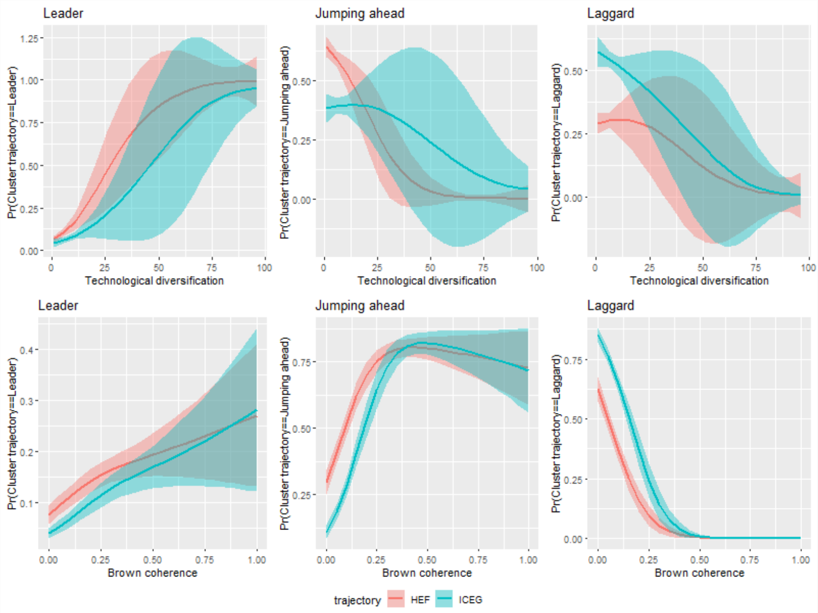
# Probability to be Leader in the HEF trajectory

| Cluster | Variables | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Leader | brown-coherence HEF | 12.71*** | 13.73*** | 13.87*** | 9.576*** | 9.180*** |
| | | (1.452) | (1.437) | (1.458) | (2.090) | (1.443) |
| | green propensity | | -1.876*** | -1.959*** | -2.016*** | -0.539 |
| | | | (0.385) | (0.394) | (0.397) | (0.439) |
| | tech.diversification | | | 0.0933** | -0.0130 | 0.128** |
| | | | | (0.046) | (0.064) | (0.054) |
| | tech.diversification* brown-coherence HEF | | | | 1.353** | |
| | | | | | (0.590) | |
| | brown-coherence ICEG | | | | | -8.723*** |
| | | | | | | (1.748) |
| | patent portfolio | 0.115*** | 0.0875*** | 0.0184 | 0.0198 | 0.00339 |
| | | (0.024) | (0.022) | (0.040) | (0.042) | (0.047) |
| | car maker | 1.192** | 0.995* | 0.742 | 0.659 | 1.108 |
| | | (0.553) | (0.568) | (0.583) | (0.597) | (0.676) |
| | supplier | 0.369 | 0.228 | 0.0367 | 0.0709 | 0.263 |
| | | (0.376) | (0.386) | (0.397) | (0.400) | (0.433) |
| | Observations | 853 | 853 | 853 | 853 | 853 |
| | LogLikelihood | -551,514 | -535,597 | -528,819 | -524,951 | -456,532 |
| | DoF | 22 | 24 | 26 | 28 | 28 |
| | Chi2 | 353,514 | 361,029 | 362,075 | 360,014 | 395,122 |
| | Continent dummies | YES | YES | YES | YES | YES |
| | Period dummies | YES | YES | YES | YES | YES |

# Probability to be Jumping ahead in the HEF trajectory

| Cluster | Variables | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Jumping ahead** | brown-coherence HEF | 12.48*** | 12.68*** | 12.74*** | 9.176*** | 8.255*** |
| | | (1.377) | (1.321) | (1.335) | (1.958) | (1.313) |
| | green propensity | | -1.007*** | -0.996*** | -1.007*** | 0.314 |
| | | | (0.223) | (0.224) | (0.224) | (0.287) |
| | tech.diversification | | | -0.0285 | -0.102* | 0.000177 |
| | | | | (0.042) | (0.058) | (0.049) |
| | tech.diversification* brown-coherence HEF | | | | 1.168** | |
| | | | | | (0.583) | |
| | brown-coherence ICEG | | | | | -6.039*** |
| | | | | | | (0.659) |
| | patent_portfolio | 0.0468** | 0.0216 | 0.0407 | 0.0371 | 0.0270 |
| | | (0.023) | (0.022) | (0.038) | (0.039) | (0.045) |
| | car maker | -0.116 | -0.267 | -0.213 | -0.202 | 0.107 |
| | | (0.497) | (0.517) | (0.518) | (0.524) | (0.621) |
| | supplier | -0.0916 | -0.165 | -0.119 | -0.0818 | 0.135 |
| | | (0.269) | (0.277) | (0.281) | (0.286) | (0.320) |
| | Observations | 853 | 853 | 853 | 853 | 853 |
| | LogLikelihood | -551,514 | -535,597 | -528,819 | -524,951 | -456,532 |
| | DoF | 22 | 24 | 26 | 28 | 28 |
| | Chi2 | 353,514 | 361,029 | 362,075 | 360,014 | 395,122 |
| | Continent dummies | YES | YES | YES | YES | YES |
| | Period dummies | YES | YES | YES | YES | YES |

# Predictive margins, ICEG vs HEF



# Summary and conclusion

# Knowing brown and inventing green? Yes

- Our findings suggest:
  - firms are more likely to lead both green trajectories if they are closer in terms of "brown" knowledge domain to the new emerging technologies
  - the amplitude of firm's knowledge explains firm's leadership in both trajectories, but does not characterize jumping ahead firms
- Our work enlightens the **continuity in knowledge domains between green and brown technologies** along both green trajectories identified in the automotive industry (ICEG and HEF)
- The persistence of ICE as a dominant design may be explained by core-rigidities and inertial procedures arising from the **complexity and broad arrays of different knowledge sources**

# Appendix

# Descriptive statistics (1)

Table 1: Descriptive statistics of the main firm-level variables

| | count | mean | sd | min | max |
|---|---|---|---|---|---|
| brown-coherence HEF | 853 | .2164986 | .2012725 | 0 | .9377893 |
| brown-coherence ICEG | 853 | .18627 | .229336 | 0 | .8535996 |
| tech.diversification | 853 | 5.882767 | 11.10832 | 1 | 98 |
| patent portfolio | 853 | 5.55803 | 19.52086 | 1 | 309 |
| green propensity | 853 | .5671121 | .4535408 | 0 | 1 |
| ln(avg sales) | 370 | 13.61593 | 3.553676 | 1.253911 | 19.3205 |
| ln(avg assets) | 400 | 13.32211 | 3.837572 | 2.491499 | 19.8363 |
| ln(avg workers) | 496 | 6.315973 | 4.019353 | 0 | 12.88463 |
| ln(sales norm) | 322 | 5.583719 | .9788954 | .3380696 | 8.579676 |

# Descriptive statistics (2)

Table 2: Categorical and dependent variables

| Variable | Elements | Frequency |
|---|---|---|
| Cluster ICEG | Laggard | 458 |
| Cluster ICEG | Jumping ahead | 322 |
| Cluster ICEG | Leader | 73 |
| Cluster HEF | Laggard | 251 |
| Cluster HEF | Jumping ahead | 491 |
| Cluster HEF | Leader | 111 |
| Period | 1 | 318 |
| Period | 2 | 535 |
| Continent | Asia | 298 |
| Continent | Europe | 359 |
| Continent | North America | 169 |
| Continent | Not classified | 2 |
| Continent | Oceania | 21 |
| Continent | South America | 4 |
| Nace | 1 - Car manufacturer | 60 |
| Nace | 2 - Supplier | 139 |
| Nace | 3 - Other | 654 |

# Correlation table

Table 3: Cross-correlation table

| Variables | (mean) hybrid | (mean) ice | tech_diversification | patent_portfolio | green_propensity | ln_avg_sales | ln_avg_assets | ln_avg_workers | ln_sales_norm |
|---|---|---|---|---|---|---|---|---|---|
| brown_coherence_HEF | 1.00 | | | | | | | | |
| brown_coherence_ICEG | -0.47 | 1.00 | | | | | | | |
| tech_diversification | -0.09 | -0.08 | 1.00 | | | | | | |
| patent_portfolio | -0.06 | -0.05 | 0.89 | 1.00 | | | | | |
| green_propensity | 0.22 | 0.17 | -0.19 | -0.16 | 1.00 | | | | |
| ln_avg_sales | -0.14 | -0.21 | 0.38 | 0.30 | -0.33 | 1.00 | | | |
| ln_avg_assets | -0.14 | -0.22 | 0.38 | 0.30 | -0.35 | 0.95 | 1.00 | | |
| ln_avg_workers | -0.12 | -0.25 | 0.33 | 0.25 | -0.36 | 0.96 | 0.95 | 1.00 | |
| ln_sales_norm | -0.11 | -0.00 | 0.16 | 0.15 | -0.05 | 0.44 | 0.36 | 0.18 | 1.00 |

# Selected CPC codes for ICEG

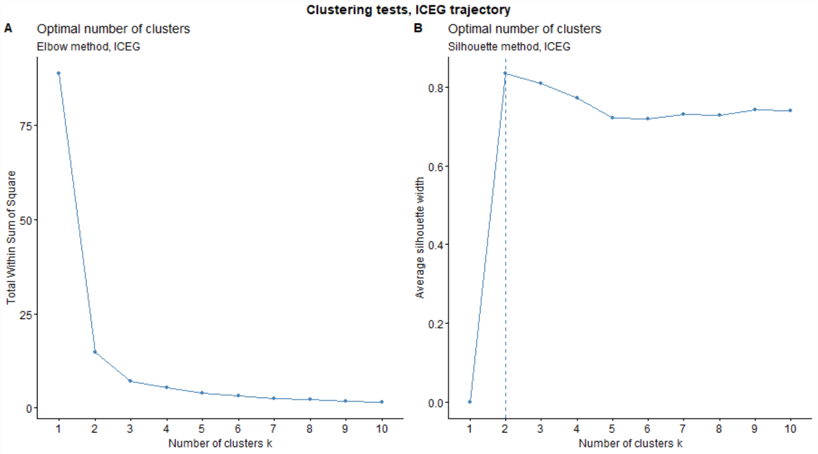
Internal Combustion Engine Green (ICEG)

| | |
|---|---|
| Y02T10/10 | Internal combustion engine (ICE) based vehicles |
| Y02T10/12 | Improving ICE efficiencies |
| Y02T10/30 | Use of alternative fuels, e.g. biofuels |
| Y02T10/40 | Engine management systems |
| Y02E50/00 | Tech. for the production of fuel of non-fossil origin |
| Y02E50/10 | Biofuels, e.g. bio-diesel |
| Y02E50/30 | Fuel from waste, e.g. synthetic alcohol or diesel |

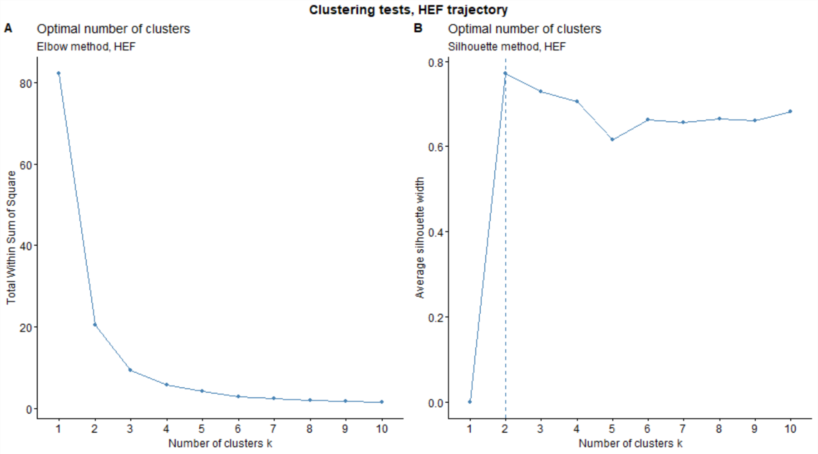
# Selected CPC codes for HEF

| Hybrid, Electric and Fuel Cell (HEF) | |
|---|---|
| Y02T10/60 | Other tech. with climate change mitigation effect |
| Y02T10/62 | Hybrid vehicles |
| Y02T10/64 | Electric machine technologies in electromobility |
| Y02T10/70 | Energy storage systems for electromobility, e.g. batteries |
| Y02T10/7072 | Electromobility charging systems or methods for batteries (..) |
| Y02T10/7005 | * |
| Y02T10/72 | Electric energy management in electromobility |
| Y02T10/92 | Charging or discharging systems for batteries |
| Y02T90/10 | Technologies relating to charging of electric vehicles |
| Y02T90/12 | Electric charging stations |
| Y02T90/14 | Plug-in electric vehicles |
| Y02T90/16 | IT or CT improving the operation of electric vehicles |
| Y02T90/167 | Systems integrating technologies for electric or hybrid vehicles |
| Y02T90/168 | * |
| Y02T90/169 | * |
| Y02E60/00 | Enabling technologies |
| Y02E60/10 | Energy storage using batteries |
| Y02E60/13 | Energy storage using capacitors |
| Y02E60/14 | Thermal energy storage |
| Y02E60/16 | Mechanical energy storage, e.g. flywheels or pressurised fluids |
| Y02E60/30 | Hydrogen technology |
| Y02E60/32 | Hydrogen storage |
| Y02E60/34 | Hydrogen distribution |
| Y02E60/36 | Hydrogen production from non-carbon containing sources |
| Y02E60/50 | Fuel cells |
| Y02E60/60 | Arrangements for transfer of electric power |

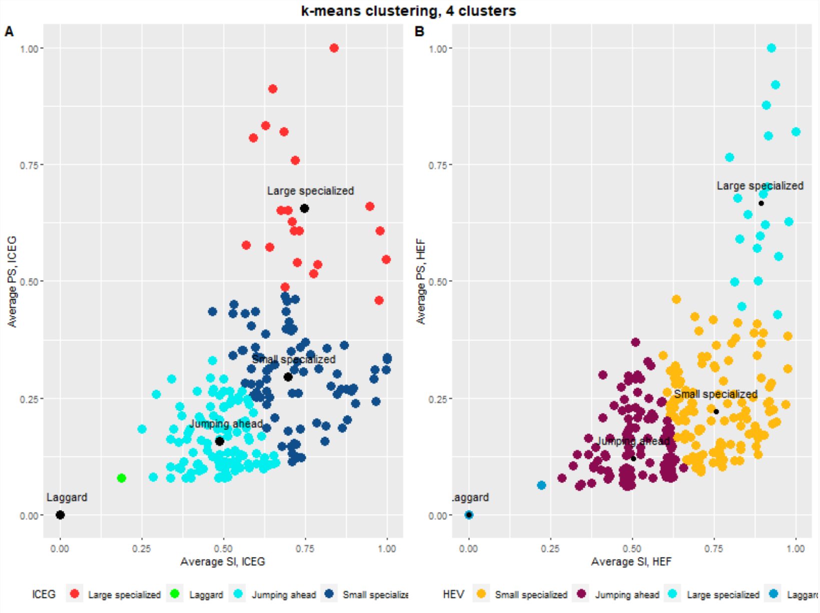
# Test for cluster selection (ICEG)



# Test for cluster selection (HEF)

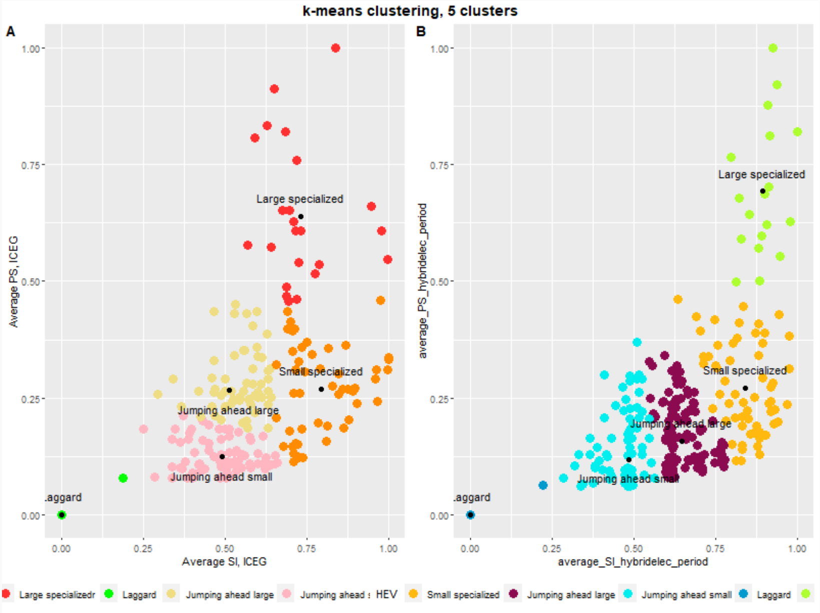


# 4 clusters



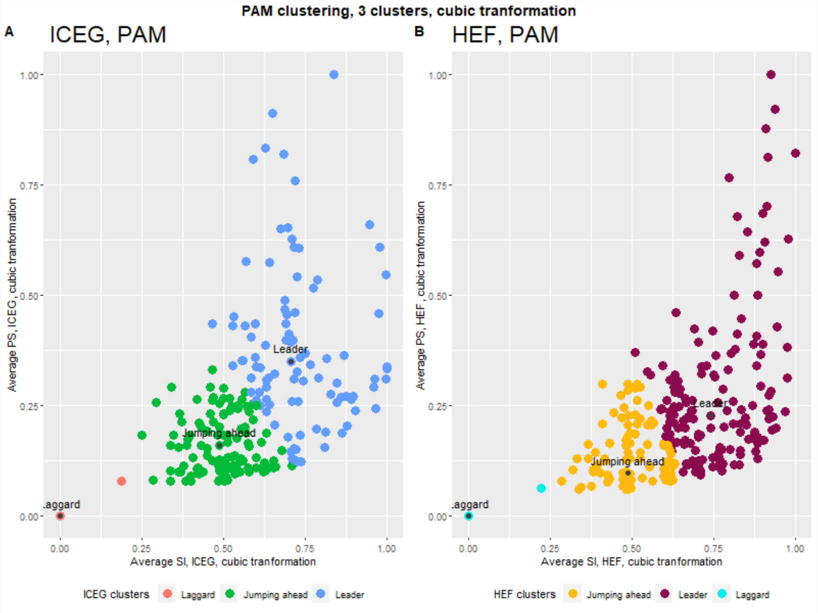
k-means clustering, 4 clusters
A
B
Large specialized
Small specialized
Jumping ahead
Laggard
Average PS, ICEG
Average SI, ICEG
Average PS, HEF
Average SI, HEF
0.00
0.25
0.50
0.75
1.00
ICEG
Large specialized
Laggard
Jumping ahead
Small specialize
HEV
Small specialized
Jumping ahead
Large specialized
Laggar

# 5 clusters

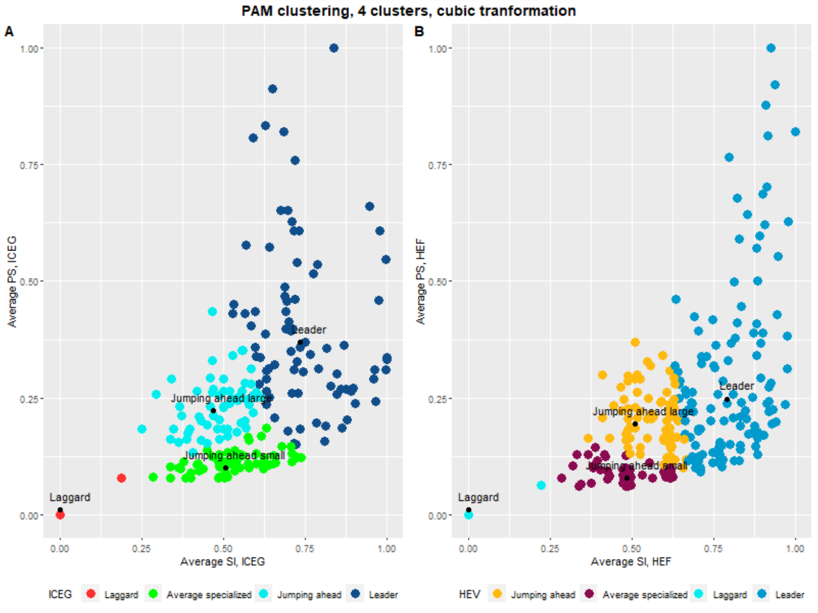


k-means clustering, 5 clusters
A
B
Large specialized
Small specialized
Jumping ahead large
Jumping ahead small
Laggard
Average PS, ICEG
Average SI, ICEG
average_PS_hybridelec_period
average_SI_hybridelec_period
0.00
0.25
0.50
0.75
1.00
Large specializedr
Laggard
Jumping ahead large
Jumping ahead : HEV
Small specialized
Jumping ahead large
Jumping ahead small
Laggard

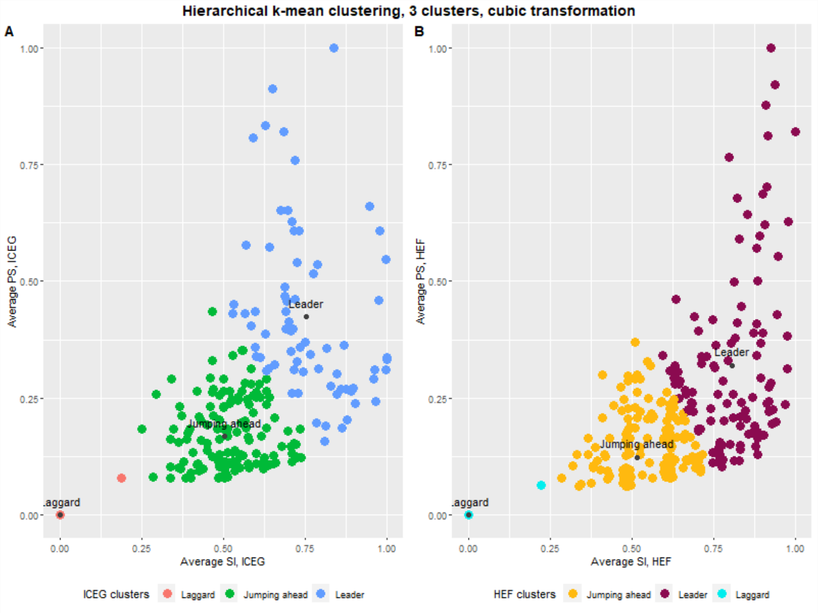
# Partitioning Around Medoids (PAM), 3 clusters



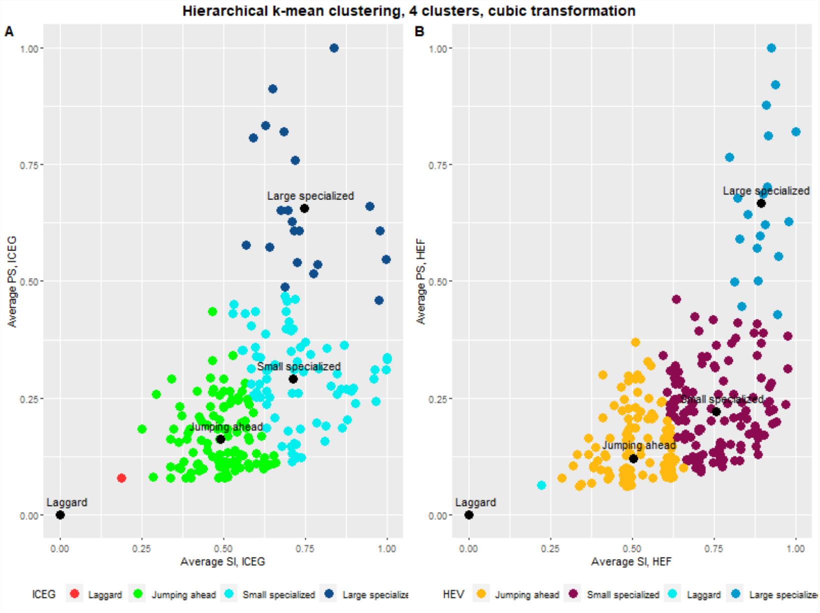
# Partitioning Around Medoids (PAM), 4 clusters



# Hierarchical K-means, 3 clusters



# Hierarchical K-means, 4 clusters



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