PAUL SCHERRER INSTITUT

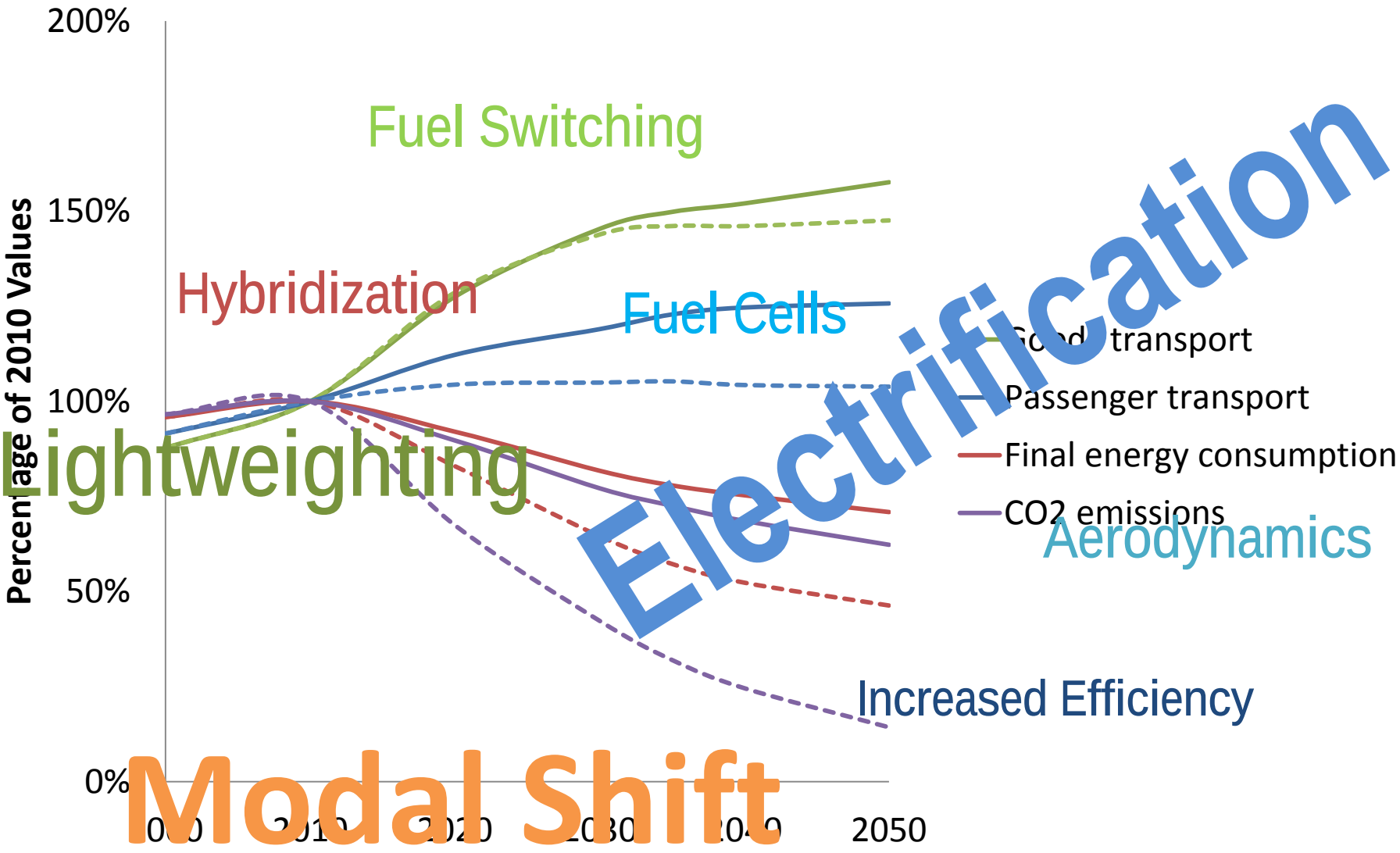
PSI

Brian Cox :: Paul Scherrer Institut

Swiss Energy Turnaround: Can we meet our mobility demands in a sustainable way?

Frontiers in Energy Research :: 16 May 2017

Motivation – Swiss Energy Strategy 2050

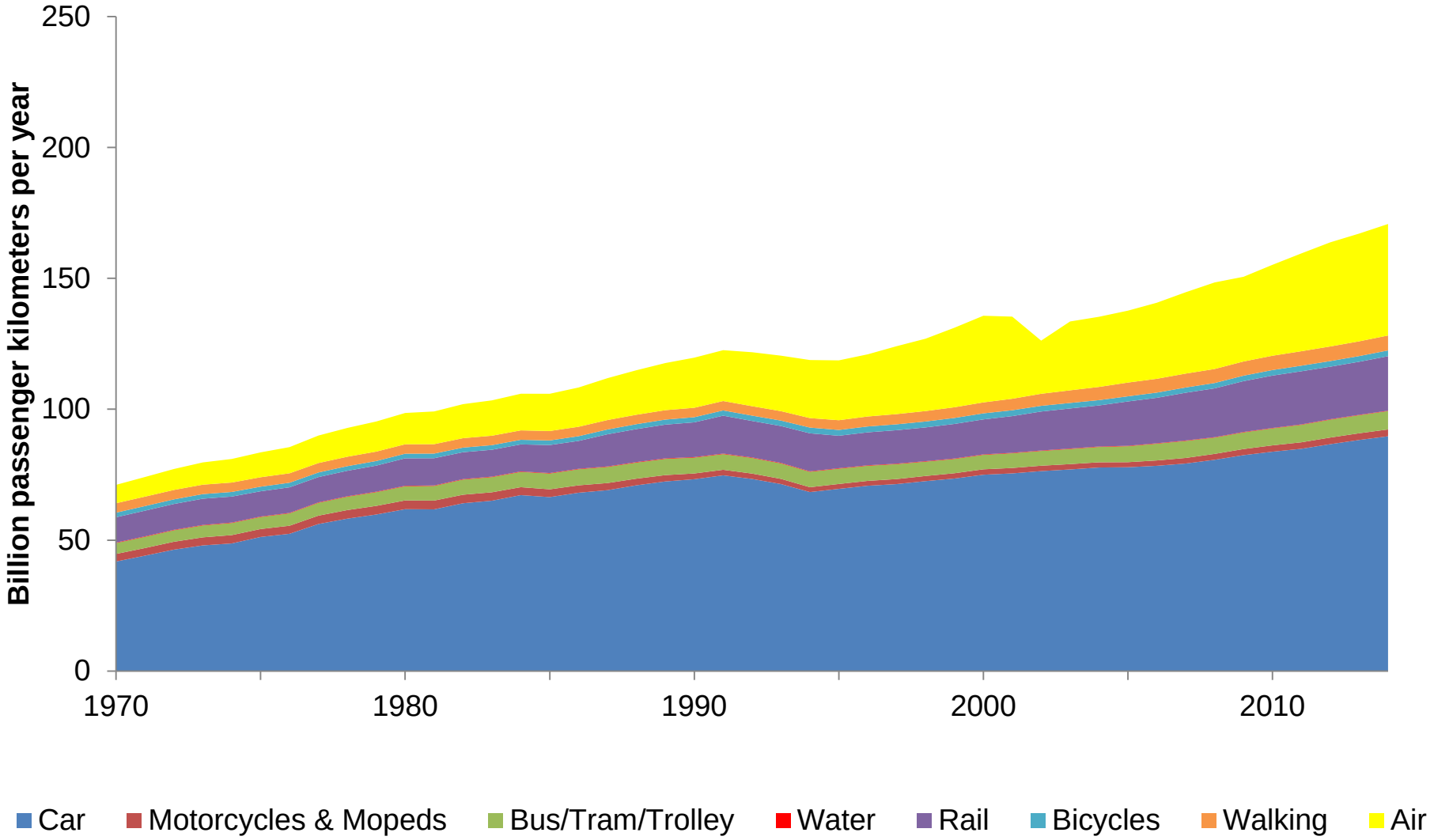


Data Source: Prognos 2012

Agenda

- Motivation
- What is LCA?
- Detailed analysis: motorcycles
- Comparison of transport modes
- What about self driving cars?
- Questions

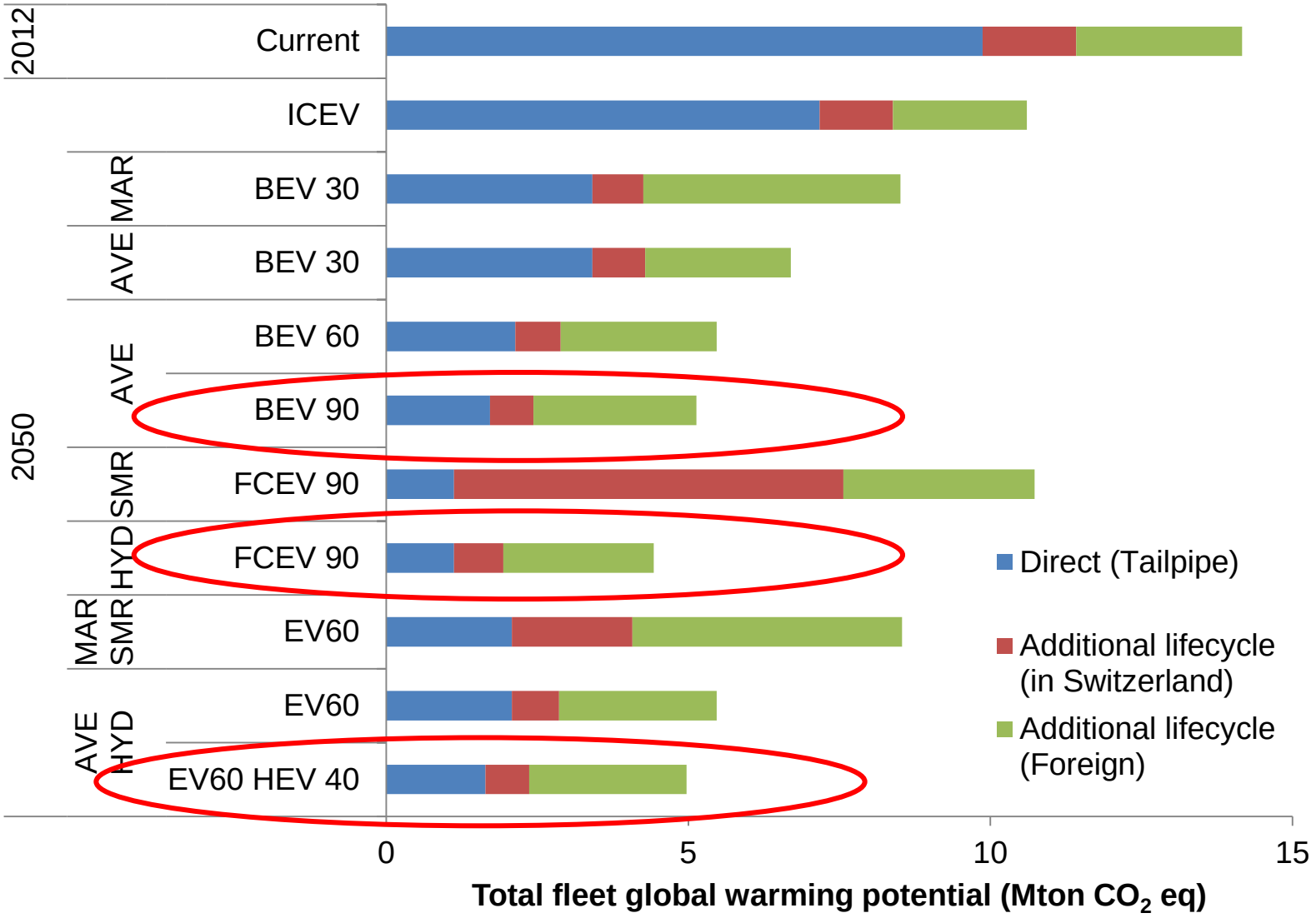
Motivation - Swiss Passenger Transport



Swiss Federal Statistical Office, 2014

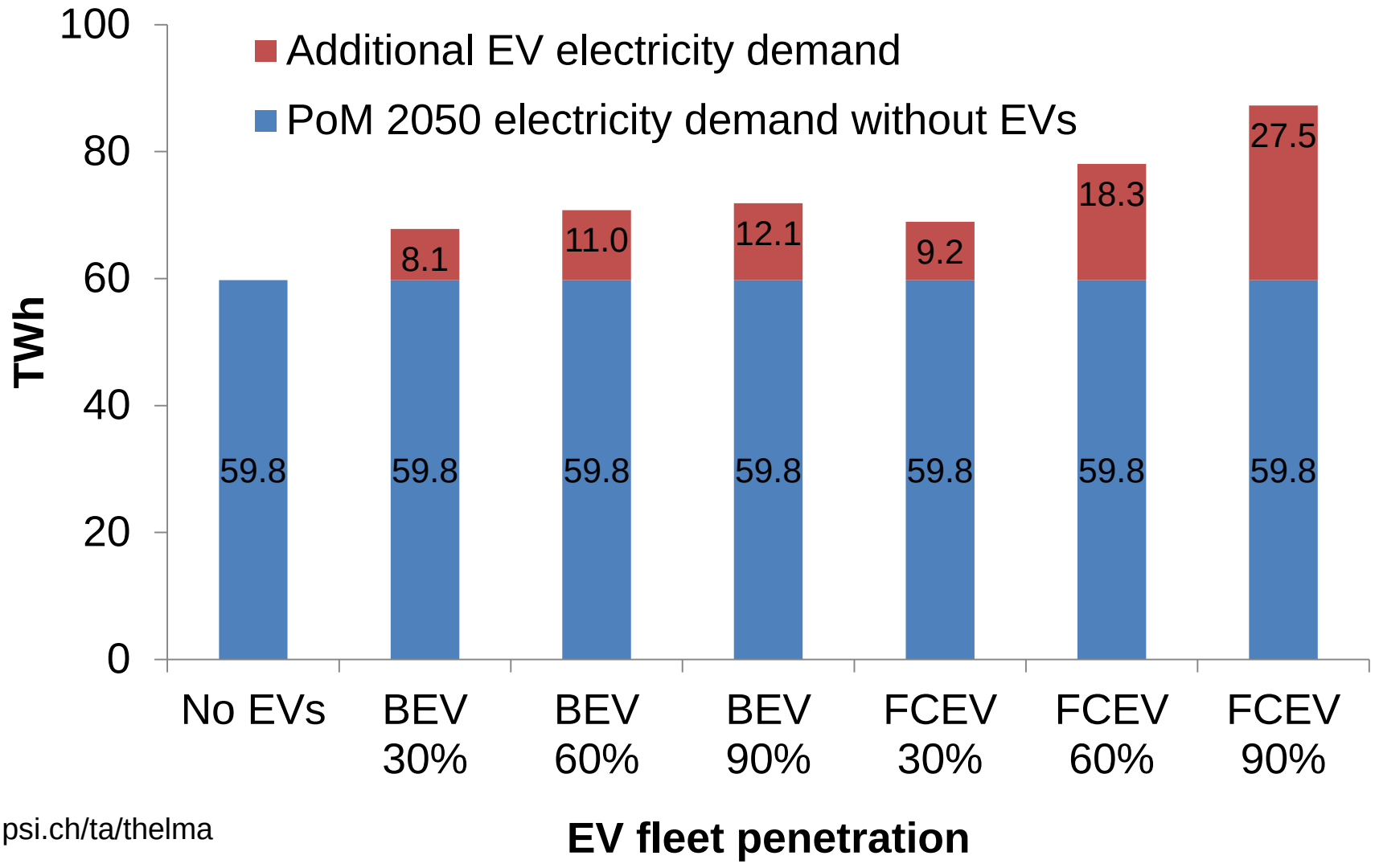
Global Warming Due to Swiss Passenger Cars

ICEV : Internal Combustion Vehicle **HEV**: Hybrid Electric Vehicle **BEV**: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle **EV**: mix of BEV & FCEV



www.psi.ch/ta/thelma

Additional electricity demand due to electric mobility



www.psi.ch/ta/thelma

ICEV : Internal Combustion Vehicle **HEV**: Hybrid Electric Vehicle **BEV**: Battery Electric Vehicle **FCEV**: Fuel Cell Electric Vehicle

Research Questions

What are the life cycle environmental impacts of **future** passenger transport in Switzerland for different:

- transport modes
- vehicle powertrains
- energy systems

and how would different scenarios compare with each other?

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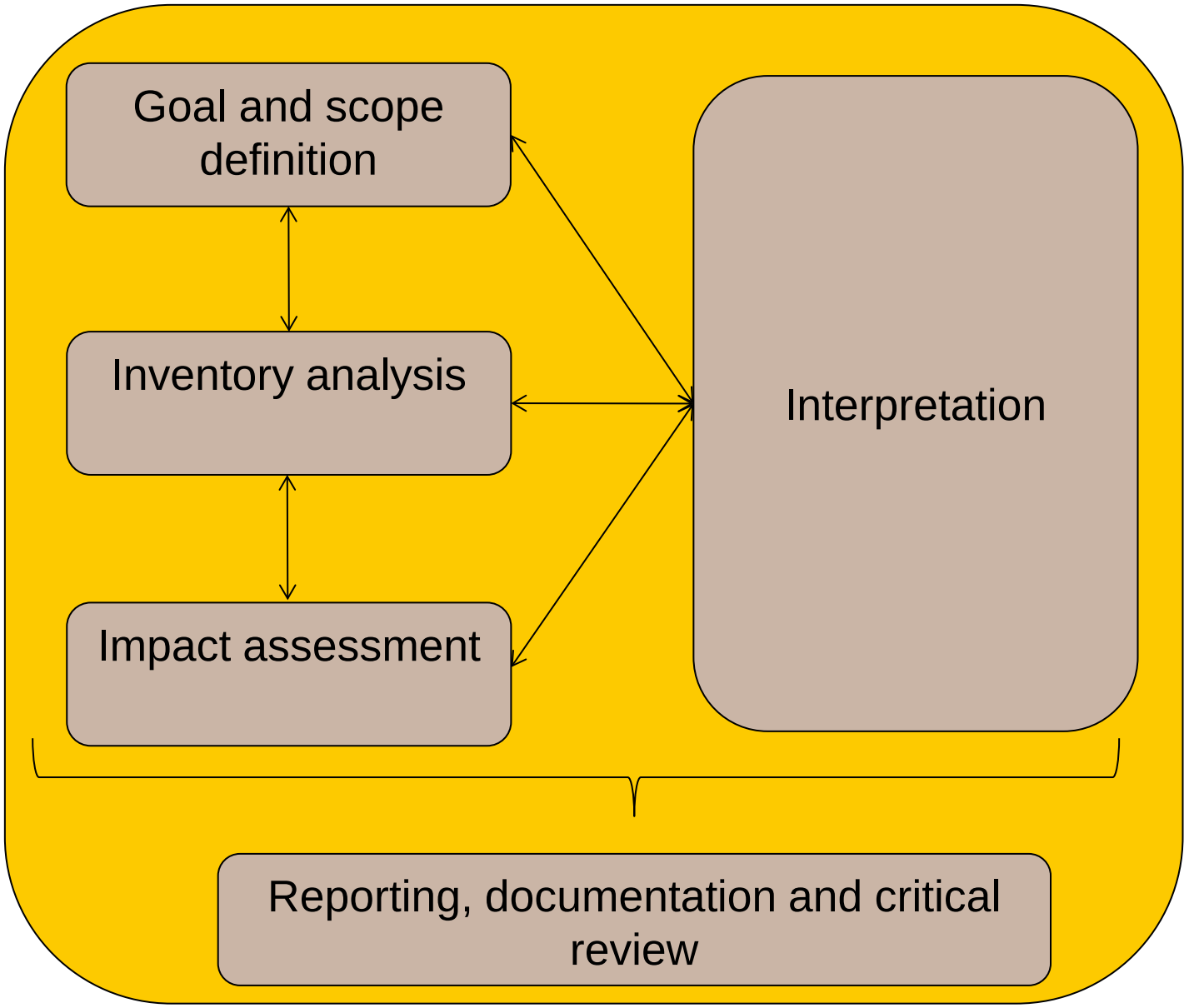
LCA according to ISO 14040/44



LCA of a motorcycle

Goal:

Calculate environmental impacts of travelling 1 km with a motorcycle in Switzerland.

Functional Unit:

1 vehicle kilometer

LCI of a Motorcycle

Data Sources:

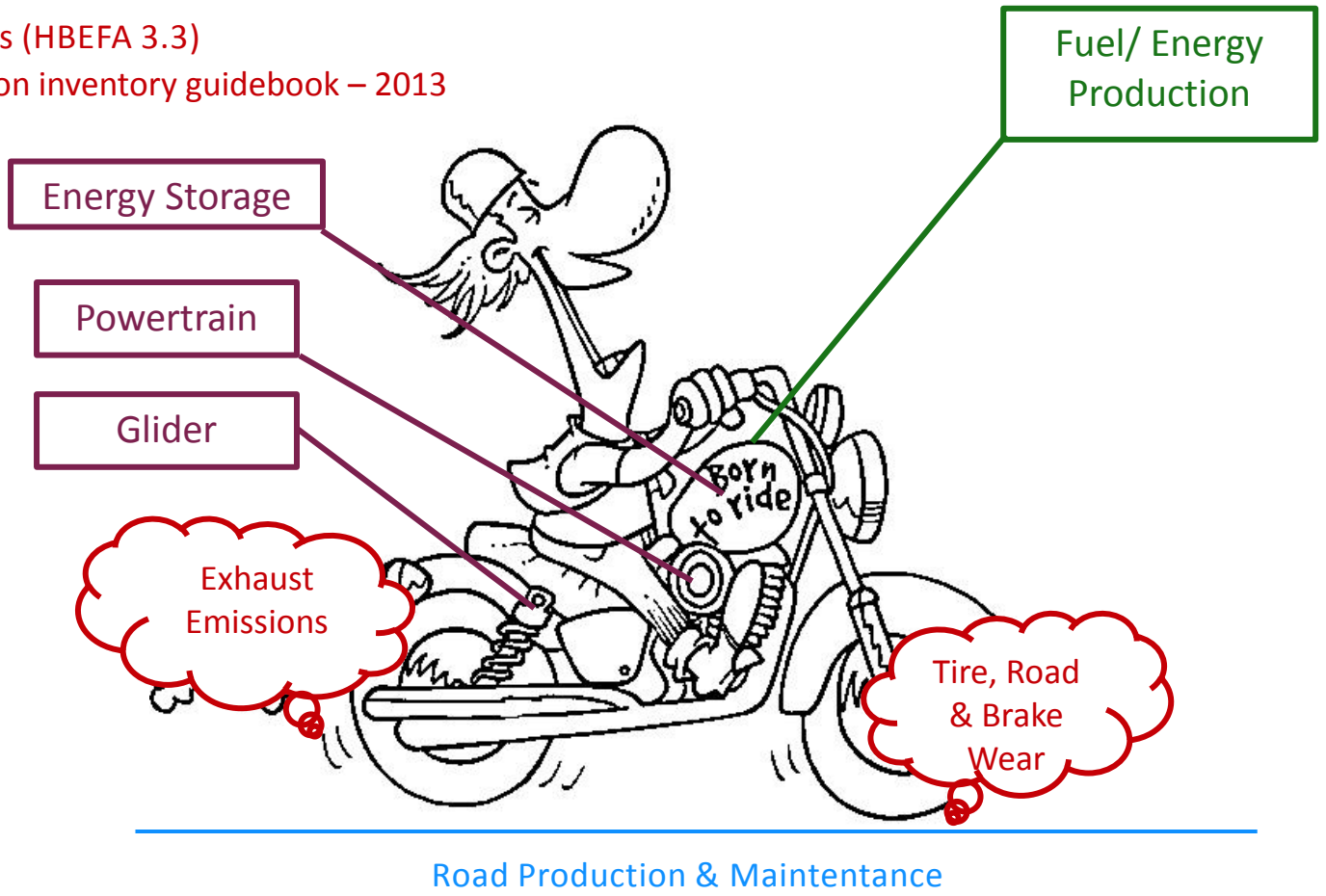
Handbook of Emission Factors (HBEFA 3.3)

EMEP/EEA air pollutant emission inventory guidebook – 2013

Own calculation
ecoinvent 3.2

Manufacturer information
Own calculation
ecoinvent 3.2
Literature review

ecoinvent 3.2



Life Cycle Inventory

	FOREGROUND			Per vehicle kilometer
Exchange Type	Name	Amount	Database	Unit
Exhaust Emission	Arsenic	3.74E-09	Biosphere	kilogram
Exhaust Emission	Cadmium	1.35E-07	Biosphere	kilogram
Exhaust Emission	Chromium	2.00E-07	Biosphere	kilogram
Exhaust Emission	Copper	5.24E-07	Biosphere	kilogram
Exhaust Emission	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2.70E-14	Biosphere	kilogram
Exhaust Emission	Lead	4.14E-07	Biosphere	kilogram
Exhaust Emission	Mercury	1.09E-07	Biosphere	kilogram
Exhaust Emission	NMVOC, non-methane volatile organic compounds, unspecified origin	1.60E-03	Biosphere	kilogram
Exhaust Emission	NMVOC, non-methane volatile organic compounds, unspecified origin	4.67E-04	Biosphere	kilogram
Exhaust Emission	Nickel	1.62E-07	Biosphere	kilogram
Exhaust Emission	PAH, polycyclic aromatic hydrocarbons	2.66E-10	Biosphere	kilogram
Exhaust Emission	PAH, polycyclic aromatic hydrocarbons	4.10E-14	Biosphere	kilogram
Exhaust Emission	Particulates, > 2.5 um, and < 10um	1.80E-05	Biosphere	kilogram
Exhaust Emission	Polychlorinated biphenyls	1.36E-14	Biosphere	kilogram
Exhaust Emission	Selenium	2.49E-09	Biosphere	kilogram
Exhaust Emission	Zinc	2.70E-05	Biosphere	kilogram
Exhaust Emission	ammonia	1.00E-06	Biosphere	kilogram
Exhaust Emission	carbon dioxide, fossil	4.03E-02	Biosphere	kilogram
Exhaust Emission	carbon monoxide, fossil	1.80E-03	Biosphere	kilogram
Exhaust Emission	methane, fossil	1.99E-04	Biosphere	kilogram
Exhaust Emission	nitrogen oxides	1.71E-04	Biosphere	kilogram
Exhaust Emission	sulfur dioxide	9.98E-07	Biosphere	kilogram
Fuel Production	petrol blending for two-stroke engines	1.25E-02	Technosphere	kilogram
Motorcycle Maintenance	maintenance, motor scooter	1.78E-05	Technosphere	unit
Motorcycle Production	internal combustion engine production, passenger car	1.13E-03	Technosphere	kilogram
Motorcycle Production	motor scooter production	1.78E-05	Technosphere	unit
	polyethylene production, high density, granulate	5.10E-05	Technosphere	kilogram
	road construction	8.77E-05	Technosphere	meter-year
	road maintenance	1.29E-03	Technosphere	meter-year
	treatment of brake wear emissions, passenger car	-2.47E-06	Technosphere	kilogram
	treatment of road wear emissions, passenger car	-6.00E-06	Technosphere	kilogram
	treatment of tyre wear emissions, passenger car	-4.31E-06	Technosphere	kilogram

Life Cycle Inventory

ecoinvent

Technosphere

Activities

$A = \begin{pmatrix} \\ \text{Products} \end{pmatrix}$

Biosphere

Activities

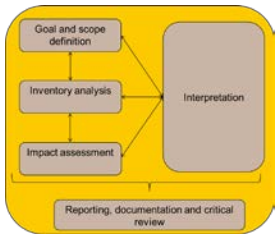
$B = \begin{pmatrix} \\ \text{Biosphere} \end{pmatrix}$

Functional Unit

$f = \begin{pmatrix} \text{Products} \\ \\ \end{pmatrix}$

$$LCI = B\ \mathrm{diag}(A^{-1} f) = \begin{matrix} \text{Activities} \\ \begin{pmatrix} \\ \text{Biosphere} \end{pmatrix} \end{matrix}$$

Life Cycle Impact Assessment



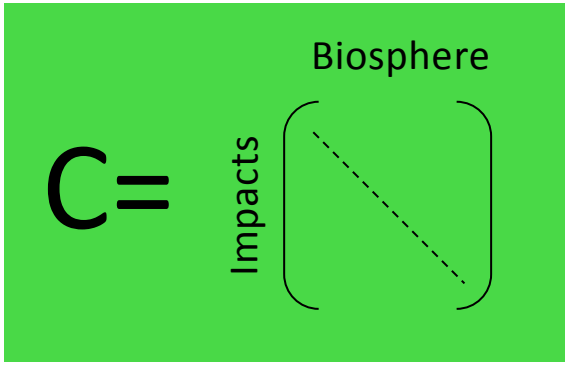
www.lcia-recipe.net/

Life Cycle Impact Assessment

Example: Global Warming Potential (kg CO2 eq)

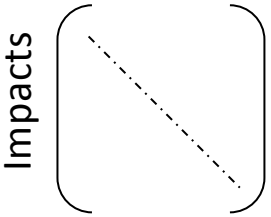
Substance	Characterisation Factor
CO_2	$\equiv 1$
CH_4	25
N_2O	298
SF_6	22800
HFC-134a	1430

Characterisation

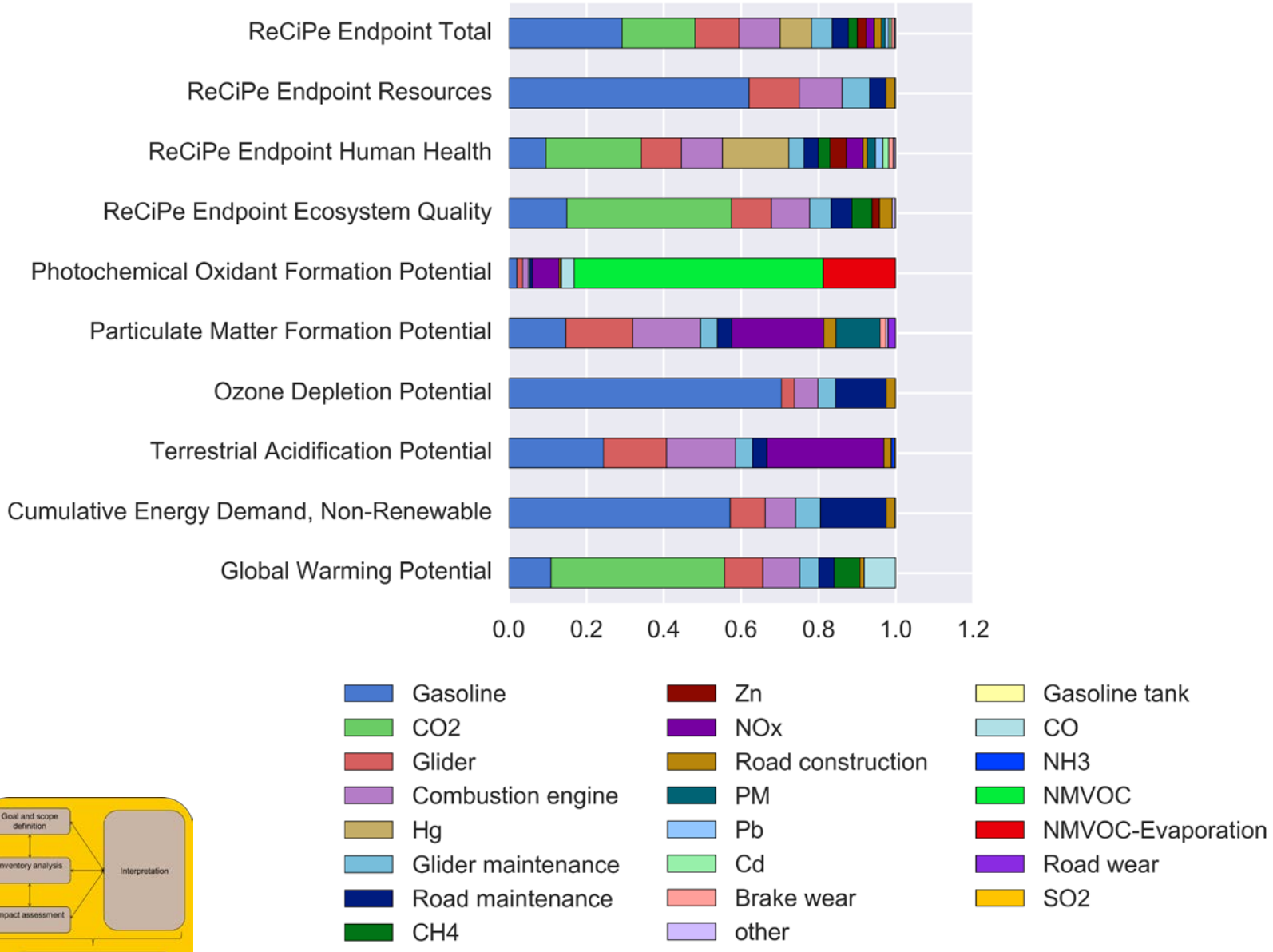


$$LCIA = CBdiag(A^{-1} f) =$$

Activities



Interpretation



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- Detailed analysis: motorcycles

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Motorcycles considered

ICEV
Internal Combstion Engine Vehicle

FCEV
Fuel Cell Electric Vehicle

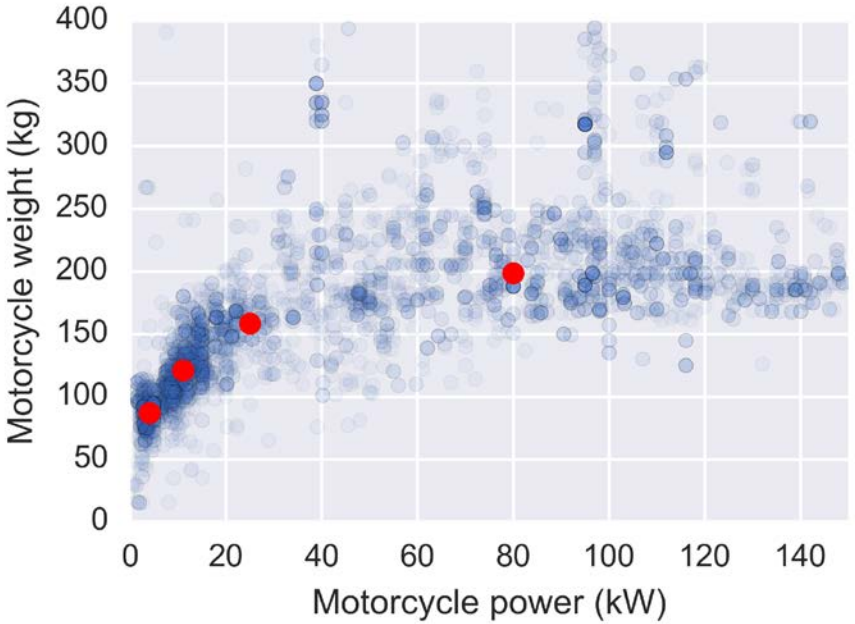
BEV
Battery Electric Vehicle

4 kW

11 kW

25 kW

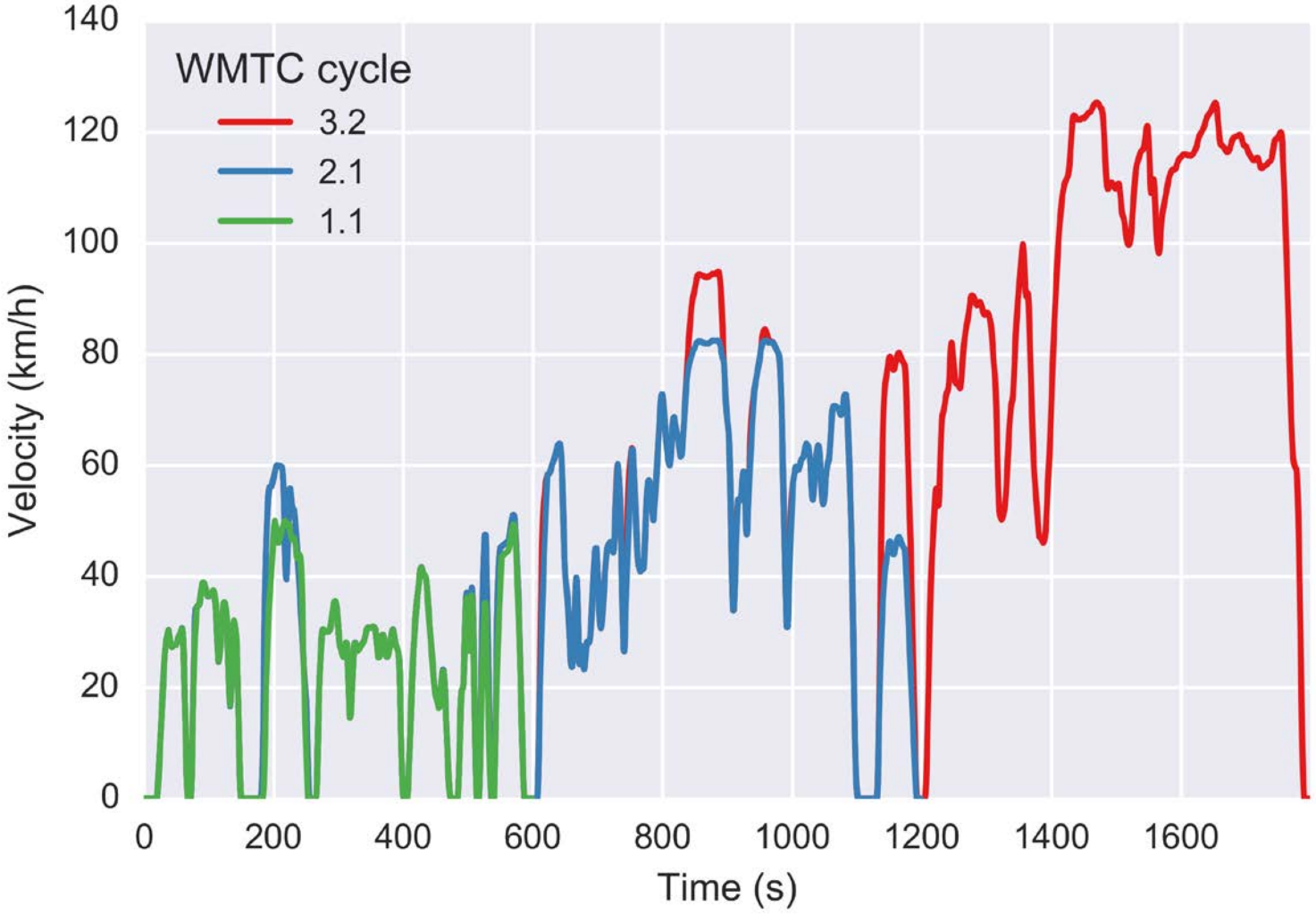
80 kW



Technology Developments 1990-2050

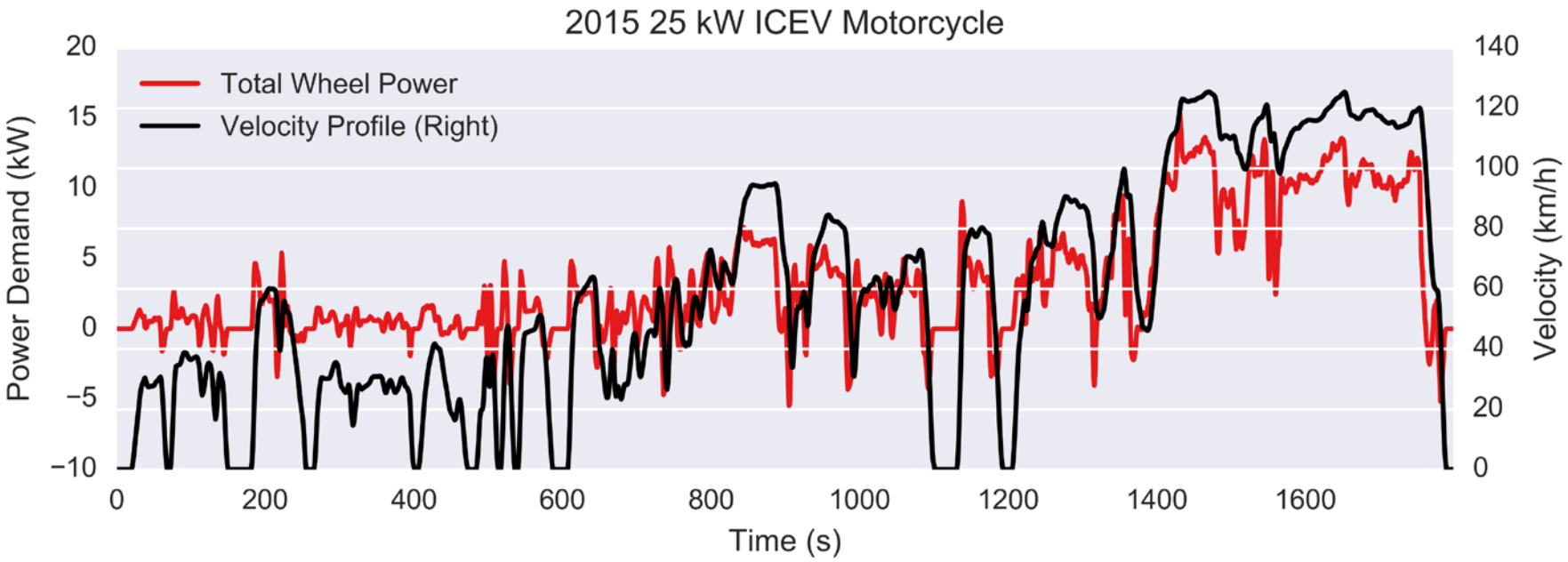
Source: motorcycledb.com

Motorcycle driving characteristics



WMTC : World harmonized Motorcycle Test Cycle

Motorcycle Power Demand



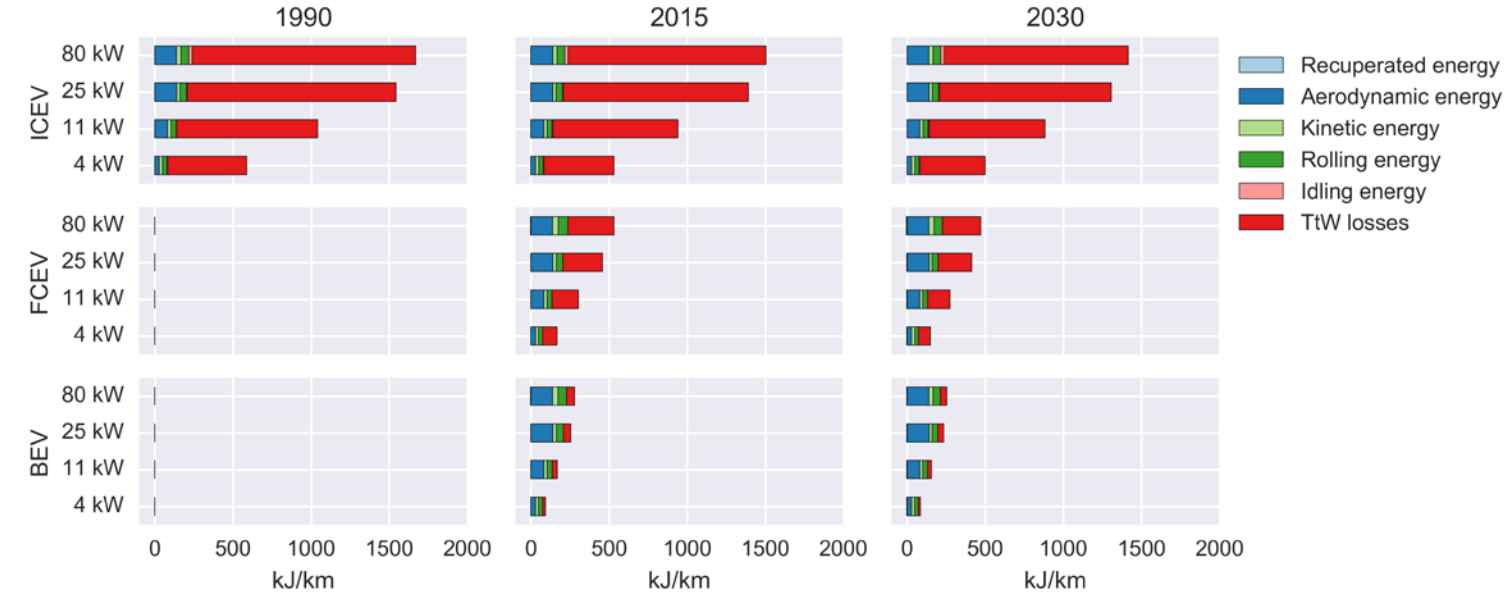
ICEV : Internal Combustion Vehicle

Energy Consumption

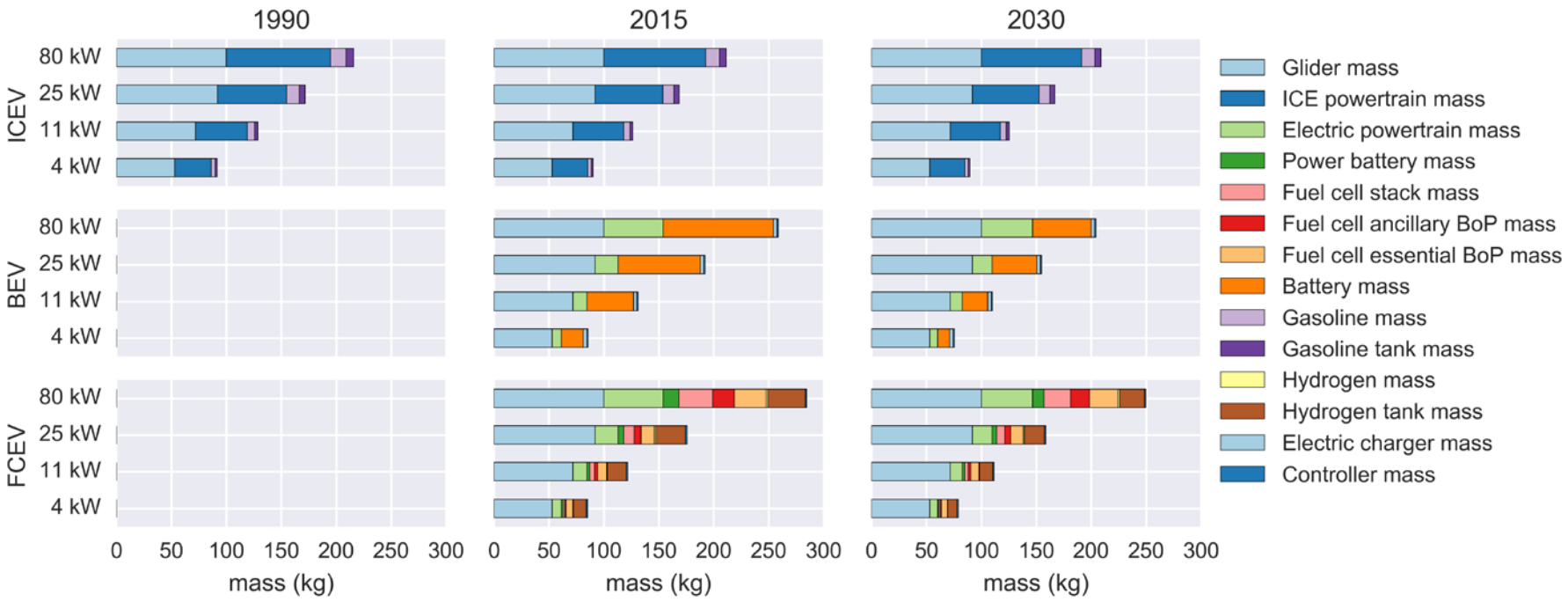
Wheel Energy Demand

ICEV : Internal Combustion Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle

Tank to Wheel Energy Demand

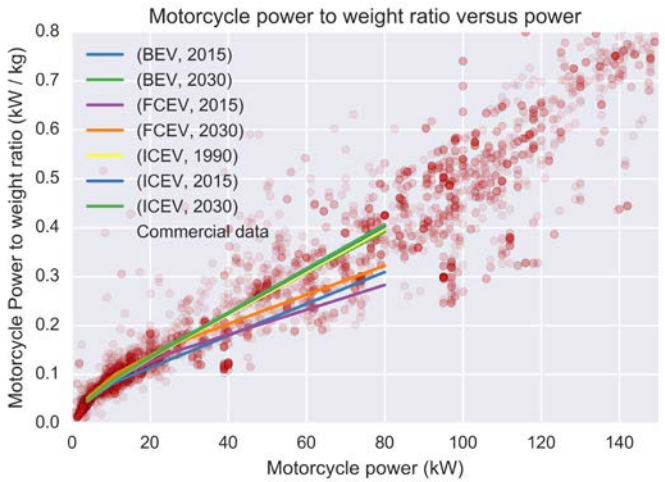


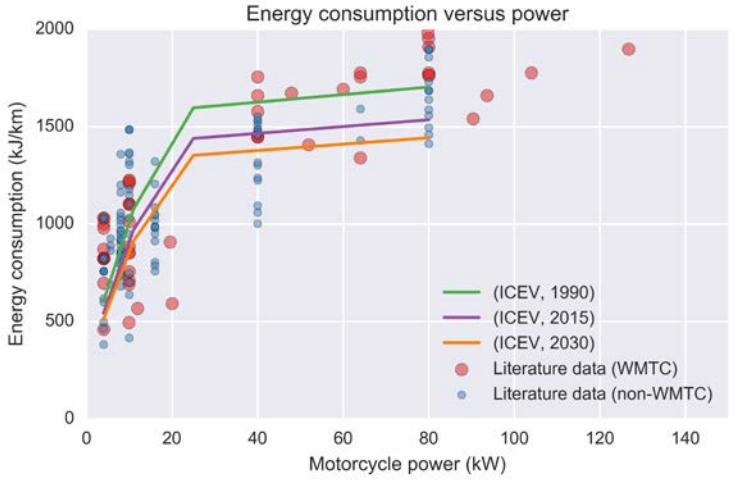
Motorcycle Mass

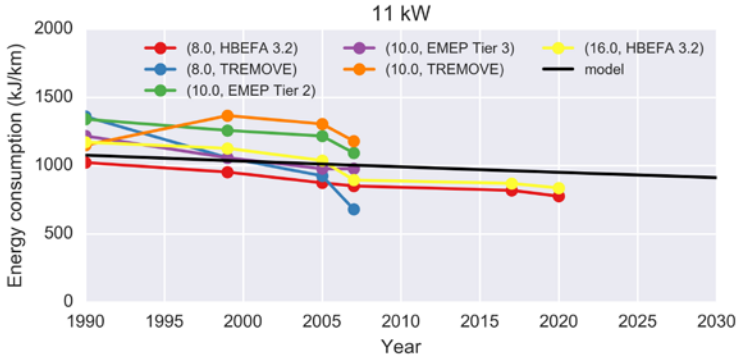


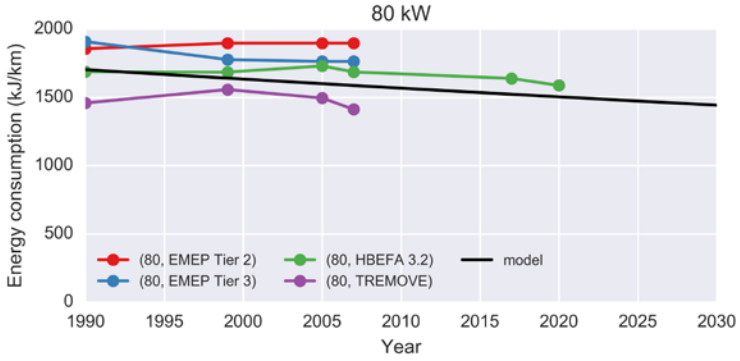
ICEV : Internal Combustion Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle

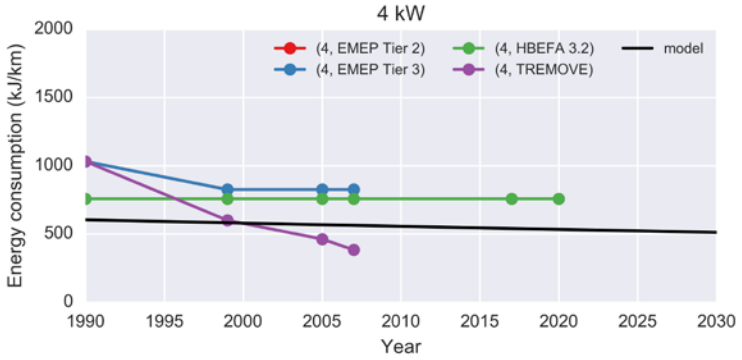
Calibrating Results

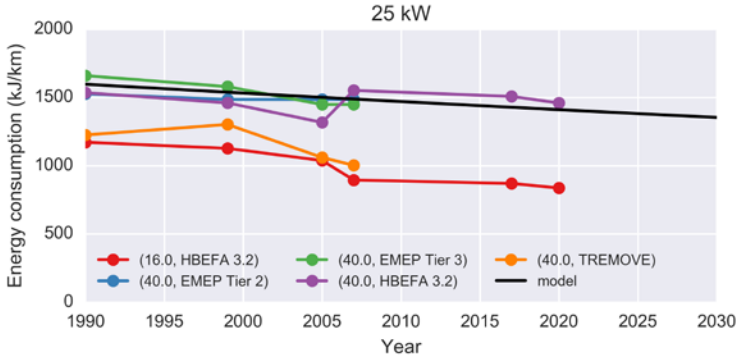




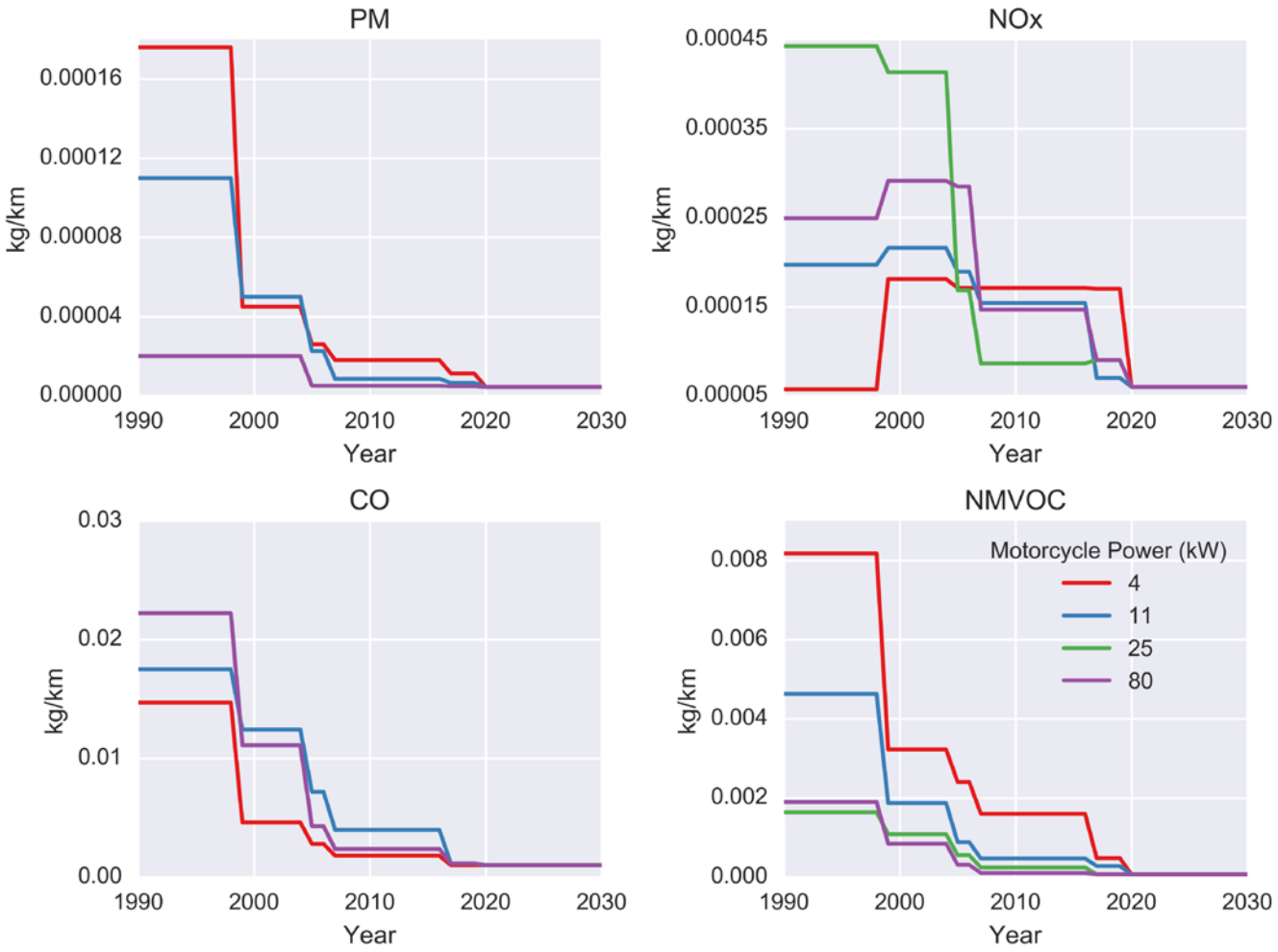


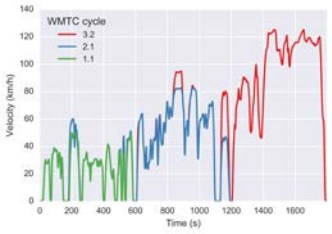






Operating Emissions

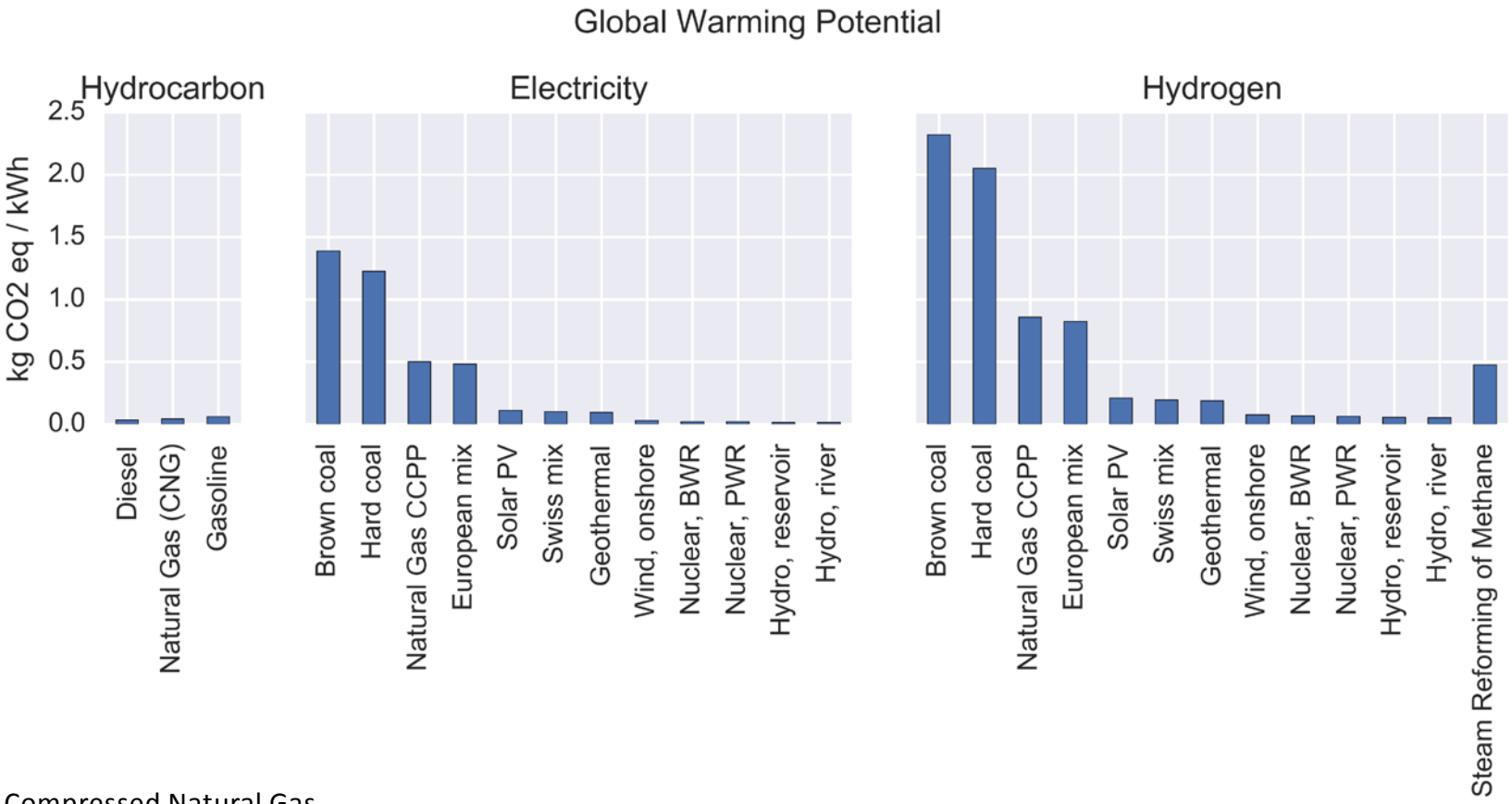




PM: Particulate Matter
CO: Carbon Monoxide
NOx: Nitrogen Oxides
NMVOC: Non-Methane Volatile Organic Hydrocarbons

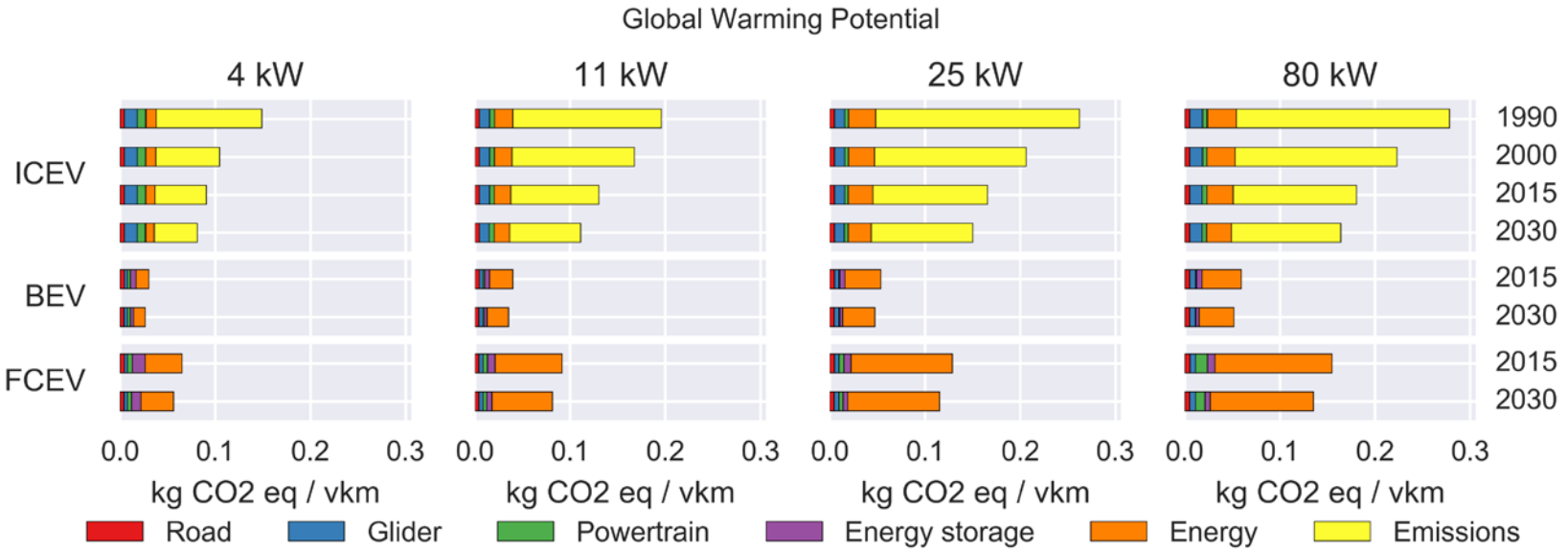
EMEP/EEA air pollutant emission inventory guidebook – 2013

Energy Chains – Upstream Impacts



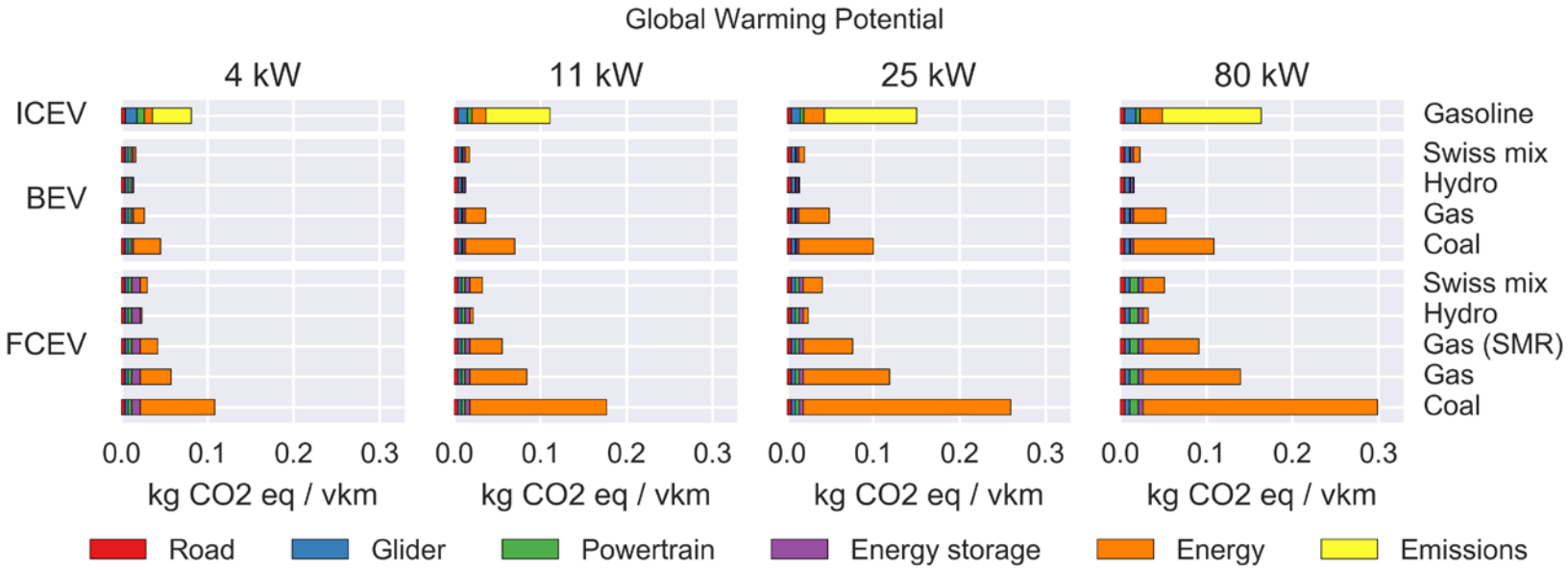
CNG: Compressed Natural Gas
BWR: Boiling Water Reactor
PWR: Pressurised Water Reactor

Result: European Average Electricity



ICEV : Internal Combustion Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
vkm: Vehicle kilometer

Result 2030 – more energy chains



ICEV : Internal Combustion Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
vkm: Vehicle kilometer
SMR: Steam Methane Reforming

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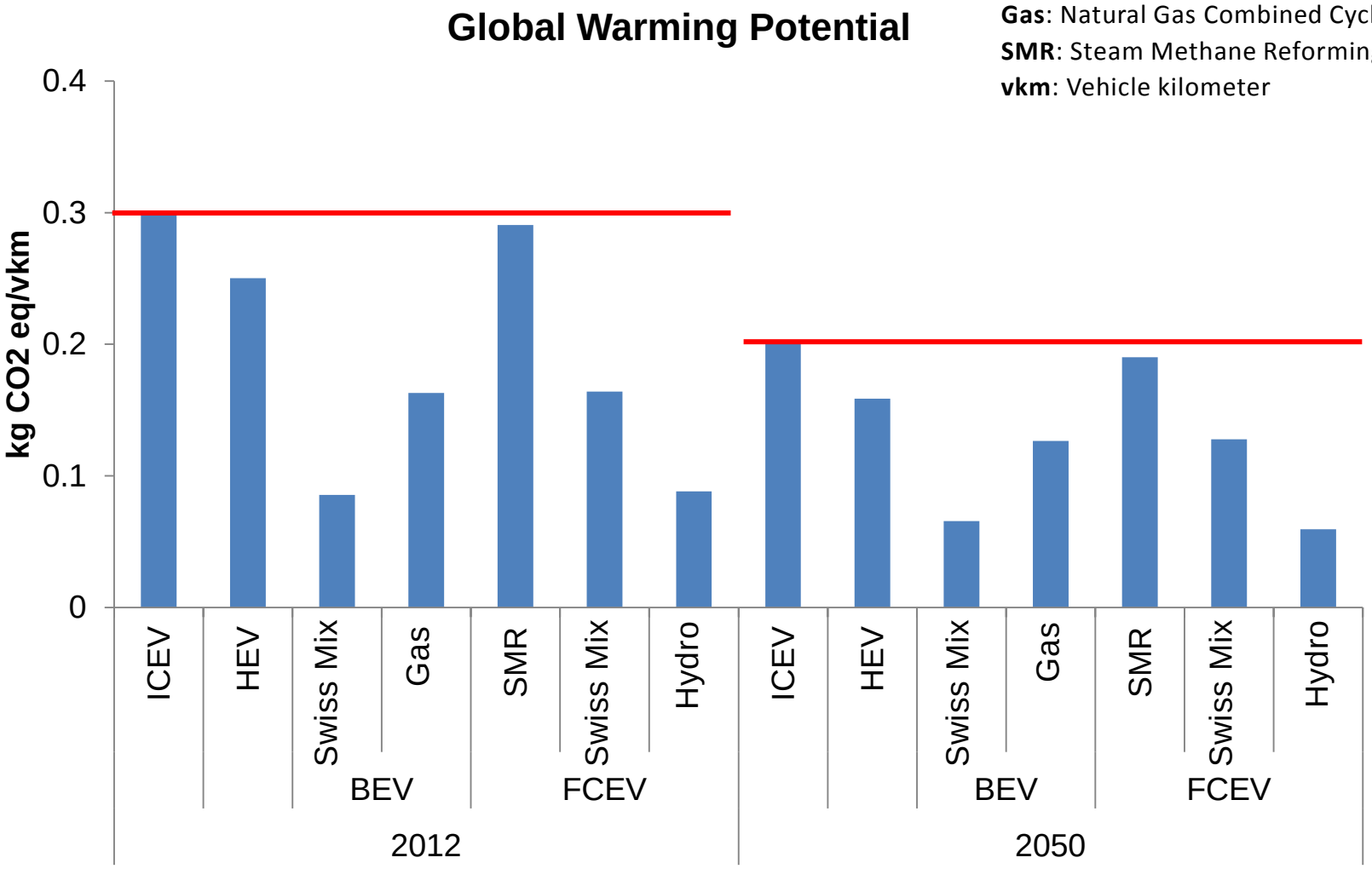
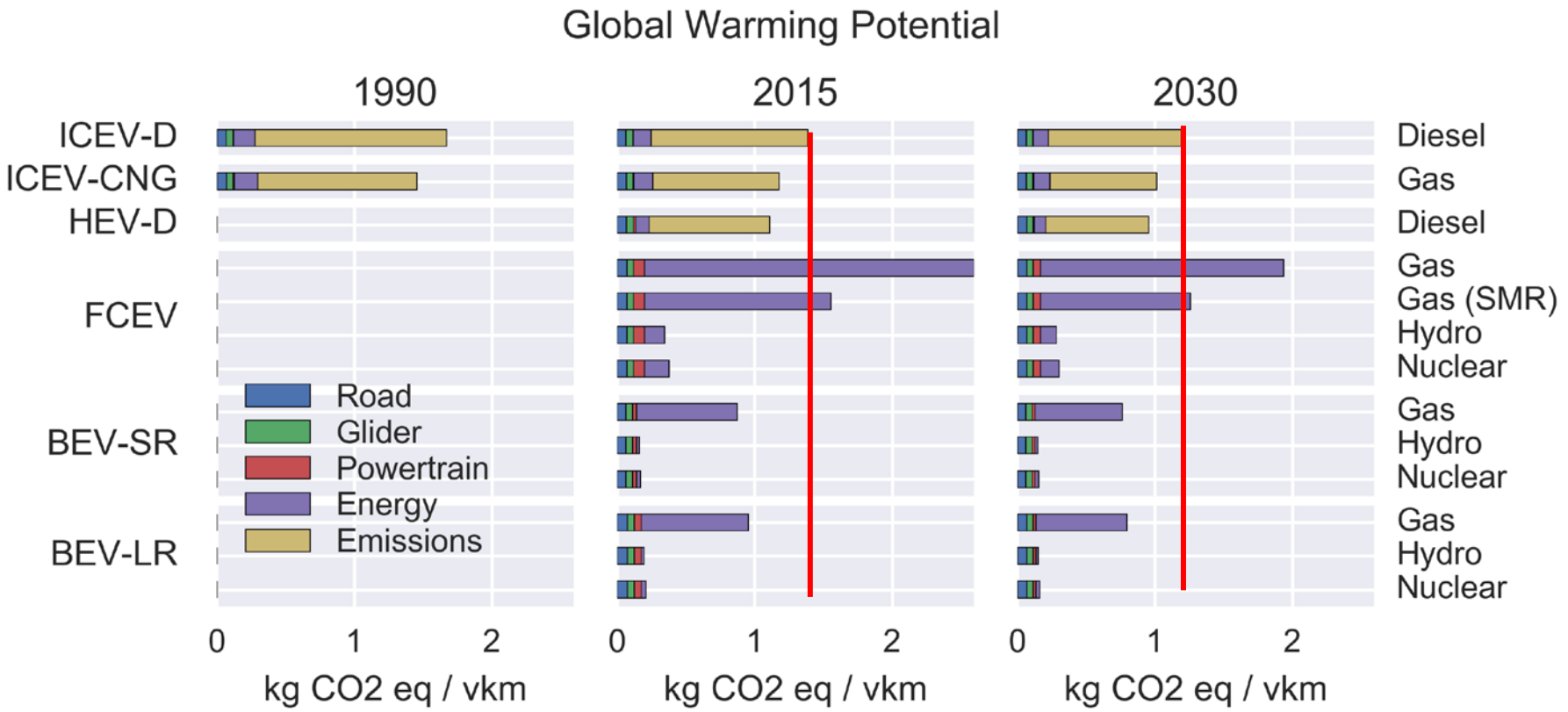
Passenger Cars

ICEV: Internal Combustion Vehicle
HEV: Hybrid Electric Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
Gas: Natural Gas Combined Cycle
SMR: Steam Methane Reforming
vkm: Vehicle kilometer



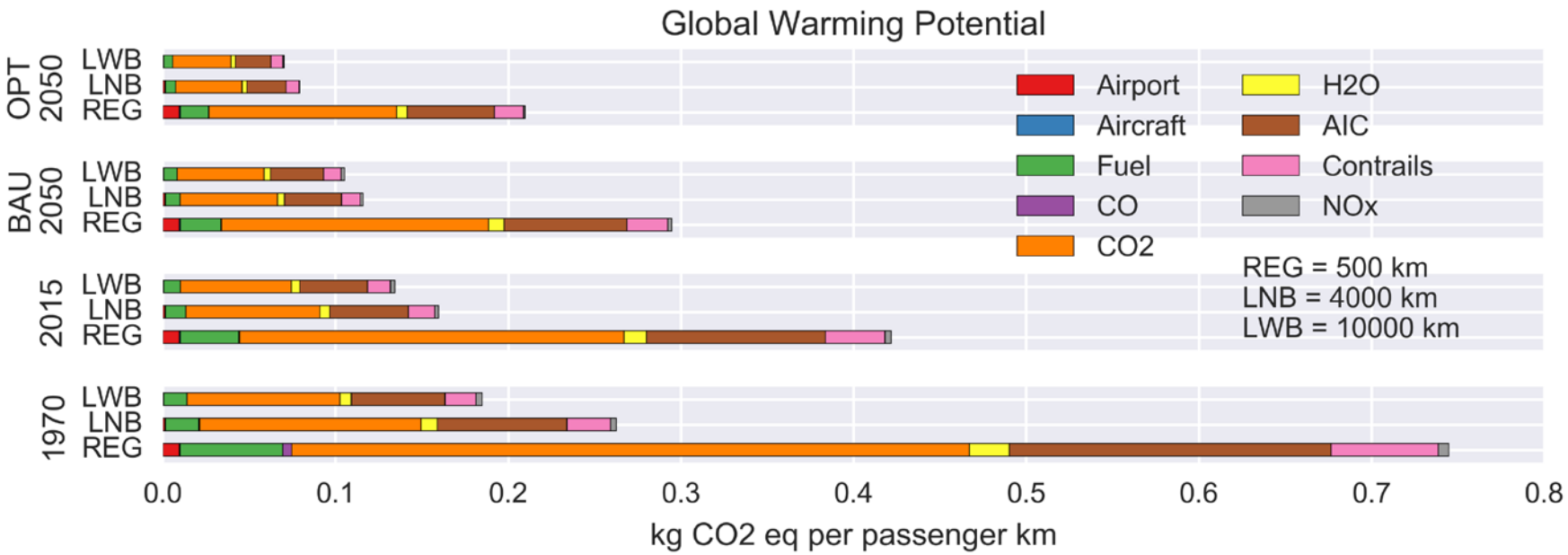
Source: Project THELMA (mid sized cars)

Urban Buses



ICEV-D : Internal Combustion Vehicle Diesel
ICEV-CNG : Internal Combustion Vehicle Compressed Natural Gas
HEV-D: Hybrid Electric Vehicle Diesel
BEV: Battery Electric Vehicle
SR: Short Range opportunity charging
LR: Long Range plug in charging
FCEV: Fuel Cell Electric Vehicle
vkm: Vehicle kilometer
SMR: Steam Methane Reforming

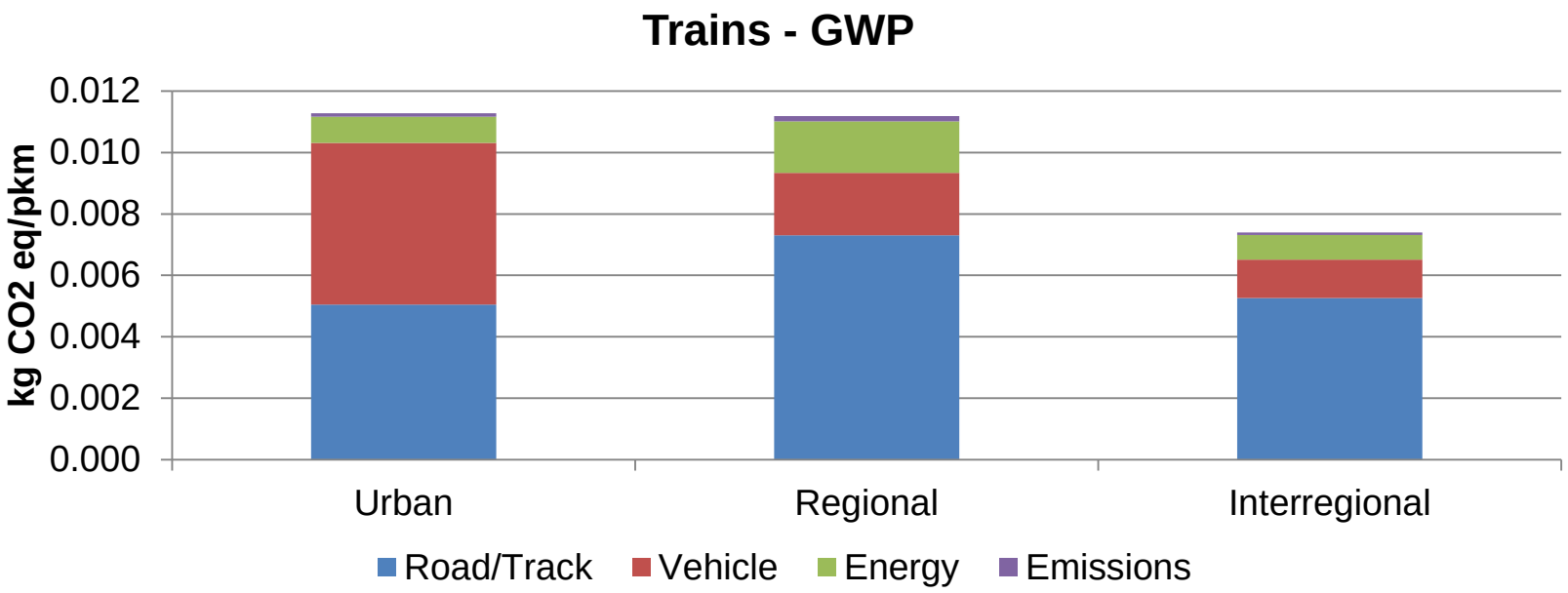
Aircraft



REG: Regional Aircraft, 500 km flight
LNB: Large Narrow Body Aircraft, 4000 km flight
LWB: Large Wide Body Aircraft, 10000 km flight
BAU: Business As Usual future technology development scenario
OPT: Optimistic future technology development scenario

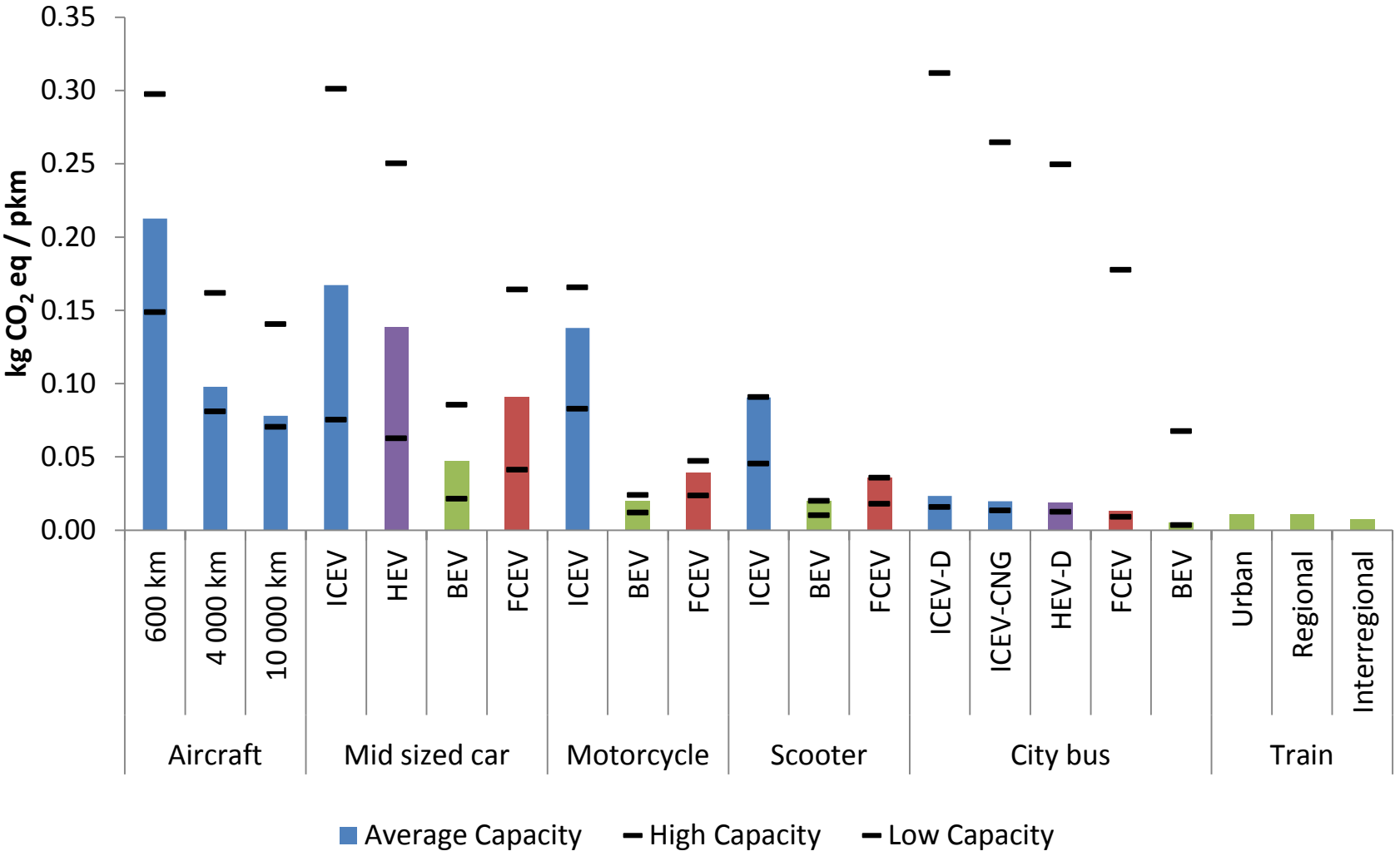
AIC: Aviation induced cirrus cloud formation

Trains



pkm: Passenger kilometer

Transport mode comparison



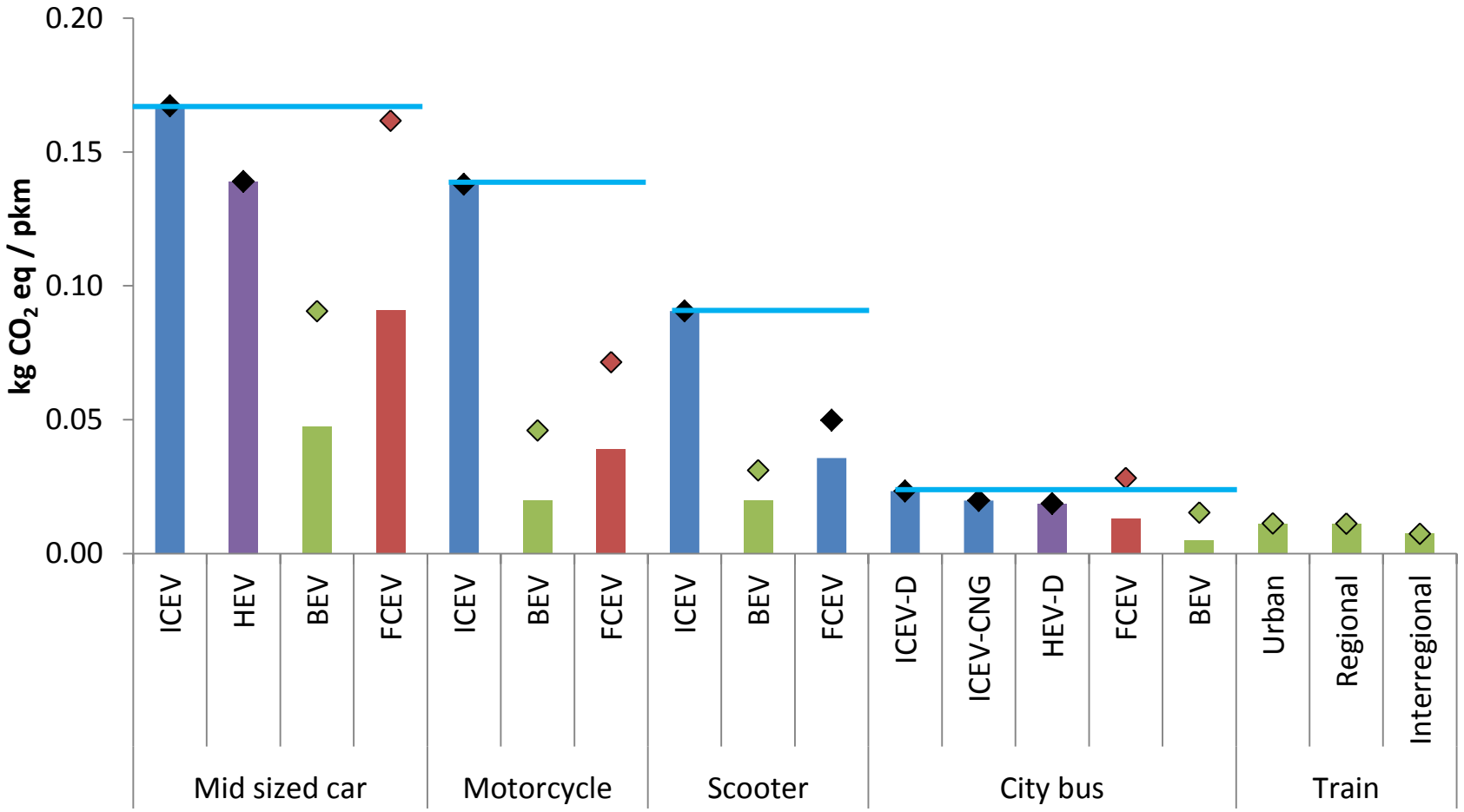
Current Swiss Electricity

ICEV : Internal Combustion Vehicle
CNG: Compressed Natural Gas
LR: Long Range plug-in charging

HEV: Hybrid Electric Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle

D: Diesel
SR: Short Range opportunity charging
pkm: Passenger kilometer

Transport mode comparison



Average load factors

ICEV : Internal Combustion Vehicle
CNG: Compressed Natural Gas
LR: Long Range plug-in charging

HEV: Hybrid Electric Vehicle
BEV: Battery Electric Vehicle
FCEV: Fuel Cell Electric Vehicle

D: Diesel
SR: Short Range opportunity charging
pkm: Passenger kilometer

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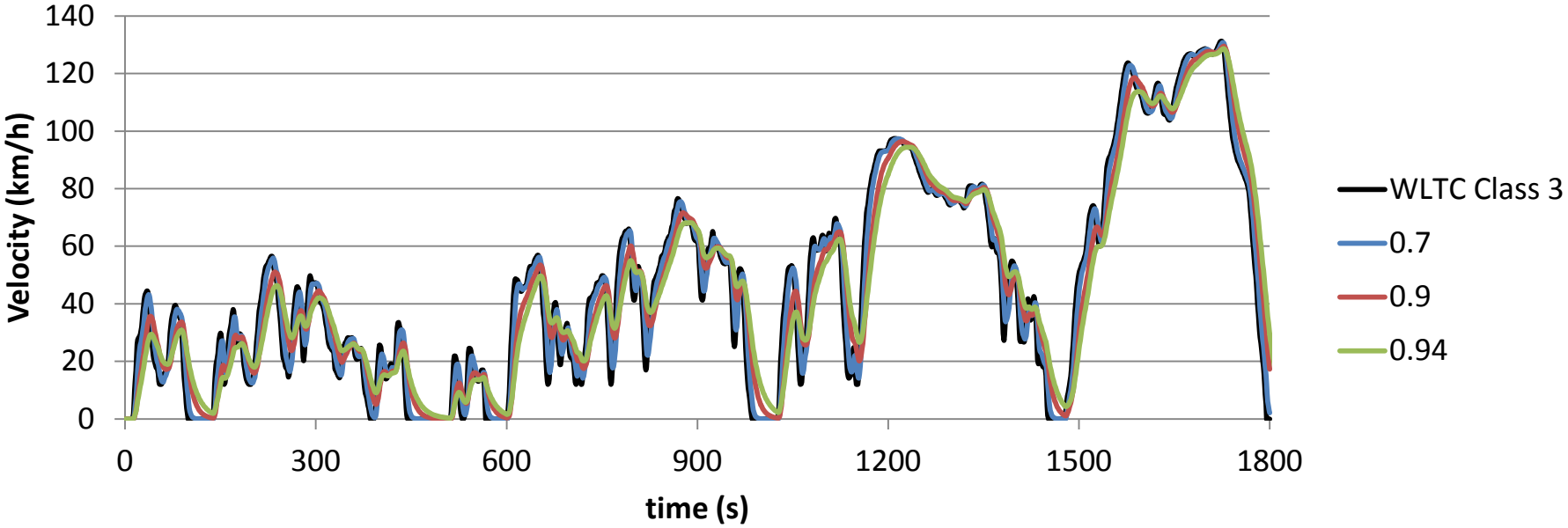
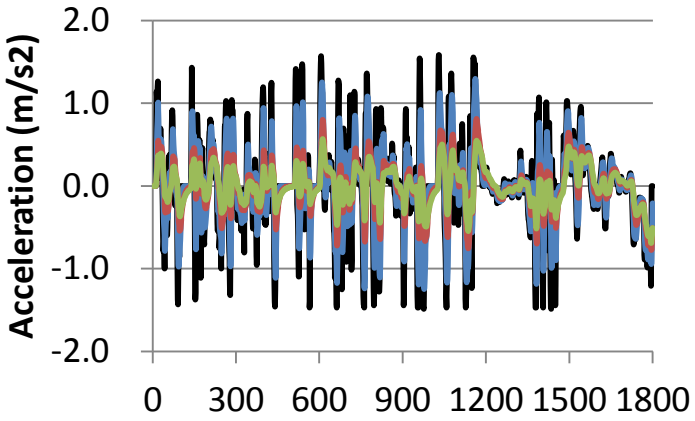
Energy consumption of autonomous cars

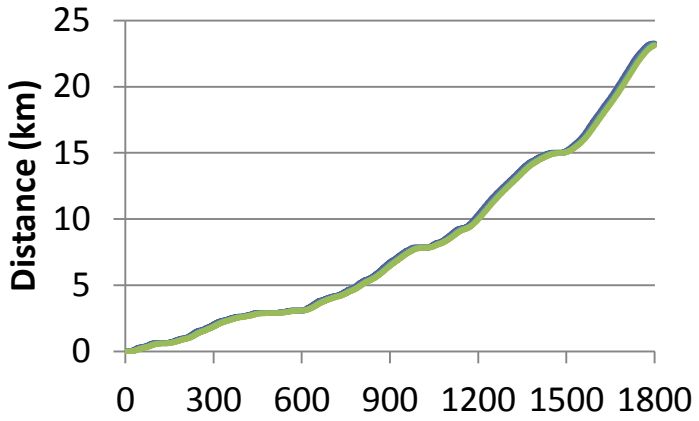
- Traffic smoothing
  - ecodrive pre-programmed
  - lower acceleration demand (rider comfort)
  - knowledge of road ahead
- Platooning
- Right Sized

- Secondary effects:
  - increased vkm
  - less congestion

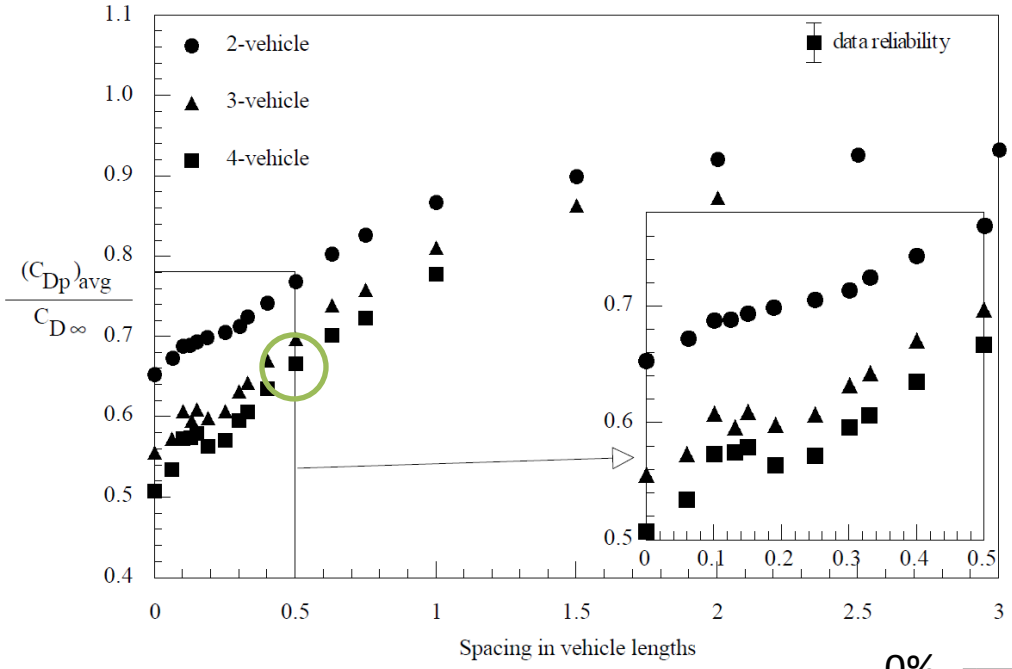
Estimating autonomous driving cycles

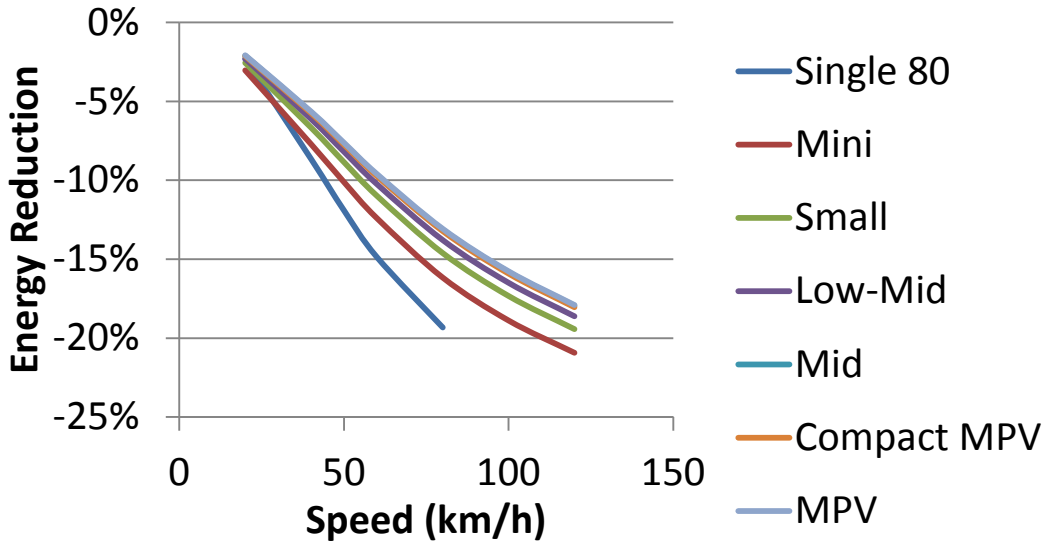




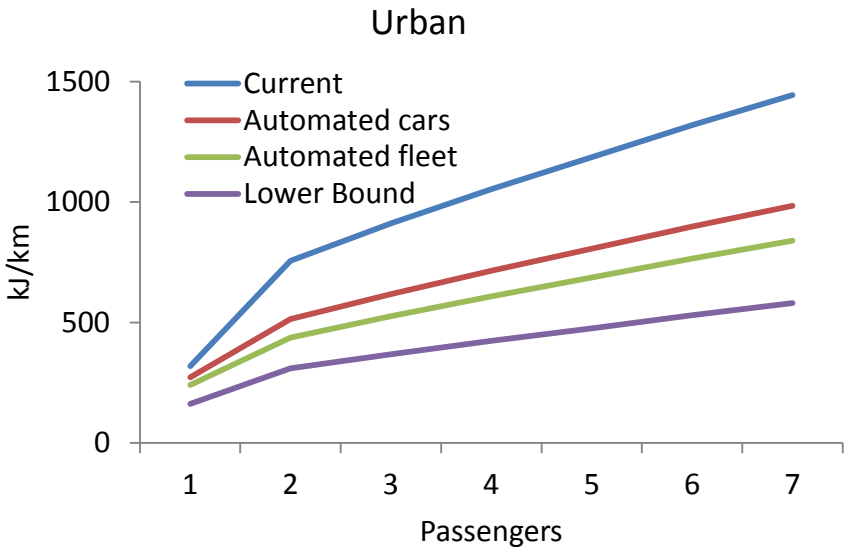


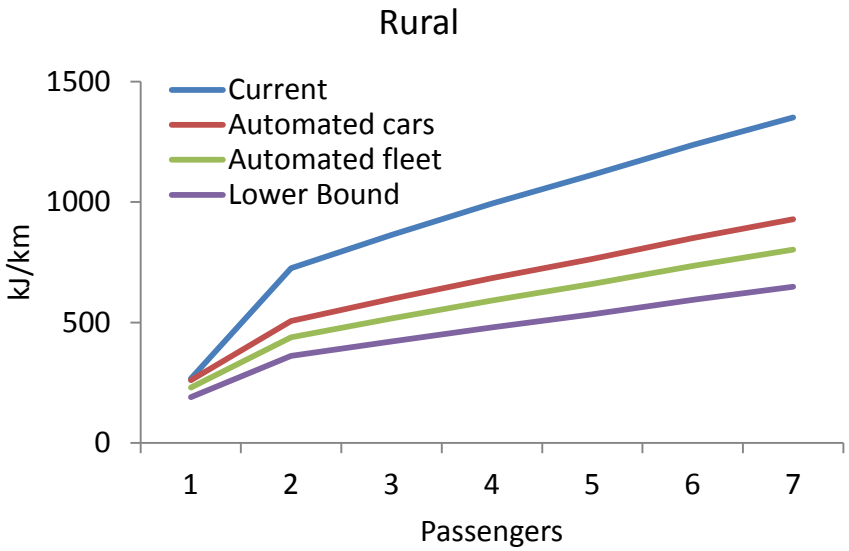
Energy reduction from platooning

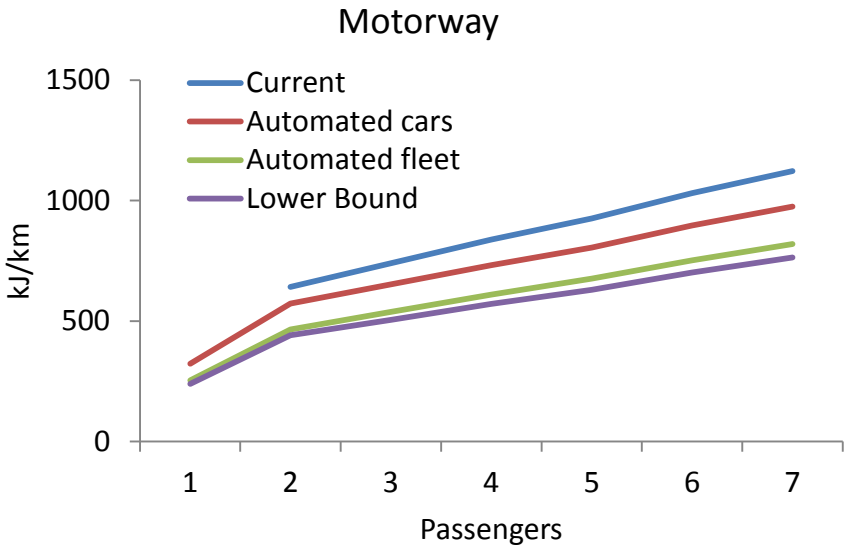


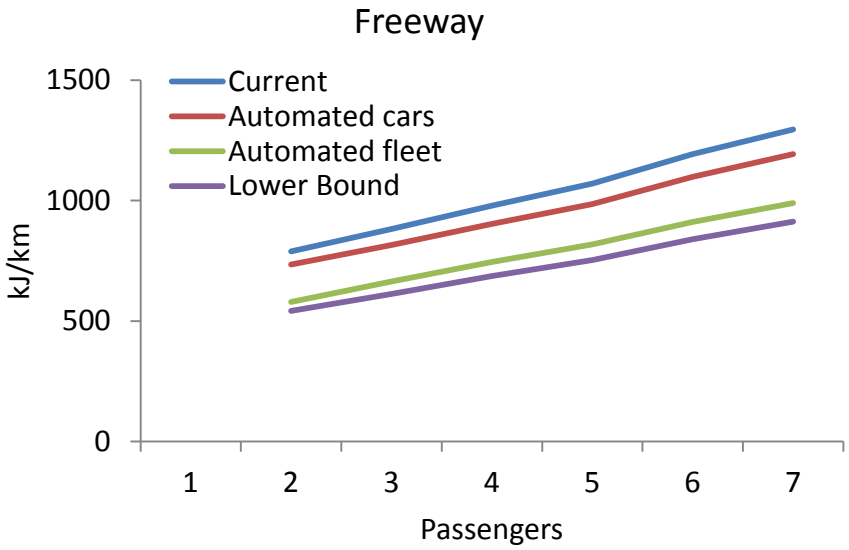


Autonomous cars: Results









Autonomous cars: Conclusions

	Urban	Rural	Highway	Freeway	Average Driving
Smoothing	50%	40%	15%	13%	26%
Platooning	2%	4%	9%	14%	9%
Right-Sizing	36%	35%	25%	23%	30%
Total Savings	59%	61%	45%	41%	50%

*These reductions are for an automated mini sized BEV compared to a human driven mid-sized BEV.

Weaknesses of the methodology

Uncertainties are very large

- future performance of technologies
- life cycle inventories and impact assessment methods
- using current background LCA database for future LCA

Energy consumption modelled simplistically

- Though energy consumption found to be very important
- However, the method allows comparison of technologies for which no data available

Future is likely to be a mix of technologies

Different transport technologies not directly comparable

- Range of BEV
- Public versus private transport

Discussion and Outlook

LCA is a useful tool to compare different transport technologies

Performance of ‘advanced’ technologies strongly depends on energy source
- BEV technologies very promising for many primary energy sources

Autonomous driving could greatly reduce impacts per kilometer
- But might increase total distance travelled

Modal shift has strong potential to reduce transport impacts
- Is modal shift still important in a world of self driving electric vehicles?
- How does mass car sharing effect the results?

Future task: combine all transport technologies into fleet scenarios
- and integrate with energy system model

Conclusions

There are 5 main ‘levers’ that we can pull to reduce impacts from passenger transport

1. Incremental improvements of current status quo
2. Electrification
3. Modal Shift
4. Demand Reduction
5. Autonomous vehicles

Most sustainable solution is likely to pull all of them.

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