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Future Automotive Challenges & Opportunities

Professor Neville Jackson
Chief Technology & Innovation Officer
Ricardo plc

22nd November, 2017

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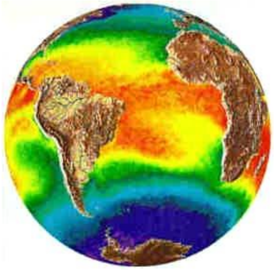
Global long term GHG targets consistent – City Authorities & Planners also increasingly focused on "healthy Lifestyles & Environments"



- **Europe:**
  - 40% reduction in GHG by 2030 (1990 basis)
  - 89-95% reduction in GHG by 2050 (1990 basis)
- **China:**
  - 20% of energy from low-carbon sources by 2030
  - CO_2/GDP reduced by 60-65% by 2030 (ref. 2005)
- **USA (prior to President Trumps withdrawal):**
  - 26-28% reduction in GHG by 2025 (2005 basis)
  - 83% reduction in GHG by 2050 (2005 basis)

- **City Planning & Policies:**
  - Ultra Low Emission Zones
  - Walking, Cycling, Public Transport Prioritised

What are the implications for energy supply, powertrain technologies & business models?

Source: United Nations Framework Convention on Climate Change

Traffic congestion, pollution, parking, air quality, safety and affordability are all driving demand for radical interventions

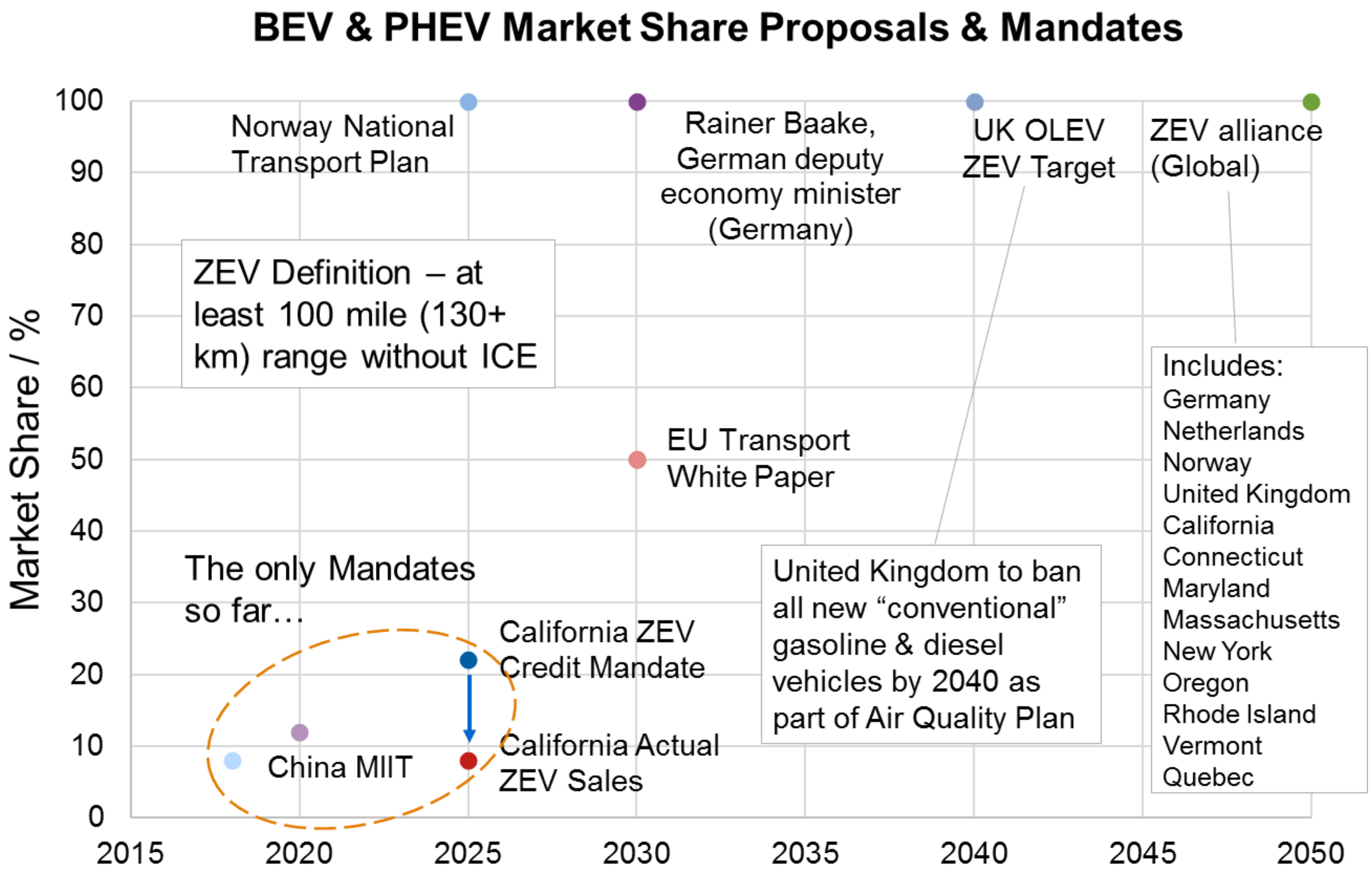



(London Smog 1952)

- **UK to ban "conventionally" fuelled cars by 2040** (excludes hybrids of all types)
  - London congestion charge & ULEZ, restrictions on diesels, alternative fuelled taxis and buses.
- **Germany's Bundesrat** resolution to **ban the internal combustion** engine starting in 2030
  - Hamburg plans 40% of city car free by 2034.
  - Vauban (Freiburg) has banned cars, residents rent a €20,000 parking space on the city outskirts
- **Finland, Helsinki** overhauling public transport via smartphones; car ownership pointless by 2025.
- **France, Paris** plans to ban diesel vehicles by 2020
- **Amsterdam** is to ban city centre cars on Saturdays, to reduce motor traffic and pollution
- **China & California ZEV mandates**: China plan to phase out vehicles powered by fossil fuels

Source: Media reports

The "clean air" agenda has driven Governments towards ZEV mandates due to a perceived lack of progress in electrification



- Many Governments have stated objectives and policies for phasing out combustion engine vehicles before 2050
- UK intention has been to eliminate conventional gasoline & diesel passenger cars by 2040 as part of a "clean air" strategy
- EU working on proposal (with UK support) to introduce EU wide mandate/credit for ZEV vehicles in 2025-2040 timeframe
- **There are already >500 individual restrictions on ICE vehicle use in specific zones in European Cities**

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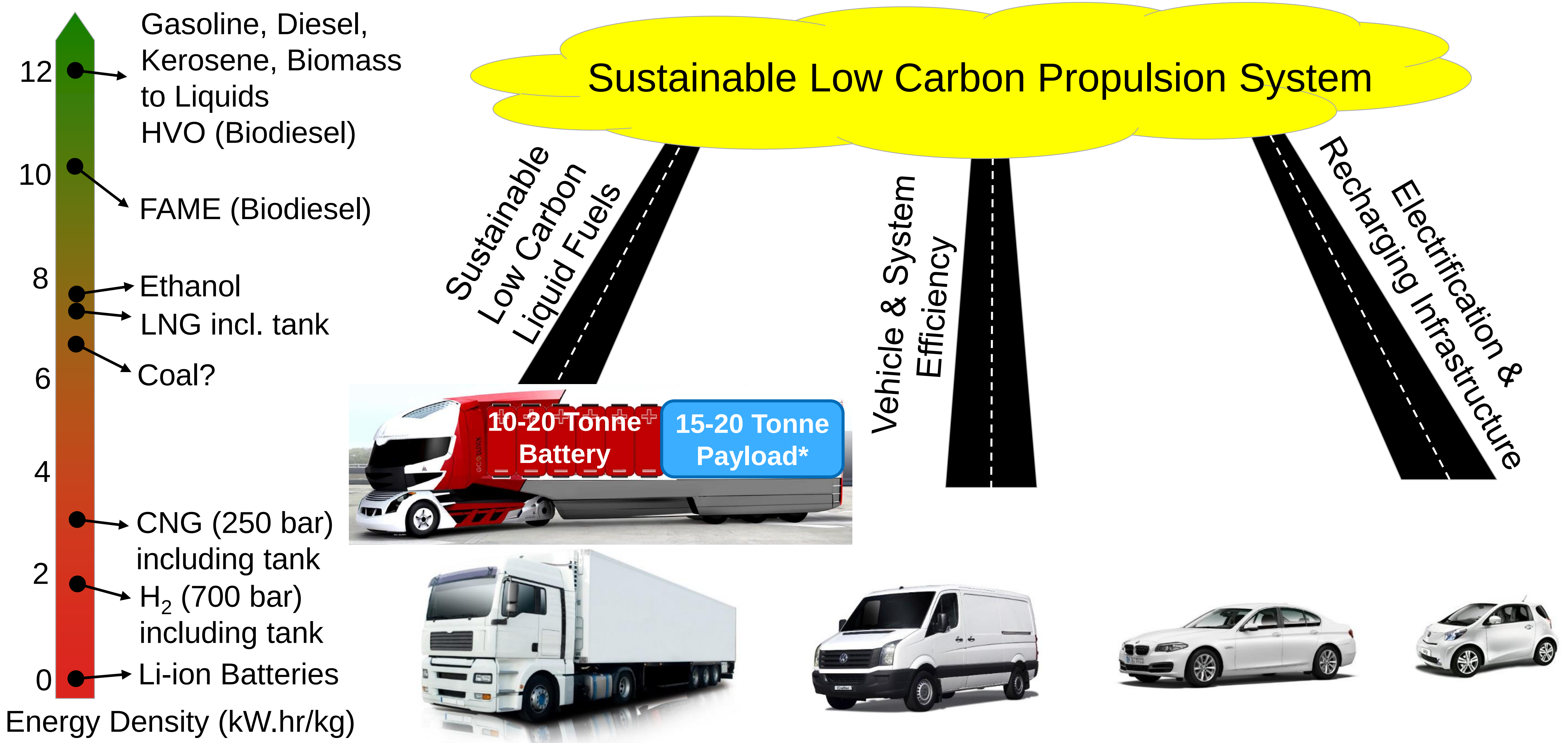
Electrification is only one part of the future transport solution – we will still require low carbon liquid fuels for many decades…



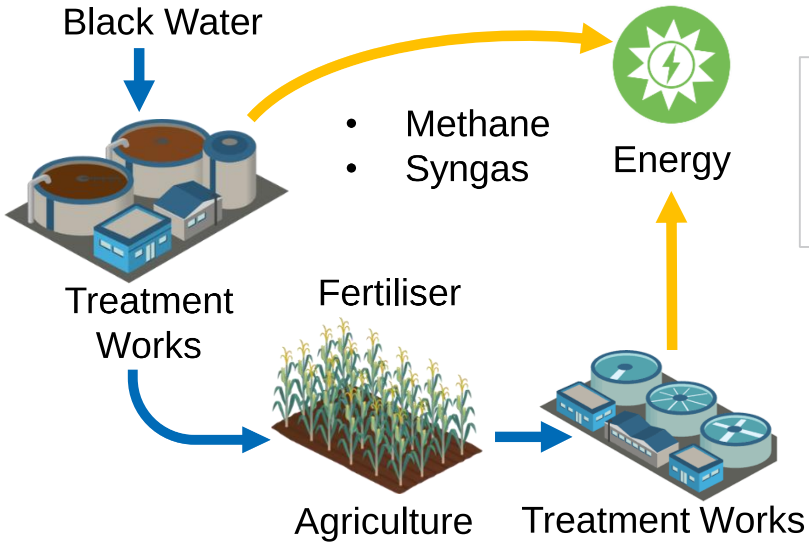
Source: Ricardo, *Steyr

Electrified roads for heavy duty applications – a possibility for specific environmental challenges?

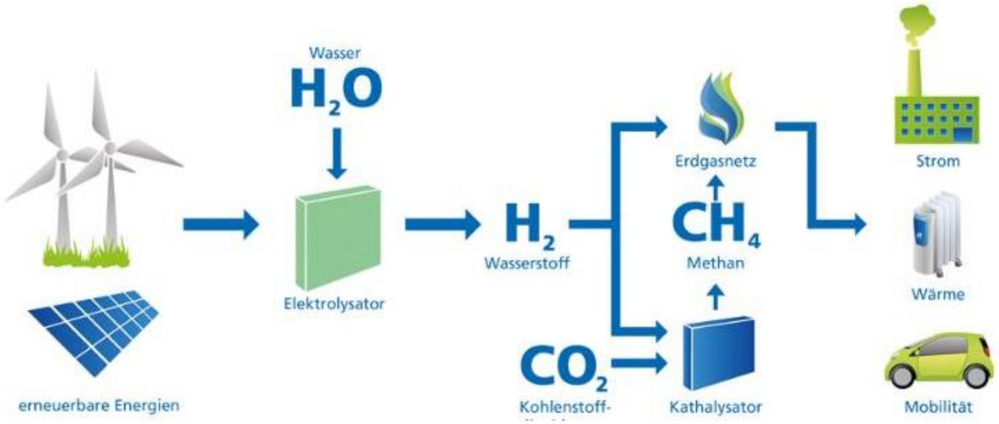
- Safety Issues:
  - Need dual catenary as no road surface connection
- Power:
  - Total power input for multiple HGV's on an incline likely to be 5-10 MW
  - Initial trials at 600 volts - not compatible with multi-vehicle demands
- Costs
  - $5–6 million per km likely to be prohibitive
  - Who pays?

Source: recombu.com:Sweden is testing electric roads for trucks, ITS International: Using electricity to power road freight

Ultra Low or Zero carbon trucks – probably a choice between H_2 Fuel cells with renewable hydrogen or Bio-Waste/Power to Liquid Fuels



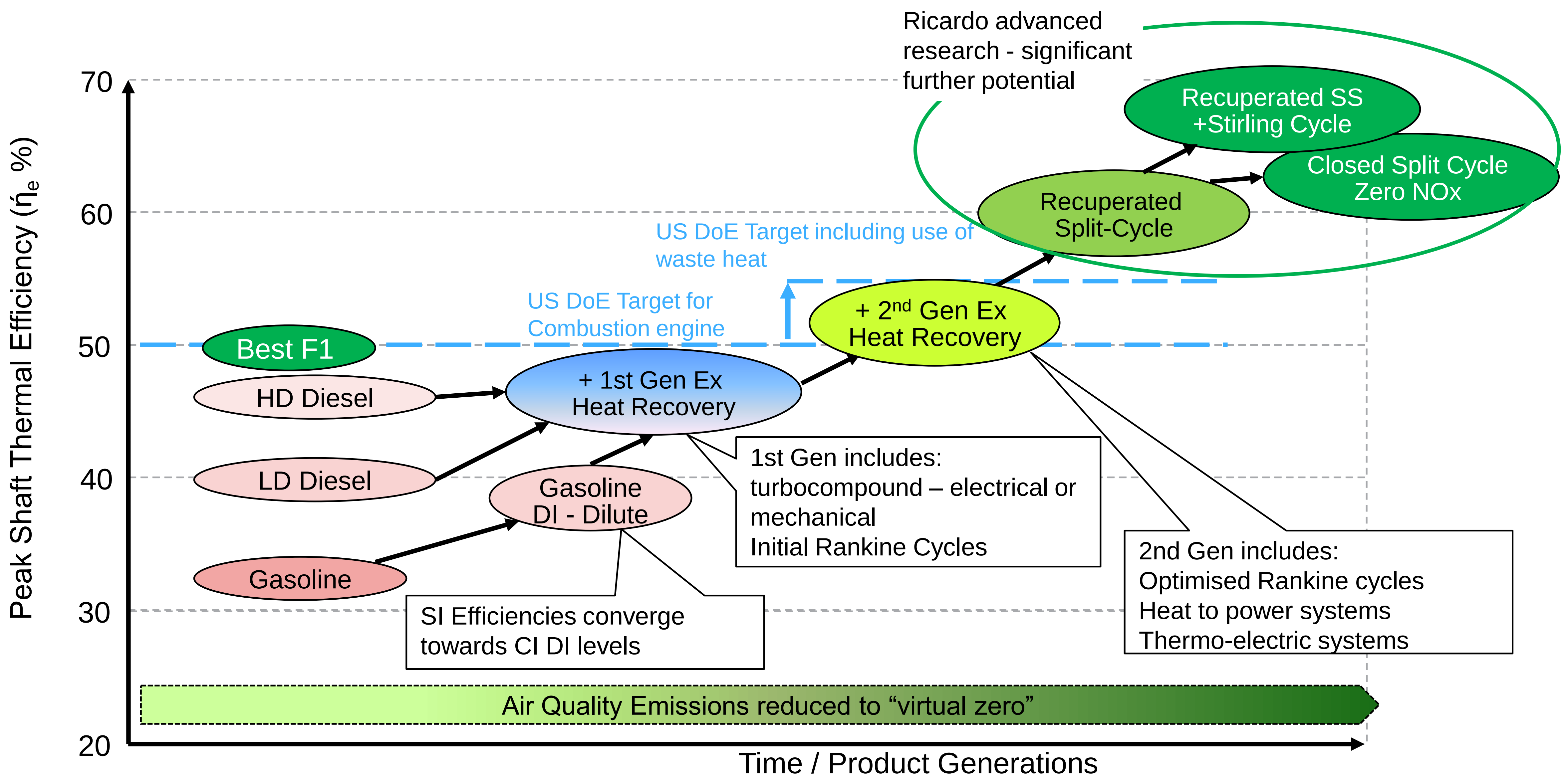
Waste to Hydrocarbon Liquid Fuels



Renewable Electricity to Liquid Fuels

H_2 Fuel Cell Trucks – Toyota/Nikola Motors **<>** **Renewable “Synthetic” Fuels**

ICE thermal efficiency ~60% in future products? – still significant further potential for improvements in combustion engine efficiency



Source: Ricardo Analysis, SAE 2015-26-0038 Opposed-Piston 2-Stroke Multi-Cylinder Engine Dynamometer Demonstration, Cousin Of The Chainsaw Engine Could Power 100-MPG Car

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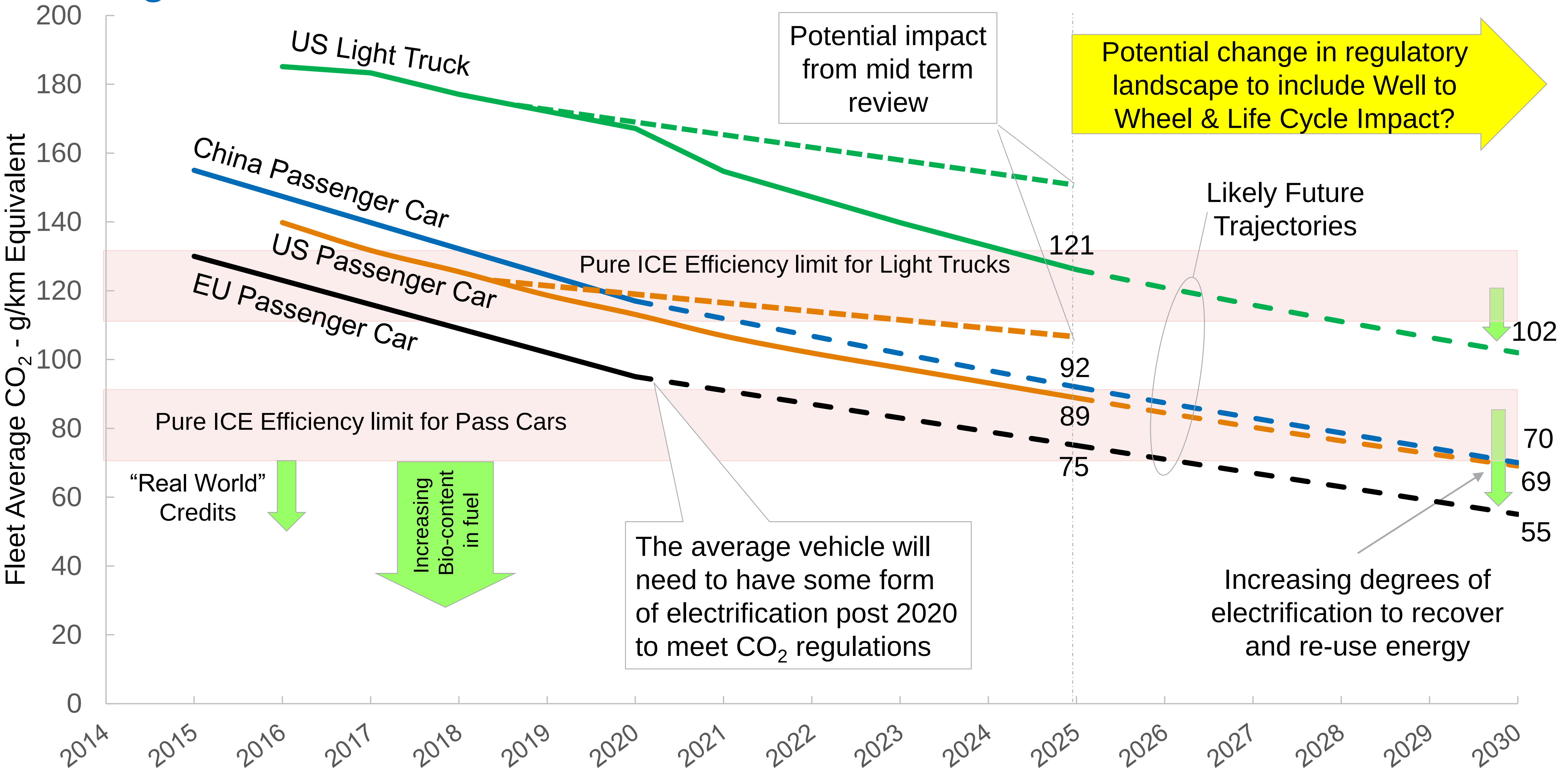
GHG reductions beyond 2025 not yet defined but likely to continue – 2030 targets defined on more holistic basis?



Source: Ricardo analysis

Electrification can be applied in a number of configurations - no "one size fits all" solution – 48 volt systems for volume & PHEV for premium

Increasing degree of vehicle electrification

Micro Hybrid → Mild Hybrid → Full Hybrid → Plug –in Hybrid → Range Extended EV → Pure EV

Micro/Mild: Solution for the "Average Car"

- **Ricardo HyBoost** ~ 95 g/km in "C" class car
- **Ricardo ADEPT** ~ 70 g/km in family car via 48v systems
- **Micro-hybrid** 48v architecture under development since 2011
- Below 60v "hazardous" threshold

Full Hybrid: Niche or High Performance

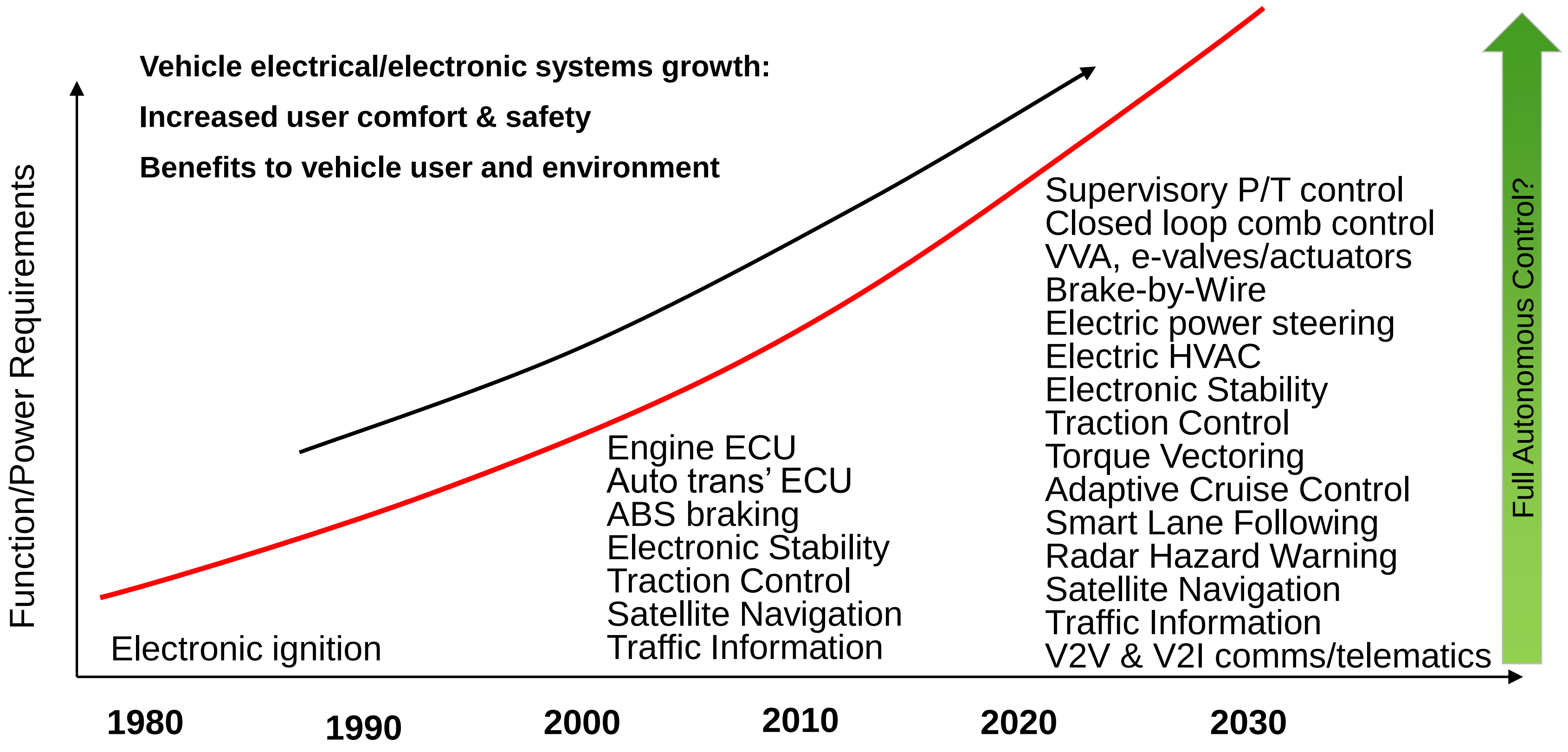
- **Prius** best-selling hybrid - but, at **70 g/km** cost/benefit eroded by 48 v systems?
- **New WLTP cycle** reduce benefits of hybrid systems
- **KERS** systems make sense in supercars

Plugged In: The Future? – From Premium to Volume

- **BMW i3** – EV with optional range extender
- **Tesla** – shows that there is a market for a premium "eco" product
- **Favourable treatment in legislative cycles** makes PHEV technology attractive in larger premium vehicles

Source: Ricardo Analysis

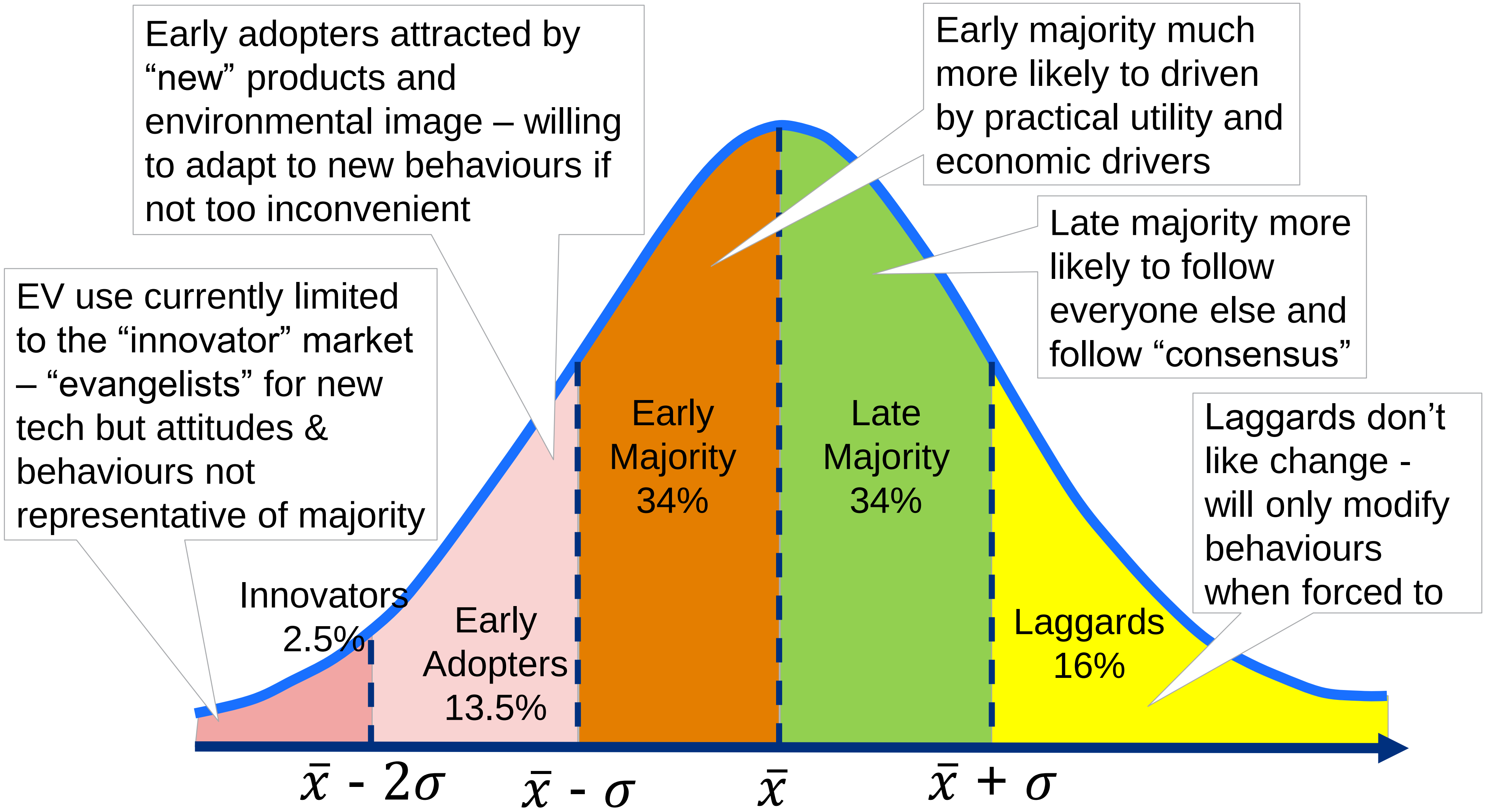
Growth in automotive electronics and electrical system functionality has led to rapid growth in power demands



- Number of vehicle electrical/electronic continuing to increase
  - Challenges for both average and peak power demands – Multiple ADAS/Autonomous processing requirements also a major future challenge
  - Power demands beyond limit of 12 volt functionality & will drive introduction of 48 volt powernet

Future Vehicle Electrical Power (Peak):		
		Power (W)
Engine	Fuel Pump/Injectors	140
	Throttle	60
	Ignition	60
	Sensors & Actuators	120
	Solenoids/Relays	25
	P/T ECU	80
	Coolant Pump	400
Transmission	Clutch Actuation	250
	Gear Selection	150
Chassis/Body	Elec Power Steering	350
	Brake by Wire	250
	HVAC	4500
	Heated Screen	500
	Window	600
	Power locks	200
	Wipers/Washers	150
	Seat Actuation	400
	Body ECU	80
Lighting etc.	Headlamps	120
	Side Lights	100
	Turn Signals	120
	Reversing	50
Infotainment	Audio System	300
	Navigation/GPS	150
	Information Displays	40
	HVAC Venting	80
	HVAC Blower	400
	Total	**9675**

To accelerate EV/PHEV penetration and move beyond the innovator/early adopter market, focus on "User Centric" attributes and requirements

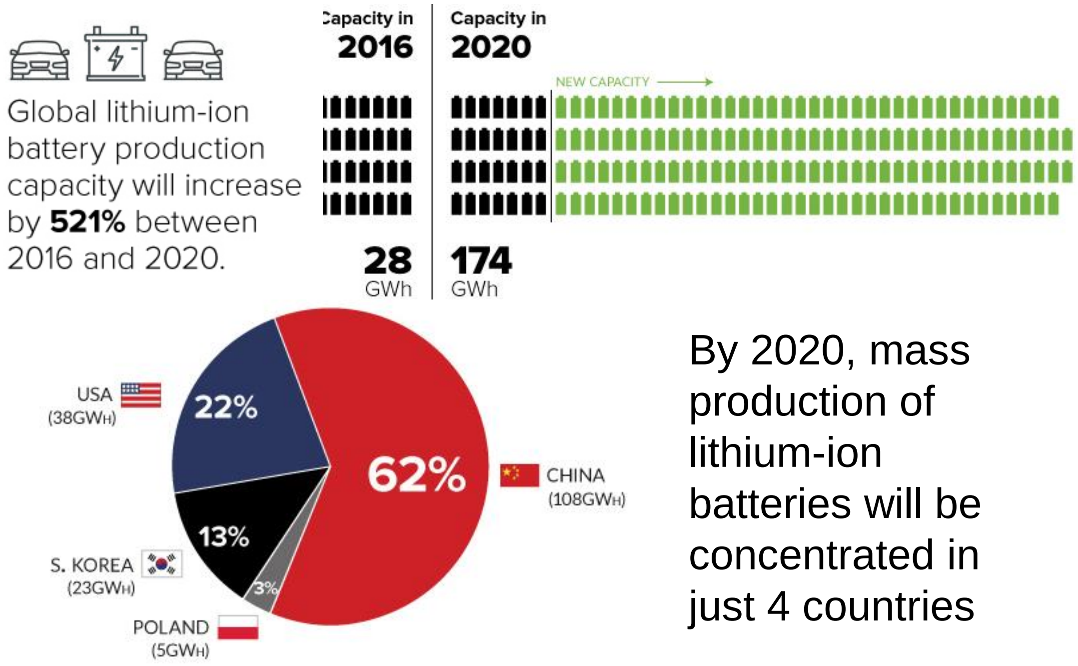


Reaching the early and late majority market:

- Focus on "User Centric" approach
- A more attractive EV/PHEV experience for consumers:
  - Ease of charging – wireless?
  - Improving charge availability?
  - More connected?
  - Preferential usage – HOV lanes/ Parking etc.
  - New ownership models?

OEM's will fit larger batteries to EV's - growth implications for Li-ion battery manufacture – mostly in China in the short term

OEM	Model	Production	Range (miles)
Chevrolet	Bolt	2016	**238**
Hyundai	Ioniq	2017	110
Ford	Focus	2017	110
Fisker	E-Motion	2017	**400**
Renault	Zoe	2017	186
Tesla	Model 3	2017-8	**200**
Audi	etron SUV	2018	**310**
Aston Martin	Rapid E	2018	**200**
Jaguar	I-Pace EV	2018	**220**
Faraday	FF91	2018	**378**
Tesla	Roadster	2019	**400**
Tesla	Model S	2019	**500**
Mercedes	Gen EQ	2019	**300**
Volvo	full size	2019	**200**
Audi	A9 etron	by 2020	**300**
Nissan	Leaf	by 2020	**200**
Porsche	Mission E	by 2020	**310**
VW	I.D. Concept	by 2020	**240**
BMW	i5 SUV	2021	**300**

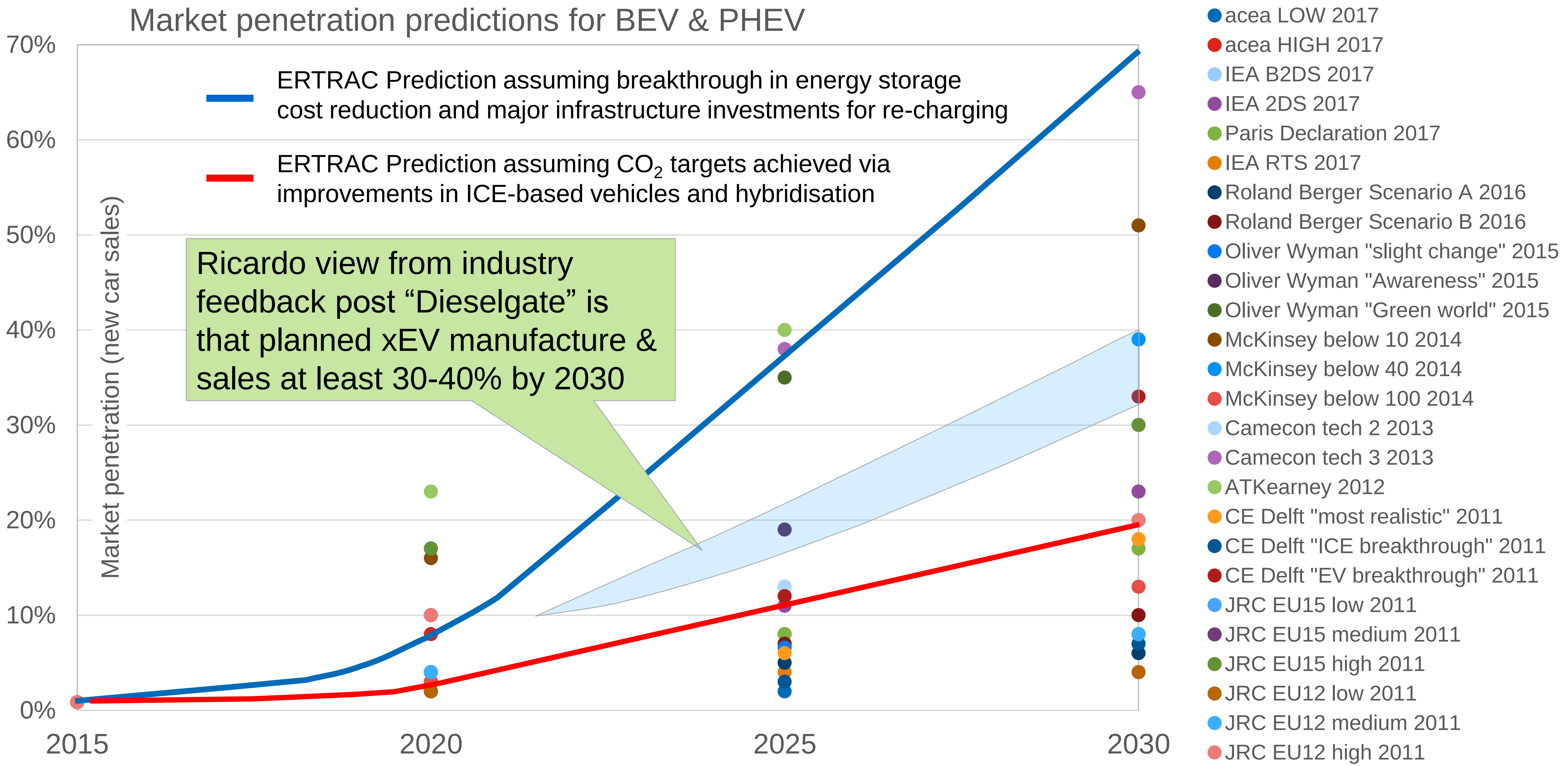


By 2020, mass production of lithium-ion batteries will be concentrated in just 4 countries

- Majority of new lithium-ion battery capacity is currently being built in China
- Many national governments are providing substantial incentives to attract EV battery manufacture
  - Battery manufacturing location may influence vehicle assembly operations

Source: carwow, inside evs, web, Visual Capitalist (Chart)

Many xEV market forecasts have been published – Recent forecasts generally less bullish but data suggests considerable uncertainty



Source: Published forecasts and Ricardo data

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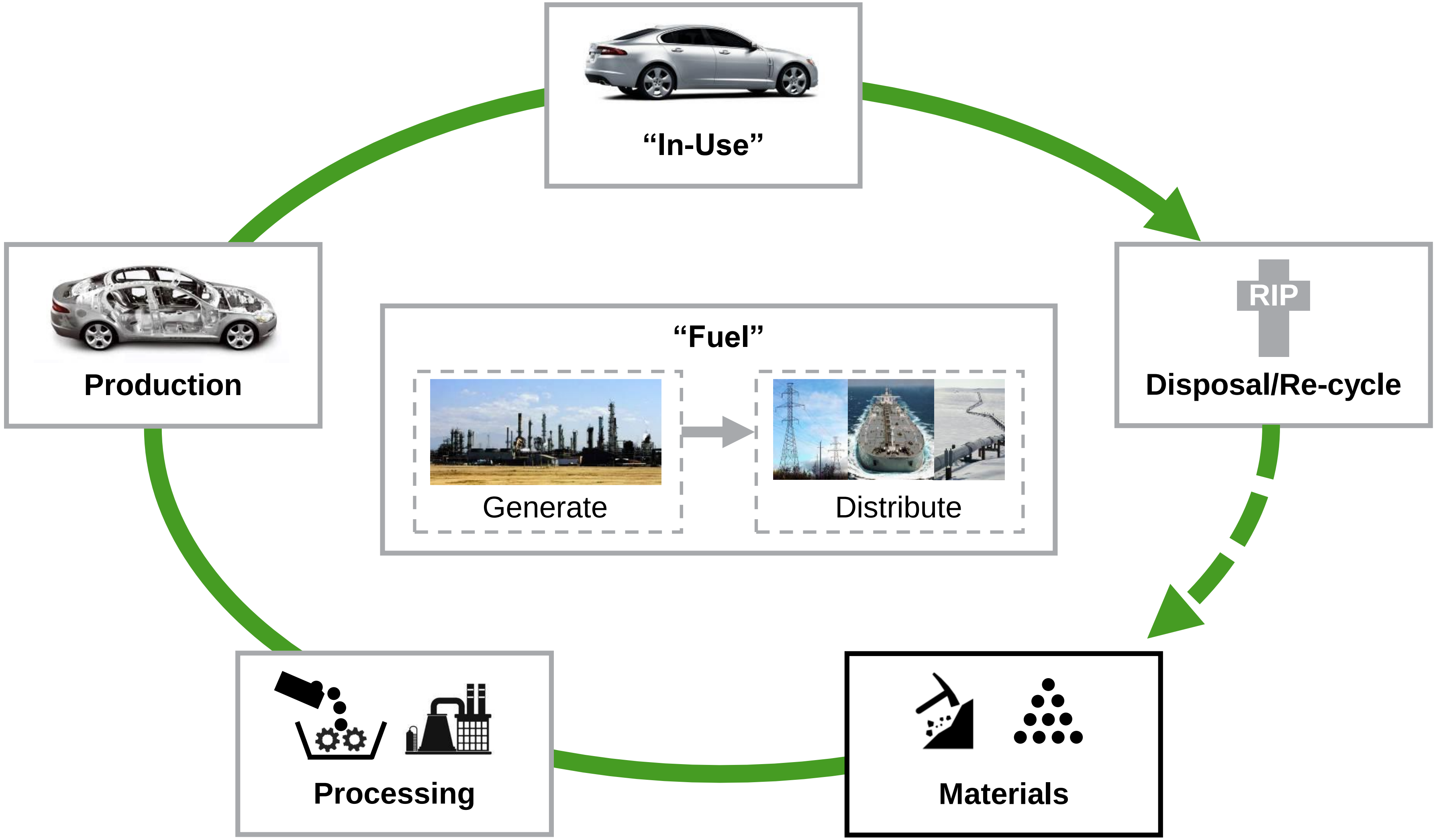
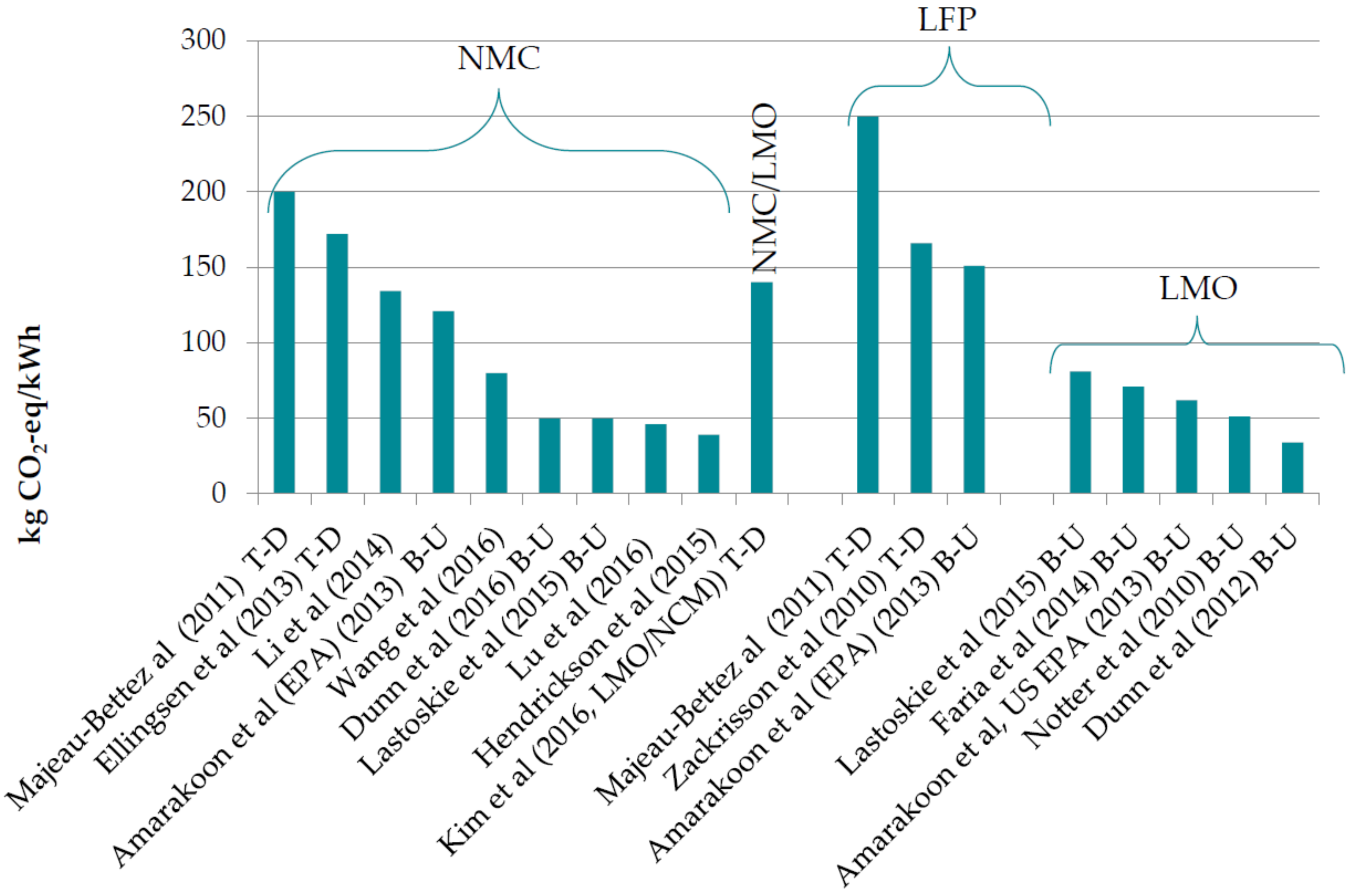
If our objective is to reduce environmental impacts and improve sustainability, are we looking at the bigger picture?



- Impacts from conventional combustion engine vehicles mostly from "in-use" phase
  - Materials, manufacturing and fuel production account for 20-30% of total life cycle
- Electric and H_2 Fuel cell vehicles currently generate most impacts from energy or fuel generation, materials, processing & production
  - 30-70% of total life cycle depending on battery size, grid carbon intensity & mileage

Source: Ricardo

A recent review of published Life Cycle Emissions for batteries suggests that embedded GHG emissions range from 150-200 kg CO_{2eq}/kW.hr



Embedded CO_2 estimated at 150-200 kg/kW.hr

About half from material extraction & processing, the other half from manufacturing:

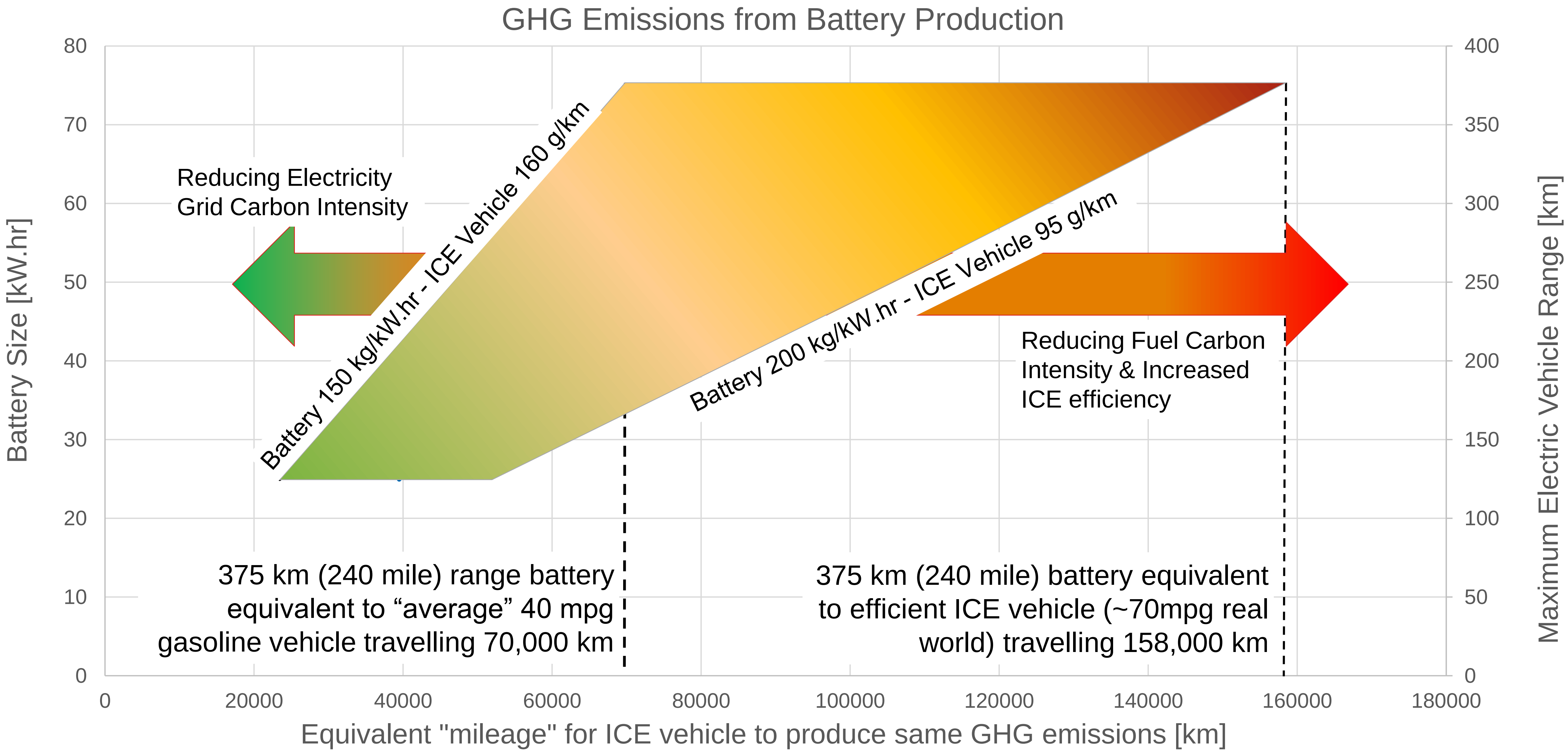
- Manufacturing emissions dominated by electricity use and associated grid carbon intensity
- Lower grid carbon intensity reduces manufacturing CO_2

The majority of embedded GHG emissions are from the battery electrodes

Re-cycling of battery materials remains challenging and adds around 15 kg/kW.hr CO_{2eq}

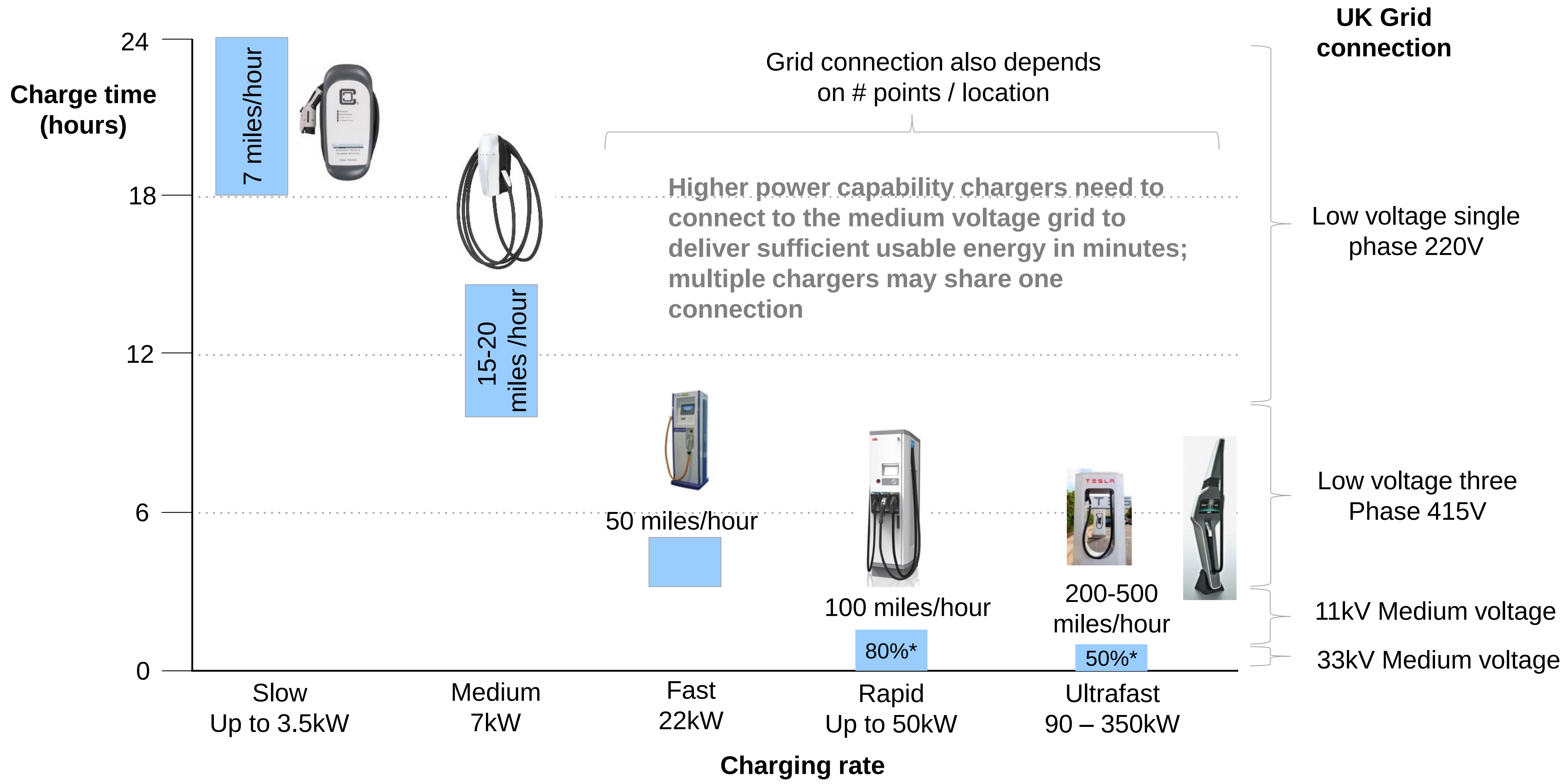
Source: The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries – Romare & Dahllof, IVL Sweden

Current battery production GHG emissions ~ 150-200 kg/kW.hr – 240 mile battery equivalent to 40 mpg gasoline vehicle travelling 70,000 km?



Source: Ricardo analysis; The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries – Romare & Dahllof, IVL Sweden

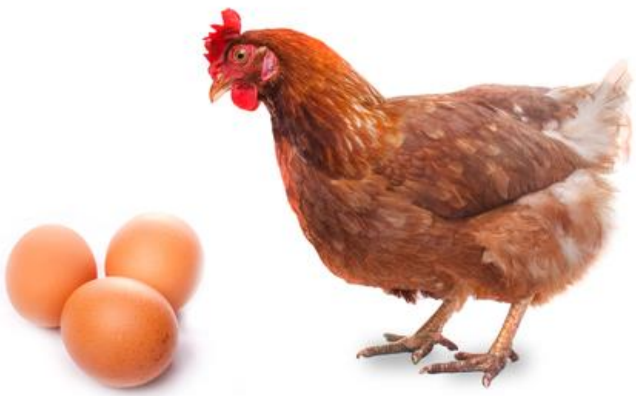
Grid voltage levels and charging times for 250+ mile range 85 kW.hr battery – to charge at >15 miles/hour need three phase supply



Source: Ricardo analysis

* = charge level within charging time from low State of Charge

Auto Industry concerned that Infrastructure will limit market penetration – Supply/Network operators currently unconvinced about early action



- To achieve EV market uptake, need **longer range** and improved **charging** facilities
- Local urban/city **networks** are **insufficiently sized** to support even low uptake of EV's and Plug-in vehicles
- Average electricity demand will only increase gradually but **"peak" demand will be an issue** (EV owners all charge at same time)

- Network Operators believe that overall average **power demand** for xEV's will be **insignificant** before 2030
- There is **no business case for recharging facilities**, particularly fast charge – all will need high subsidies
- Local network issues will be resolved by **demand control** and **strategic positioning** of recharge facilities

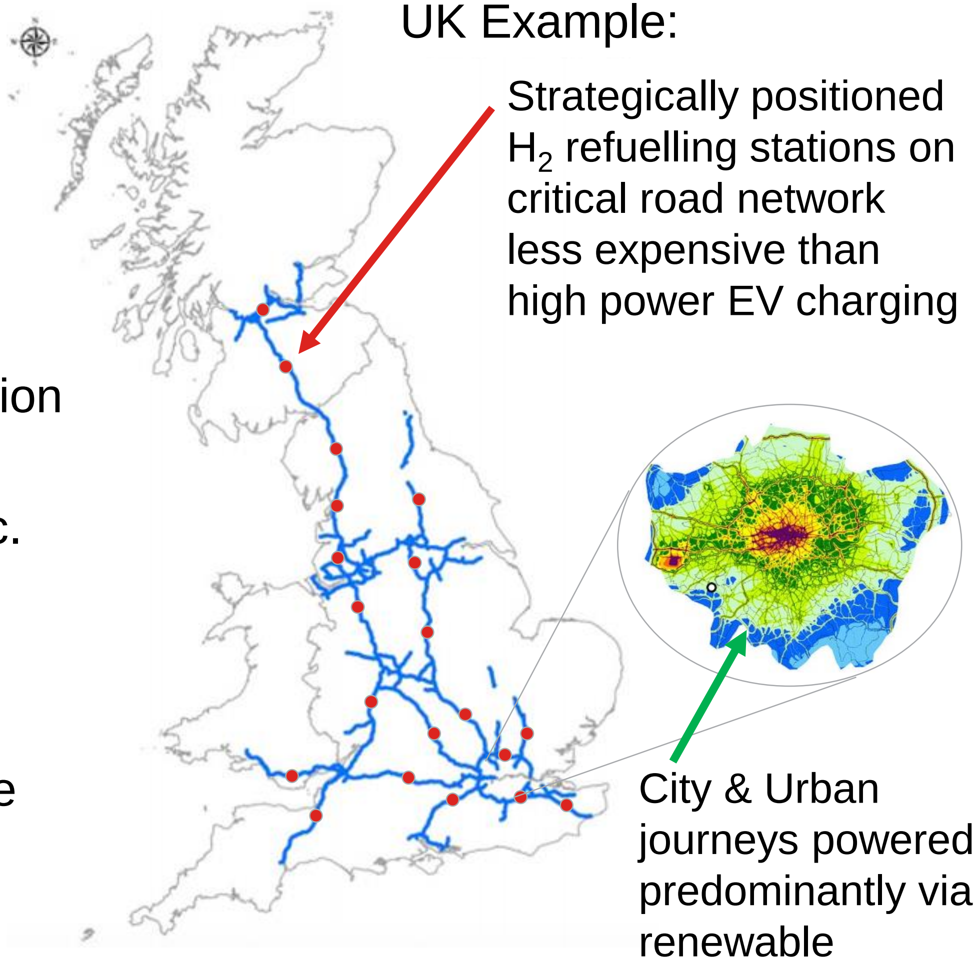
Note: EU Directive 2014/94/EU4 provides an obligation on member state governments to expand the network of charging points (CP), as the number of vehicles in service grows – there is no guidance on funding requirements

Source: Ricardo Analysis, UK OLEV, Role of the power sector for Electromobility - Iberdrola

City/Urban journeys dominated by ZEV mobility - Infrastructure & the Built Environment likely to be the controlling limit on EV penetration

- **Future Cities:**
  - Focus on healthy living & sustainable utilities
  - Air Quality - Imperative for Zero Tailpipe Emissions
  - Drive towards multi-modal (road/rail/metro) mobility:
    - Walking, Cycling, Ride Sharing (public & private)
- **Battery Giga-factories:**
  - 15-20 in EU alone (at €4-€5 billion each[1]) for 30-40% EV penetration
  - Need to assess and minimise total environmental impact:
    - Embedded CO_2, rare material mining/extraction, toxic waste etc.
- **Refuelling/Recharging infrastructures:**
  - Introducing new infrastructures prohibitively expensive
    - Extensive “smart grid” system – implementation?
    - Electricity *distribution* capacity insufficient to support large scale (350+ mile range) EV penetration – upgrade costs:
      - Germany - €150b+[2], UK €15b+[3] & smart grids?
    - Smaller batteries and lower ranges more compatible with existing city/urban networks
  - Intercity/longer range refuelling/recharging better served by low/zero carbon “drop-in” conventional fuels or renewable hydrogen network

UK Example:

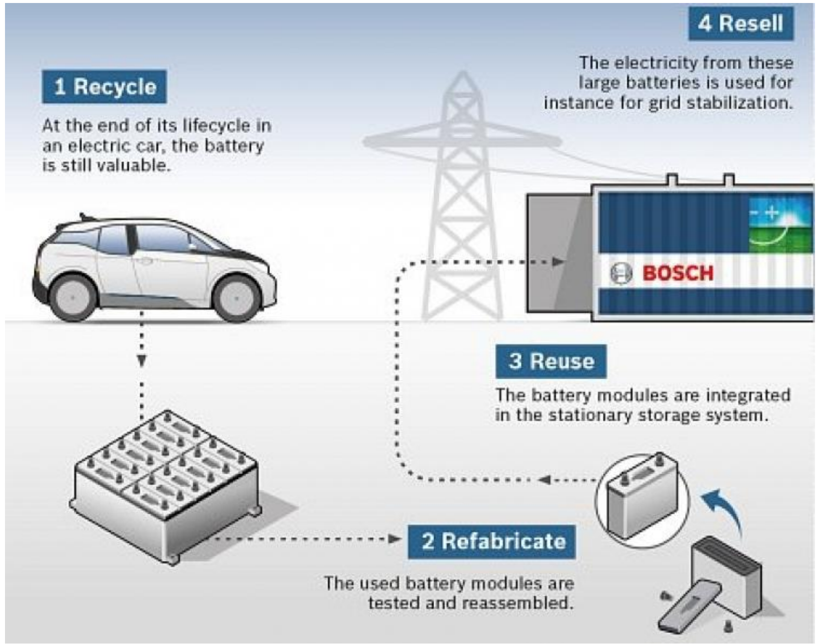


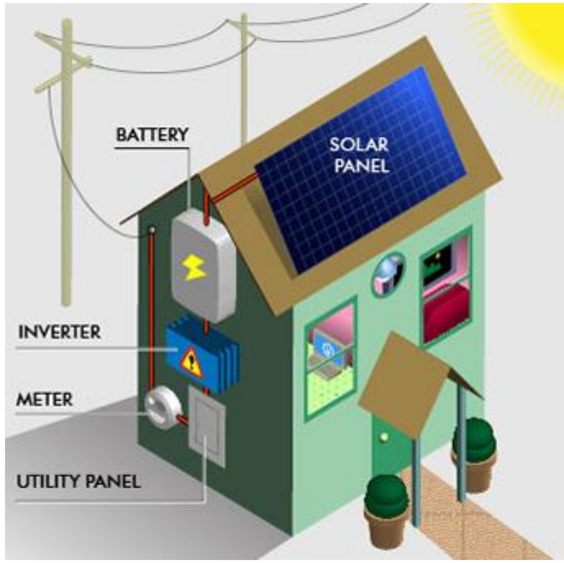
Strategically positioned H_2 refuelling stations on critical road network less expensive than high power EV charging

City & Urban journeys powered predominantly via renewable electricity

Source: 1) Tesla, 2) Julich - Germany, 3) UK Energy Technology Institute

Grid distribution limitations & intermittent domestic solar PV will drive home storage market – Large/expensive packs required for fast charge





Opportunity:

- Total annual electricity demand to support 30% EV pass car market relatively small
- Main issue is timing of demand & local grid capacity for anything more than 3-7 kW charging
- Domestic Solar PV growth could reduce grid demand if combined with local/home storage
- Potential market growth for home storage or fast charge “battery banks” i.e. as developed by BMW i

Challenges:

- Embedded CO_2 in battery materials/manufacture
- Continuous battery cost reduction may make second life more expensive than use of “new” cells

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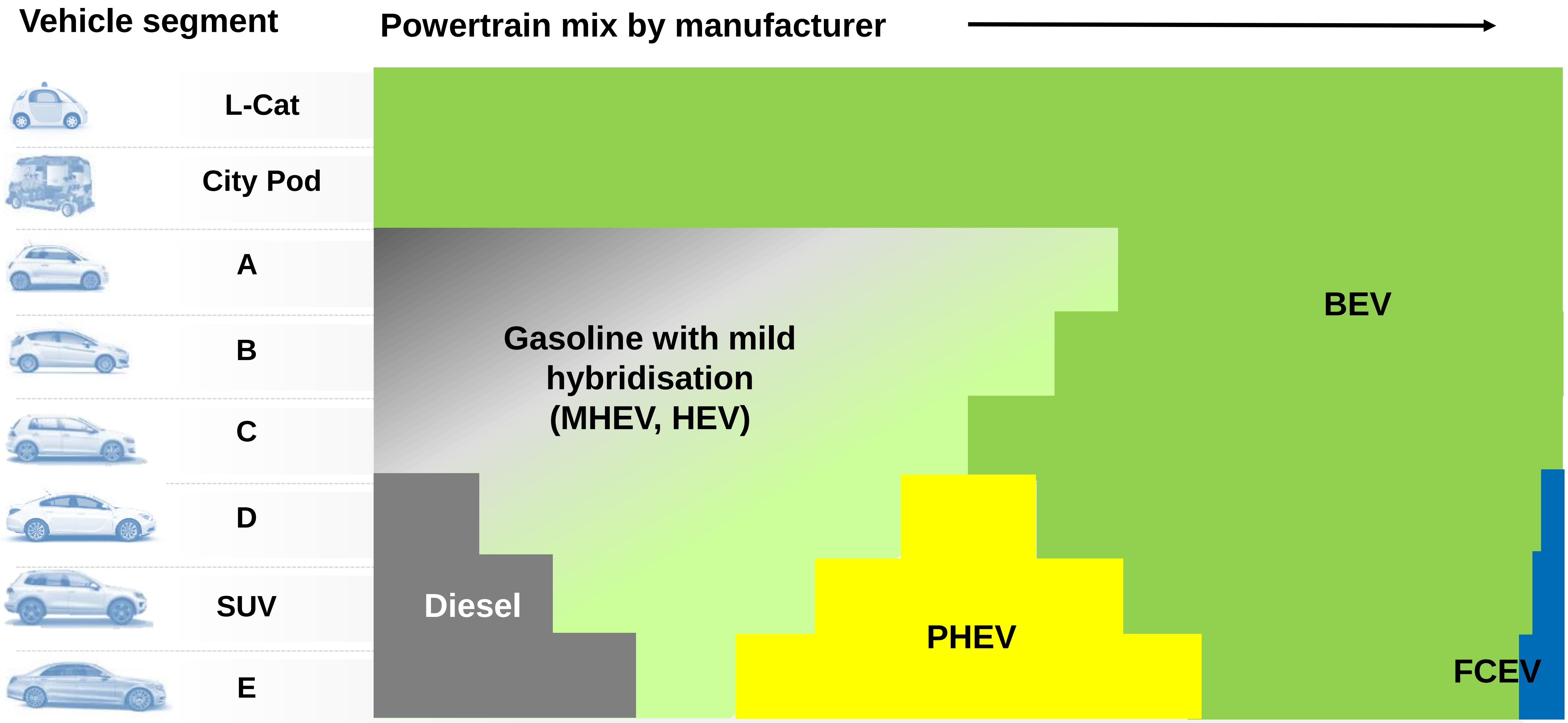
Ricardo view of the 2030 passenger vehicle electrified powertrain mix - penetration rates by powertrain type will vary by segment

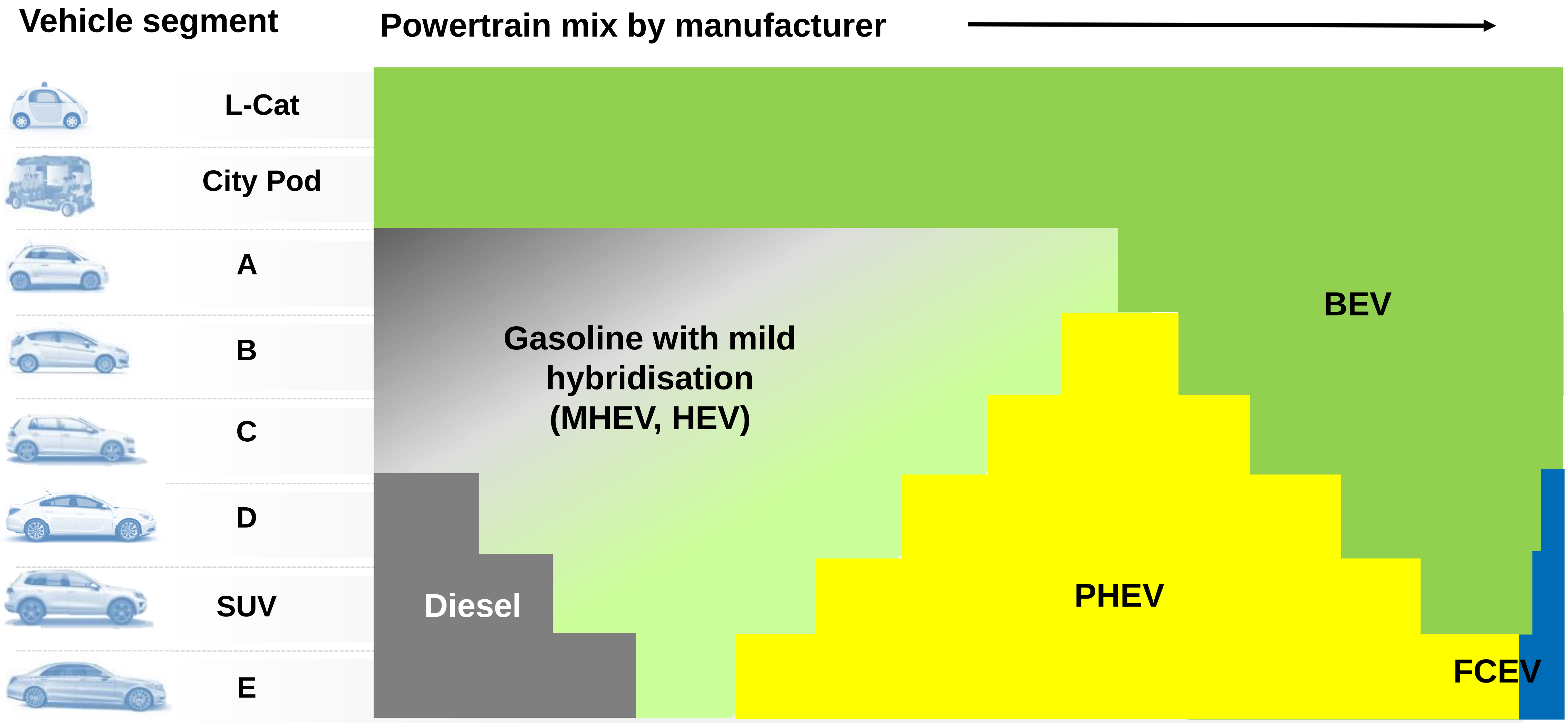
Powertrain mix 2030 – developed markets – *high level of charging infrastructure*



Source: Ricardo analysis

Ricardo view of the 2030 passenger vehicle electrified powertrain mix - penetration rates by powertrain type will vary by segment

Powertrain mix 2030 – developed markets – ***Limited charging infrastructure***



Source: Ricardo analysis

COP21 GHG targets in transport not straightforward – Need efficiency improvements, new energy vectors & carbon intensity reductions

Without technology innovations, road transport CO_2 will be 4x 2050 target due to increased demand

Propulsion technologies, light-weighting, aerodynamics, rolling resistance etc.

2050 Targets (-80+% GHG)

- Efficiency improvements
  - Vehicle (energy per vehicle km)
  - Passenger, Goods (energy per pass. km or tonne km)
- Reducing carbon intensity of energy/fuels

Mobility System focus: Logistics/ride sharing & Mobility as a Service via connected & autonomous technologies

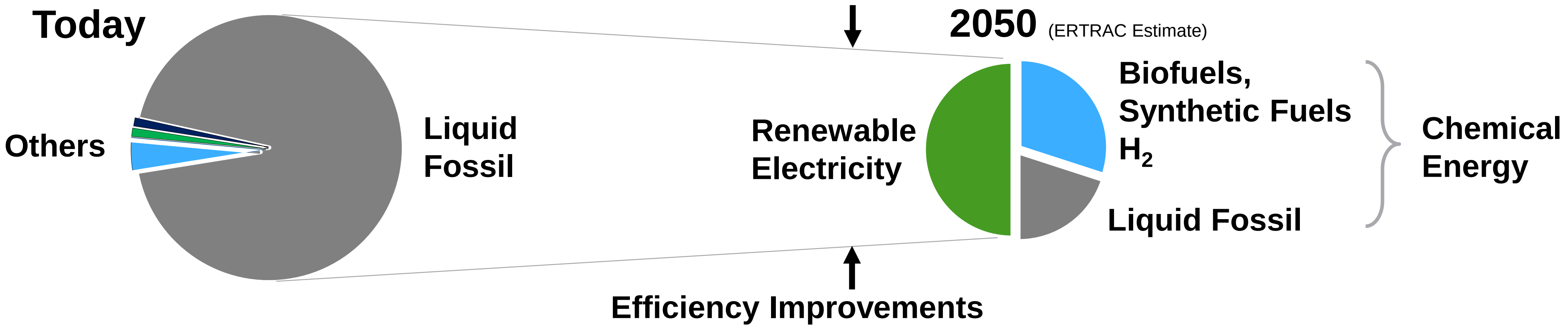
- Reducing carbon intensity of energy/fuels:
  - Gasoline/Diesel → Increasingly renewable content – sustainable bio, algal & synthetic fuels
  - Natural Gas → Increasing H_2 content, biogas and e-gas
  - Electricity → Increasing renewables/low carbon intensity/central & distributed storage
  - Hydrogen → From Natural Gas reforming to renewable sources (e.g. large scale electrolysis)

Increasing requirement for intermittent renewable energy storage – H_2 may be lowest cost approach?

Multiple options for renewable H_2:
- Heat (via NG networks)
- Transport
- Displacing fossil H_2 in oil refineries

Source: Ricardo analysis

ERTRAC analysis for 80% reduction in road transport GHG - half of energy from electricity by 2050 – remainder from Bio & Waste



- By 2050, ~50% of all road transport energy from electricity. The remainder comes from chemical energy
  - Chemical energy (including H_2) for energy intensive transport (HGV & high speed journeys / intercity)
- Choice will be between decarbonising legacy (diesel/gasoline) fuels or investing in new infrastructures for H_2 generation & supply for transport – largely defined by economics and national fiscal policies
- Fuel Cell propulsion system cost challenges will be overcome - renewable H_2 supply driven by need for “storage” of intermittent renewable electricity and to reduce carbon intensity of domestic heating
- Increasing focus on “total environmental impact” will drive more holistic balance between use of critical materials, embedded and emitted emissions and recycling/re-use

Source: Automotive Council, *ERTRAC, E4tech, Element Energy, Ricardo analysis

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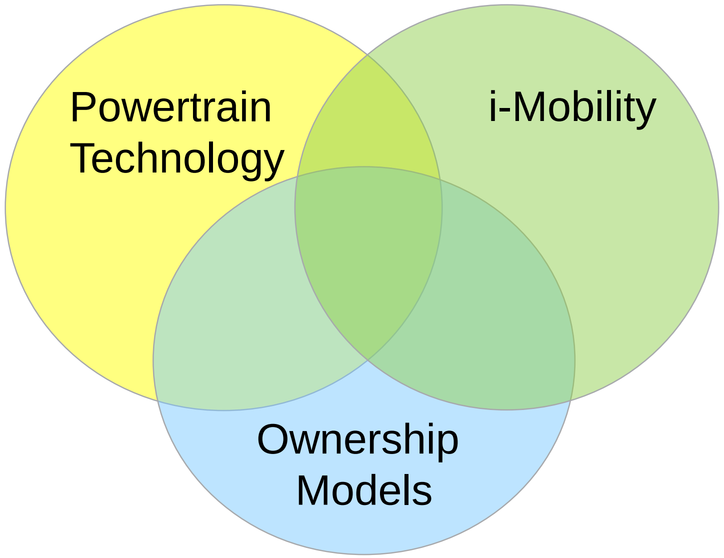
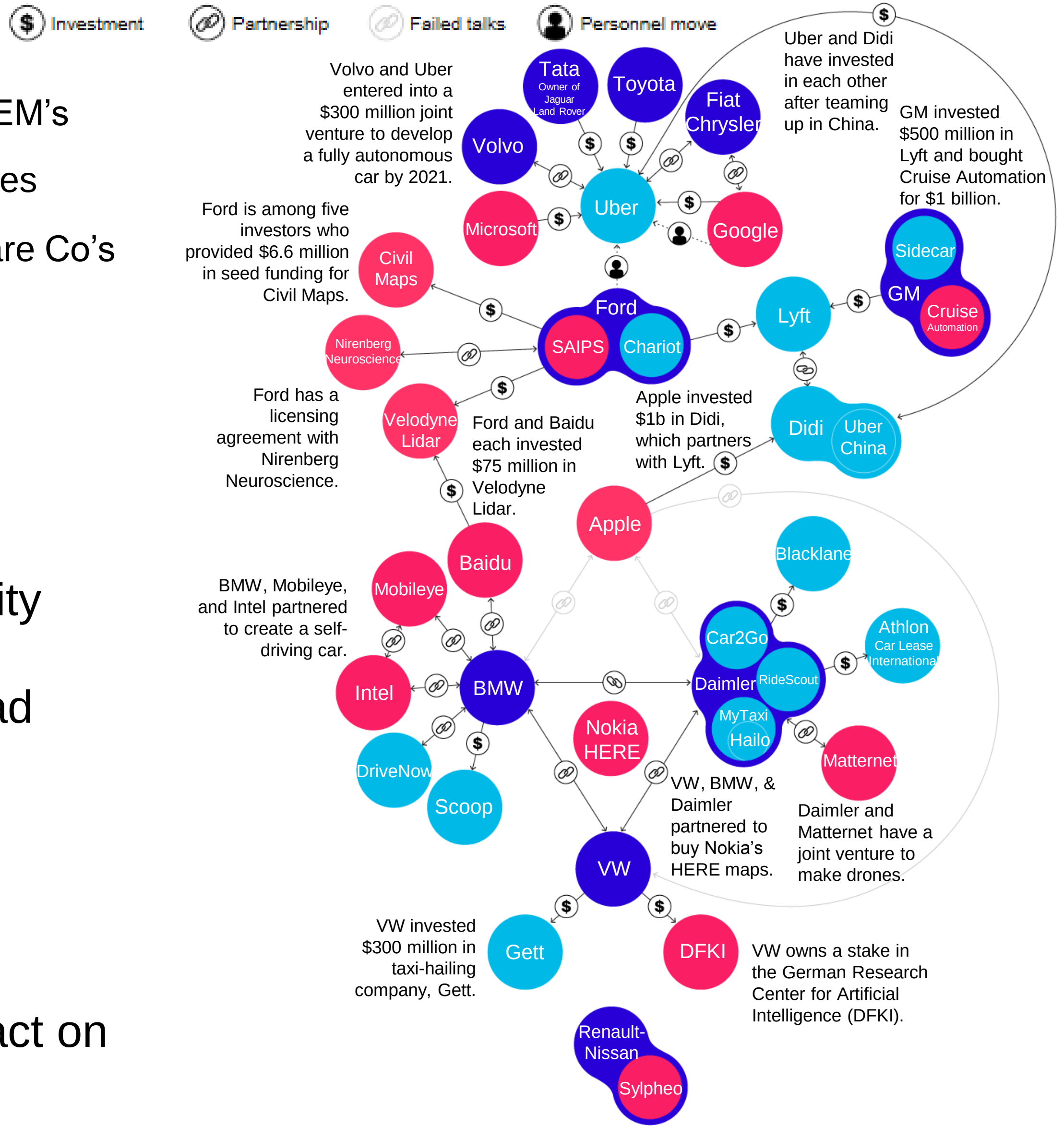
Future Powertrain choices more dependent on new Ownership /Business models than technology developments?



Automotive OEM's

Tech Companies

Tech Ride Share Co's

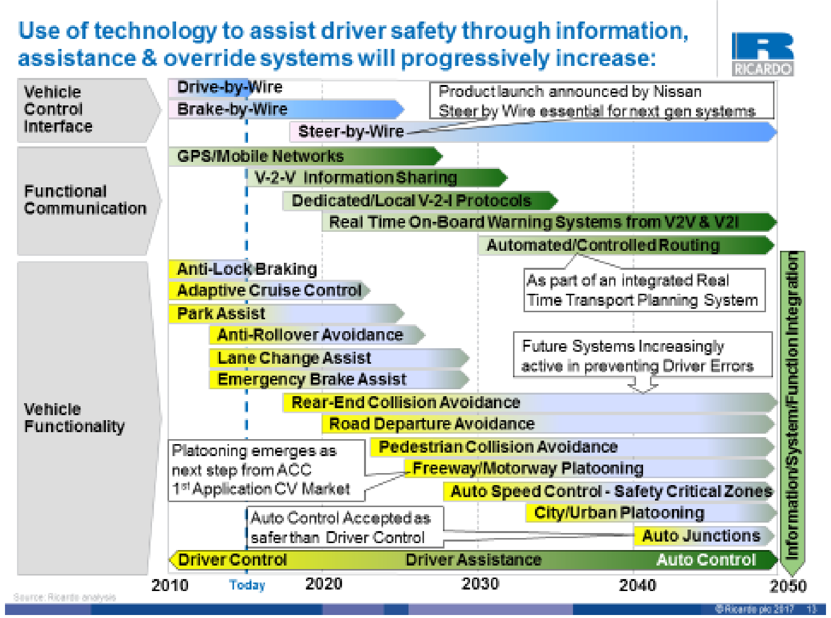


- Current ownership model require powertrains with broad utility
- i-Mobility technologies will increase "on-demand" services
  - Ability to increase passengers/vehicle, improve vehicle road utilisation & reduce parking requirements
- "on demand" vehicles enables more dedicated utility:
  - Electric Vehicles for inner city use
  - Plug-in for urban mobility
  - Advanced ICE/Low GHG fuels for intercity
- Change in business/ownership models may have more impact on future powertrain diversity than technology advances

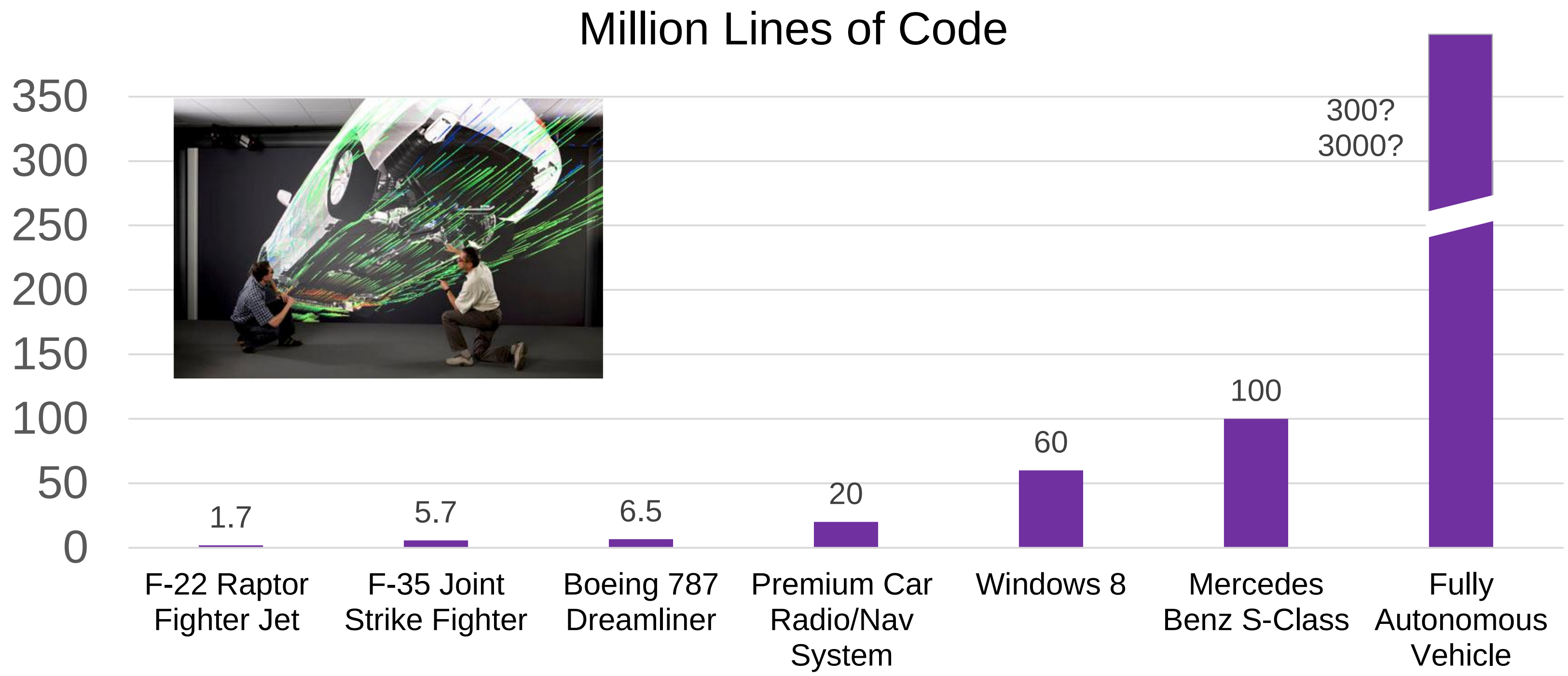
Source: Bloomberg - The Merging Worlds of Technology and Cars

Connected & Autonomous functionality offers a range of benefits to both consumers and city/local authorities

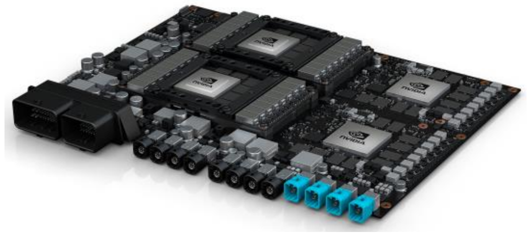
- **Key drivers for autonomous control of vehicles:**
  - **Improved safety:**
    - We will not achieve targeted reductions in road transport casualties without addressing human error – responsible for 90+% of road transport accidents
  - **Consumer benefits:**
    - Less "wasted" time commuting or travelling using road transport
  - **Improved vehicle utilisation** – passenger cars spend ~95% of their life parked:
    - The interaction with connected services offers an opportunity to develop "on-demand" services where vehicle utilisation can be increased – both passenger car and goods transport
    - Can reduce parking demand – a major issue in most cities
  - **Improved use of infrastructure** – average vehicle occupancy is 1.4 people/car
    - Increasing the number of passengers per vehicle or goods per vehicle via the interaction with connected services offers potential reductions in congestion and reduced journey times



Passenger cars more complex than any other volume product – Significant implications for future vehicle electrical systems



- Global automotive electronics industry estimated at $275bn/year by 2020
  - ~70% of vehicle value in electronics/control/software by 2030?

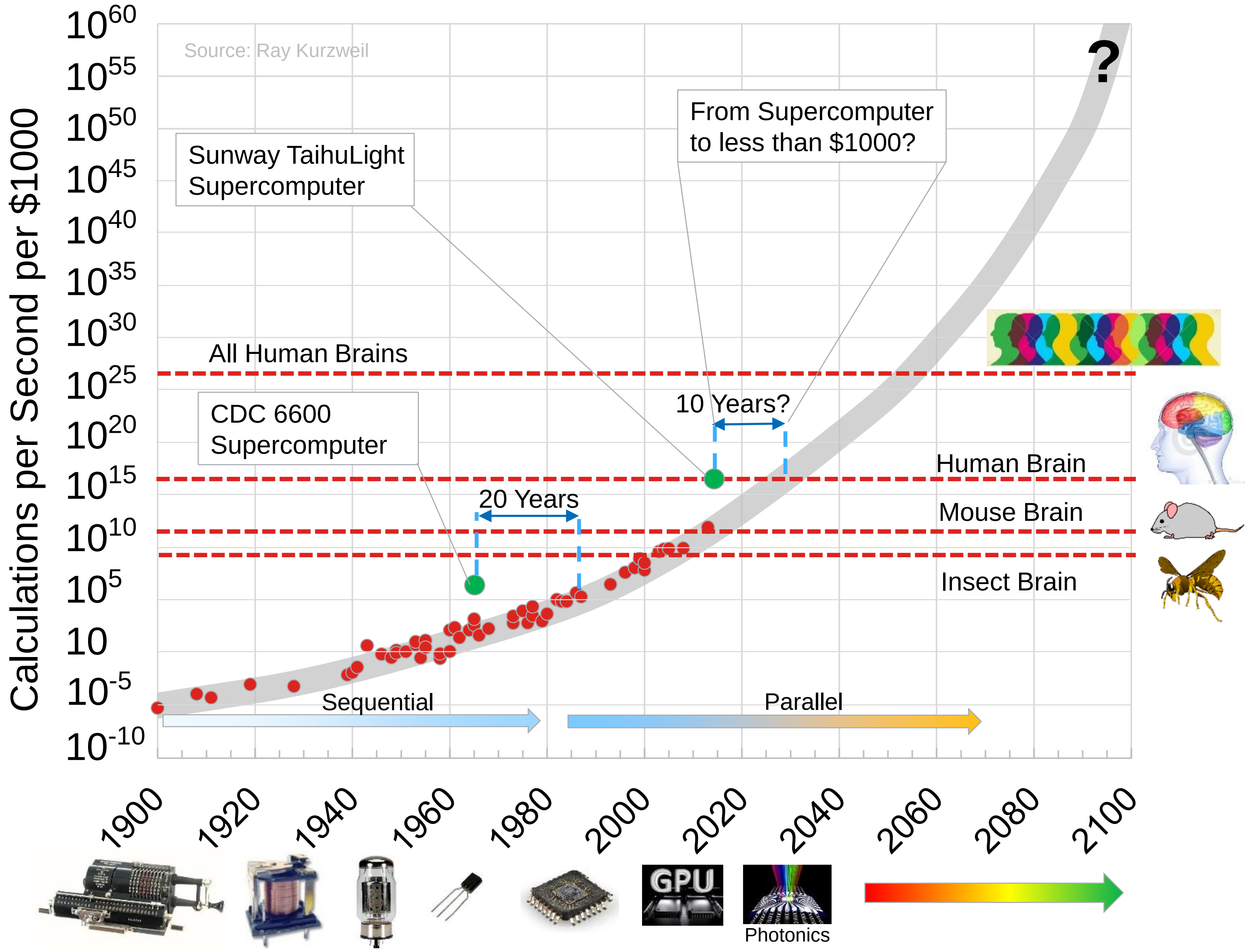


- Premium vehicles contain ~ 100 microprocessors networked throughout the car
  - More than an Airbus A380
- Current "autonomous" vehicles process around 1 teraflop of information and continues to grow – predictions suggest processing at petaflop capacity required in practice
  - GPU power consumption ~ 1 kW/10,000 processing cores
  - Latest NVIDIA Pegasus board ~ 10^{14} FLOPS - consumes 0.5 kW + air cooling

Source: IEEE Spectrum: This Car Runs on Code; Image: Daimler

! Teraflop = 10^{12} Floating Point Operations per Second

A human brain has ~ 100 billion neurons & 1000 trillion connections – when will a computer match this capability?

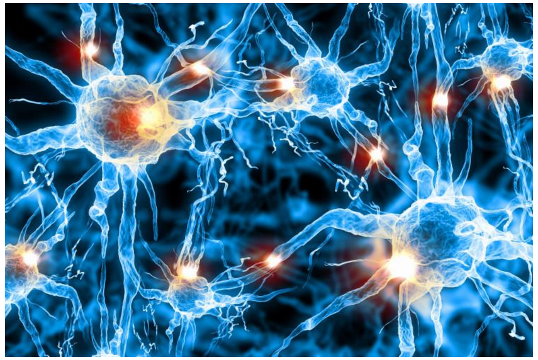


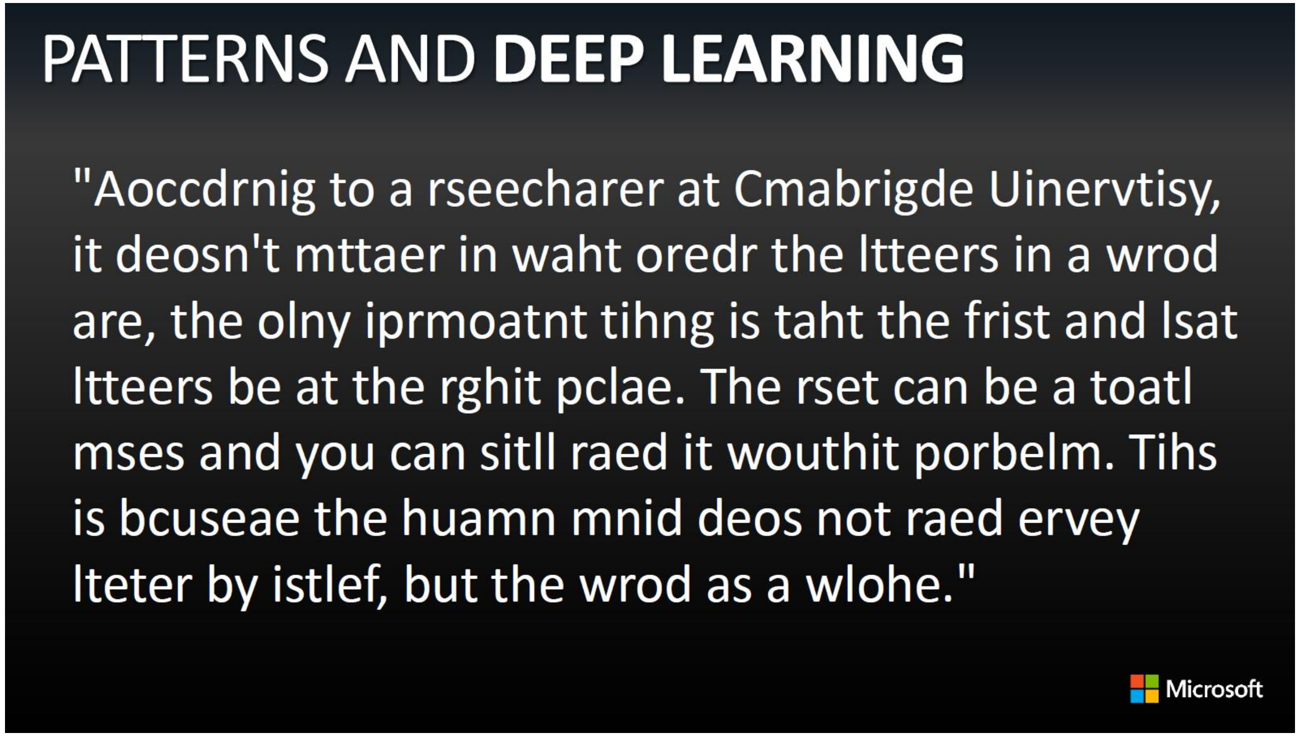
- 1964 First Supercomputer (CDC 6600) rated at 3 megaflops (10^6 calculations/second)
- Single core (CPU) and cost ~$60 million equivalent today

- 2016 Chinese Sunway TaihuLight Supercomputer rated at 10^{17} FLOPS (similar to human?) using 10,649,600 cores
- Power consumption estimated at 15 MW
- Total computer system occupies around 80 m^3
- Human brain consumes ~20 W

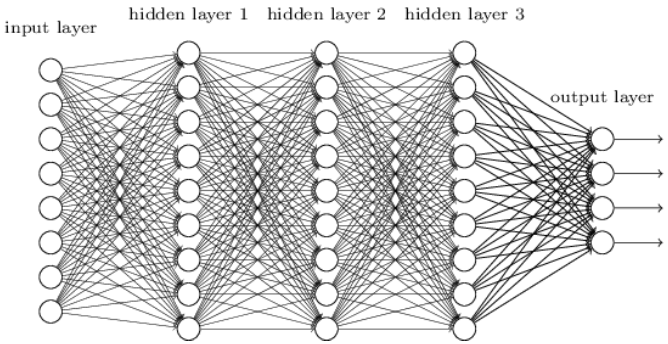
A qualitative/pattern recognition route to autonomous control more effective than an algorithm & rule based approach?

- Will we be able to deliver fully autonomous vehicle functionality via an algorithm and rule based approach?
- Or will we need to move to a “qualitative” rather than “quantitative” processing approach:
  - An analogue rather than digital processing environment that recognises and responds to pattern recognition via pre-defined reaction – much like we do?



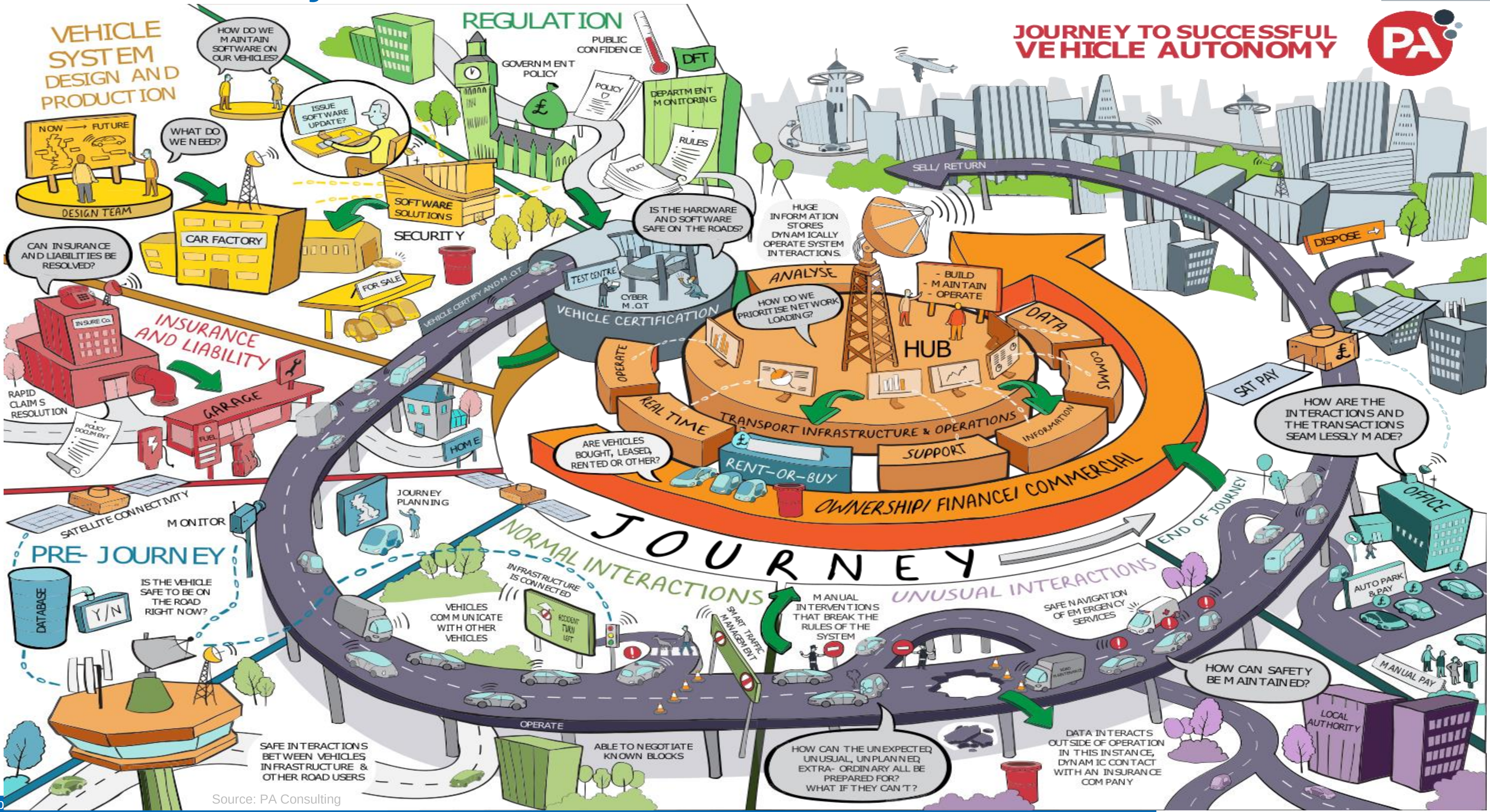


Neural networks:



Focus on the right outcome from a recognised input rather than a rule-based (and very time consuming) objective analysis

There are many regulatory, legal and financial challenges facing the introduction of fully autonomous vehicles

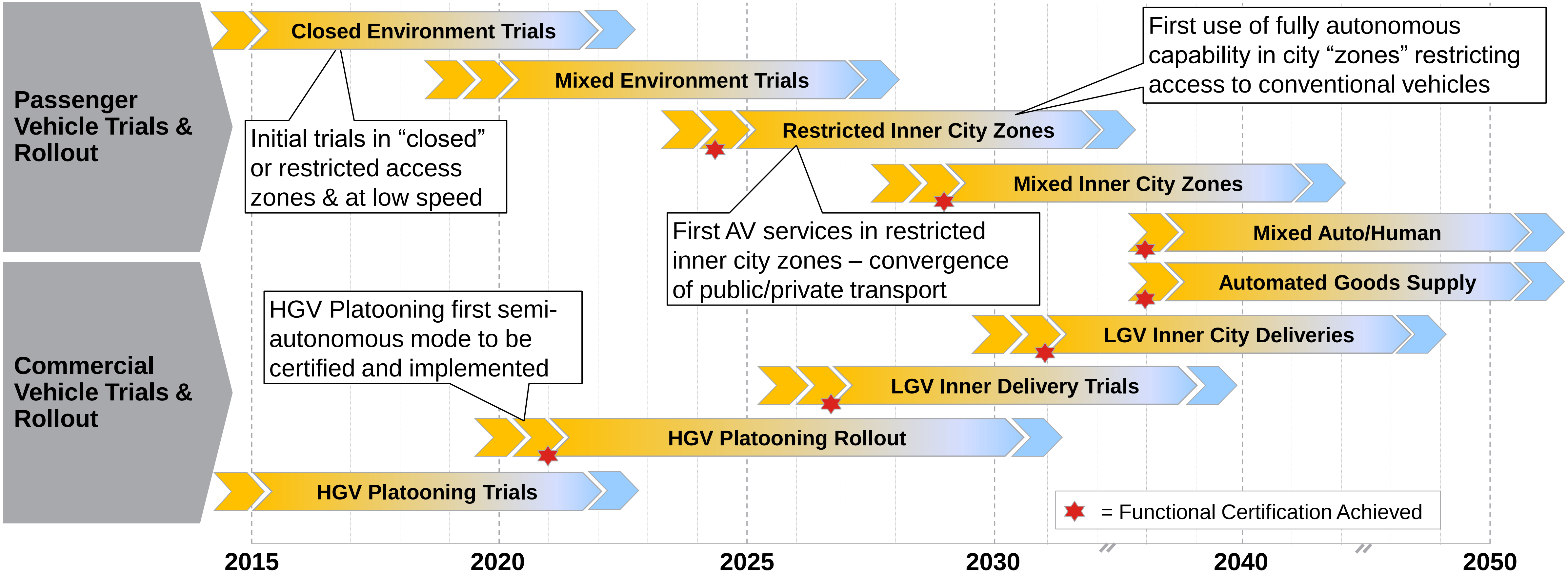


Source: PA Consulting

Autonomous rollout via initial trials in restricted environments for both people & goods - Certification process also critical

Level	Name	Definition	Steering/Speed	Monitoring	Backup	Capability
0	No Automation	Human driver in control at all times	Human	Human	Human	N/A
1	Driver Assistance	Either steering or speed control assistance	Human & System	Human	Human	Some Modes
2	Partial Automation	Steering and speed control assistance	System	Human	Human	Some Modes
3	Conditional Automation	Auto steering & speed control - human backup	System	System	Human	Some Modes
4	High Automation	Automated control - limited human intervention	System	System	System	Some Modes
5	Full Automation	Full automated driving without intervention	System	System	System	All Modes

Level 3-4 - human intervention may prove non-viable



A Vision of Future Mobility – Fully co-operative, multi-modal on-demand systems – Public & Private transport converges….

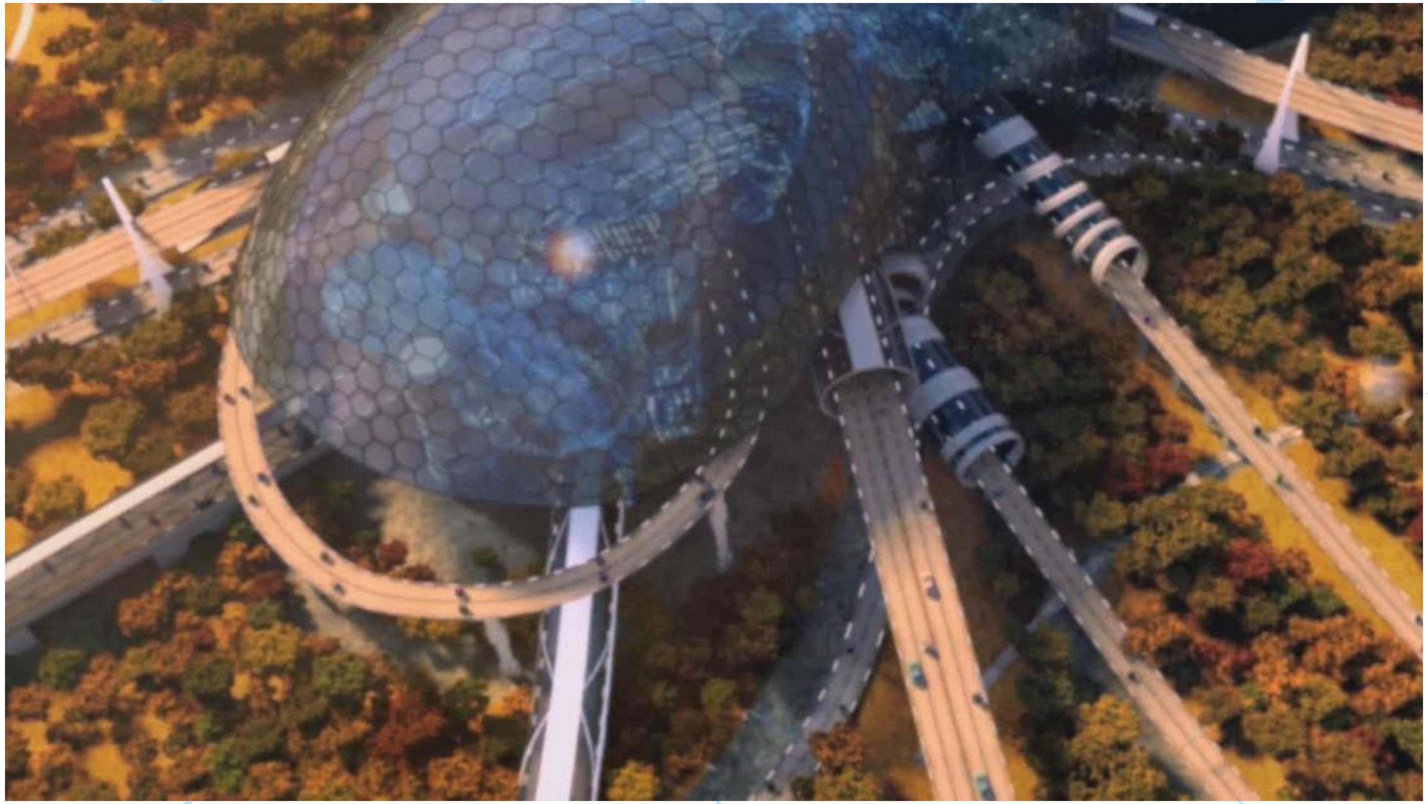
RICARDO

On-demand Availability

Multi-Connectivity

Utility on Demand

Self Parking



Fully Autonomous

Auto Charging (Inductive)

Zero Crashes

Co-operative Platooning

Source: General Motors / Shanghai Expo