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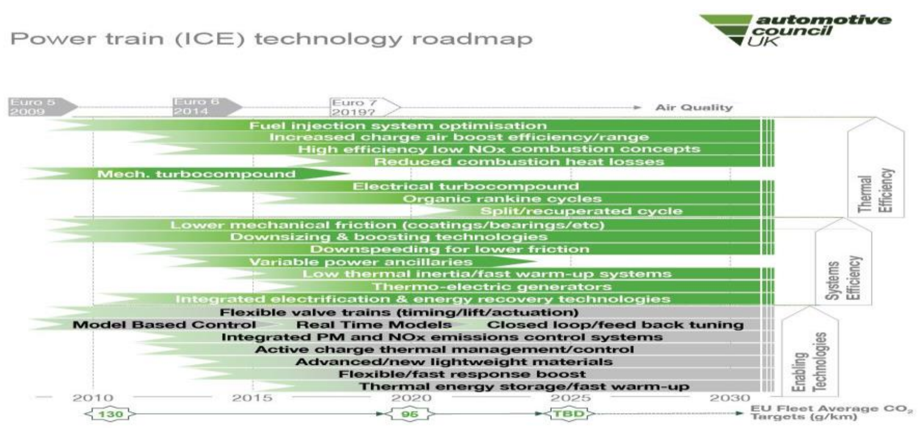
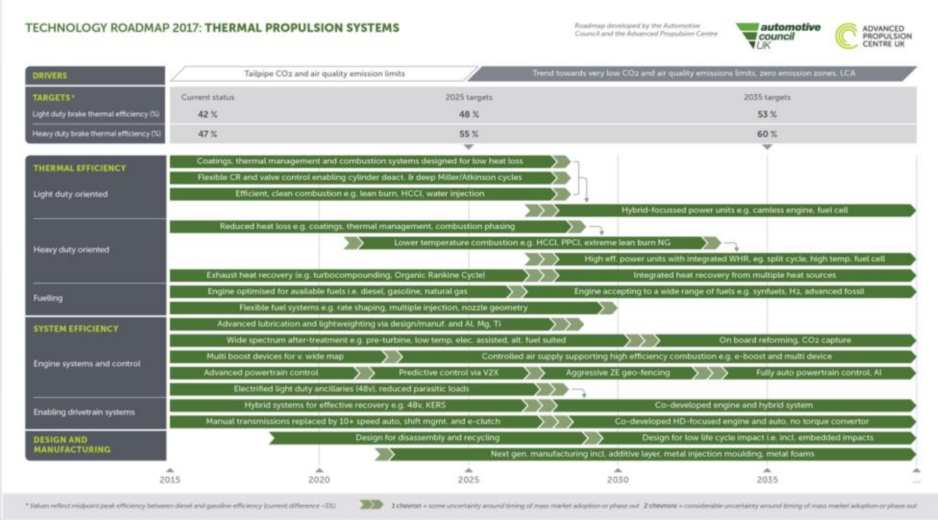
Thermal Propulsion Systems Roadmap

Updated by the Advanced Propulsion Centre in collaboration with and on behalf of the Automotive Council

Executive summary: *Thermal propulsion systems*





- **The 2013 roadmap focused on thermal efficiency, system efficiency and enabling technologies** that support continued engine innovations.

- **The 2017 roadmap builds upon the 2013 approach** and recognises that light duty and heavy duty base engines may take different approaches.

- **The 2017 roadmap has introduced stretched targets for future light and heavy duty systems,** focussing on wider emissions spectrum in order to maintain market relevance and competitiveness.

- **The roadmap reflects that thermal propulsion systems are part of a wider powertrain system,** and its performance and compliance with regulation is dependent on the integration of pre and post combustion sub-systems.

- Similar to the 2013 roadmap, **alternative operational cycles through alternative engine designs and control systems** are highlighted in the roadmap.

- **There is a stronger recognition of the integration of transmissions and energy recovery devices** to further enhance hybrid system performance.

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Update process: *The 2017 Thermal Propulsion Systems Roadmap was updated via a structured consensus-building process involving 52 experts*

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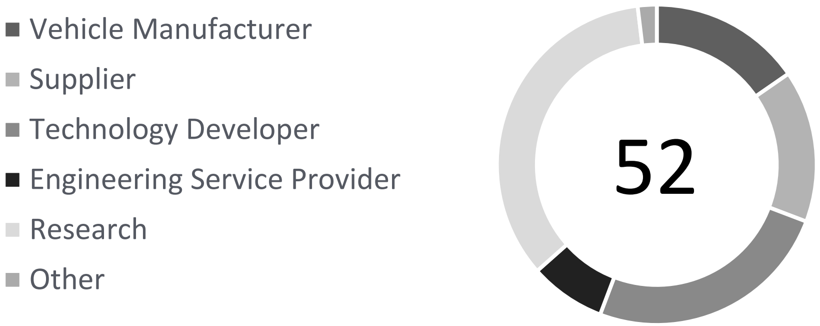
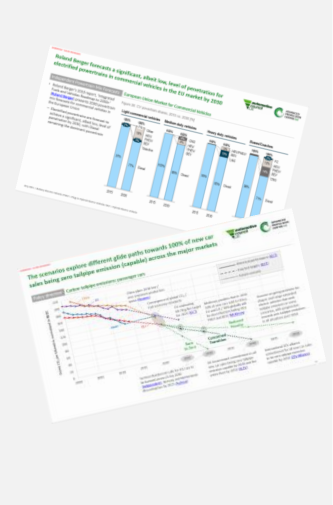
- **A public workshop** was held at the University of Bath on the 31st January 2017
- The process was co-ordinated by the **Advanced Propulsion Centre on behalf of Automotive Council**
- The **Advanced Propulsion Centre Thermal Efficiency and System Efficiency Spokes**, supported by an expert Steering Group, helped to shape the roadmap before and after the workshop.

Thermal Propulsion Systems Steering Committee and Workshop Attendees



Pre-Event Email — **1 day workshop with 45 attendees** — **Post-Event Email**

Pre-event Common Assumptions Briefing



Collective Briefing Process

Breakout Sessions

Post-Event Debrief

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Technical targets: *Mass market adoption of increasingly hybridised vehicles drives challenging cost and performance targets for future thermal propulsion systems*

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Drivers of change

- Incremental innovations in thermal propulsion systems has provided steady improvements over a long period, but **bigger changes are required**.
- **Ambitious targets, that are unobtainable with existing engine technology, have been set** to drive significant innovation. These targets must be achieved without compromising customer demands of exceptional cost effectiveness, range requirements, power density and recyclability.
- **Reducing air quality and CO_2** emissions challenges the current application of all TPS powertrains using conventional fuels. Future sustainable fuels and the associated engine technology are actively being developed, potentially near carbon neutral operation. Air quality and efficiency will remain key drivers.
- **Life cycle measures and materials security** will challenge all propulsion technologies, supporting the acceptability of TPS with suitable performance against these metrics
- For light duty vehicles, TPS will feature in all hybrid vehicles before the potential advent of fuel cell hybrids. **Hybridisation implies a change in the nature of TPS and offers higher efficiencies.**
- For heavy duty the TPS remains core to future propulsion due to the absence of alternatives. **Further improvements to efficiency and emissions are needed, including new fuel types and energy recovery.**

Light Duty	2017	2025	2035
Engine System Brake Thermal Efficiency (%)[1,2]	42	48	53
Tailpipe NOx & Particulates (Mass & Number)	In line with legislated limits	Zero in emissions controlled zones[3]	
Heavy Duty	**2017**	**2025**	**2035**
Engine System Brake Thermal Efficiency (%)[1]	47	55	60
Tailpipe NOx & Particulates (Mass & Number)	In line with legislated limits	Zero in emissions controlled zones[3]	

1) Peak efficiency values shown. Increasingly important to achieve high efficiency across a wider operating range, in keeping with testing cycles based on real world performance
2) Values reflect mid point between diesel and gasoline efficiency (current difference ~5%)
3) Below measureable limits or below ambient (background) levels

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Technology categories: *To meet tough targets parallel development is needed in thermal efficiency of base engines and efficiency of the wider system*

DRIVERS

Tailpipe CO2 and air quality emission limits

Trend towards very low CO2 and air quality emissions limits, zero emission zones, LCA

TARGETS*	Current status	2025 targets	2035 targets
Light duty brake thermal efficiency (%)	42 %	48 %	53 %
Heavy duty brake thermal efficiency (%)	47 %	55 %	60 %

THERMAL EFFICIENCY

- Light duty oriented
- Heavy duty oriented
- Fuelling

Engine architecture and fuelling determine thermal efficiency. Improvement approaches mostly differ between thermal propulsion sysems that experience light vs heavy duty cycles. Note that some heavy vehicle platforms may experience light(er) duty cycles and vice versa

SYSTEM EFFICIENCY

- Engine systems and control

Air, heat, exhaust gas management, parasitic loss reduction and engine control are crucial to efficiency and emissions

- Enabling drivetrain systems

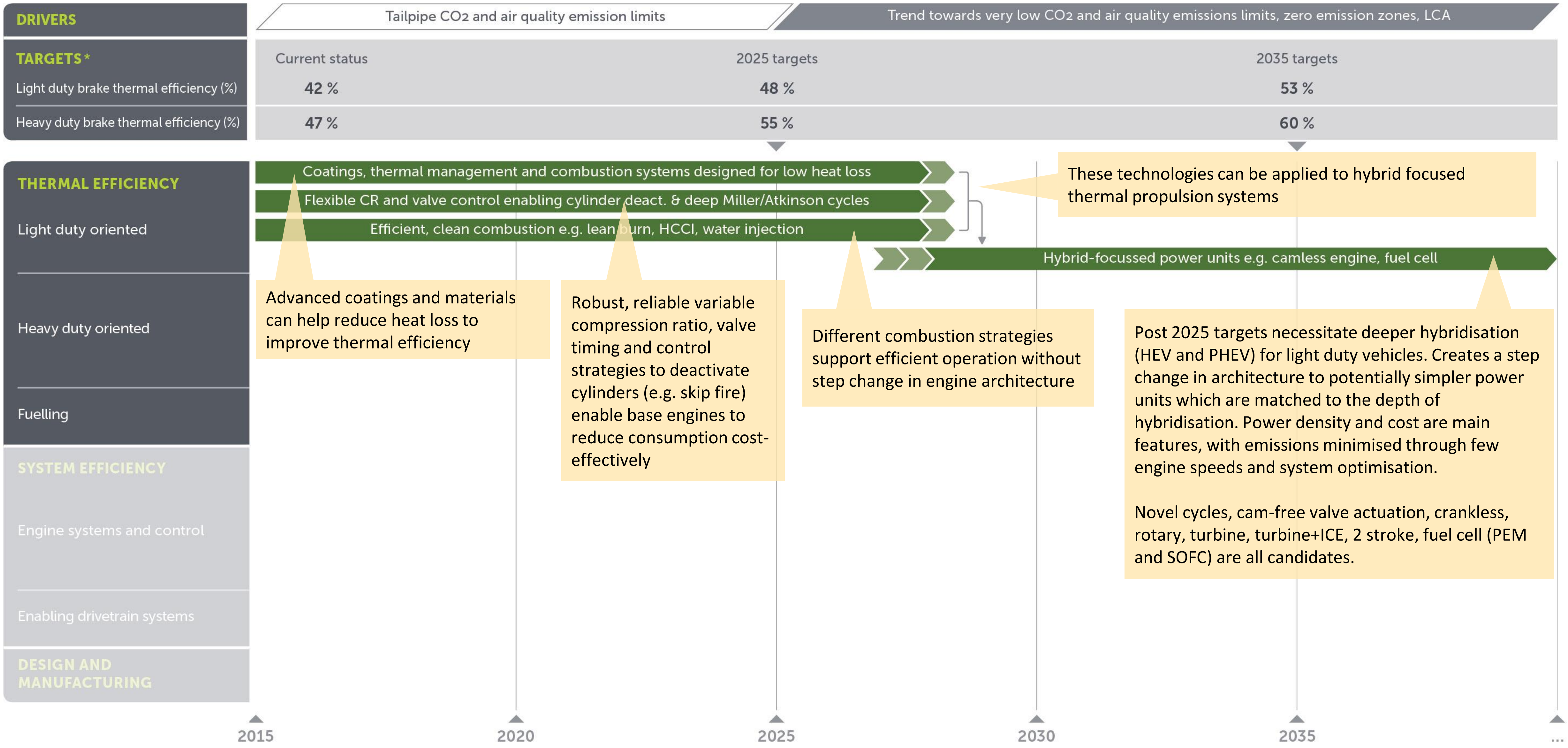
Drivetrain systems enable thermal propulsion systems to operate in a reduced speed / load envelope, allowing significant efficiency and emissions improvements

DESIGN AND MANUFACTURING

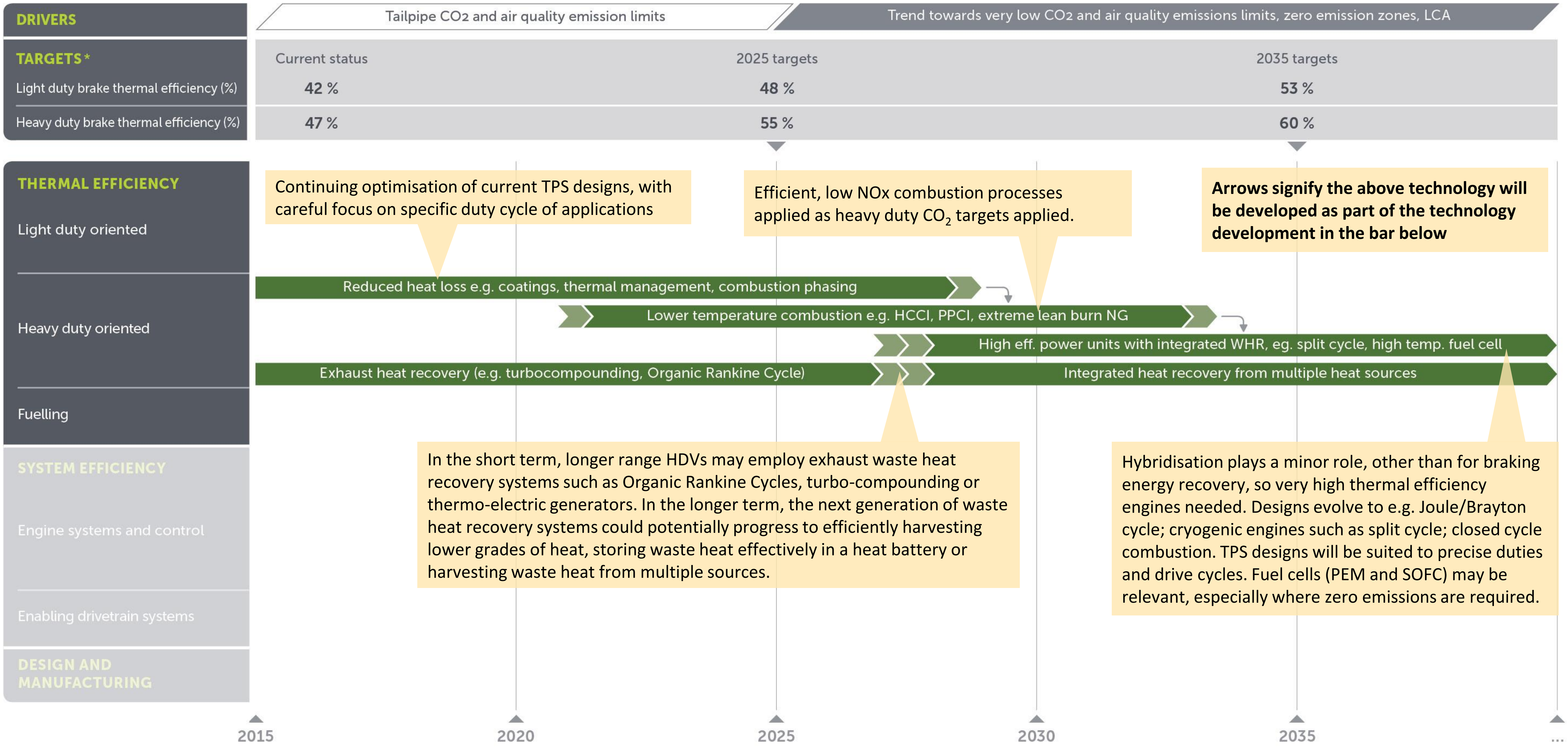
Design, material and manufacturing choices affect total environmental impact

2015 | 2020 | 2025 | 2030 | 2035 | ...

Thermal efficiency: *Existing light duty thermal propulsion systems need to improve, but will reach a point where they transition into hybrid focussed power units for mass market applications*



Thermal efficiency: *Heavy duty thermal propulsion systems require continuous improvement to evolve towards very high efficiency*



Thermal efficiency: *Both light and heavy duty engines will need to adapt to a wider range of fuels to later also informing the development of fuels*

DRIVERS

Tailpipe CO_2 and air quality emission limits

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Light duty brake thermal efficiency (%)	42 %	48 %	53 %
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THERMAL EFFICIENCY

Light duty oriented

Heavy duty oriented

Fuelling

Continuing close collaboration with fossil fuel refiners to optimise existing fuels and optimised engines that can run on alternative fuels such as biofuels and natural gas (CNG, LNG). There is also the potential for dual fuel engines to lower emissions (diesel/gasoline and hydrogen, diesel and natural gas)

Ultra-low emission combustion processes developed alongside advanced low carbon fuels e.g. bio and synthetic components such as ethanol/methanol, refined fossil fuels using renewable hydrogen

Engine optimised for available fuels i.e. diesel, gasoline, natural gas

Engine accepting to a wide range of fuels e.g. synfuels, H_2, advanced fossil

Flexible fuel systems e.g. rate shaping, multiple injection, nozzle geometry

More precise fuel delivery through higher pressure and variable injection, gasoline pre-mix. Water injection where relevant.

Note: Fuel injection systems will still continue to be developed beyond 2030. However the technology will be developed in conjunction with heavy duty orientated, high efficiency power units or light duty hybrid focussed power unit (see thermal efficiency)

SYSTEM EFFICIENCY

Engine systems and control

Enabling drivetrain systems

DESIGN AND MANUFACTURING

2015 2020 2025 2030 2035 ...

System efficiency: *A wide range of improvements in engine systems and control will support developments in existing engines and the emergence of more novel designs*

DRIVERS

Tailpipe CO2 and air quality emission limits → Trend towards very low CO2 and air quality emissions limits, zero emission zones, LCA

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THERMAL EFFICIENCY

Light duty oriented

Heavy duty oriented

Fuelling

Friction and weight reduction continue to be assisted by advanced design and manufacturing techniques *(also refer to Lightweight Structures Roadmap).*

Note: Focus on lightweighting and better lubrication will still continue to be developed beyond 2030. However new materials and lubrication will be developed in conjunction with heavy duty orientated, high efficiency power units or light duty hybrid focussed power unit (see thermal efficiency)

Retrofit aftertreatment is a very near term priority for e.g. taxis and buses. The emphasis shifts towards systems that can provide wide-spectrum performance even as waste heat declines (especially HD). Longer term very novel techs such as on board reforming and CO_2 capture could play a role, mainly for HD. LD aftertreatment shifts beyond 2025 to managing emissions across narrower engine operating range

Boost systems provide wide range of effective operation through combining devices. These devices continue to improve through material and bearing developments (higher temp, lower friction). Higher voltages (48v+) then enable widespread application of e-boosting to complement multi device approach

SYSTEM EFFICIENCY

Engine systems and control

- Advanced lubrication and lightweighting via design/manuf. and Al, Mg, Ti
- Wide spectrum after-treatment e.g. pre-turbine, low temp, elec. assisted, alt. fuel suited → On board reforming, CO2 capture
- Multi boost devices for v. wide map → Controlled air supply supporting high efficiency combustion e.g. e-boost and multi device
- Advanced powertrain control → Predictive control via V2X → Aggressive ZE geo-fencing → Fully auto powertrain control, AI

Enabling drivetrain systems

- Electrified light duty ancillaries (48v), reduced parasitic loads

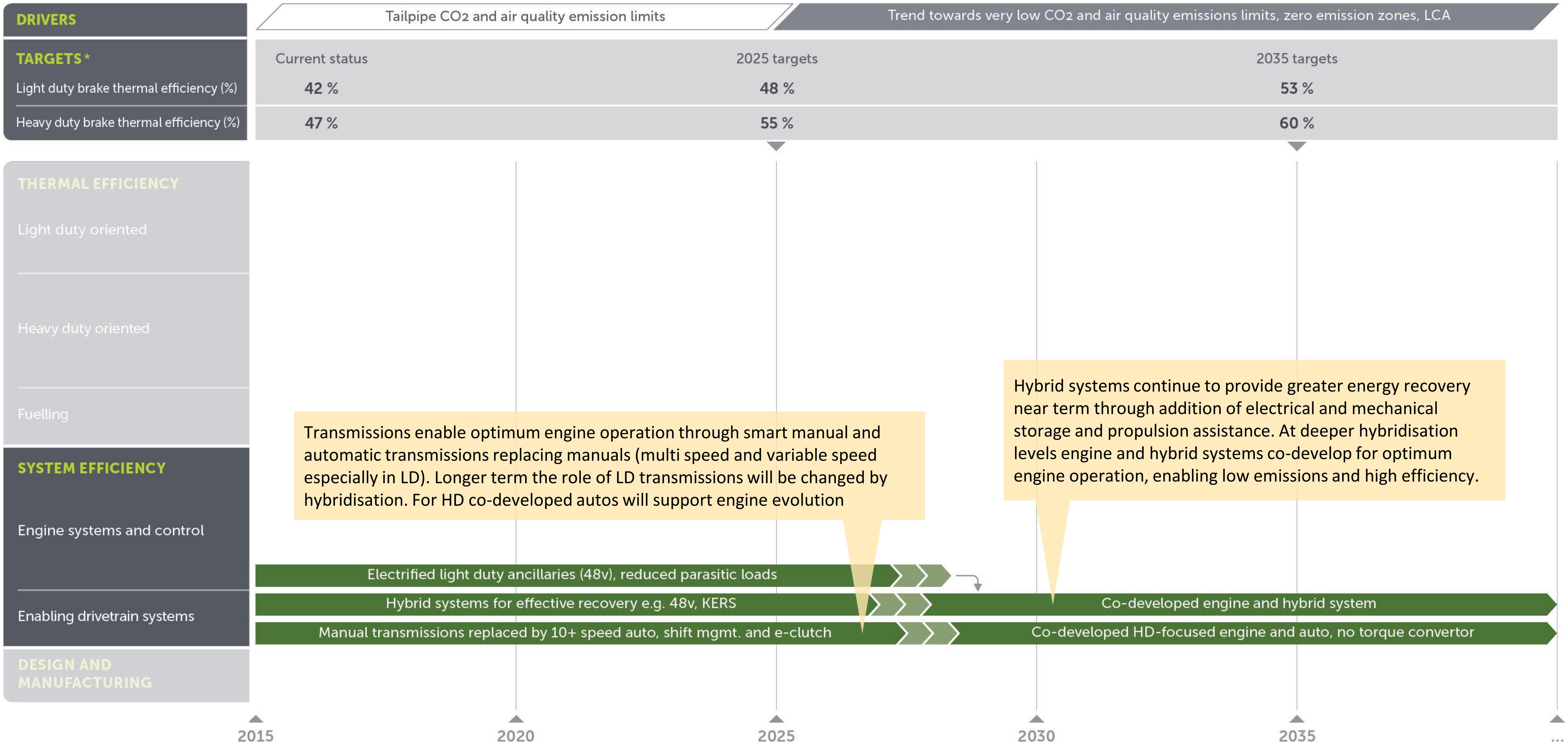
Increased engine complexity in the near term runs risk of increasing parasitic loads. Electrification of ancillaries such as water pump, air boost, turbo-generator can be used to mitigate these demands for LD and HD. Simplified designs later on (especially LD) should reduce this need

Smarter powertrain management is already improving fuel consumption. Predictive control based on V2X, complex model based control and known road/traffic conditions will soon supplement this. Aggressive geo-fencing to ensure zero emission zone compliance in cities could manage engines to off or ultra clean mode. Beyond this fully automated control possible, especially in conjunction with CAV

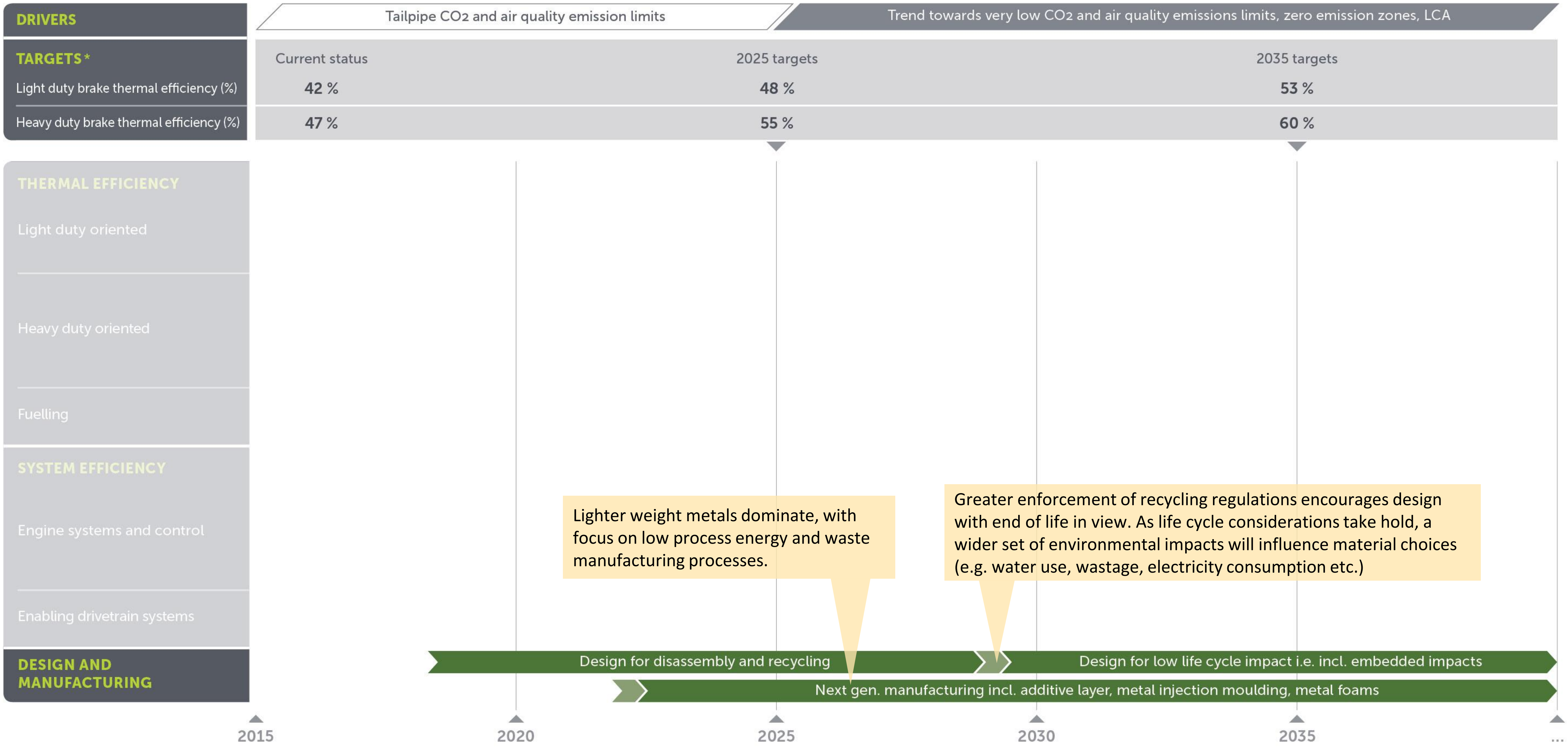
DESIGN AND MANUFACTURING

2015 | 2020 | 2025 | 2030 | 2035 | ...

System efficiency: *Transmissions and hybridisation are vital enablers for propulsion system efficiency; co-development will allow them to be operated closer to peak efficiency*



Design and manufacturing: *Design approaches, materials choices and manufacturing technologies must all evolve to support other technology developments and drivers*



TECHNOLOGY ROADMAP 2017: THERMAL PROPULSION SYSTEMS

Roadmap developed by the Automotive Council and the Advanced Propulsion Centre

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DRIVERS

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TARGETS*

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Light duty brake thermal efficiency (%)	42 %	48 %	53 %
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THERMAL EFFICIENCY

Light duty oriented

- Coatings, thermal management and combustion systems designed for low heat loss
- Flexible CR and valve control enabling cylinder deact. & deep Miller/Atkinson cycles
- Efficient, clean combustion e.g. lean burn, HCCI, water injection
- Hybrid-focussed power units e.g. camless engine, fuel cell

Heavy duty oriented

- Reduced heat loss e.g. coatings, thermal management, combustion phasing
- Lower temperature combustion e.g. HCCI, PPCI, extreme lean burn NG
- High eff. power units with integrated WHR, eg. split cycle, high temp. fuel cell
- Exhaust heat recovery (e.g. turbocompounding, Organic Rankine Cycle) → Integrated heat recovery from multiple heat sources

Fuelling

- Engine optimised for available fuels i.e. diesel, gasoline, natural gas → Engine accepting to a wide range of fuels e.g. synfuels, H_2, advanced fossil
- Flexible fuel systems e.g. rate shaping, multiple injection, nozzle geometry

SYSTEM EFFICIENCY

Engine systems and control

- Advanced lubrication and lightweighting via design/manuf. and Al, Mg, Ti
- Wide spectrum after-treatment e.g. pre-turbine, low temp, elec. assisted, alt. fuel suited → On board reforming, CO_2 capture
- Multi boost devices for v. wide map → Controlled air supply supporting high efficiency combustion e.g. e-boost and multi device
- Advanced powertrain control → Predictive control via V2X → Aggressive ZE geo-fencing → Fully auto powertrain control, AI
- Electrified light duty ancillaries (48v), reduced parasitic loads

Enabling drivetrain systems

- Hybrid systems for effective recovery e.g. 48v, KERS → Co-developed engine and hybrid system
- Manual transmissions replaced by 10+ speed auto, shift mgmt. and e-clutch → Co-developed HD-focused engine and auto, no torque convertor

DESIGN AND MANUFACTURING

- Design for disassembly and recycling → Design for low life cycle impact i.e. incl. embedded impacts
- Next gen. manufacturing incl. additive layer, metal injection moulding, metal foams

2015 | 2020 | 2025 | 2030 | 2035 | ...

** Values reflect midpoint peak efficiency between diesel and gasoline efficiency (current difference ~5%)*

1 chevron = some uncertainty around timing of mass market adoption or phase out 2 chevrons = considerable uncertainty around timing of mass market adoption or phase out

Glossary: *Explanation of acronyms and terms not described in the roadmap due to space constraints*

- **BTE (Brake thermal efficiency) -** *Brake thermal efficiency represents, in percentage terms, the amount of energy converted into useful mechanical work by a base engine at the crankshaft (excludes transmission and driveline losses)*
- **HCCI (Homogeneous charge compression ignition)** – *A combustion cycle in which well-mixed fuel and oxidizer (typically air) are compressed to the point of auto-ignition at conditions that do not form emissions*
- **KERS (Kinetic energy recovery systems)** – *Systems that can recovery waste energy (i.e. from braking)– these can be electrical, mechanical, hydraulic or pneumatic systems.*
- **LCA (Life cycle analysis)** – *Identifying the total environmental impact of a given product.*
- **NG (Natural gas)** – An *alternative fuel source to petrol and diesel, examples are liquefied natural gas (LNG) and compressed natural gas (CNG).*
- **PPCI (Partially-premixed compression ignition)** – *A hybrid combustion system where the majority of the fuel burns lean (similar to an HCCI engine) but part of the fuel still burns in a diffusion flame*
- **TPS (Thermal propulsion systems)** – *A thermal propulsion system is a device that integrates an engine or fuel cell with thermal and / or electrical systems to manage power delivery to the wheels and recover waste energy to improved performance and efficiency. The key feature of a TPS is that the primary energy is stored chemically (rather than electrochemically like in a battery)*
- **V2X (Vehicle-to-X)** – *Vehicle-to-X refers to an intelligent transport system where all vehicles and infrastructure systems are interconnected with each other.*
- **WHR (Waste heat recovery) –** *Technologies that can capture waste heat from base engines (i.e. from the exhaust) and convert it into useful energy.*

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