Future Light and Heavy Duty ICE Powertrain Technologies

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1 Introduction

1.1 Scenario and future trends

The Mobility of people and transportation of goods are fundamental needs of modern society. Any approach to fulfil these needs must meet sustainability criteria in addition to achieving customer acceptance. Accordingly solutions and services have to comply with safety, energy efficiency and security, environmental compatibility and affordability criteria.

To fulfil these criteria, the evolution of the transportation system will advance by combining improvements and changes in powertrain and vehicle technologies in close connection with fuels & energy scenario development. The already developing electrification of the powertrain will continue progressing according to the different vehicle development goals, whilst the need to increase the energy security and to reduce the use of fossil and oil based fuels will push for a wider use of renewable energy sources. Based on a global need this process will be deployed at local level according to the availability of raw materials and local policies.

Long term trends related to the evolution of personal mobility needs, but also in relation to goods transportation, will participate in shaping the market portfolio of transport solutions. More people are expected to live in large agglomerations and they will continue ask for “clean” and efficient solutions. This “clean” factor will be provided not only by vehicle technological advances but also by the optimisation of their use thanks to the increasing role of connectivity. Likewise the long haul transportation system will benefit both from connectivity, which will enhance automated driving conditions especially on intercity and highway routes, and from a wider diffusion of intermodal model schemes.

Based on long-term planning information from industrial partners ERTRAC’s Strategic Research Agenda expects that 60% or more of the new passenger vehicles in Europe will still be powered by an Internal Combustion Engine (ICE). Even in the long term horizon until 2050: Powertrain applications will include ICE, Hybrids, Range Extender architectures as well as dedicated alternative fuels (e.g. Natural Gas) engines. Similarly the Heavy Duty market is expected to be dominated by ICE for some time to come given the need for energy density in the propulsion of larger vehicles.

The mid-term trend until 2030 and the long-term trend up to 2050 will depend on several technical and political events that will drive on the one hand the progress of the current technologies and, on the other hand, the take-off of new solutions. Concerning the first aspect:

- New combustion processes and technologies to make ICE even cleaner, efficient and cost competitive are expected to be developed to support the integration of new hybrid architectures. They will also derive the maximum benefit from the use of clean, alternative fuels. In parallel, political measures put in place to comply with air quality legislation for large cities could lead to acceleration towards "clean" powertrains based on electric propulsion or alternative fuels and a consequent limitation in the use of conventional ICEs.

- Nevertheless, considering and targeting a larger use of electric driven powertrains in the future (e.g. by car sharing services), this transition process still requires improvements in battery energy density, the development of the appropriate grid and the charging infrastructure as crucial elements for an effective market penetration of electric vehicles, including improvements in cost effectiveness as well as technology.
- In the longer term, the development stage of a European hydrogen infrastructure and the costs of the technologies will prevent Fuel Cell electric vehicles from moving away from a few niche applications for a relatively long time. With a few exceptions, they remain in very early stages of development with limited opportunities. New vehicle concepts that better suited for future integrated mobility systems and urban-mobility need to be established.
- Drastic cost reductions, the production of renewable hydrogen and the build-up of a European wide hydrogen infrastructure are needed to support fuel cells to market success.

Generally it is clear that new alternative powertrain solutions will find the right environment to penetrate the market only if an integrated approach is ensured at the political level by continuing support for further strategic R&D, providing conditions to generate fuel/energy distribution infrastructures, leveraging progressive fleet renewal conditions and supporting customer acceptance through education.

The automotive and associated industries will continue to respect their societal responsibilities for sustainable solutions, emphasising the need for pragmatic, cost-effective and user-friendly approaches, which will ensure true sustainability for environment, economy and society and maintaining EU industry competitiveness.

1.2 Vision for the future of internal combustion engines

Highly efficient and ultra-clean internal combustion engines that use renewable low carbon fuels are a key element of an electrified / hybridised powertrain.

Whilst looking back into the history of combustion engines it becomes obvious that, for most of the time, the development was primarily determined by continuous improvements instead of step-changes or revolutionary breakthrough technologies. The introduction of direct fuel injection in combination with turbo-charging was one of the rare and visible exceptions to this trend. This technology bundle, known as "downsizing", led to a significant efficiency increase in fuel efficiency by about by about 15%. Figure 1.1 shows in anticipation of the following details, the proposed internal combustion engine roadmap that supports the common vision of a highly efficient and ultra-clean combustion engine that is using sustainable fuel as an integral element of an electrified powertrain. The Steps 1 to 3 are described in more details in Chapter 3.

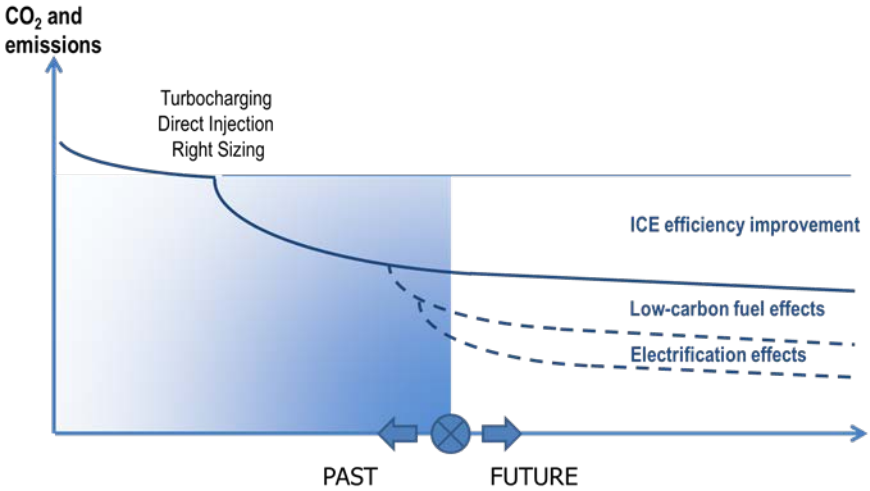

Figure 1.1 Trend of CO_2 and emissions caused by Internal Combustion Engines (ICE) along with accompanying measures of low-carbon fuels and electrification of powertrains for on road vehicles

1.3 The role of the EU collaborative research

In this future scenario, which involves complex and interdisciplinary approaches, collaborative research acts as an essential enabler for sharing of common understanding on new processes and technologies, and to accelerate the development of effective solutions able to be part of an integrated system. In particular, for mature technologies like the ICE, the further improvement opportunities must be discussed comprehensively. It is crucial to allow the right development paths to be followed and to achieve the possible advances in conventional powertrain technologies as described below in Section 3. The European Framework Programmes offer the only opportunity for comprehensive collaborative research in integrated projects, with agreed targets and RTD agendas ranging from joint analysis of requirements to the assessment of results.

Actually this requirement goes beyond the technical RTD and engineering projects. In general, the road map activities such as those resulting in this report would not be possible without the contributions from leading researchers from all relevant stakeholder groups. For research topics that are still in a pre-competitive TRL [1] this collaboration is well-established between OEMs, supply industry and research providers. In addition, the European Framework Programmes are the only programmes worldwide where any kind of international collaboration is possible, this is especially important for global challenges like greenhouse gas reduction, in global research themes like fuels and engines.

In the recent past EU funding was essential to support and accelerate the development of technologies that today are part of the OEMs product portfolio to

[1] See section 6

comply with the need in increase efficiency, lower pollutant emissions whilst still providing competitiveness to the EU automotive industry.

1.3.1 Impact so far from collaborative research

Important collaborative research projects with relevant work on ICE improvements have been executed in the 6th and 7th EU-research framework programme, such as NICE (2004-08), InGas (2008-12), Powerful (2010-14). FUEREX (2011-15), OPTIMORE (2012-13), CORE (2012-15) and CONVENIENT (started in 2013 and to be finished in 2016).

The results achieved from these projects had an impact for reaching various objectives along with improved collaboration within the industry:

- **Fulfilment of emission legislation**: NICE (achievement of EU6 level) and Powerful (Low Temperature Combustion to meet emissions < EU6).
- **EU CO_2 emission fleet reduction**: NICE (SI combustion system with 20% reduction of fuel consumption), InGas (16% CO_2 emission reduction compared to Diesel engine), Powerful (extreme SI engine downsizing to meet 40% fuel consumption reduction and CI engine downsizing to meet 20% fuel consumption reduction).
- **Significant GHG emission reduction**: CORE (total 15% fuel consumption reduction for truck powertrains due to engine improvements, hybridization and fulfilment of EU VI), CONVENIENT (total 30% fuel consumption reduction for trucks due to combined system effects).
- **Support of EV market introduction**: FUEREX and OPTIMORE (highly integrated ICE range extenders for EV).
- An additional example concerns the development of technologies related to the use of Natural Gas (see Figure 1.2), where EU collaborative research was essential in both passenger car and heavy duty sectors to stimulate and share the costs and the risks for new dedicated solutions initially devoted to a niche market. In the early 90's first multipoint injection systems and dedicated after-treatment formulations have been studied; then (starting from 1996) first applications on LD and HD CNG engines were successfully introduced to the market. Some years later, with the InGas project, a wide consortium composed by OEMs, suppliers, engineering companies and academia drove a 360° approach on CNG technologies focusing on downsized engine families and innovative lightweight storage system, solutions that recently have been proposed on the EU market as first in kind.
- Within the framework of H2020, GasON and HDGAS projects focus on the next technological step represented by the potential adoption of CNG Direct Injection systems.

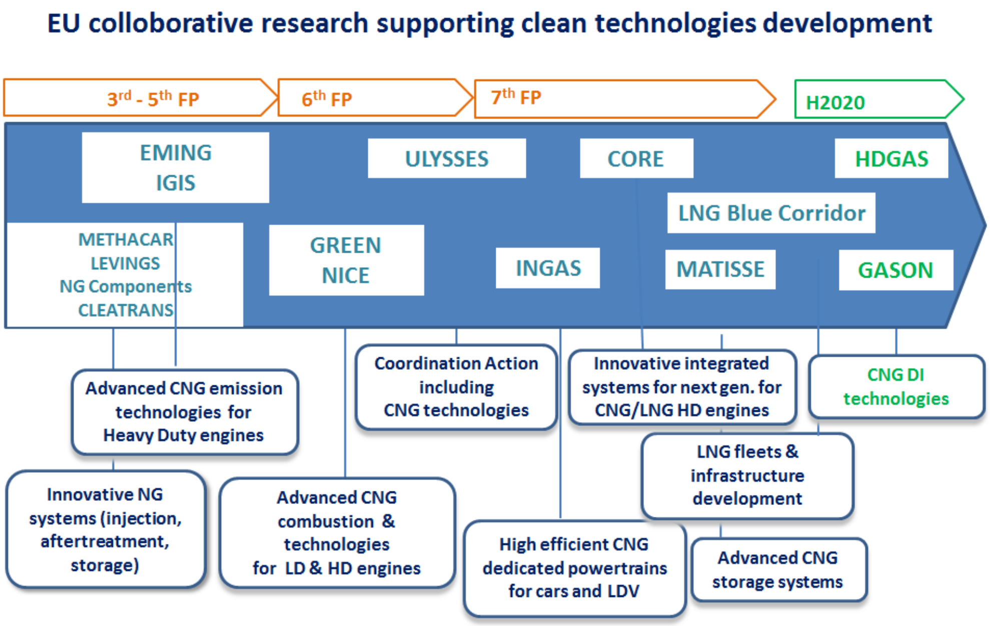

Figure 1.2 EU funding actions and industrial outcomes on Natural Gas technologies

Today, it is clear that the future needs with regard to the evolution of ICE technologies have to consider a different use of the engine as electric hybrid architectures are applied more frequently. On the other side, the development of future ICE platforms fully dedicated to the use of different alternative/renewable fuels (e.g. Natural Gas, alcohols, DME, etc.). This implies the development of new engine architectures and advanced combustion processes, suitable for the integration into hybrid powertrains, as well as new technologies and materials, including sensors and controls for the full exploitation of fuel characteristics and optimization of the vehicle energy management.

In order to deliver this, ERTRAC considers EU collaborative actions in the domain of ICE an essential enabling step also in the next decades as boundary conditions are changing, and future efficient and clean powertrains will be require new and adapted ICE technologies.

Whit this reference, the roadmap documented here highlights the landscape and challenges associated with developing these approaches as well as future research needs to allow them to be delivered.

2 EU road transportation scenario

2.1 EU Climate and Energy Framework

The EU Climate and Energy Framework is the basis for emissions reduction in all sectors including transportation in Europe [1]. The framework states an objective of reducing GHG emissions in the EU from all sectors by 80 to 95% by 2050 compared with 1990 levels. This target also sets out boundaries for the transportation sector which is further defined in the Transport White Paper which was issued in 2011 [2]. The latter document states the objective to reduce the GHG emissions from the transport sector by 60% by 2050 compared to 1990 and by 20% by 2030 compared to 2008 levels. In 2014 targets for 2030 were announced as follows:

- **At least 40% cuts in GHG emissions (from 1990 levels)**
- **At least 27% share for renewable energy**
- **At least 27% improvement in energy efficiency.**

The European Commissions “reference scenario” attempted to define transport trends in 2030 consistent with the targets (extrapolated out to 2050).

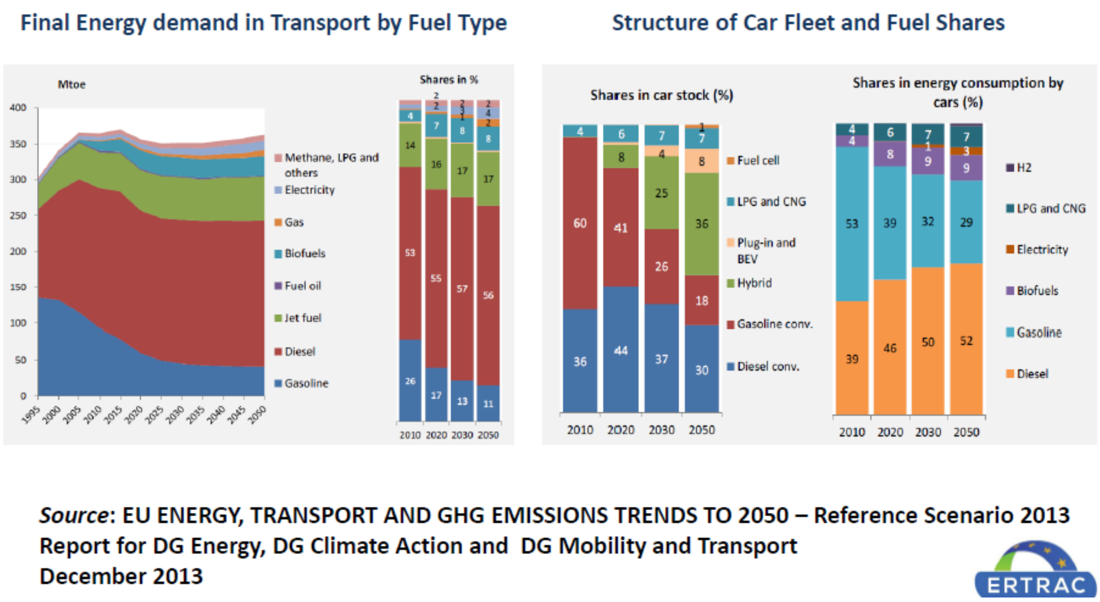

Figure 2.1 EC’s Reference scenario 13

However, according to EC’s reference scenario 13, together with those existing, additional measures are needed to control CO_2 emissions, as can be seen in Figure 2.2. Passenger transport CO_2 emissions decrease by 18% between 2010 and 2030 and then stabilize. Freight transport emissions steadily increase.

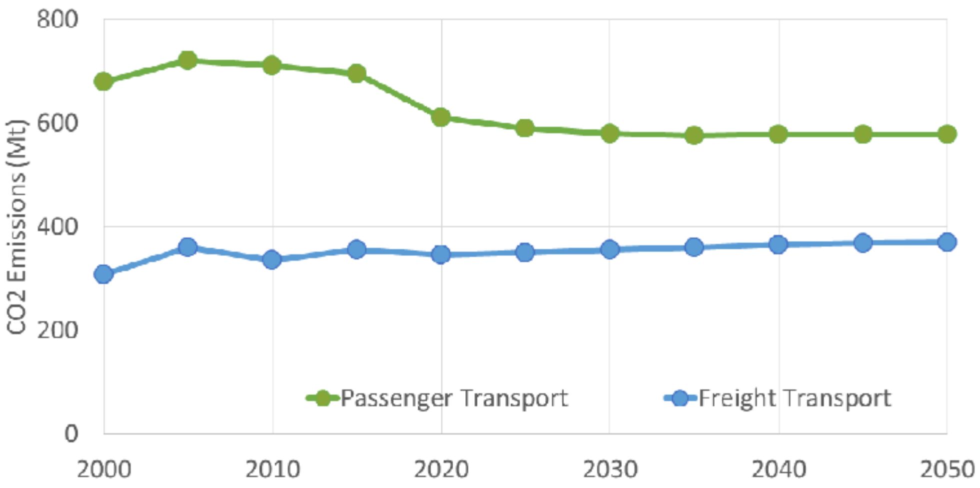

Figure 2.2 CO_2 emissions for passenger and freight transport

In order to facilitate these reductions from the fuel/energy side a number of directives have been issued over the years for example in 2009 the renewable energy directive (RED) [3], which gives targets for the use of renewable energy in transportation and other sectors, and the Fuels Quality Directive (FQD) [4], which gives greenhouse gas emissions reduction targets for member states. These have been recently reviewed resulting in the so-called "ILUC directive" in 2015 [5], which give further clarification and emphasis on use of sustainable alternatives. In addition, the Alternative Fuels Infrastructure Directive was issued in 2014, which gives minimum requirements in terms of numbers of refuelling points for alternative fuels such as natural gas and electricity [6].

2.2 ERTRAC's Perspective

ERTRAC's Strategic Research Agenda [7] advocates a systems approach to reductions in CO_2 emissions from transportation where the vehicle and the fuel (energy) contribute a part of the overall reduction potential. Other contributions come from infrastructure improvements, logistics and mobility services (Figure 2.3); these are addressed in other ERTRAC roadmaps.

Within the vehicle category there are contributions not only from the propulsion and energy side but also from other aspects related to the vehicle body rather than the powertrain, such as aerodynamics, weight, size, friction, tyres etc. This roadmap concentrates on the powertrain technologies for both light and heavy duty vehicles that are needed for propulsion as well as the energy sources that are available to these powertrains. Finally the dependency of powertrain design on new vehicle concepts needs to be further explored.

Within the evolution of the transportation sector the expectation is that fossil-based fuels will dominate the energy pool for road transport until 2030 and, even on the longer time horizon (2040+), the road transport energy supply mix will be composed of four main sectors: oil based fuels, natural gas, renewable liquid fuels and electricity, itself mostly produced from renewables. Whilst electrification will progressively penetrate the powertrain sector, conventional fuels, Power-to-X (Liquid and Gaseous) and advanced biofuels together with an increasing amount of natural gas will play a major role in combination with Internal Combustion Engine (ICE) technologies. The majority of the scenarios investigated consider that various types of powertrains using liquid or gaseous C-based fuels would still cover up to 80% of the fleet (even if the major part of these powertrains will certainly be hybridized and partly electrified) in 2050 (see Figure 2.4).

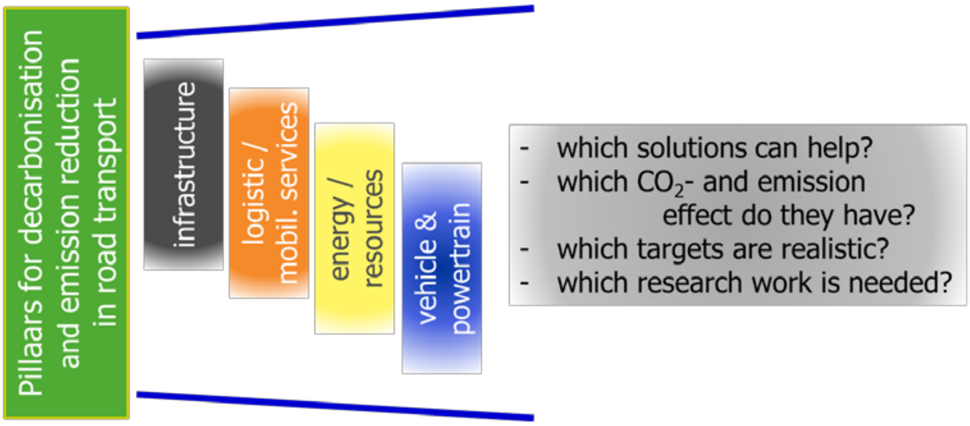

Figure 2.3 ERTRAC systems approach

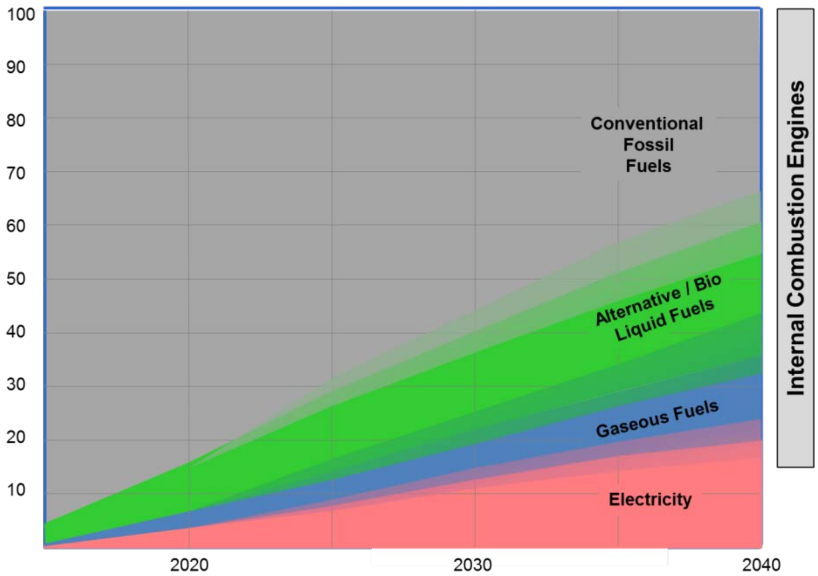

Figure 2.4 The evolution of passenger road transport energy towards 2040

As a consequence, powertrain development has to aim at taking a sustainable approach to both ICE based powertrains and fuels given that powertrains involving certain types of ICE will be the major contributor to the transportation sector. The evolution of the ICE based powertrains can be described by the following two-step pathway:

- Development of new combustion-based propulsion technologies (gasoline, diesel, PtX, advanced biofuel blends and ICE with fossil and renewable gaseous fuels) in order to achieve optimal performance on a Well-to-Wheel basis and to ensure both energy security and GHG emission mitigation. Integration of emissions control systems to give excellent real world emissions performance will be the key to acceptability of these technologies, for example catalyst performance with methane based fuels.
- Additional decarbonisation will then occur through the uptake of electrically-powered drivetrains (battery electric vehicles (BEV) and hybrids (HEV)) and the development of new ICE concepts to complement in synergy the electric drive. In this case, these new engine families will also be fuelled with the future fuel pool (conventional, PtX, advanced biofuels or natural gas). However, having a suitable vehicle on-board storage technology to provide energy density for the electricity and the development of the right-sized infrastructure for e-charging still present challenges.

For heavy duty vehicles the accompanying plug-in electrification could be less compared with light duty transport and the main CO_2 reduction must be gained through powertrain efficiency improvement and/or a wider use of alternative and bio fuels.

In large cities and conurbations, fully electric city vehicles and hybrids will dominate in the future, since range anxiety related to limited battery capacity and long charging times is less crucial during city driving. Nevertheless, vehicles driving in non-city environments can be expected to represent the larger share.

At the same time, the decarbonisation process will be sustained by the progressive uptake of low carbon fuels, such as advanced biofuels and PtX, allowing an effective and consistent use of renewable/waste energy sources and of natural gas with a lower carbon footprint. It should be noted that even the potential of advanced biofuels will be limited due to limited resources, such as biomass (arable land) and water.

	ERTRAC Vision 2030		EC Reference 13 Intensity	
	Efficiency	Intensity	2030	2050
Urban passenger transport	+80%	-45%		
Long distance freight	+40%	-28,5%		
Overall road transport	+50%	-33%		
Road passenger transport			-29%	-35%
Road freight transport			-13%	-20%

- ❑ **ERTRAC's targets are expressed as efficiency – The EC uses intensity**
- ❑ **Efficiency: transport work over energy input (pkm/kWh or tkm/kWh)**
- ❑ **Intensity: Energy input over transport work (kWh/pkm or kWh/tkm)**
- ❑ $\Delta Int = 1 - \frac{1}{1-\Delta Eff}$

Figure 2.5 ERTRAC Vision reducing CO_2 emissions compared with EC Reference 13 Intensity

There is always a chance of a significant role for hydrogen in the transportation sector, but this will still be affected by uncertainties due to high system costs, currently a poor hydrogen distribution grid and infrastructure and the lack of renewable produced hydrogen. Of course, hydrogen can be produced locally and stored depending on the temporary availability of renewable sources. Thus fuel-cell vehicles could play an important role in road transport and, if successful, they could change the future powertrain scenario fundamentally; nevertheless, this seems to be a longer term scenario. On the other hand, it is expected that in the near future the necessary technical progress will be made in battery technology and development of grid/recharging stations to support an effective market penetration of electrified vehicles.

With this perspective vehicles with ultra-efficient ultra-clean Internal Combustion Engines – particularly developed for use of low-carbon fuels such as gas - will still play a dominant role in mobility to 2030, retaining a major role until 2040 and beyond.

When the EC Reference scenario 13 is compared with the ERTRAC view towards 2030, there are some differences in units as ERTRAC uses efficiency whilst the EC only uses intensity. The EC also goes out to 2050. When the ERTRAC numbers are recalculated and compared the overall road transport in the ERTRAC vision is roughly comparable with the road passenger transport in the EC Reference 13 intensity, although the overall EC intensity is likely to be lower (Figure 2.5).

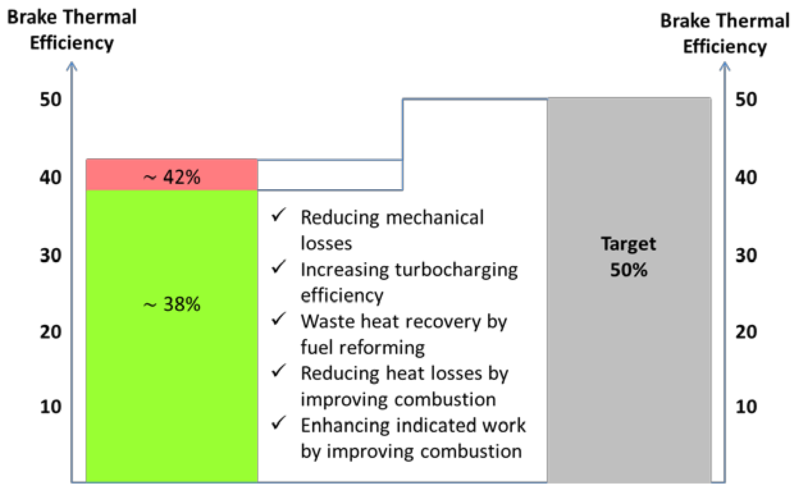

Figure 2.6 Japan's R&D programme on Internal Combustion Engines

Comparison of the outlooks for the fleet – in Figure 2.1 and Figure 2.3 – show that the EC outlook has a less optimistic view for electric vehicle penetration and a large modern Diesel penetration. Nevertheless, both outlooks have ICE as the dominant technology whether as stand-alone or as part of a hybrid configuration.

Improving ICE thermal efficiency is also consistent with targets in other parts of the world. For example, Figure 2.6 shows Japan's brake thermal efficiency targets of 50%. In the US the SuperTruck programme is targeting a goal of 55% thermal efficiency (Figure 2.7).

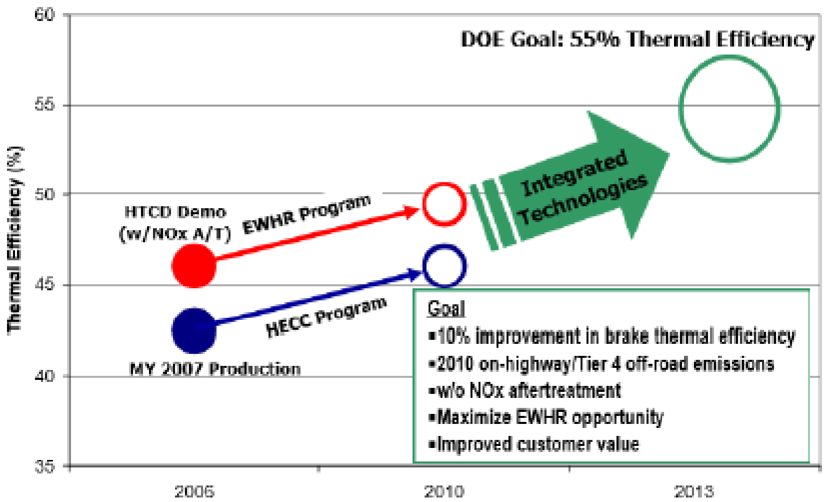

Figure 2.7 US DOE SuperTruck Programme

In general the European Commission and ERTRAC targets are similar and consistent with global strategies for meeting GHG reduction targets.

2.3 The European industry and market perspective

European OEMs and suppliers are world leaders in ICE technology; maintaining this lead is essential therefore to support export opportunities in a growing global automotive market, with the EU automobile exports currently running at over 120 bn € annually. Moreover, the non-OECD market is expected to triple between 2010 and 2035 according to IEA.

From one side there is therefore a need to continue development of battery technologies especially for urban mobility whilst, on the other hand, ICE and electric powertrains will coexist for the small and mid-sized vehicle ranges (especially for Heavy Duty Truck applications).

A specific pathway to a significant increase of powertrain efficiency lies in an unbiased reallocation of powertrain functions and redesign of powertrain architecture. The reallocation aims to utilize the specific advantages each type of propulsion engine and consequently avoid respective weaknesses. High dynamics are only difficult to realize with an ICE whereas an electrical motor easily provides almost instant torque. Constant full power and long ranges are exhausting for the electrical drive but strong points of the ICE. The redesign requires novel transmissions and breaks with the off the shelf recombination of existing modules from non-hybrid powertrains into a hybrid powertrain. On the other hand, it offers the chance to provide full powertrain functionality at reduced complexity and cost. The latter being of paramount importance for customer acceptance and fast market penetration of electrified powertrains. All these scenarios expect a further diversification in powertrain technologies. On-road vehicles will be powered by and include combinations of:

- Ultra-efficient and ultra-clean Internal Combustion Engines (ICE) with dedicated Spark und Compression Ignition (SI & CI) combustion systems for particular low-carbon fuels and application profiles.
- Electric propulsion systems.
- Various forms of hybridisation, from mild to full-hybrid, mainly targeting PHEV (Plug-in Hybrid Electric Vehicle).
- Liquid fuels for SI and CI ICE (Diesel, gasoline, biofuels and biofuel blends including advanced liquid biofuels).
- Gaseous fuels (CNG/LNG, H_2) for ICE and fuel cells, including different bio-methane paths and power-to-gas for ICE.
- Electricity provided on-board by batteries and fuel cells.

To fulfil these roles efficiently, increasing ICE thermal efficiency, reducing heat and friction losses in particular still represent important fields to recover and save energy. The role and use of advanced materials should not be underestimated here. The evolution towards electrified powertrains will also enable new functionalities and opportunities to optimise the energy balance of the engine. **ICE must also meet societal requirements for air quality, where the development of emissions**

control systems to meet cost and performance targets for future legislation will remain a challenge.

To enable a balanced approach, it is necessary to consider the entire energy and carbon footprint of the solutions, including the upstream contribution related to the fuel production and distribution. This would highlight the need to ensure “green” production of electricity based on renewable energy sources and, on the other hand, the benefit related to the introduction of advanced biofuel pathways.

The usage of liquid fuels will remain dominant for aviation and shipping in the long term. With the limited potential of biofuels, the development of technologies for Power-to-Gas and Power-to-Liquid is inevitability. The usage of Power-to-Liquid (P2L) as drop-in fuels, not only for aviation and shipping but also for ground vehicles, offers the benefit of reducing CO_2 emissions even for the existing vehicle fleet and of limiting additional costs that are associated with P2L in comparison to fossil fuels.

However, it should be noted that current 443/2009 CO_2 PC-legislation and the upcoming 2018 HD-declaration consider only tailpipe CO_2 emissions, leaving out the potential benefits coming from the use of renewable based fuels such as advanced ethanol, methanol, HVO, DME and other ethers, bio-methane. It will also be vital to consider how to make highly efficient high technology solutions usable for lower quality fuels that are generally widespread in global markets outside Europe.

To support these long term goals, it is fundamental that a common vision is shared at policy level to develop the so called “integrated” approach. This enables the conditions where new technologies can penetrate the market, providing the expected benefits in terms of environmental preservation, of personnel mobility and goods transportation, safety as well as maintaining EU industry competitiveness.

Generally, it is clear that new powertrain solutions will find the right conditions to penetrate the market only if an integrated approach is ensured at a political level, creating the appropriate political environment, supporting future R&D as well as safety and security, generating the fuel/energy distribution infrastructures, leveraging the progressive fleet renewal conditions and supporting customer acceptance through education.

3 Challenges and technology potential for ICE based powertrains and the impact of new ICE technologies

3.1 ICEs in general

As discussed above, ICE technologies will continue to play a major role for the next decades mainly due to the energy and power density capability provided by liquid and gaseous fuels and the widespread existing infrastructure. The energy density of chemical energy storage in hydro-carbon based fuels and, thus, the vehicle range, will always be greater than electro-chemical storage (the current difference is 2 orders of decimal magnitude). Also from the recharging/refilling time standpoint, liquid and gaseous fuels offer the best performance and flexibility in use.

Synthetic fuels produced in chemical plants based on renewable energy sources can lead to a net carbon free energy cycle with high energy and power density, thus, providing a similar solution with respect to package/weight and infrastructure as fossil fuels. However, a challenge remains on efficiently recovering sufficient carbon for the fuel synthesis itself.

Chemo-thermo-mechanical energy conversion with combustion/thermal engines has the potential for high efficiency, very high power densities and very high reliability. Thus the resources (material, energy, etc.) needed are specifically low compared to the energy turnover achievable.

As described in the introduction, the progress to further improve the internal combustion engine system and, thus, the powertrain can be divided in three steps (see Figure 1.1) – i.e.:

1. improvement of the engine efficiency itself, particularly regarding the properties of low-carbon fuels,
2. the use of low carbon/near net zero carbon fuels as well as,
3. electrification including hybridization.

Steps 2 and 3 are covered in the activities and roadmaps of DG MOVE and the supporting Sustainable Transport Fuels Expert Group, on the one hand, , and the ERTRAC Electrification Roadmap on the other hand. Thus, these considerations are not elaborated on here.

A detailed analysis and breakdown of the inefficiencies of a modern gasoline and Diesel combustion engines for passenger cars and commercial vehicles is given in the Technical Annex - Section 6.1. It can be concluded that overall efficiency improvements of about 15 %-points are possible for spark ignition engines –

particular in the case of highly knock resistant gas combustion systems - and approximately 10 - 12 %-points for compression ignition engines.

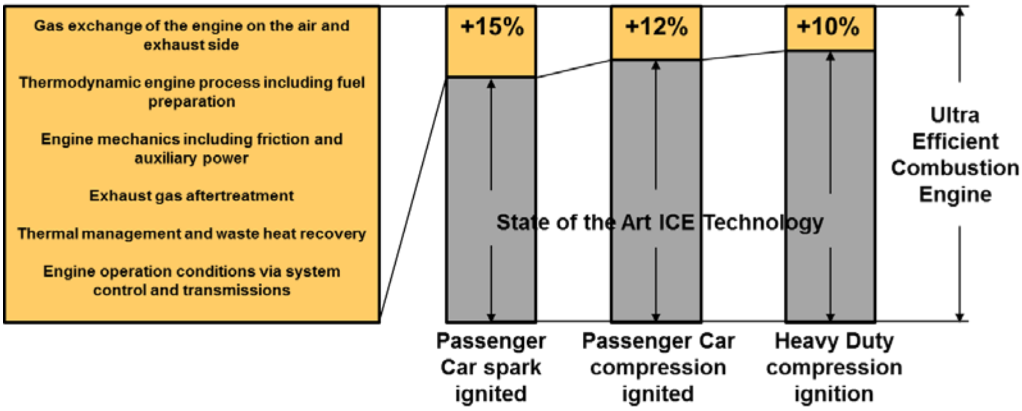

Figure 3.1 Efficiency improvement potentials for spark- and compression ignited engines

This improvement potential is nearly equally distributed between the areas of volumetric, thermal as well as mechanical efficiency. Massive downsizing should be mentioned since it increases efficiency first of all by reducing relative impact of heat and friction losses – just by increasing the specific power of smaller engine. The straightforward effect of turbocharging on volumetric efficiency and engine gas exchange losses will be mentioned further.

To harvest the remaining opportunities, a large number of technologies, which are shown in the appendix need to be developed and implemented. On a high level these technologies can be grouped in the following categories addressing the root cause of inefficiency **and control air pollutant emissions.**

- **Gas exchange of the engine on the intake and exhaust side and influence of (turbo)charging system efficiency, decisive for positive downsizing effect (Section 6.2)**
- **Dedicated thermodynamic engine process including fuel preparation – particularly for low-carbon fuels (Section 6.1)**
- **Engine mechanics including friction and auxiliary power (Section 6.1)**
- **Exhaust gas aftertreatment (Section 6.2)**
- **Thermal management and waste heat recovery including on-board fuel reforming (Section 6.3)**
- **Engine operation conditions via system control and transmissions (Section 6.4)**

The details of the technologies to be further developed related to these areas are presented and discussed in Chapter 6 – Technical Annex.

To solve these competing challenges in the future, the further research needs can be summarized as follows with an emphasis on affordability of all new developments:

- **Further development on components and systems, based on existing engine technologies and application of advanced materials**
- **New combustion processes and new engine concepts, new combustion sensing methodology & control; with special focus on gas and other low-carbon fuels**
- **Emissions control systems development (including aftertreatment)**
- **Radical approach to highly efficient, dedicated and robust combustion engines for the usage of alternative/ low carbon and high knock resistant fuels**
- **Development of dedicated ICEs for electrified powertrains including dedicated transmissions**
- **Solutions for recovery of engine heat losses including on-board chemical reforming of fuels**

3.2 Light Duty ICE

In the future, it will be of major importance for the ICE to have increased the thermal efficiency over its entire operating range. Figure 3.2 shows the main contributions to the energy efficiency increase according to the different operating conditions and, on the right side, a list of potential technological approaches. Moreover, shifting WOT bmep up, increased brake efficiency occurs everywhere due to relative reduction of load-independent part of losses - Figure 3.3. Increased TC efficiency is the main condition for higher boosting and using of unconventional cycles, mentioned below.

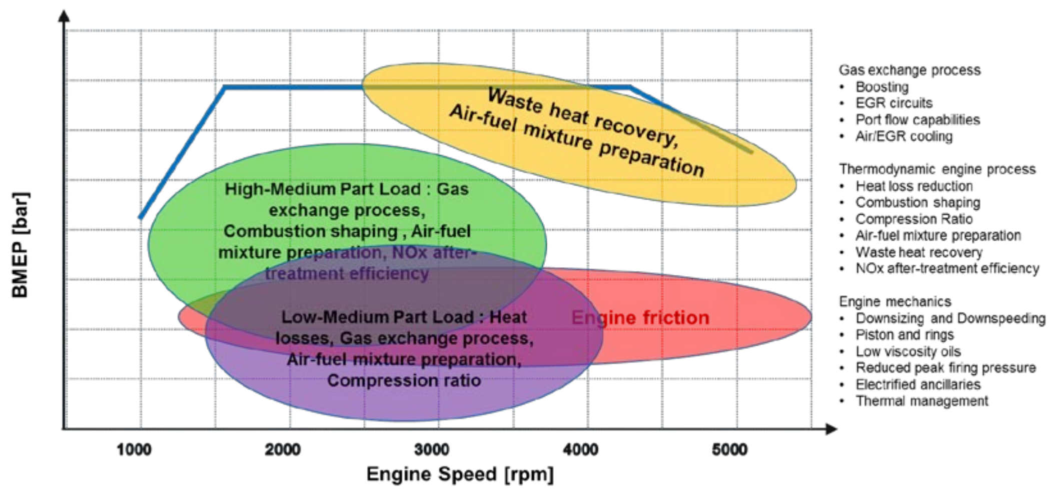

Figure 3.2 ICE improvement areas towards higher energy efficiency

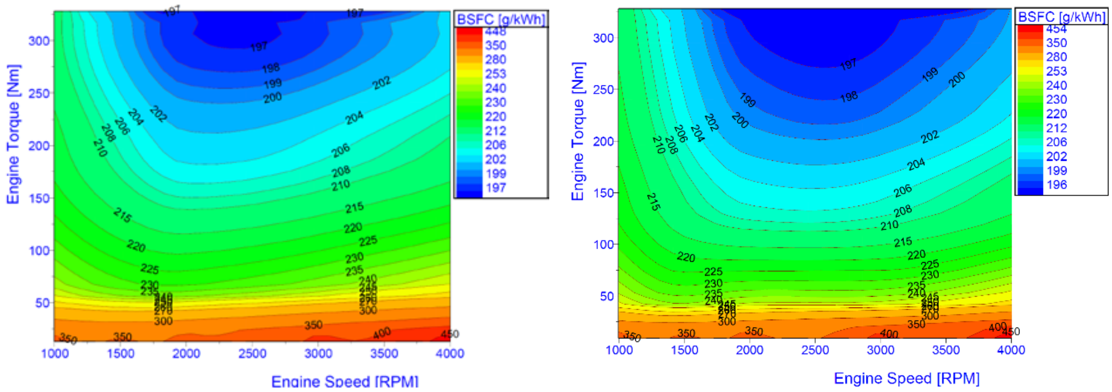

Figure 3.3 Diesel ICE bsfc improvement due to downsizing at the same torque (left bmep 25 bar, displacement of 1.67 dm^3, right 35 bar, 1.18 dm^3). Effect is visible at all loads

Friction reduction and throttling losses at part load conditions consistently affect Spark Ignited engines: this could be addressed by the combination of advanced systems for valve-train control (leading also to a cylinder deactivation approach) and the implementation of technological solutions for surface coatings and use of low viscosity lubricants.

Efficiency increases at medium to high engine load will require an extended use of non-conventional thermodynamic cycles (e.g. Atkinson or Miller) in combination with Variable Compression Ratio (VCR) and advanced valve train systems plus charge dilution to mitigate, at higher load, knocking phenomena thus avoiding the need for over-fuelling the charge mixture.

There are many synergies between individual ways to improvement: downsizing itself decreases relative thermal and friction losses due to reduction of relative impact of load-independent part of them. The crucial condition is high efficiency of a turbocharging system, otherwise gas exchange losses may overlay them. Diluted mixture reduces heat losses but it poses higher demands on boosting again, etc. That is why system approach is highly important.

With regard to passenger car applications, the brake thermal efficiency baseline is for SI engines about 38% and for CI engines about 42% (peak values). Current and short term developments aim to increase, as a first step, the gasoline engine efficiency targeting that of the CI engine; however, the long term goal is to reach a brake thermal efficiency of approximately 50%. Such a level is needed to contribute to the energy saving and CO_2 emissions reduction targets but it will also require the progressive optimisation of the ICE waste energy control or use and the introduction of radically new technologies and combustion approaches. This process will be parallel and complimentary to the development of powertrain electrification and hybridisation technologies.

Figure 3.4 shows the reality of CO_2 emissions in the NEDC related to the efficiency for a mid-class vehicle of 1360 kg. Beside the need for maximum efficiency increase keeping the reasonable values at lower speeds/loads is crucial for good real-life driving results (see Figure 3.3, as well).

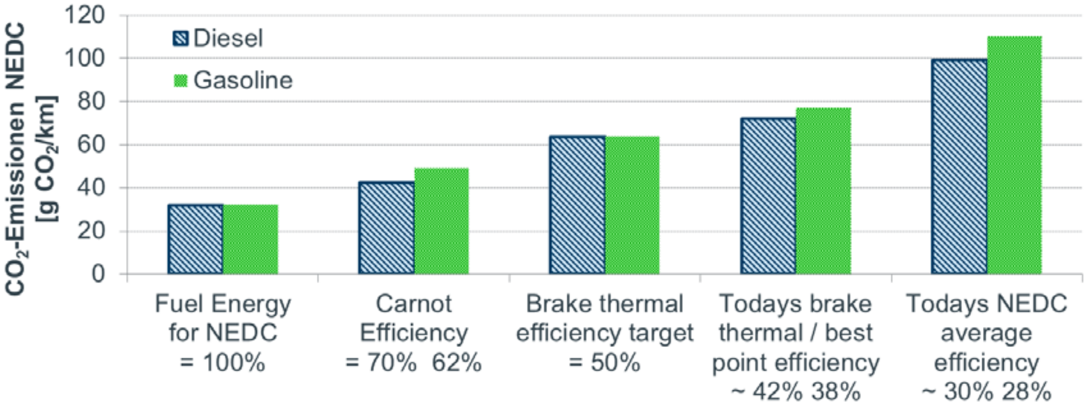

Figure 3.4 Reality of Efficiency and CO_2 over the NEDC

In relation to the data shown in Figure 3.3, a 50% peak thermal efficiency means a brake specific fuel consumption of 172 g/kWh, today's brake thermal efficiency of 38% is 226 g/kWh; if the efficiency was 42% this would give 205 g/kWh. From today's view and knowledge a 50% brake thermal efficiency can be reached only with radically different ICE technologies. To achieve even higher efficiency, it is necessary to have electrification of the powertrain, i.e. for hybridisation. Only with the whole system i.e. with an electrified ICE powertrain (ICE + electrical support) higher efficiencies can be realised.

The developments suggested above will progressively extend the most efficient areas of the powertrain to wider operating conditions closing the current gap between the homologation testing and real driving conditions. For hybrids and PHEVs closing this gap is even more challenging, because fuel consumption is a function of battery size and the share of electric travel, as well as the potential optimization of regenerative braking.

The wider use in the longer run of low-carbon and renewable fuels coupled with highly efficient dedicated combustion systems will even further enhance the beneficial impact on fuel consumption, CO_2 output and pollutant emissions of all the above ICE technology improvements.

3.3 Air Quality Enhancement

For the reduction of emissions different technologies both in cylinder and as exhaust aftertreatment systems are conceptually available and individually demonstrated.

The optimum solution will consist of a "systems" approach, as both technical as well as cost aspects are part of the same solution. Development of high efficiency ICEs result in a mean increase of peak temperatures in the combustion chamber, leading to higher NO_x formation. On the other hand, efficient ICEs are associated with lower exhaust gas temperatures, with consequent critical issues with regard to the aftertreatment system activation and efficiency. Only in some cases the technologies which improve the thermal efficiency are also helpful in reducing emissions, e.g. highly diluted charge motion controlled combustion or microwave ignition.

For this reason, combining the engine and exhaust gas aftertreatment system is a challenging task that needs further and intense research work. Moreover, the introduction of sustainable fuels introduces new chemistries with further research challenges. Even if today there are already technologies for emission reduction, such as Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), NO_x Storage Reduction (NSR) and Selective Catalytic Reduction (SCR), a strong necessity exists for further research. Improvements in aftertreatment technologies in combination with improvements of the combustion process itself are to be realised, for example aftertreatment and filtration technologies for lean gasoline engines need to be researched.

3.4 CO_2 challenges for future Heavy Duty ICEs

For the Heavy Duty sector, the realisation of the EU GHG targets for 2050 will require a **CO_2 yearly reduction of at least 3% on the complete annual new Heavy Duty Vehicle (HDV)** fleet sales in the EU (see Figure 3.5).

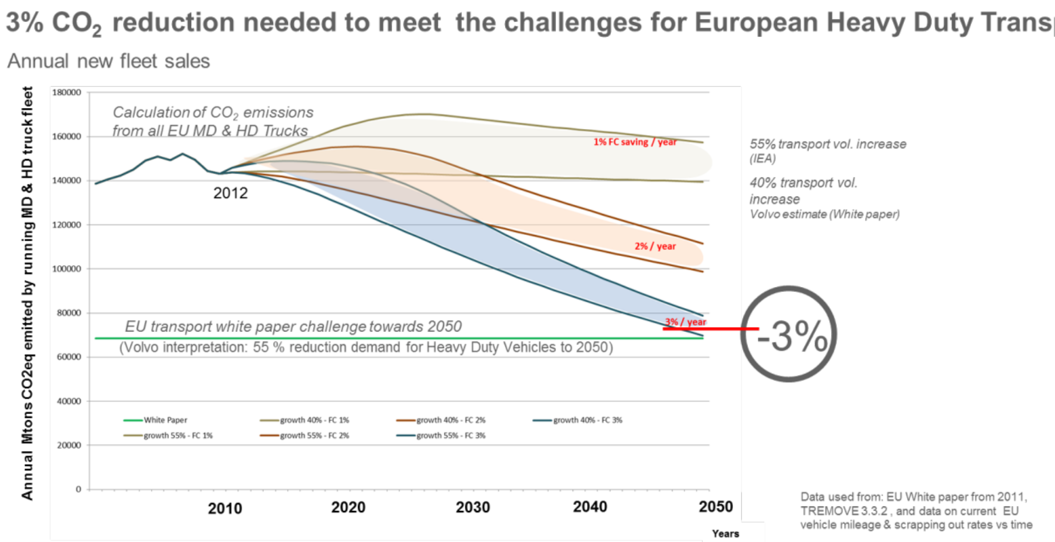

Figure 3.5 From Volvo Keynote paper ICPC 2015 – 1: CO_2 challenges for future HD propulsion

Input data for this Volvo analysis are the GHG targets set by the EU white paper for 2050, and analysis from World Energy Outlook's (IEA) New Policies Scenario 2013. In addition, EU/US data of vehicle usage and mileage reduction and vehicle scrapping rates vs. time have been used. This analysis shows clearly the significant challenge to change the current trend of non-sustainable growth of CO_2 and GHG emissions in the markets in order for the political and societal targets to be met.

All aspects of HDV operations need to be scrutinised if these targets are to be met from a pure CO_2 and energy balance perspective. Aspects ranging from utilising low CO_2 footprint energy carriers, improving energy efficiency for the Heavy Duty Engine (HDE), the drive train and the vehicle, as well as improving transport solutions to an overall sustainable level need to be addressed.

The HDE needs to increase in efficiency both with and without low CO_2 fuel and with or without electrification aid.

A large scale introduction of alternative fuels is also necessary to accomplish a reduction of GHG emissions of the required magnitude: efficiency measures are simply not sufficient. On the vehicle side, aerodynamics, rolling resistance, optimised vehicle loading factor and vehicle operation diversity needs to be worked on.

HD ICE research for competitive efficiency needs to focus around future possibilities in-basic well known areas of diesel engine efficiency, that are related both to light and heavy duty application. However, as in many development processes, significant research is needed into sub-technologies, separately or in combination, in order to reach new heights of HD ICE efficiency. The durability demands of HD products require a specific need for HD duty related research and in the selection of new technology solutions starting with advanced materials.

HD transportation is today increasing over the entire spectrum of operation. Both volume limited as well as weight limited transportation is increasing, which is being replaced in some areas by long combination transports. The load operation for the HD engine and its performance and efficiency for every transportation need are thus more challenging than before. At the same time plug-in charging electrification, in comparison to light duty transportation, will have low impact on the CO_2 reduction for HD transport, due to the absence of infrastructure or due to the power demand that makes it inefficient. Thus, the HD reduction in CO_2 needs to be derived from efficiency improvement and by efficient utilization of renewable fuel and fuel blends.

Figure 3.5 schematically illustrates the evolution path of the HD IC engine, with some significant technology steps in the past such as the introduction of efficient turbocharging advanced SW control, etc., and with some examples of potential future development steps. Many of the future ICE steps are expected to be enabled by development by both the HD vehicle evolution and/or by part of HD powertrain hybridization. Vehicle development result in terms of e.g. improved aerodynamics and rolling resistance or infrastructure information, and changes in vehicle operation will influence the ICE operation.

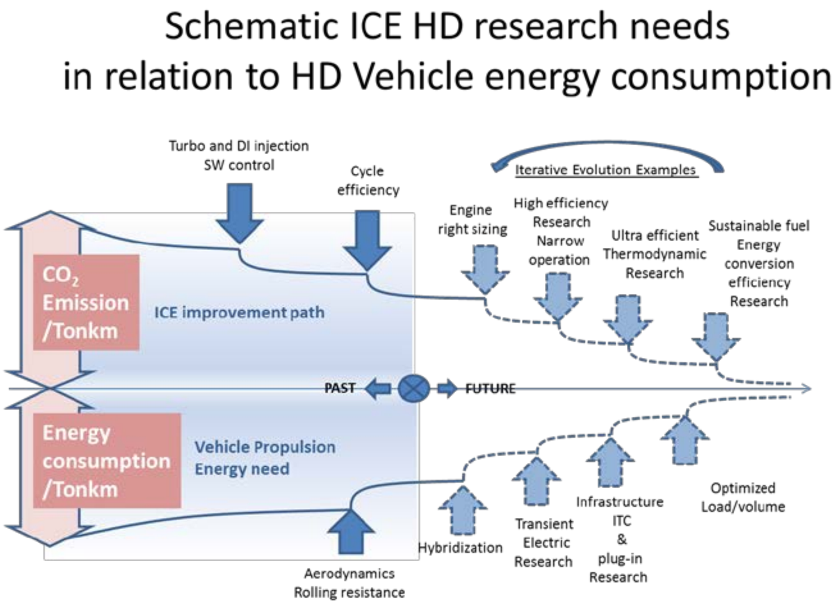

Figure 3.6 Illustration of HD ICE research need in relation to the vehicle and transmission system evolution

In summary, to meet this diversity demands HD ICE research needs to focus on areas such as:

<u>Research needs on HD engine/ powertrain systems for:</u>

- Improved HD ICE operational cycle efficiency for:
  - Full aerodynamics vehicles operation
  - An increased diversity of transport tasks, e.g. longer/ heavier combinations
  - Operability in ultra-low noise and emission zones
  - Greater truck electrification (PHEV with electrified major roads)
  - Autonomous vehicle and energy management
- High efficient use of combined use of conventional and low carbon fuels;
  - Combustion concepts and exhaust gas after treatment for e.g. Methane and its derivatives from fossil or renewable sources
- Primary durability focused energy conversion efficiency HD ICE improvements
  - Engine down-speeding and/or engine right or downsizing technology with synergies mentioned in LD part of this contribution
  - Combustion process improvements (cylinder pressure, chamber shape, improved heat rejection, fuel injection etc.)
  - Improvement of fundamental engine thermodynamics
- Engine downspeeding and/or engine right or downsizing (where applicable)
- For conventional and low carbon fuels: ignition and combustion concepts and exhaust gas aftertreatment for Natural $Gas_{2,}$ in particular for reduced exhaust temperature levels
  - Charging efficiency, e.g. Turbocharge efficiency/ turbo-compound Waste Heat Recovery
  - Waste Heat Recovery efficiency in combination with hybridization
  - Engine friction and fluid pumping, e.g. in combination with hybridization

- Ultra-low engine-out emissions control in combination with e.g. hybridization and low CO_2 fuel combustion
- Engine control and adaptation for hybrid and renewable fuel/electricity use

3.5 The role of alternative fuels

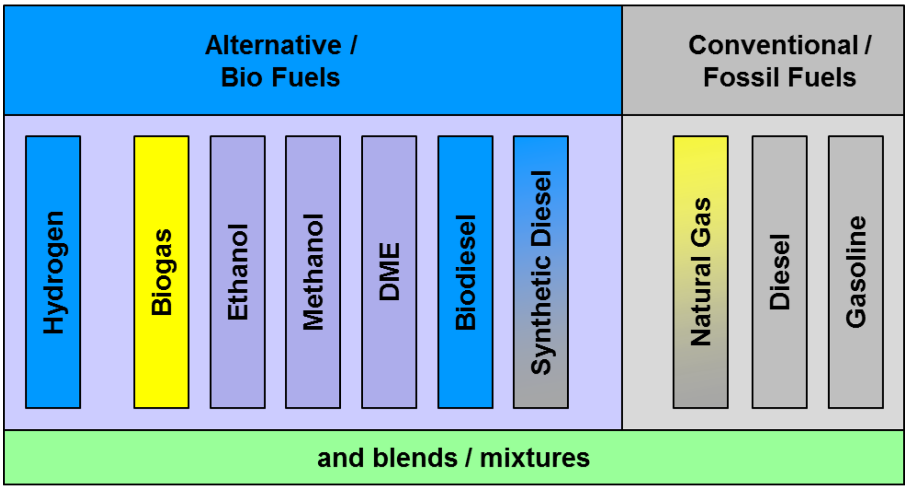

Figure 3.7 Conventional and Alternative / Bio Fuels for Transportation

For the HD transport sector it is apparent that the required reduction of GHG emissions cannot be met by efficiency measures alone, a progressive introduction of advanced renewable fuels is needed in addition. For passenger cars, city distribution and buses electrification can be a viable route; however, alternative fuels engines and hybrid solutions with alternative fuels might be more advantageous than full electrification for many applications. The evolution of conventional ICE will be supported by the progressive introduction of **advanced liquid biofuels** that will need to yield real overall WTW GHG savings, be economically affordable without structural subsidies and will have to comply with sustainability criteria and to technical specifications necessary to enable higher blending rate with the conventional fossil fuels, especially with regard to diesel fuel as well as synthetic fuels produced by "**Power-to-X**" processes using renewable electricity, water, carbon dioxide and biomass for example as feedstocks. Power-to-X processes typically have low conversion efficiencies – hence their production only makes sense when they truly make use of excess renewable power which cannot be used in a structural way to displace fossil fuel-based power.

On the **Spark Ignited engine** side, the trend in developing highly boosted down-speeded engines will require high octane fuels, which could be achieved by conventional means as well as including bio-alcohol (ethanol, methanol) and bio-ether (e.g. ETBE) blending but also potentially including bio-butanol or other tailored synthetic / renewable hydrocarbons. These will provide the capability to further increase engine thermal efficiency; moreover, thanks to the future introduction of VCR (Variable Compression Ratio) and a wider use of advanced VVA (Variable Valve Actuation) system, engines will be able to manage in real-time a wide spread of gasoline-alcohol blends without any need in engine base configuration maintaining optimal engine control parameters regulation ensuring in this way best fuel economy and emission figures. Additionally, it will be necessary to ensure that components are adapted to meet lifetime demands with the alternative fuel types. This may require further research in the area of materials to achieve current standards.

Concerning **Diesel fuel evolution**, the evolution from 1st to 2nd and 3rd generation biodiesel process will be necessary to overcome current limitations in blending FAME derived biodiesel in modern diesel engines. Current trends in increasing the pressure of injection systems and the complexity of the after-treatment system together with the durability requirement demand bio/ renewable Diesel fuels that could be produced from vegetable oils, waste oils, sugars and biomass, using such processes as hydro treating (HVO), hydrogenation, sugar-to-diesel and Fischer-Tropsch (FT) for example. In parallel with “conventional” advanced biodiesel fuels, new processes for sustainable bio-methanol production will also pave the way for a wider use of DME (Dimethyl-Ether) as well as, on the engine combustion side, advanced concepts for dual-fuel approaches which could provide the solution to maintain Diesel engine efficiency whilst introducing different kinds of alternative fuels. Looking further into the future, work is being done to explore the use of algae to produce liquid as well as gaseous biofuels.

Together with the progressive efficiency increases coming from engine technology evolution, the use of Low-Carbon Alternative Fuels, such as **Natural Gas** (Methane), from bio-gas sources will play an accompanying role in accelerating the process of decarbonisation of the transportation sector that is part of the European targets for the 2050 time horizon.

Derived from the mainstream technological developments for gasoline engines, the high octane rating of pure methane (RON = 130) is an enabler for significant and additional gains in engine efficiency combining high engine compression ratio and high boosting rate. This will demand improved ignition systems and the progressive adoption of structurally robust engines able to cope with high combustion peak pressures and temperature profiles. Future dedicated Spark Ignited CNG engines will open the way to real Diesel-like engine efficiencies and will also potentially allow the use of 100% renewable energy sources, in the form of bio-methane, produced from anaerobic digestion, thermal gasification or power-to-gas processes (synthetic methane). Bio-methane and synthetic methane are fully compatible with CNG engines for direct use and for injection into the natural gas distribution grid.

On the Heavy Duty application side, CNG is already widely used for short range journeys like those conducted by urban buses and refuse collection trucks and has huge potential for extension of use to long haulage applications. The latter will arise from the development and dissemination of LNG technologies providing an alternative and cost competitive solution to Diesel, thanks to a lower fuel operating cost, a better environmental footprint and a simpler after-treatment system (3 way catalysts in case of lambda = 1 approach versus DPF+SCR system). For Diesel-like efficiency and taking advantage of the CNG’s improved hydrogen to carbon ratio in comparison to

Diesel, a lean diffusive combustion concept needs to be developed in conjunction with an appropriate exhaust gas aftertreatment system. The CO_2 benefit potential of such a Natural Gas concept with respect to Diesel combustion could be as high as 20%.

4 Conclusions and impact

There is a common understanding that more efficient, clean powertrain solutions will find the right environment to penetrate the market only if an integrated approach is ensured. The optimal powertrain solution depends upon the vehicle type and use case (e.g. light duty vs. heavy duty, urban vs. interurban) and hybridisation seems to be an attractive model for a smooth transition phase. Furthermore, lower net carbon fuels will also play a role. However, all scenarios reach the common conclusion that ICE technologies will keep their significant role in future propulsion systems for some time.

It is expected that the role of the ICE in future powertrains for light and heavy duty vehicles will still be **dominant** (combining conventional and hybrid powertrains). With the average vehicle age of 9 to 10 years for light duty and about 3 to 5 years for heavy duty vehicles in Europe, the **impact on reducing carbon emissions** from road transport between 2020 and 2035 through **efficient and optimised ICE systems is significant**. Furthermore, the new optimisation potential in future ICEs, from hybridisation and alternative fuels, can be utilised already during this period.

The main objective is to develop an **optimised, clean ICE system solution for future powertrains**; for highly integrated ICE hybrid solutions targeting zero emission, utilizing a sustainable renewable fuel at 50^{+}% conversion efficiency. Providing an on-road efficiency of 70^{+}%, due to optimal powertrain control and intelligent transport system (ITS) integration. There are a number of challenges, including increasing the thermal efficiency and control of air quality (pollutant emissions), especially for the light duty vehicles and control of CO_2 for heavy duty vehicles. There is a global recognition of the necessity to address these challenges with optimised ICE system solutions.

The **optimised ICE system solution for future powertrains** considering light and heavy duty applications target these research topics:

- High efficiency light and heavy duty combustion engine technologies[3]
- Alternative fuel engines technologies
- Electrified propulsion and dedicated transmissions
- Transversal (e.g. control etc.) technologies and methodologies (e.g. simulation) and their combinations (e.g., model-based predictive approach)

All improvements in the ICE technology will have significant beneficial impacts on fuel consumption, on people and goods transport efficiency, on CO_2 output and on emissions reduction, with a wider use of low-carbon fuels (such as natural gas) and renewable fuels (advanced liquid biofuels and different paths for bio and synthetic methane), over a long period of time. These improvements, when integrated with the electrification of vehicles in the form of hybridization, will maximize impact at the lowest cost.

The automotive and associated industries will continue to respect their societal responsibilities for sustainable solutions, emphasising the need for pragmatic, cost-effective approaches that ensure true sustainability for the environment, economy and society and maintain EU industry competitiveness.

5 References

- Climate and Energy package
- Transportation white paper
- Renewable energy directive
- Fuels Quality Directive
- ILUC Directive
- Alternative Fuels Infrastructure Directive
- Strategic research agenda
- ERTRAC roadmaps
  http://www.ertrac.org/index.php?page=ertrac-roadmap

6 Technical Annex

To address the challenges presented in chapters 3.2 - 3.4, the following research areas have been identified. In large part, these areas follow two main lines: drastic improvement of energy/fuel consumption of powertrain systems and reduction of pollutant emissions. A major research effort has also to be directed towards guaranteeing that real world performance of all systems is at the same level as during certification, closing the gap that has emerged in some cases. The main research topics are explained below.

It is essential to maintain focus on improvements to the ICE for light- and heavy-duty vehicle application, while R&D is carried out in parallel on components and systems for electrification of the vehicle. Decarbonisation of the ICE itself will be achieved through efficiency improvements and the use of low carbon fuels, particularly biofuels and Power-to-X. This approach will ensure the contribution of ICE technologies to sustainable mobility. To achieve these advancements, further research is needed now and in the future.

In the following sections a detailed presentation is made of the different technologies that can contribute to the achievement of the targets described in chapter 3, provided that the necessary research is supported. In addition to the description, the expected fuel consumption benefits of their introduction over the state of the art technologies are also given. The following need to be taken into account:

- The values have a large focus on engine peak effective thermal efficiency but they are applicable to NEDC as well.
- To give a clearer view the technologies are grouped and the expected figures refer to larger groups, not to each individual technology.
- The figures cannot be summed up simply, since they are not generally additive (e.g. engine efficiency improvement is associated with a reduction of the potential for waste heat recovery). It is up to the developers and the OEMs to decide the optimum combinations.

6.1 ICE Technologies

Further downsizing and increased power densities are key concept for achieving higher break thermal efficiencies and future emission legislations for internal combustion engines. These necessitate advanced turbocharger technologies such as e-boosting systems in combination with fully variable valve trains and high compression ratios for optimized fuel consumption in part load operation. Additional fuel consumption reductions result from improved knock limit by charge cooling using water injection and high dilution with EGR. Dethrottling of the engine by (ultra-) lean combustion concepts or HCCI offer fuel consumption reduction potential but pose challenges with respect to NO_x emissions and engine control. Advanced ignition systems enable robust operation of highly efficient combustion concepts. Optimized fuel injection systems with improved mixture preparation (nozzle design, spray layout and injection strategies) operating at higher injection pressure offer potential for lower engine out raw emissions such as PN and HC. Alternative fuels such as e-fuels and natural gas have additional potentials to reduce (well-to-wheel) CO_2 and pollutant emissions. Emissions from cold start, start-stop and highly instationary engine operation in real driving are mitigated by engine operating strategies, electrical heating of exhaust gas aftertreatment system and electrical support by hybridized powertrains (mild/-strong hybrid, PHEV).

6.1.1 Current level of development (State of the Art)

The ICE technology available and applied currently in mass production allows the fulfilment of emission and CO_2-feet targets, e.g. for passenger cars, where all EU OEMs are well on track having met the 2015 limits:

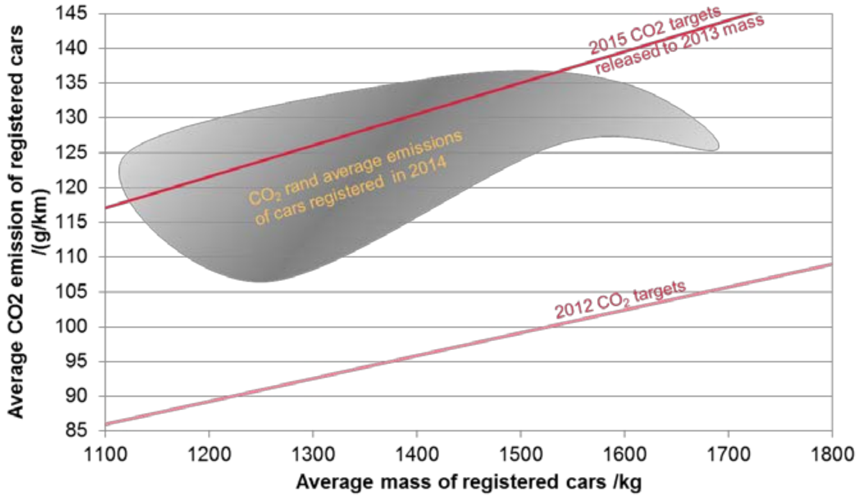

Figure 6.1 Overview CO_2 average [FEV]

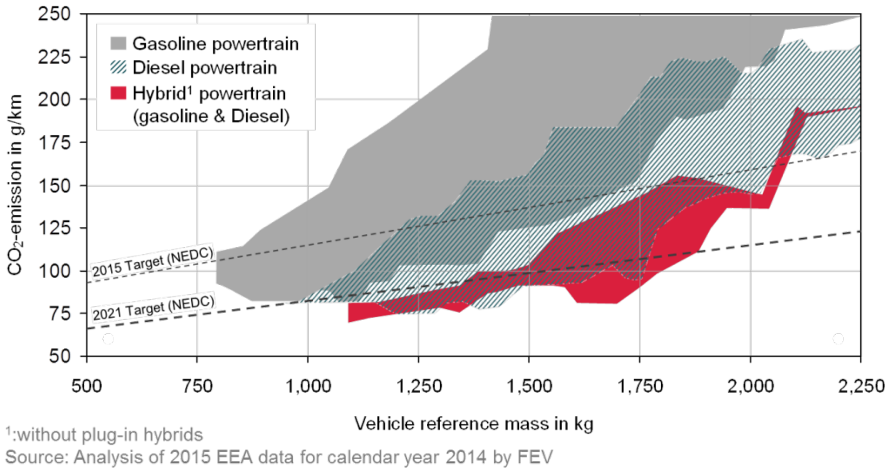

Figure 6.2 Scatter Band of passenger car NEDC CO_2-Emissions in Europe 2014 [FEV]

Today's state-of-the-art in use ICE technologies comprises:

Air and exhaust gas management:

- high efficient turbo compressors with extended map width (passenger car) and high pressure ratios (heavy duty);
- variable turbine geometry for Diesel and gasoline engines;
- low friction bearing and low inertia wheel design for improved transients;
- combined/controlled 2-stage charging including supercharging;
- high and low pressure EGR

Fuel preparation and injection systems:

- high pressure common rail direction injection;
- multiple injection and rail pressure control;

Thermodynamic combustion engine process:

- variable valve cam phasing;
- variable valve timing and lift;
- high energy ignition systems;
- stoichiometric homogenous SI combustion;
- lean homogenous and stratified SI combustion;
- diffusion CI combustion (lean and stoichiometric); engine architecture for high peak firing pressure (heavy duty)

ICE control systems:

- model based control systems incl. virtual sensors;
- multi-mode combustion control

6.1.2 Research Needs and impact of the successful implementation of the technology

The improvement of engine efficiency and reduction of engine out raw emissions – particularly regarding near and long term RDE regulations - has to be the primary focus of any short to long term research. This will entail reduction of raw emissions in order to meet the emission targets under all operating conditions (e.g. cold start) and to minimise the requirements of exhaust gas after-treatment. Such improvements will require improved and/or new technologies leading to improved and/or new subsystems (such as air management, fuel preparation, ignition etc.). Significantly better performing subsystems will allow the development of significantly improved thermodynamic engine processes – i.e. with higher efficiency and lower emissions. However, in order to achieve a fast market penetration of improved/new technologies, costs, robustness and reliability need to be taken into account.

The progress achieved with such improvements can be both, either incremental/continuous or disruptive in its kind depending on the degree of the novelty introduced.

Regarding the particular contributions of the different technologies given in %-points below, it has to be pointed out that most of them do not sum up linearly when introduced jointly.

6.1.3 Air and exhaust gas management

Efficiency of combustion engines is very much dependent on the efficiency of the gas exchange. In future, nearly 100% of all engines will be equipped with charging systems, most likely consisting of one or more turbo compressors, one or more gas turbines or mechanically coupled in turbochargers. Some systems may also contain mechanically driven compressors. Gas management also has to cover precise control of cylinder charge composition and conditioning (i.e. EGR).

<u>Short term research needs and their impact:</u>

- Improved aerodynamics of compressor and turbine stages (isentropic efficiency > 80%)
- Increased pressure ratios per stage of turbo machinery (>3 for LD and >4 for HD applications)
- Reduction of rotating masses for improved transients (reduction of T_90 by 30%)
- Reduction of mechanical friction losses of charging systems (particularly for cold start)
- Precise exhaust gas recirculation (EGR) and control of cylinder charge composition (even gas distribution, reduction of pressure losses, fast valves, sensors, virtual sensors – see control chapter)
- Air and exhaust gas conditioning (improved charge air cooling, reduction of heat losses upstream of turbine and after-treatment system)
- Sensors and actuators for gas management
- Numerical modelling for gas management system control (precise physical & real time models for charging system)
- Reliability and durability of gas management (EGR cooler fouling, depositions on parts of charging devices, …)
- Cost reduction (application of new materials, new production technologies)
- Accelerated component development (combined virtual & real advanced simulation and testing)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1.5%-points to the overall ICE efficiency improvement.

<u>Mid/ Long term research needs and their impact:</u>

- Flexible machinery for variable flow rates (extension of range of flow rates by 50%)
- Internally cooled compressors (for isentropic efficiencies >1)
- Reduction of heat losses in turbines (for improved transient performance and faster after-treatment system light-off)

- Highly integrated multi-stage compressors and turbines (for cost, packaging and mass reduction, improved power density and better transient response)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1%-point to the overall ICE efficiency improvement.

6.1.4 Fuel preparation & injection system:

Dedicated preparation and precise metering of the fuel is particularly essential for efficient and “equivalent zero emission” combustion. Main objective is an ideal oxidation of each fuel molecule generating a maximum of heat energy out of a particular fuel quantity and simultaneously avoiding any undesired chemical side reactions. A trend towards more synthetic fuels will continue due to the increasing importance of low/zero-carbon fuels (from a LCA perspective) – i.e. fuels from various sources, which has to be utilised as a support to achieve these objectives.

Generally, following the flow of fuel, the fuel has to be prepared and subsequently metered. Research along this path has to cover:

Short term research needs and their impact:

- Physical preparation of the fuel (rate of mass flow, increased & variable pressure, temperature, spray pattern)
- Sensors and actuators for fuel systems (for faster closed loop control, for adaption to fuel mass, composition and/or quality, e. g. flex fuel)
- Numerical modelling (precise physical & real time models for fuel system, “virtual sensors”
- Reliability and durability of fuel systems (depositions on injection system devices, reduced wear, reduced tolerances, etc.)
- Cost reduction (new materials, new production technologies)
- Accelerated component development (combined virtual & real advanced simulation and testing)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 0.5 (SI-engine) – 1.0 (CI-engine) %-points to the overall ICE efficiency improvement.

Mid/Long term research needs and their impact:

- Chemical preparation of the fuel (composition, thermo-chemical pre-treatment of fuels, including on-board fuel reforming using waste-heat recovery)
- Flexible fuel metering (flow rate, flow pattern, variable & flexible rate and pattern, multi-fuel capability)
- Numerical modelling (improved models using advanced methods, e. g. big-data or machine learning techniques)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1 (SI-engine) – 1.5 (CI-engine) %-points to the overall ICE efficiency improvement.

Research in this field has to be closely linked to advances in combustion processes but also to the progress of future (synthetic) fuels.

6.1.5 Thermodynamic combustion engine process

Objective of further improvements of the thermodynamic engine process is the maximisation of mechanical work generated (i.e. optimisation of efficiency) and elimination of any kind of toxic emissions. This process includes the gas exchange, the compression, the combustion (incl. the ignition system in case) and the expansion. Also the minimisation of losses, particularly heat but also friction has to be addressed. Hence, research is to be performed in:

<u>Short term research needs and their impact:</u>

- Optimisation of selection of engine/combustion operation modes and parameters (situational/adaptive processes during steady state and transient operation)
- Flexible/variable gas exchange (high flexibility, simple and robust design, low cost)
- Flexible/variable compression (high flexibility, simple and robust design, low cost, high reliability)
- Precise and powerful ignition systems (flexible system with high power density)
- Mass reduction by lightweight materials and design (housings and moving parts, use of anisotropic materials)
- Next generation of auxiliaries on demand (precise power control)
- Simplified engine architecture for electrified powertrains
- Efficiency optimised/flexible thermal management
- Combustion sensors (high precision/low cost/high reliability, “heat release” sensor)
- Numerical modelling (precise physical & real time models for engine core system incl. raw engine out emissions)
- Reliability and durability of emission decisive(?) systems (EGR, after-treatment) and of variable systems (var. valve timing, variable compression ratio, flexible ignition)
- Cost reduction (new materials, new production technologies, enhanced capabilities of low emission combustion concepts to mitigate EAT cost)
- Accelerated component development (combined virtual & real advanced simulation and testing)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1.5 (CI-engine) – 2.5 (SI-engine) %-points to the overall ICE efficiency improvement.

<u>Mid/Long term research needs and their impact:</u>

- Extended & flexible/variable expansion (high flexibility, simple and robust design, low cost, high reliability)

- Dedicated combustion processes of synthetic fuels (“zero-particle combustion” with/for liquid and gaseous fuels, efficiency controlled combustion)
- Reduction of wall heat losses by means of materials and charge motion (new materials/new composites, charge control)
- Reduction of friction losses (new bearings, new materials, controlled auxiliaries)
- Optimized charge motion and turbulence with respect to efficiency and emsissions employing (fully) variable valve trains and flow-guiding devices (baffles, flaps, vane etc.)
- Gasoline high Lambda, lean concepts, e.g. with pre-chamber ignition
- Gasoline highly diluted charge motion controlled combustion system
- Innovative ignition, e.g. microwave ignition, simultaneous ignition at multiple locations
- Advanced high-resolution predictive models (LES, DNS) for mixture formation, engine combustion and emissions, derived from in-depth understanding of physical/chemical in-cylinder processes to support the design process
- Advanced real-time models to optimize the instantaneous trade-off between efficiency and emissions for RDE applications

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 2 (CI-engine) – 3.5 (SI-engine) %-points to the overall ICE efficiency improvement.

6.1.6 ICE Control Systems

Research and technology development in the field of control systems has to focus on the empowerment of those systems regarding short term RDE needs and the requirements in view of mid-/long term powertrain/vehicle automation. Adaptive control of flexible combustion engine systems will remain a corner stone. It therefore needs to be fostered in order to guarantee best powertrain efficiencies (thus, lowest possible fuel consumption) and to maintain the leadership of EU automotive industry. Embedded control algorithms (model based & multivariable control) and hardware (multi core technology) development has to go hand in hand mutually providing best boundary conditions for future generations of control systems.

Further, the engine/powertrain control has to be embedded in upcoming generations of connected vehicle (control) systems. Therefore, it has to be as “predictive” (regarding future states of engine operation) as the entire vehicle control (in view of routing/road profile, traffic conditions, driving behaviour). Further automation of the vehicle might not have a severe impact on the control functions themselves but more on the interface and exchange of information between the engine/powertrain control system and the vehicle control system respectively vehicle periphery.

Special attention has to be given to the development of advanced control systems because these have a direct and significant impact on the fuel consumption of road transport (in case even w/o expensive new engine hardware). Potentially, fuel savings up to 30% can be achieved under real driving conditions by means of optimised powertrain control.

Flexibility of engine is crucial for efficient use of control systems. If an engine is equipped by cylinder de-activation, the control system may enhance partial load efficiency. If twin-engine powertrain is developed, the enhancement may be much higher.

Short term research needs and their impact:

- Control of engine intake and exhaust gas management
    - Advanced charging systems (multi stage, variable)
    - Fast sensor signals for precise control of transients
- Emission control
    - Precise models of emission sources such as NO_x raw emission models & emission reduction devices i.e. SCR model
    - Situation/journey based trade-offs between different emission reduction measures
    - Advanced real-time models to optimize the instantaneous trade-off between efficiency and emissions for RDE applications
- Robust and efficient algorithms for (nonlinear) system identification, design of multivariable control, multiple-input-multiple-output (MIMO) systems
- Accelerated SW development methods (integrated MiL-/SiL-/HiL-development environment and testing)

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1 (SI-engine) – 2 (CI-engine) %-points to the overall ICE efficiency improvement.

Mid/Long term research needs and their impact:

- More sophisticated and more detailed physical models embedded in control units
    - Detailed state information using virtual sensors (i.e. IMEP, engine back pressure, max. cylinder pressure, etc.)
    - Predictive control approaches (e.g. MPC – model predictive control)
    - Reduction of complexity in calibration
- Simple & accurate & robust nonlinear embedded plant models and control
    - Coordination with vehicle/hybrid controller
    - Control models for connected powertrains/vehicles
    - Predictive emission and energy control in real world driving
    - Mission based control
    - Model-based on-board diagnosis

After achievement, industrialization and implementation of the technologies listed above, these advancements should contribute approx. 1.5 (CI-engine) – 3.0 (SI-engine) %-points to the overall ICE efficiency improvement.

The continuous industrialization (period 2020 – 2045) of the above mentioned technologies – leading to the efficiency improvements indicated above have a direct impact on the CO_2-fleet emissions. In a scenario where only these efficiency improvements are taken into account (i.e. the composition of vehicle-powertrain population would remain unchanged after 2020), the fleet emission will drop from 70 to approx. 55 gCO_2/km in.

6.2 Exhaust Gas Aftertreatment (EAT)

The automobile industry is faced with the challenge to achieve simultaneously near zero exhaust emissions and high fuel efficiency. The key technologies developed for the highly efficient engines and powertrains also define the boundary conditions for the development of EAT (Exhaust gas Aftertreatment) systems.

Although the focus of the efforts presented here is specific to light-duty vehicles, it is expected that many technological advancements will be transferable to heavy-duty vehicles as well.

6.2.1 State of the art

The fuel efficient engines will create lower temperature conditions in the exhaust and, in turn, challenging conditions for catalyst systems to achieve emissions reduction. Thus, catalysts that are active at lower exhaust temperatures are needed to enable future EAT systems. Thus, both "evolutionary" and "revolutionary" technology developments are foreseen for the catalyst R&D community.

The state of the art EAT technologies have been defined by Euro 6 standards and include:

For gasoline vehicles:

- Three-Way Catalysts (TWCs)
- NO_x reducing catalysts
- Gasoline Particulate Filters (GPF)

For diesel engines:

- Catalysed Continuously Regenerating Technology (CCRT) (Diesel Oxidation Catalyst (DOC) + Diesel Particulate Filters (DPF)
- NO_x Control Technology: Selective Catalytic Reduction (SCR) and Lean NO_x Traps (LNT)

For natural gas vehicles

- Optimization of the TWC for methane conversion based on reduced noble metal loading with modified composition

Modelling/Simulation

- Modelling at all levels (from fundamental to vehicle scales) to systemize our knowledge of EAT and fully exploit current and future engine technologies that maximize fuel efficiency while meeting environmental constraints.

EAT has measurable influence on engine efficiency. In most cases, emissions control devices increase fuel consumption, either directly by reducing the efficiency or indirectly by requiring the use of additional energy.

In particular the choice of $deNO_x$ technology and EAT system design (modularity and catalyst reaction kinetics) has a multifaceted impact on overall fuel efficiency. Since SCR systems are near the limits of their NO_x conversion capabilities, further engine-out NO_x reductions will be required, and/or additional heat should be provided to the catalyst to maintain optimum temperature. The thermodynamics associated with those changes may result in worse fuel efficiency and increased CO_2 emissions. In parallel, for LNT regeneration, improved engine control strategies are required to counterbalance the effect on CO_2 emissions of an increase in reductant quantity. These strategies lead to increased fuel consumption.

The table below summarises the expected fuel consumption benefits of the state of the art of EAT technologies.

Technology	LD effect (over Euro 6)	HD effect (over Euro VI)
Gasoline	NA	NA
Diesel	< + 2%	< + 1%

Improving the EAT system must be considered as an integral part of the 21st century vehicle development process. This effort is complementary to the development of combustion processes that would minimize the fuel consumption and in-cylinder formation of criteria pollutants. An overall (vehicle + EAT) modelling that would account for the strategy to optimize EAT operation and the effects on engine operation and fuel consumption is of paramount importance.

6.2.2 Research needs

EAT research needs focus on developing new technologies and on gaining an enhanced fundamental understanding of catalysis and governing phenomena limiting the effectiveness of current approaches. Key areas of research include:

- Surface chemistry and physics for high-efficiency, low-temperature catalysis and filtration
- Interactions between reaction and diffusive transport phenomena to enable low back-pressure, high filtration, and reduced gaseous emissions in a single device
- Robust simulation models providing insights on performance and methods of optimizing configurations
- Multiple EAT functionalities into a single unit

6.2.3 Gasoline Vehicles

The TWC technology commonly found on the majority of gasoline passenger cars today can be effectively utilized to control the pollutants; however, increased use of turbocharging and resulting lower exhaust temperatures may require additional measures to light-off catalysts effectively during cold start. Moreover, RDE requirements may require extended catalysts performance for non-stoichiometric mixtures, rich or lean, encountered at high loads. For lean burn technologies, the exhaust will contain high levels of oxygen that will prevent the TWC technology from performing. Thus, dilute gasoline combustion with air will require NO_x reducing catalysts for lean, oxygen-rich exhaust. This in turn requires the development of significant improvements in our understanding of surface chemistry processes in EAT systems.

<u>Short term research needs:</u>

- TWC – technology:
  - New catalyst materials that efficiently store and oxidize HCs at lower temperatures
  - Oxygen Storage Component (OSC) - adaptation to non-stoichiometric operation at high load due to air short circuiting
  - PGM reduction through innovative deposition processes
  - Improvement of high temperature resistance of PGM and wash-coat for durability concern
- Particle Filtration (PF) for direct injection spark ignition:
  - Improvement of filtration in cold conditions
  - Effect of fuel sulphur or other contaminants (e.g. ash)
  - Combination of filtration and 3-way catalysis
- SCR technology:
  - Optimize control of NO_x and temperature for lean-burn gasoline combustion
  - Optimization of $NO:NO_2$ control
  - Direct utilization of NH_3 stored on solid state materials
  - Quantification of the effect of SCR on fuel consumption
- LNT technology:
  - Improve robustness with low fuel penalty - Quantification of the fuel penalty
  - Fuel sulphur effects and potential mitigation strategies
  - Improve NO_x reduction selectivity towards N_2
- EAT system integration
  - Active thermal management of the EAT system to maximize lean-NO_x conversion
- Combined EAT systems
  - Reduction of higher NO_x concentration via combinations of catalyst EAT systems
- Non-regulated pollutants: NH_3
- Real driving emissions
  - Performance of EAT system under real driving conditions

<u>Mid / Long term research needs:</u>

- Particle Filtration (PF) for direct injection spark ignition:

- o Characterization and better understanding of particulate emission from dilute combustion characteristics and particle chemical composition
- SCR technology
  - o Assessment of stoichiometric operation effects (effect of NH3 storage on SCR catalysts / Surface reactions affected)
  - o Passive SCR with on-board NH3 generation
- LNT technology
  - o New catalyst materials and regeneration strategies may be needed to maintain high efficiency and low fuel penalty over a wide exhaust temperature range typical of gasoline-based engines
- EAT system integration
  - o Overall greenhouse gas emission assessment to account for any system interactions.
- Production and use of H_2 for light-off temperature lowering

6.2.4 Diesel Vehicles

The higher cost of diesels relative to gasoline PFI technology is primarily attributable to the cost of the combustion system technology (air handling, fuel injection, higher pressure engine operation) and emission control equipment. Overcoming the barriers will help maximize fuel economy, improve EAT system effectiveness and durability, and reduce overall costs. In addition, understanding the impacts of emerging fuel changes (i.e., biofuels) is critical.

<u>Short term research needs:</u>

- Diesel Oxidation Catalyst (DOC):
  - o Lower HC light-off temperature with reduced PGM
- Cold-start emission trapping technologies:
  - o HC and NO_x trapping
- DPF:
  - o Effect of biodiesel blends on soot oxidation/regeneration rate.
  - o Improvement of filtration in cold conditions
- SCR technology:
  - o Catalysts with high cell density and thinner durable substrate walls
  - o Development of approaches directly utilizing NH_3 stored on solid state materials to reduce costs associated with urea handling, eliminate urea deposit formation, and improve low temperature NO_x reduction performance
  - o Quantification of the effect of SCR on fuel consumption
- LNT technology
  - o Reduction of the pgm content to reduce commercial risk due to pgm market volatility - novel formulations need to be investigated (i.e., perovskite-based LNTs)
  - o Improve NO_x reduction selectivity towards N_2
  - o Quantification of the fuel penalty
- Real driving emissions
  - o Performance EAT system under real driving conditions

Mid / Long term research needs:

- Cold-start emission trapping technologies
  - Monitor greenhouse gas emissions from new DOC formulations (minimization of N_2O and CH4 emissions)
  - Durability and history effects on catalyst performance ('memory effects') – implications on testing procedures
- DPF:
  - New materials to improve thermal durability, PM trapping efficiency, improvement in filtering nanoparticles (<23 nm), and weight
  - Reduction of the fuel penalty required for soot oxidation/regeneration (control and DPF-based strategies and advanced sensors for reduction of the regeneration frequency and/or shortening the length of the process)
- SCR technology:
  - Development of HC-SCR approaches (Lean NO_x Catalysis) and "dual SCR" approaches (HC-SCR and NH_3-SCR catalysts where NH_3 is produced by the upstream LNT catalyst)
- LNT technology:
  - Expansion of the temperature window for NO_x reduction to lower temperatures to reduce both overall LNT size requirements and cost
- Highly efficient thermoelectric generators:
  - New non-toxic skutterudites that allow partial recovery of heat that would otherwise be lost from the exhaust pipe
  - Development of a reliable interconnecting technology and an efficient thermal coupling;
- Novel passive thermal management technologies:
  - Low- and high-temperature phase change materials that minimise the need for heating of the catalyst system
- Combined EAT Systems:
  - Combination of DPF with NO_x catalyst systems (both SCR and LNT) for reducing system volume
  - Combination of LNT with SCR catalysts for lowering precious metal loadings, expanding the temperature window of operation, and elimination of urea as a NO_x reductant.

6.2.5 Natural Gas Vehicles

The catalytic converters for NGVs still are coated with a higher amount of precious metals due to the methane conversion requirements

Short term research needs:

- Lean NGV combustion: new materials (e.g. perovskites, mixed oxide) and concepts (CH_4-SCR)
- Stoichiometric NGV combustion: new materials for a high stable NO_x conversion rate and a long-run stability (bus 300 Tkm, truck 700 Tkm) with low creation of ammonia

Mid / Long term research needs:

- Effect of hybridization on exhaust system thermal management and resulting pollutant conversion
- Catalyst durability and usage of rapid ageing procedures

6.2.6 Modelling/Simulation

Modelling provides the practical and scientific understanding as well as the analytical base required to enable the development of efficient, commercially viable emissions control solutions for ultra-high efficiency vehicles. Fundamental experiments and modelling needed to address key knowledge gaps pertaining to low temperature EAT.

Short term research needs:

- Surface chemistry and physics for high-efficiency, low-temperature catalysis and filtration
- Interactions between reaction and diffusive transport phenomena to enable low back-pressure, high filtration, and reduced gaseous emissions in a single device
- Robust models providing insights on performance and methods of optimizing configurations
- Modelling of the ageing processes in exhaust systems (thermal, poisoning, ash effects)

Mid/ Long term research needs:

- Multi-dimensional flow/thermal/catalytic process modelling of heavily downsized multi-functional packages
- Overall (vehicle+) engine + EAT) modelling that would in principle also account for the strategy to optimize EAT operation and the effects of EAT on the engine operation and fuel consumption.

6.3 Waste heat recovery

The re-use of waste heat represents a great opportunity to improve the internal combustion engine efficiency, in particular at high load operation and at heavy duty vehicle applications. Up to 70% of the combustion energy is converted to heat that is rejected in the exhaust and by the engine cooling. So, being able to re-use a considerable part of this heat means a significant overall efficiency increase of the powertrain.

However, although the efficiency of modern internal combustion engines is increasing, the cooling requirements are rising due to higher demands on power output. There are also increased demands due to air conditioning and other vehicle based functionality. There is therefore potential to improve fuel consumption through optimisation of engine temperature control (lubricant and coolant) and through optimisation of whole vehicle thermal management

6.3.1 State of the art

Waste-heat recovery

Technology application is generally more advanced for HD vehicles due to larger packaging space and higher load duty cycles, for example mechanical turbocompounding has been on the market for truck applications and ORC demonstrated on buses. Progress for passenger car applications has been slower due to a lack of supply chain development and a diminishing cost benefit compared to other technologies offered. Key challenges for the implementation of waste heat recovery across both HD and LD vehicles are packaging, transient behaviour and cost/benefits. Research has revealed that some advanced technologies can be applied to further improve waste heat recovery efficiency. Several technologies have been studied such as thermodynamic cycles (Organic Rankine Cycle (ORC)), thermoelectric generators and turbocompounding systems.

Specific WHR may be achieved of waste heat is used for reforming of fuel to compounds of higher calorific value.

A summary of expected fuel consumption benefits or waste heat recovery technologies is shown in the table below. It is expected that only one of these technologies will be applied at a time, therefore the total contribution that can be expected is up to 5% for passenger car and up to 10% for Heavy Duty vehicles.

Technology	LD benefit, NEDC	HD benefit
Organic Rankine Cycle	3 - 5%	4 - 6%
Thermoelectric Generators	2 - 4%	1 - 2.5%
Turbocompounding	1 - 3%	1 - 3%

Thermal management

Unlike naturally aspirated engines that eliminate heat to the environment through the exhaust gas, more rejected heat in modern ICEs will be transported into the underhood environment from heat exchangers, especially intercoolers and EGR coolers. With the underhood space already limited by passive safety and styling constraints, thermal interactions between hot parts will need to be taken into account and used more efficiently. Due to the increasing number of auxiliary systems, the cooling circuit is becoming more and more complex. This makes it very difficult to integrate and control the different components like the radiator shutter and thermostat while different coolant temperatures are necessary to operate in the specified temperature range (e.g. gear box, high voltage battery, charge air cooler).

Below are a range of technologies available to improve powertrain thermal management in development, as shown in the table below. Maximum benefits for passenger car and HD for this technology group are estimated to be 5% - 7%.

Function	Technology	LD benefit, NEDC	HD benefit
Coolant	Flexible pump control	1.5%	1 - 2%
	Split coolant jacket	~1%	<1%
	Electric thermostat	1.5%	1%
	Coolant heat storage flask	1-2%	1% (warm-up cycles)
	Exhaust heat recovery	0.5 - 1.5%	1%
Coolant and lubricant	Engine encapsulation	2%	1%
	Integrated exhaust manifold	0.5 - 1%	N/A
Lubricant	Variable flow lubrication	1 - 3%	1 - 2%
	Split oil sump	1 - 3%	N/A
	Oil heat storage	3%	N/A
	Heat to oil	2 - 3%	1 - 2%

Integrated vehicle thermal management

Improved thermal management within the vehicle can improve fuel efficiency in a number of ways, particularly at start-up and low load. Intelligent design and advanced technologies can harness thermal energy rejected from the engine to improve heat flow around the entire vehicle. The two main benefits of this are the ability to reduce the radiator size, which will reduce the frontal area and the Cd value, the other is the ability to warm up the lubricants quicker to decrease viscosity and therefore frictional losses.

A summary of potential benefits for passenger car and heavy duty vehicles is shown in the table below. A maximum total benefit for this type of technology is estimated at up to 3% for passenger car, up to 4% for heavy duty vehicles.

Technology	LD benefit, NEDC	HD benefit
Advanced heat exchangers	0.5%	0.5 - 1%
Multi temperature radiators	0.5 - 1%	0.5 - 1%
Water charge air cooler	0.5 - 1%	0.5 - 1%
Nanofluids	N/A	0.5 - 1%
Improved fan drive systems	N/A	<2%
Integrated transmission and oil cooling	1 - 2%	1 - 2%
Engine encapsulation (vehicle mounted)	2%	1%

6.3.2 Research needs

Key research areas in waste-heat recovery include:

- Improvements on organic Rankine cycle efficiency, materials advancement and packaging that will make the system more attractive
- Improvement of energy recovery efficiency, durability and cost of thermoelectric generators
- Back-pressures and pumping losses due to turbocoumpounding systems.

Key research areas in thermal management and integrated vehicle thermal management include:

- Reduction of the complexity of the coolant circuits and advanced cooling strategies via integration of prediction tools regarding driving pattern and routing to forecast engine operating conditions
- Cost reduction to enable greater penetration within mainstream market and Integration and control of combinations of these technologies

6.3.3 Organic Rankine Cycle

Organic Rankine cycle recovers exhaust waste heat via a heat exchanger, using a phase change of the organic working fluid to drive a turbine and generate mechanical or electrical energy. Working prototypes have developed for bus, HD long haul, MD urban, and passenger car. Impact so far from collaborative research includes the development of heat exchangers and expanders for durability and production project and vehicle demonstration, e.g. Ricardo Wrightbus.

<u>Short term research needs:</u>

- Development of heat exchangers and expanders for durability and production project and vehicle demonstration e.g. Ricardo Wrightbus

<u>Mid/ Long term research needs:</u>

- Packaging, transient performance and cost benefit
- Prototypes to be tested in real world conditions over a period of time
- Optimisation for lower exhaust temperatures in passenger cars compared to heavy duty
- Cost reduction
- Improvements in control due to information on traffic and route information

6.3.4 Thermoelectric Generators

Thermoelectric generators use the Seebeck effect to generate a voltage from a thermal gradient between two dissimilar semi-conductors, this energy is then used to reduce fuel consumption for example by powering electrical ancillaries. Thermoelectric generators can reduce fuel consumption by up to 4%. Volvo/Renault Trucks have made steps towards using thermoelectrics on their HD trucks. Also, the technology was investigated in the US DoE Supertruck programme. The technology is not currently in use for buses. Prototypes tested in passenger car; BMW, VW, Mercedes-Benz, GM, JLR.

Short term research needs:

- Materials assembly, thermomechanical fatigue and reducing cost

Mid / Long term research needs:

- Improvement of energy recovery efficiency
- Durability

6.3.5 Turbocompounding

Turbo-compounding recovers energy from the exhaust via a turbocharger. In mechanical turbocompounding, energy is fed back into the driveline via a high speed transmission. Electric turbocompounding combines a turbine with an electrical generator to recover energy. Mechanical turbocompounding has been commercialised in heavy duty engines - Daimler 2008, DD15 whereas electrical turbocompounding systems are in development, for example CPT 2012 system, TIGERS turbogenerator, Integral Powertrain SuperGen. Impact so far from collaborative research includes the development of electrical turbine for production project and production for power generation engine application.

Short term research needs:

- Impact on exhaust backpressure, reducing transmission losses, especially at low load
- High speed electric motors

Mid / Long term research needs:

- New design of turbine blades with higher efficiency
- Combining functionalities on electric turbocompounding / torque assistance for best system efficiency versus cost

6.3.6 Advanced Heat Exchangers

Heat exchangers are a key part of thermal management systems. Development of new and improved designs and materials involved in heat dissipation can have proportional effects on CO_2 reduction. By improving the heat transfer, the radiator has less load and so can be reduced in size, this in turn can lead to improved aerodynamics. The state of the art includes, metal/graphite foams, advanced fin and tube design, cuprobrazed heat exchanger, powercold and compact cooling system. Heat exchangers are in mass production.

Short term research needs:

- Cost/availability of materials
- Heat exchanger fouling in dusty environments will require extra maintenance

Mid / Long term research needs:

- Durability of system
- Reducing material and manufacturing costs

6.3.7 Multi-temperature Radiator

Use of radiator with different fluids (engine‘s coolant, engine‘s oil, transmission‘s oil) and different thermal levels (engine‘s coolant temperature and low temperature coolant for other components such as: fuel, electronics, EGR, precooler/WCAC). Instead of having different separate radiators for coolant and oil, a radiator with different fluids could help improving the packaging. In case of different coolant temperature level needs, a compromise could be found in terms of: air pressure drop, coolant temperature level with the aim of using only one radiator with 1 coolant inlet and multiple coolant exits. Reduction of heat exchanger size leads to a reduction in frontal area and air inlet surface areas which will lead to a reduction in Cd due to powertrain and HVAC cooling. Innovations introduced to the market include EGR cooling at lower temperature than engine's coolant temperature (passenger cars), precooler/charge air cooler (heavy duty) and cooling loop components for power electronics cooling (Hybrid EVs).

Short term research needs:

- Development of modeling processes to assess synergistic benefits of combining cooling loops

Mid / Long term research needs:

- Development to manage increasing system complexity due to hybridisation (5-7 separate cooling circuits with different radiators)

6.3.8 Water charge air cooler Intercooler

A water-cooled charge air cooler is a charge air cooler where the charge air is cooled by a cooling agent, and not by the passing air. A traditional cooler is designed in a way that enables it to provide maximum cooling whenever necessary, but under normal circumstances only approx. 70-80% of the maximum cooling capacity is required. Here a combination cooler is the optimum solution, as the size of the cooler may be reduced by 20-30% without sacrificing efficiency. This concept means lower weight, easier installation, and substantial energy savings, while making it easier to comply with current emission standards and demands (better NOx/CO_2 trade-off for Diesel).

Short term research needs:

- Improving efficiency through reduction of working temperature

Mid / Long term research needs:

- Possibility to cool down below ambient temperature using coupling between water CAC and air conditioning circuit

6.3.9 Nanofluids (nanocoolant)

Nanofluids which consist of a carrier liquid dispersed with tiny nano-scale particles are potential heat transfer fluids with enhanced thermo physical properties and heat transfer performance. The use of nanofluid as coolants would allow for smaller size and better positioning of the radiators. It also increases the efficiency of the system with less amount of fluid. It results that coolant pumps could be shrunk and engines could be operated at higher temperatures. The development of the field is hindered by lack of agreement of results obtained by different researchers, poor characterization of suspensions and lack of theoretical understanding of the mechanisms responsible for changes in properties. Research activities are conducted in US DoE, Caterpillar and Cummins and some government funded programmes are underway (US DOE, UK (lubricants), France)

Short term research needs:

- Long term stability of nanoparticles dispersion-overcoming erosion risk
- Increased Pressure drop & pumping power
- Higher viscosity and lower heat capacity

Mid / Long term research needs:

- Durability
- Cost reduction

6.3.10 Improvement to fan drive systems

Basic fan design is a mature technology. Only very small incremental improvements can be gained by altering fan design. Most improvements come from fan installations such as vehicle mounted instead of engine mounted fans and intelligent control strategies that only use the minimum amount of fan power required. Hydraulic fans are commonly used for off-highway vehicles, pulse-width modulation (PWM) fans are used on passenger cars and 3 speed fan clutches are used on HD trucks.

Short term research needs:

- Improving efficiency (air flow)

Mid / Long term research needs:

- Potential for 48V to enable cost reduction and efficiency improvement

6.3.11 Integrated transmission and engine oil cooling circuit

Integrating the engine cooling circuit with transmission oil temperature control system can reduce warm up time for the transmission oil using engine waste heat, thereby reducing frictional losses. The transmission oil temperature is controlled thanks to the use of an additional thermostat installed on the transmission oil cooler. The technique is suitable for LCV, LD and HD with transmission oil cooler and is surrently on the market for passenger car (BMW).

Short term research needs:

- Improved cooling circuit design

6.3.12 Engine Encapsulation

Engine encapsulation can be used to retain heat during times of low or no load. The intent is to warm the engine up faster to reduce frictional losses at start up whilst also giving potential to improve combustion efficiency, and reduce engine out HC and CO emissions. Engine encapsulation systems have recently appeared on the market (BMW, Mercedes) and are being investigated by several vehicle manufacturers.

Short term research needs:

- Packaging within engine bay
- Material – thermophysical properties improvement for better insulation

The re-useing of waste heat represents a great opportunity to improve the internal combustion engine efficiency, in particular at high load operation and at heavy duty vehicle applications. Up to 70% of the combustion energy is converted to heat that is rejected in the exhaust and by the engine cooling. So, being able to re-use a considerable part of this heat means a significant overall efficiency increase of the powertrain. Technology application is generally more advanced for HD vehicles due to larger packaging space and higher load duty cycles, for example mechanical turbocompounding has been on the market for truck applications and ORC demonstrated on buses. Progress for passenger car applications has been slower due to a lack of supply chain development and a diminishing cost benefit compared to other technologies offered. Key challenges for the implementation of waste heat recovery across both HD and LD vehicles are packaging, transient behaviour and cost/benefits.

A summary of expected fuel consumption benefits or waste heat recovery technologies is shown in the table below. It is expected that only one of these technologies will be applied at a time, therefore the total contribution that can be expected is up to 5% for passenger car and up to 6% for Heavy Duty vehicles.

Technology	LD benefit, NEDC	HD benefit
Organic Rankine Cycle	3 - 5%	4 - 6%
Thermoelectric Generators	2 - 4%	1 - 2.5%
Turbocompounding	1 - 3%	1 - 3%

Further details on each technology are shown below.

6.3.13 Organic Rankine Cycle

Organic Rankine cycle recovers exhaust waste heat via a heat exchanger, using a phase change of the organic working fluid to drive an expansion machine and generate mechanical or electrical energy

State-of-the-art

- Working prototypes developed for bus, HD long haul, MD urban, and passenger car

Impact so far from collaborative research

- Development of heat exchangers and expanders for durability and production project and vehicle demonstration e.g. Ricardo Wrightbus

Impact of the successful implementation of the technology

- Organic Rankine cycle can reduce fuel consumption by up to 5% for passenger car and up to 10% for heavy duty vehicles

Future challenges and research needs

- Key challenges for the technology are packaging, transient performance and cost benefit
- Prototypes to be tested in real world conditions over a period of time
- Packaging
- Optimisation for lower exhaust temperatures in passenger cars compared to heavy duty
- Cost reduction

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.14 Thermoelectric Generators

Thermoelectric generators use the Seebeck effect to generate a voltage from a thermal gradient between two dissimilar semi-conductors, this energy is then used to reduce fuel consumption for example by powering electrical ancillaries

State-of-the-art

- Volvo/Renault Trucks have made steps towards using thermoelectrics on their HD trucks
- The technology was investigated in the US DoE Supertruck programme
- The technology is not currently in use for buses
- Prototypes tested in passenger car; BMW, VW, Mercedes-Benz, GM, JLR

Impact so far from collaborative research

- Development of EGR cooler and exhaust heat exchanger with thermoelectric materials by suppliers, technology is not currently production ready

Impact of the successful implementation of the technology

- Thermoelectric generators can reduce fuel consumption by up to 4%

Future challenges and research needs

- Key challenges are materials assembly, thermomechanical fatigue and reducing cost

- Current materials are expensive – Cost reduction needed
- Improvement of energy recovery efficiency
- Durability

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.15 Turbocompounding

Turbo-compounding recovers energy from the exhaust via a turbocharger. In mechanical turbocompounding, energy is fed back into the driveline via a high speed transmission. Electric turbocompounding combines a turbine with an electrical generator to recover energy.

State-of-the-art

- Mechanical turbocompounding has been commercialised in heavy duty engines - Daimler 2008, DD15
- Electrical turbocompounding systems are in development, for example CPT 2012 system, TIGERS turbogenerator, Integral Powertrain SuperGen

Impact so far from collaborative research

- Development of electrical turbine for production project and production for power generation engine application

Impact of the successful implementation of the technology

- Turbocompounding can reduce fuel consumption by up to 5%

Future challenges and research needs

- Future challenges for turbocompounding include the impact on exhaust backpressure, reducing transmission losses, especially at low load
- High speed electric motors
- New design of turbine blades with higher efficiency
- Combining functionalities on electric turbocompounding / torque assistance for best system efficiency versus cost

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.16 Powertrain and vehicle thermal management

Although the efficiency of modern internal combustion engines is increasing, the cooling requirements are rising due to higher demands on power output. There are also increased demands due to air conditioning and other vehicle based functionality. There is therefore potential to improve fuel consumption through optimisation of engine temperature control (lubricant and coolant) and through optimisation of whole vehicle thermal management.

Unlike naturally aspirated engines that eliminate heat to the environment through the exhaust gas, more rejected heat in modern ICEs will be transported into the underhood environment from heat exchangers, especially intercoolers and EGR coolers. With the underhood space already limited by passive safety and styling constraints, thermal interactions between hot parts will need to be taken into account and used more efficiently. Due to the increasing number of auxiliary systems, the cooling circuit is becoming more and more complex. This makes it very difficult to integrate and control the different components like the radiator shutter and thermostat while different coolant temperatures are necessary to operate in the specified temperature range (e.g. gear box, high voltage battery, charge air cooler). Therefore research is necessary on the one hand to reduce the complexity of the coolant circuits, while on the other hand to enable advanced cooling strategies via integration of prediction tools regarding driving pattern and routing to forecast engine operating conditions.

6.3.17 Powertrain thermal management

There are a range of technologies to improve powertrain thermal management in development, as shown in the table below. Maximum benefits for passenger car and HD for this technology group are estimated to be 5%-7%.

Function	Technology	LD benefit, NEDC	HD benefit
Coolant	Flexible pump control	1.5%	1 - 2%
	Split coolant jacket	~1%	<1%
	Electric thermostat	1.5%	1%
	Coolant heat storage flask	1-2%	1% (warm-up cycles)
	Exhaust heat recovery	0.5 - 1.5%	1%
Coolant and lubricant	Engine encapsulation	2%	1%
	Integrated exhaust manifold	0.5 - 1%	N/A
Lubricant	Variable flow lubrication	1 - 3%	1 - 2%
	Split oil sump	1 - 3%	N/A
	Oil heat storage	3%	N/A
	Heat to oil	2 - 3%	1 - 2%

<u>Impact so far from collaborative research</u>

- These technologies have been investigated in a range of research programmes including the US DoE Supertruck programme
- Many technologies are now on the market

Future challenges and research needs

- Cost reduction to enable greater penetration within mainstream market
- Integration and control of combinations of these technologies

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.18 Integrated vehicle thermal management

Improved thermal management within the vehicle can improve fuel efficiency in a number of ways, particularly at start-up and low load. Intelligent design and advanced technologies can harness thermal energy rejected from the engine to improve heat flow around the entire vehicle. The two main benefits of this are the ability to reduce the radiator size, which will reduce the frontal area and the Cd value, the other is the ability to warm up the lubricants quicker to decrease viscosity and therefore frictional losses.

A summary of potential benefits for passenger car and heavy duty vehicles is shown in the table below. A maximum total benefit for this type of technology is estimated at up to 3% for passenger car, up to 4% for heavy duty vehicles.

Technology	LD benefit, NEDC	HD benefit
Advanced heat exchangers	0.5%	0.5 - 1%
Multi temperature radiators	0.5 -1%	0.5 - 1%
Water charge air cooler	0.5 - 1%	0.5 - 1%
Nanofluids	N/A	0.5 - 1%
Improved fan drive systems	N/A	<2%
Integrated transmission and oil cooling	1 - 2%	1 - 2%
Engine encapsulation (vehicle mounted)	2%	1%

More information on each technology is shown in the following section.

6.3.19 Advanced Heat Exchangers

Heat exchangers are a key part of thermal management systems. Development of new and improved designs and materials involved in heat dissipation can have proportional effects on CO_2 reduction. By improving the heat transfer, the radiator has less load and so can be reduced in size, this in turn can lead to improved aerodynamics.

State-of-the-art

- Metal/Graphite Foams – Research studies

- Advanced fin and tube design
- Cuprobrazed Heat Exchanger
- PowerCold
- Compact Cooling System
- Heat exchangers are in mass production

Impact so far from collaborative research

- Advanced tech in development to improve efficiency above 90%
- Development by Tier 1, 2 and SMEs

Impact of the successful implementation of the technology

- 0.5-1% reduction in fuel consumption through reduction in drag from smaller radiator

Future challenges and research needs

- Cost/availability of materials
- Heat exchanger fouling in dusty environments will require extra maintenance
- Durability of system
- Reducing material and manufacturing costs

What is the effect of automation on the above?

- None

6.3.20 Multi-temperature Radiator

Use of radiator with different fluids (engine‘s coolant, engine‘s oil, transmission‘s oil) and different thermal levels (engine‘s coolant temperature and low temperature coolant for other components such as: fuel, electronics, EGR, precooler/WCAC). Instead of having different separate radiators for coolant and oil, a radiator with different fluids could help improving the packaging. In case of different coolant temperature level needs, a compromise could be found in terms of: air pressure drop, coolant temperature level with the aim of using only one radiator with 1 coolant inlet and multiple coolant exits. Reduction of heat exchanger size leads to a reduction in frontal area and air inlet surface areas which will lead to a reduction in Cd due to powertrain and HVAC cooling.

State-of-the-art

- On the market in passenger car (for EGR cooling at lower temperature than engine's coolant temperature)
- HD for precooler/CAC
- On the market in Hybrid EVs for power electronics cooling

Impact so far from collaborative research

- Research led by Behr, Modine and Valeo, 2004-8.
- Technology is on the market now

Impact of the successful implementation of the technology

- 0.5-1% reduction in fuel consumption

Future challenges and research needs

- Development to manage increasing system complexity due to hybridisation (5-7 separate cooling circuits with different radiators)

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.21 Water charge air cooler Intercooler

Use an air to water Charge Air Cooler (WCAC) instead of an air to air charge air cooler (CAC) with a low temperature cooling circuit (with a low temperature radiator and a mechanical or electrical water pump)

State-of-the-art

- Off-the-shelf component in passenger cars (VW, Mercedes, Audi, BMW, Ford, Opel) and HD markets

Impact so far from collaborative research

- Widespread on the market

Impact of the successful implementation of the technology

- 0.5-1% reduction in fuel economy due to cooler intake air temperature in gasoline reduces knock, better NOx/CO_2 trade-off for Diesel

Future challenges and research needs

- Improving efficiency through reduction of working temperature
- Possibility to cool down below ambient temperature using coupling between water CAC and air conditioning circuit

What is the effect of automation on the above?

- Improvements in control due to information on traffic and route information

6.3.22 Nanofluids (nanocoolant)

Using nano particles in the coolant to improve thermal conductivity whilst maintaining viscosity.

State-of-the-art

- Research activities in US DoE, Caterpillar and Cummins
- No production

Impact so far from collaborative research

- Some government funded programmes are underway: US DOE, UK (lubricants), France

Impact of the successful implementation of the technology

- 0.5-1% reduction in fuel consumption due to reduced radiator size improving aerodynamics

Future challenges and research needs

- Overcoming erosion risk
- Durability
- Cost Reduction

What is the effect of automation on the above?

- None

6.3.23 Improvement to fan drive systems

Basic fan design is a mature technology. Only very small incremental improvements can be gained by altering fan design. Most improvements come from fan installations such as vehicle mounted instead of engine mounted fans and intelligent control strategies that only use the minimum amount of fan power required.

State-of-the-art

- Off-the-shelf components (hydraulic fans are commonly used for off-highway vehicles; PWM fans are used on passenger cars; 3 speed fan clutches are used on HD trucks)

Impact so far from collaborative research

- Currently on the market
- Could qualify for CO_2 credits as an Eco-Innovation technology
- PWM controller integrated inside the motor to reduce electromagnetic radiation

Impact of the successful implementation of the technology

- Fuel consumption reduction of up to 2%

Future challenges and research needs

- Improving efficiency (air flow)
- Potential for 48V to enable cost reduction and efficiency improvement

What is the effect of automation on the above?

- None

6.3.24 Integrated transmission and engine oil cooling circuit

Integrating the engine cooling circuit with transmission oil temperature control system can reduce warm up time for the transmission oil using engine waste heat, thereby reducing frictional losses. The transmission oil temperature is controlled thanks to the use of an additional thermostat installed on the transmission oil cooler.

State-of-the-art

- Currently on the market for passenger car (BMW)
- Suitable for LCV, LD and HD with transmission oil cooler

Impact of the successful implementation of the technology

- Fuel consumption reduction of up to 1-2%

Future challenges and research needs

- Improved cooling circuit design

What is the effect of automation on the above?

- None

6.3.25 Engine Encapsulation

Engine encapsulation can be used to retain heat during times of low or no load. The intent is to warm the engine up faster to reduce frictional losses at start up whilst also giving potential to improve combustion efficiency, and reduce engine out HC and CO emissions.

State-of-the-art

- Past studies between 1990 and 2000 in OEMs
- Advanced engineering level – presentation of a concept by BMW at the end of 2009. BMW is using air shutters to have air flowrates inside the engine encapsulation

Impact so far from collaborative research

- On the market for BMW, Mercedes

Impact of the successful implementation of the technology

- 2% CO2 benefit on NEDC (LCV) and in real life driving conditions

Future challenges and research needs

- Packaging within engine bay
- Material – thermophysical properties improvement for better insulation
- Design improvements for better efficiency – improvement of surface coverage

What is the effect of automation on the above?

- None

6.4 Transmissions

Increasing the efficiency of a manual transmission involves minimising frictional losses. In a transmission system the frictional losses can be grouped into torque dependent losses and speed dependent losses.

Automotive transmission is a key element in the powertrain that connects the power source to the wheels of a vehicle. Transmission design affects vehicle fuel consumption in two ways: First, increasing the number of gear ratios and providing a larger ratio spread allows the internal combustion engine to operate more often in regions of high efficiency. Second, reducing parasitic losses within the transmission improves transmission efficiency and reduces vehicle fuel consumption.

6.4.1 State of the Art

To provide more fuel-efficient vehicles to customers, manufacturers have introduced a number of transmission improvements. The manual transmission is (MT) the most efficient transmission type, although automated transmissions (AT) with higher numbers of gears and increased ratio spread and new technologies such as the dual clutch transmission (DCT), continuously variable transmissions (CVT) and hybrid transmissions may be able to provide improved powertrain fuel economy in certain applications / drive cycles.

Manual transmission:

- Reduction of oil interaction losses by.
- Incorporation of oil catchers to reduce the dynamic oil level.
- Partitioned oil sump to reduce “active” dynamic oil level.
- Reduced viscosity lubricating fluid.
- Controlled electrical pumping of lubricating fluid to reduce dynamic oil level.
- Optimised gear ratios based on vehicle and drive cycle simulation.
- Optimised synchroniser clearances.
- Optimised design (in terms of mass).
- Analytical techniques e.g. optimised low mass shift forks.
- Magnesium casings.
- Optimised gear sizes through better understanding of duty cycle and materials data.
- E-Clutch (sailing / coasting).
- Abuse limiting measures (e.g. inhibit to rapid clutch release).

Automated manual transmission:

- Is broadly similar to manual transmissions, however in addition.
- Optimised actuation technology (power consumption, v. cost, v. mass, v. speed of operation).
- Optimised gear selection strategies.
- Torque filled architectures may provide a slight benefit to fuel consumption depending on implementation, but mainly they make this transmission type acceptable in the market.
- Increased gear numbers and ratio range may also offer powertrain fuel consumption improvement opportunity if not using an MT as the hardware base.

Dual Clutch Transmission:

- Generally both wet and dry DCT are broadly similar to AMT, apart from, by their very nature, DCTs are effectively torque filled AMTs, where the torque filling task is carried out by the opposing half of the gearbox. DCT state of the art compared to AMT has in addition.

- Clutch clamp energy use reduction mechanisms, LUK moving pivot, magnet assist etc.
- Control strategies associated with pre-selection etc. to minimise open transmission half losses.
- In addition, considerations specific to wet clutch DCT include,
- Low power loss actuation of clutches e.g. CSC operated, not "snout".
- Controlled oil cooling flow for clutches for lower open side losses.
- Optimised pump arrangements for lowest energy cost (e.g. mix of mechanical / electrical for different pressure flow requirements).

Automatic transmission:

- Many similarities exist as for MT, AMT and DCT (Wet Clutch), however in addition;
- Optimised AT architectures: providing the maximum number of gear ratios and gear ratio span, for a minimum number of shift elements and planetary gear groups. Current conventional trend is heading to 10+ ratios.
- Optimised Torque Converter designs and optimised TC lock up clutch strategies.
- Replacing / supplementing clutches and brakes with mechanical engagement dogs where possible (ZF 9 speed) to reduce open element drag losses.
- Optimising hydraulic circuit line pressure control strategies with torque requirements to reduce actuator system losses.

Continuously variable transmissions:

- Similar comments apply as for all previous transmission types, in addition specifically for CVT's.
- Optimised variator control and design (applying only the minimum required clamp force at any time).
- Incorporation of downstream geared ranges (2 or more), to provide both a reduced ratio span requirement and a reduced output side clamping pressure requirement for the variator, resulting in reduced actuation system energy requirements.

Transmission control:

- For a conventional transmission controller, the current state of the art is to use both known "maps" for the engine, along with any relevant live sensed parameters, and similarly known and live parameters for the transmission. The controller then uses this information to make a live calculated decision about which gear would be the optimum gear to be in at any given time to satisfy the driver request whilst minimising CO_2 output.

Transmissions for electric vehicles:

- High contact ratio gears for low NVH.
- Low loss actuation systems and range change mechanisms, when present.

- Oil thermal management considerations due to cooler electric drives.

CO_2 benefits from increased transmission efficiency are very difficult to quantify in a simplistic manner. This is because transmission modifications that simply improve the basic efficiency of the transmission itself, usually have only a small effect. However, transmission modifications can also enable significant improvements to the overall powertrain CO_2 output by regulating the ICE in a more sympathetic manner (often these two improvement types can be mutually opposing). Clearly any improvements derived through improved regulation of another powertrain component are highly dependent on the details of the precise nature of that other component in order to provide an accurately quantifiable result. Additionally, once hybridisation is applied to a powertrain, the improvement in CO_2 output that can be obtained is highly dependent on whether the other components in the powertrain are then also modified with the new configuration in mind or not, since sympathetic modification of ICE and transmission would create significantly more benefit than just applying hybridisation to a conventional powertrain with no modifications. The table below summarises the expected fuel consumption benefits of the state of the art of transmission technologies.

Technology	FC benefit
Manual Transmission, Automated Manual Transmission, Dual Clutch Transmission	~1%
Automated Transmission, Continuously Variable Transmissions	~2%

If conventional powertrain configurations are considered as a whole, with transmission modifications such as ratio quantity, ratio range and ratio control strategy considered in conjunction with transmission efficiency improvements, including their effects on the overall powertrain fuel consumption, then improvements of up to ~5% could potentially be achieved on overall vehicle fuel economy.

Finally, if we consider hybridisation of the drivetrain (vehicle driveline based), and assume suitable modifications to ICE and transmission are applied in conjunction with a suitable control strategy to enable recuperation, EV drive etc., total vehicle fuel economy benefits of at least 10% should be achievable.

Heavy trucks, specifically for long haul highway use, have quite a specific duty cycle. As a consequence of this largely “narrow” operating condition, transmission efficiency is a far more dominant factor in determining overall powertrain CO_2 output than for passenger cars where duty is much more transient and hence the way the transmission works in conjunction with the ICE is more dominant. Because transmission efficiency has such an influence on truck powertrain efficiency, MT and

AMT transmissions dominate this sector. Other transmission types, DCT, AT and CVT do exist for heavy trucks, but these tend to only be used for specialist applications such as for off-highway use, for specific highly transient / hilly drive cycle useage, or for delicate haulage operations where torque interrupt due to shifting would be less acceptable. Improvements in efficiency of both MT and AMT transmissions are very difficult to find as these are both highly efficient transmission types.

6.4.2 Research needs

Transmission research needs to focus on designs which combine top-of-the-range efficiency with a high degree of flexibility for the widest range of requirements and customer wishes. Key areas of research include:

Manual transmission:

- Frictional losses minimization.
- Transmission mass reduction.

Automated manual transmission:

- Similar to MT; in addition.
- Optimization of the actuation system.
- Improving gear selection strategies.

For heavy trucks, the main improvements that could be introduced are similar to those of passenger cars, however in addition to those items; the following additional areas of improvement exist for heavy truck:

- Retarder “off-condition” drag reduction and specifically for AMT.
- Reduction in lays haft brake drag losses.
- Reduction in pneumatic losses for the actuation system.
- Losses improvements in various power takeoff (PTO) systems (emergency steering pumps, hydraulic systems for different truck applications).

Dual clutch transmission:

- Similar to AMT; in addition.
- Flexible connections in the actuation system to prevent interferences caused by static and dynamic errors (dry DCT).
- Minimization of parasitic energy losses due to the energy-absorbing pump needed to deliver cooling oil to the clutch plates.

Automatic transmission:

- Improving losses through interaction with oil, minimizing losses of the actuation system and losses of the open shift elements.
- Optimisation of the gear and shift element arrangement.
- Optimisation of the conjunction with the torque converter launch device.

Continuously variable transmissions:

- Oil interaction and torque dependant losses as for MT, AMT, DCT and AT.
- Optimum adjustment of the variator device.

Transmission control:

- Optimum gear ratio at any given moment, based on the driver request.

Transmissions for electric vehicles:

- Multiple ratios to allow the primary drive to sit at a best BSFC point.
- Minimisation of energy consumption from the battery.

6.4.3 Manual transmission

Increasing the efficiency of a manual transmission involves minimising frictional losses. In a transmission system the frictional losses can be grouped into torque dependent losses and speed dependent losses. The major frictional losses in a manual transmission are speed dependent losses due to oil interaction (churning, windage and inertia transfer) with rotating components (gears, shafts, bearings and synchronisers). The next major contributor to frictional losses is the torque dependent losses of gears and bearings. Of increasing interest is transmission mass reduction and e-clutch (for coasting) which, although not necessarily directly associated with transmission efficiency, does improve powertrain fuel consumption. Increased number of transmission speeds is not an opportunity for manual transmissions as customer acceptance of increased “gear planes” is unlikely. Continued increase in ratio range (given a maximum of 6 speeds) is likely to reach a natural “plateau” due to 1st gear being set by gradeability / creep speed requirements and 6th gear being set by desire for downspeed, but limited by driveability at “normal” highway speeds. Ratio range could potentially increase if driveline located E-machine torque assistance is offered, as this could improve launch capability, top gear driveability and regulate lower creep speeds.

Collaborative research is resulting in oil suppliers offering transmission oils of reduced viscosity and / or low viscosity index. Another example of collaborative research is the ULTRAN - collaborative UK project to save 25% mass on drivetrain using lightweight transmission technologies.

Transmission efficiency improvements through reduction in oil viscosity and other assorted drag reductions, all tend to have a negative impact on transmission NVH performance (gear rattle). In conjunction with downspeeding of ICE along with increased ICE boosting etc. the ICE also is tending to make transmission NVH worse (increased torsional signature). Reduced mass and consequentially reduced rotating inertia transmissions may go some way to combating these worsened NVH issues, but it seems likely further development of technology such as dual mass flywheels would be required alongside these developments. Improvements to NVH combating devices such as DMFs (e.g. weight reduction) would also need to be investigated.

Effect of powertrain hybridization:

- Manual transmissions could potentially be hybridised, however this would require a minimum a clutch sensor, or more likely a clutch by wire implementation. In any case, it should be recognized that drive cycle results achieved with such a hybrid implementation may not be reflected in the real world as the driver will still be able to “override” the hybrid system and make un-informed gear selection choices / clutch operations

Effect of autonomous vehicles on the above:

- N/A for manual transmission. By virtue of a manual requiring some human interaction, a vehicle with a manual transmission cannot be autonomous.

Short term research needs:

- Continued research into oils and lubrication technology
- Continued development of methods using waste heat to rapidly warm transmissions
- Continued research in material and processes to achieve light-weight transmissions
- High performance, low cost steels
- Low mass, low cost materials and processes
- Research into viability of significant hybridisation of manual transmissions

Mid / Long term research needs:

- Future challenges for manual transmissions will involve making additional small improvements in a number of areas. The challenges, to achieve maximum benefit, will require an increased level of integration of traditionally separate subsystems (e.g. transmission, engine, exhaust etc.) and close co-operation and working between sub-system suppliers in order to provide an optimized installation
- Optimisation of synchronisers, bearing geometries, oil properties, sealing technologies, materials development
- Methods to heat up the oil to rapidly reduce its operating viscosity by utilising waste heat
- Cost effective technologies for mass reduction (e.g. skeletal “structural” casing with lightweight skin for oil containment)

6.4.4 Automated manual transmission

Increasing the efficiency of an AMT requires similar considerations as for an MT, but in addition, efficiency improvement opportunities exist for the optimisation of the actuation system in terms of its own energy consumption as well as opportunities for powertrain fuel consumption improvements via improved gear selection strategies. Additionally, if the AMT is not based on an existing manual transmission (as they usually are), then opportunities for increased ratios and ratio range also exist to enhance powertrain fuel consumption.

Collaborative research is resulting torque fill techniques, which although not particularly beneficial to fuel consumption in and of themselves, allow AMT technology to become “palatable” which therefore could increase the market appeal of this inherently efficient automated transmission type.

Successful implementation of the technology results in

- AMTs can be considered similar to MTs, but in addition
- Actuation systems are reducing in mass and power consumption (e.g. 48V)
- Torque fill methods can be introduced to make AMT more alluring
- Optimised ratios and ratio range along with increased number of ratios could lead to improved powertrain fuel consumption

Effect of powertrain hybridization:

- Hybridisation of AMT transmissions can change them from disliked, low cost, automated products to potentially one of the best transmission solutions available. This is because hybridization of AMT can, depending on the motor size and system architecture, provide a solution to address the “torque interrupt” disadvantages of AMT by providing torque infill from the electric motor during gear shifts to produce seamless shifting in a low cost, efficient transmission package. In addition, hybridisation:
- Can impact gear train and bearing duty due to regeneration requirements
- Requires consideration of lubrication and warming of the transmission if used extensively in EV mode
- Requires system optimisation and good hybrid control strategies to extract the most benefit from the introduction of hybridisation
- Requires the introduction of more powerful electric machines will also allow reduced numbers of speeds to be used, maybe down to only 4 required as the motor can now adjust the engine BSFC point at any given speed

Effect of autonomous vehicles on the above:

- AMTs are highly unlikely to be used in autonomous vehicles with conventional powertrains, as customer acceptance of torque interrupt is very low
- With torque fill capability of hybridized powertrain enabling seamless shifts, this arrangement could comfortably be used in autonomous vehicles.

Short term research needs:

- Are broadly similar as for MTs, however in addition
- Low cost torque fill methods would increase uptake of this transmission type
- Synchronisers with lower losses due to not requiring “shift feel” characteristics could be created

Mid / Long term research needs:

- Optimum hybridised architectures eliminating synchronisers and reducing ratios could result in an ultra-efficient transmission with very good powertrain fuel consumption
- Control strategies to complement hybridised AMT architectures
- Low power actuation systems to complement hybridised architectures and de-featured (e.g. synchroniser less) transmissions

6.4.5 Heavy truck transmission

Clearly, all sort of systems for heavy-duty applications referred previously bear scrutiny for improvements to their losses. However these items are highly application specific and hence are too detailed and numerous to be covered adequately here

Manual transmission:

Manual truck transmissions tend to have high numbers of speeds ~16. These tend to be made up of a main manual transmission shift section with a “splitter” in front which can be air operated and often used only if highly laden, along with a “range change” section at the rear, again which can be air operated. Using MTs on trucks is fairly labour intensive and as such, in Europe, AMTs have gained significant market share. This is additionally because MT drivers are able to “abuse” the transmission (accidentally or otherwise) and are also able to negatively influence fuel economy through poor shift choices. Both these problems can be controlled with use of AMT and hence fleet operating cost can actually be reduced despite higher initial capital cost.

Automated Manual transmission:

AMT transmissions tend to follow much the same format as described above for MT transmissions, but the shifting of all sections is undertaken automatically through air power. Often the number of ratios is slightly reduced ~12, this is because through improved (shortened) shift times, deceleration of the truck during shifting is reduced and hence less ratios are required. AMT truck transmissions tend to have had their synchronisers removed from the main gear train and replaced with a layshaft brake, this is to reduce losses from multiple synchronisers and just have losses from a single brake device

Effect of powertrain hybridization:

Hybridisation of heavy truck powertrains is quite challenging, depending on the functions that are expected to be achieved. Electrification of various powertrain ancillaries, or even systems such as trailer refrigeration should be feasible in conjunction with fairly small quantities of energy storage. This, in conjunction with an engine powered generator, could also be used for non-continuous BSFC modification and maybe even capable of torque filling activities to aid the AMT. However, significant levels of EV driving would require significant quantities of energy storage which without significant improvement in electrical energy storage density would seem an unlikely prospect.

Effect of autonomous vehicles on the above:

As with passenger cars, MTs will not be able to be used with autonomous vehicles, but AMTs would be quite suitable. If the AMT is not torque filled, the transmission type may still be considered acceptable for heavy truck, however, whereas currently due to driver interaction, torque interrupt is considered acceptable, if a driver where to become more of a “caretaker” and less involved in the driving process, then torque interrupt may become more of an issue that needs resolving for the product to be acceptable.

It would seem sensible to focus on AMT as the transmission type to focus future research on. Based on this, the following areas should be considered:

Short term research needs:

- Improvements to basic gear and bearing losses
- Improved oil management to minimize interaction losses
- Reduced losses in layshaft brake
- Reduced retarder losses
- Reduced pneumatic actuation system losses

Mid / Long term research needs:

- Potential low cost, efficient torque fill solutions (focused toward reducing engine transients for emission reasons rather than for driver comfort reasons)
- Improved powertrain matching and control
- Improved understanding and adjustment for intended duty cycles where possible
- Improved powertrain predictive control, using known route information e.g. hills etc. / interaction with forward objects e.g. traffic lights etc.

6.4.6 Dual Clutch Transmission (DCT)

DCT can be broken in to 2 categories, dry clutch DCT and wet clutch DCT. Increasing efficiency of dry clutch DCT's can be considered to be broadly similar to AMTs, apart from a DCT requires actuation of a clutch during driving, so this is an area where improvement could additionally be focused. For a wet DCT, increasing efficiency is broadly similar to that of a dry DCT, apart from there is additionally a need to supply cooling oil for the clutch plates, so this is a further area where improvement could be focused.

Considerations for AMT described above apply to DCT as well. In addition, work has been carried out on reducing clutch clamping energy consumption and improved geartrain arrangements such as "multi-path" where fewer components can be used to achieve more ratios. Challenges are the similar to AMT, but in addition:

- Closer control of wet clutch required in order to safely control / reduce coolant flow
- Use of anti-roll back mechanisms / brake sensing required to reduce loading / cooling requirements for wet clutches
- Improved system understanding required to select appropriate balance between pump types for optimum energy consumption

Effect of powertrain hybridization:

- Hybridisation would have a similar effect on DCTs as for AMTs, apart from the torque fill function that is added to AMTs is already present in DCTs
- In addition DCTs tend to be hybridized in a modular fashion (P2 location, preceeding the clutch) which can result in lower torque motors as a range of

transmission ratios can be used with powershifting between them, however it does necessitate the fitting of a K0 clutch between the engine and motor in order to undertake EV drive.

- Positioning a motor in a P3 location, could improve efficiency by eliminating a bank of synchros, but it would need to be sized sufficiently to cope with a selectable single speed ratio if torque interrupt drive in EV mode was considered unacceptable.
- The most major outcome of hybridization for DCT might be to make other transmission types more attractive and therefore decrease sales for DCT as a consequence.

Effect of autonomous vehicles on the above:

- DCT architectures in any form, offer seamless shift capability and as such could easily be used as part of an autonomous vehicle powertrain.

Short term research needs:

- Similar requirements for DCT as AMT, but in addition;
- Clutch latching mechanisms or other power saving clutch clamp measures
- Optimised clutch cooling strategies for wet clutches
- Active cooling techniques for dry clutches
- Improved clutch cooling fluid feed arrangements (non-contacting) for reduced losses

Mid / Long term research needs:

- Dedicated DCT synchronisers as not only is feel not required, but also slower speed can be accepted for pre-select activity

6.4.7 Automatic transmission (AT, epicyclic gear train)

AT architecture is quite different to MT, AMT and DCT architecture in that it is made from epicyclic geartrains linked together with various brakes and clutches to cause gear ratios through operation of different groups of brakes and clutches. As a consequence of this, the means to improving AT efficiency is generally different than for MT, AMT and DCT. Similarly to MT, AMT and DCT, improving losses through interaction with oil would be a benefit as would improving torque dependant losses through gears and bearings, however minimising losses of the open shift elements is a large influence in AT efficiency. Similarly to AMT and more so DCT, actuation system losses are a dominant factor in AT efficiency and means to improve clutch / brake clamp energy usage, or reduce actuation system losses would be of significant benefit, however this is more difficult to achieve in such a transient and complex system. Of far greater opportunity for AT is the optimisation of the gear and shift element arrangement allowing greater numbers of gear ratios and gear ratio spread to be achieved for similar amounts of geartrain and shift elements, resulting in overall improved powertrain fuel economy (without significantly increased transmission inefficiency). Additionally for AT transmissions, they are commonly used in conjunction with a torque converter launch device, this is another area which can be improved or eliminated in order to yield further efficiency benefit.

Similar considerations and challenges for MT and AMT and DCT apply also to AT. Additional outcomes include:

- Layout development to achieve greater numbers of gears.
- Shift strategy optimisation due to the more significant number of gear options.
- Optimization of actuation system power sources, making use of some “on-demand” capability is more challenging due to the more continuous nature of the AT actuation system.

Effect of powertrain hybridization:

- The effects of hybridisation on an AT will have similarities to MT, AMT and DCT.
- Hybridisation of ATs currently tends to be modular in construction with the addition of a P2 motor and K0 clutch replacing the TC. This does not really derive the full benefits hybridisation could bring, but is understandable due to simple modularity.
- Dedicated hybrid variants of AT products could replace one or more shift elements with electric machines to enable fewer parts to be used in a more efficient arrangement (e.g. AVL multi-mode hybrid).
- Equally, adding a P2 motor to a simpler, lower number of ratio AT (e.g. 5 or 6 speed) could also offer improved overall powertrain fuel consumption with reduced cost, weight and complexity.
- Depending on Electric machine location (e.g. P3) the torque density advantage offered by ATs may be weakened through a hybrid arrangement.

Effect of autonomous vehicles on the above:

- Similarly to DCT, ATs lend themselves well to use in autonomous vehicles due to their good shift quality.
- It would seem likely however that autonomous vehicle torque requirements would be lower than for conventional vehicles and as such ATs may not offer their torque density advantage that would have them selected over competing transmission types.

Short term research needs:

- Similar challenges as for MT, AMT and DCT, but in addition.
- Continued research in to optimized architectures.
- Research in to alternative means of launching with acceptable feel in order to delete the torque converter.

Mid /Long term research needs:

- Similar challenges as for MT, AMT and DCT, but in addition.
- Research in to very efficient electrically operated actuation systems, especially, if ATs are to be used as PHEV or EV variants.

6.4.8 Continuously variable transmissions (CVT)

For increased CVT efficiency the same general considerations regarding oil interaction and torque dependant losses apply as for MT, AMT, DCT and AT. The CVT resembles most closely the AT in that it normally incorporates a torque converter and a planetary gear set. However, the CVT also incorporates a variator device (such as a belt and pulleys) which has a large impact on transmission efficiency due to its clamping requirements and continuous hydraulic control. Due to the variator and actuation system, the CVT is relatively inefficient in and of itself, however due to its capability to always be able to place the engine at its best BSFC point, depending on its control strategy, it can lead to a relatively good overall powertrain fuel consumption figure, especially over more transient drive cycles. Similar considerations apply as for all previous transmission types.

Effect of powertrain hybridization:

- Hybridisation of CVT currently tends to add a P3 motor to an existing CVT.
- Use of a variator range change device in conjunction with a P3 E-Machine may lead to improvements due to simplifying range change sequence.
- As hybridisation moves towards more powerful motors, CVTs as a hybrid choice become less attractive as the electric machine can undertake much of the BSFC point adjustment the CVT currently undertakes.

Effect of autonomous vehicles on the above:

- CVTs seem an unlikely choice for highly electrified drivetrains, however for ICEs, their capability of maintaining steady engine RPM and being capable of no discernible shift feel means that they may be able to offer NVH benefits that might be highly prized in autonomous vehicles.

Short term research needs:

- Similar considerations apply for MT, AMT, DCT and AT, but in addition,
- Develop lower loss variator adjustment systems that make use of macro and micro adjustment of the variator or similar improvement,

Mid / Long term research needs:

- Similar considerations apply for MT, AMT, DCT and AT, but in addition.
- Improved control strategies for the variator system, potentially including fixed ratio periods, to blend improved transmission efficiency with slightly sub-optimal engine BSFC to arrive at the optimal powertrain fuel consumption.

6.4.9 Transmission control

In conventional powertrain control, the engine controller tends to ensure that for any given torque / speed request (provided by other controllers / the throttle pedal, depending on the situation), the engine operates in an optimal manner to achieve the request whilst taking care of any emission control / warm-up / physical limitation concerns. The transmission controller tends to take the driver torque request from the throttle pedal and based on its own calibration as regards driveability, knowledge of the engine BSFC map, NVH awareness etc. makes a decision on which gear should be applied (or a direct gear command from a manual selection device e.g. tiptronic could be applied). Due to this, the transmission controller has far more influence, in a conventional powertrain, over how much fuel is burnt to achieve a particular drivecycle, than the engine controller.

Controllers for transmission and engine generally tend to be separate. One reason for this is the rather different speed requirements of each control system. The engine has to control multiple components (e.g. injectors) at a very fast rate whereas the transmission control requirements are comparatively slow. Another significant reason for maintaining separate controllers is so that manufacturers of only an engine, or of only a transmission, can sell their product with its own individual controller. This also allows different transmissions and engines to be mated to each other more easily.

It is necessary for the transmission control software to be able to make the right choices about which gear should be selected at any one time. The level of CO_2 saving that could be provided by hardware improvements through increased numbers of ratios and increased ratio span can only be demonstrated through applying suitable control software to make appropriate use of this improved hardware.

Effect of powertrain hybridization:

- Hybridisation brings a whole new level of complexity to the control of the powertrain as this now brings multiple torque sources, multiple energy stores and means of being able to access each energy type at discrete times, or in conjunction, but at varying rates.
- It seems likely that individual controllers will exist for each major element of the powertrain, e.g. battery controller, motor controller, engine controller and transmission controller. However it is necessary for a master controller to take charge of the overall system and to arbitrate between the various different systems in making the right overall energy use decisions to achieve the lowest overall energy consumption for any given drive situation. This master controller can either be a further separate controller which interacts with all the other powertrain controllers, or it can be built in to one of the other controllers such as the transmission or engine controller.
- Regardless of exactly where the master controller is physically situated, the same research needs exist for this set of controllers as for improvement of conventional powertrain controllers. More and better real time information about each sub-system and improved communication with and decision making by the master controller.

Effect of autonomous vehicles on the above:

- Autonomous vehicles and the infrastructure that is likely to exist around them, offer even greater opportunity for reduced energy consumption for any given powertrain to complete any given route.
- It seems likely that the hybrid powertrain ecosystem as described above would become interactive with the vehicle controller system and any external data

sources / interactive controllers that would be both compatible and useful in making improved energy use decisions. Much of what is described below could be applied to both conventional powertrain and hybrid powertrain, but until the human is removed or demoted from the decision making process of driving (i.e. making the overriding torque request or brake request at any time) then the full benefits of interacting with these extra systems can not be realized.

- Enhancing the master controller to additionally take account of the information as listed below, would in conjunction with the previously described improvements in controller interaction and optimal decision making, allow improved energy usage for the autonomous vehicle resulting in minimal energy usage for undertaking the desired journey. Information that could be useful in this process includes.
- State of traffic lights and other traffic interaction street furniture.
- State of traffic on route.
- State of surrounding vehicles.
- Known weight of vehicle and gradient of the route being travelled.
- Known route being travelled, along with any information on opportunities for electrical recharging on route or at destination.

Short / Mid / Long term research needs:

- In order to maximize the level of CO_2 savings achievable with any given conventional powertrain, it is necessary to select the optimum gear ratio at any given moment, based on the driver request. Changing to a situation where the engine controller provides more detail about its operating state, e.g. live transient BSFC maps, to the transmission controller in a real time manner, the more able the transmission controller would be to be able to select the optimal gear. Improved processing capability on board both the engine controller and the transmission controller and improved levels of communication between them in conjunction with improved control software, would result in reduced CO_2 output for the same given powertrain.

6.4.10 Transmissions for electric vehicles

Transmissions for electric vehicles have far less need to have multiple ratios to allow the primary drive to sit at a best BSFC point as E-machine efficiency maps have large islands of peak efficiency and efficiency drops away much less dramatically than with ICEs away from the peak point. Additionally, in order to minimise energy consumption from the battery, the transmissions must be in themselves as efficient as possible. These different demands than for conventional ICE transmissions has led to current EV transmissions tending to be simple single speed or 2 speed devices to obtain best overall powertrain energy consumption.

Effect of autonomous vehicles on the above:

- If autonomous vehicles will be primarily electrically powered, then these type of transmissions will increase in volume sold significantly, in line with increasing autonomous vehicle sales. Anything other than single speed would only be accepted if the shift can be made to be imperceptible. Single speed may also suffice in autonomous vehicles as it is assumed that acceleration rates would be reduced and top speeds required would be reduced, hence torque needs and adjustment of speed range for efficiency reasons would not be as necessary.

Short term research needs:

- Improvements in the cost of electric vehicle powertrains by utilizing more than one speed to reduce the motor torque requirements and improving its higher speed efficiency
- Integrated motor/transmission systems to provide increased system power density
- Lubrication technology to reduce losses due to oil churning and lubricant thermal considerations due to potentially very slow transmission warm up.
- Lightweight design solutions, although this is less advantageous than with conventional powertrains as energy used to accelerate inertias are recovered (minus efficiency loss) rather than lost as heat in the braking system.

Mid / Long term research needs:

- Seamless means to be able to shift ratios, but with minimal efficiency impact
- Development of novel transmission layouts focussed on seamless ratio change, low cost and high efficiency