



Passenger Vehicle Greenhouse Gas Emissions Reduction Technology Review



MARCH 2021

ACKNOWLEDGEMENT

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ABOUT

Change Energy Services

Change Energy Services engages in policy development that supports clean energy innovation. Working with government and industry, we identify commercially viable opportunities to deploy alternative fuels, and innovative business models that encourage market uptake. This creates a demand for clean fuel technologies, as well as fuel distribution infrastructure – for which we serve as designer and systems integrator. The practical knowledge acquired on the frontlines of alternative fuel use then informs new policy development, furthering the cycle of sustainability and progressive decarbonization of society.



Pollution Probe

Pollution Probe is a Canadian charitable environmental organization that is a leading agent of change at the intersection of communities, health and environment. Since 1969, we have been defining environmental problems through research, promoting understanding through education and pressing for practical solutions through advocacy. Pollution Probe has a proven track record of working in successful partnership with industry and government to develop practical solutions for shared environmental challenges.



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EXECUTIVE SUMMARY

Change Energy Services and Pollution Probe undertook an extensive review of available literature recently published on advanced vehicle technologies that could serve to reduce future greenhouse gas emissions from light-duty vehicle use in Canada. Auto industry experts and stakeholders were also consulted through a series of interviews to gather their informed perspectives on what technologies appear most promising to market uptake in North America. The research was driven by two questions:

- What is the potential of emerging advanced vehicle technologies (AVTs) to reduce GHG emissions, considering Canadian operating conditions and market preferences?
- What are the estimated costs and payback times of AVTs for consumers?

Of the literature sources scanned, more than 60 publications from around the world were included in a detailed review, representing academic papers, industry journals, government assessments and civil society reports published within 2014-2020. Complementing this research were exploratory interviews with 13 world-class experts and industry stakeholders, representing academia, automotive sector manufacturers, design and engineering firms, regulatory agencies, testing laboratories and non-government organizations. The scope of the AVTs studied included:

- Advanced combustion and emissions control strategies;
- Advanced powertrains; and
- Alternative fuels (where contributing to improved thermal efficiency in automotive engines).

Not in scope were plug-in and fuel cell electric platform technologies, as well as light-weight vehicle and component designs.

Key findings, as per interview insights and literature review, include:

- For North American markets, which represent a unique mix of consumer demand and regulatory frameworks, most experts favour stoichiometric gasoline engines over lean-burning engines, due to superior compliance performance with clean air standards. Most of the thermal efficiency improvements delivered by lean-burn can be achieved under stoichiometric operation through air-fuel charge dilution measures, such as cooled-Exhaust Gas Recirculation.
- Compression ratios in excess of 15:1 deliver diminishing fuel efficiency improvements, which may practically limit the market uptake of Homogenous Charge Compression Ignition.
- With current best-in-class engine thermal efficiencies at roughly 40%, it is estimated that an additional 5% efficiency can be achieved through the application of commercially available technologies, such as advanced turbocharging and hybridization. Efficiency beyond 45% is attainable in theoretical simulation, but the practical engineering solutions do not yet exist.
- Hybrid-electric powertrains are by far the most potent opportunity among combustion engine platforms. Aggressive hybridization can deliver fuel consumption reductions of 20% at the low end and upwards of 30% for the most sophisticated (and expensive) systems.

As aggressive hybridization increasingly isolates the engine from transient loads, it is freer to operate in its most efficient range. This may undermine the prospects for some technologies designed to support engine downsizing across a range of operating conditions, such as cylinder deactivation, variable compression ratio and, to some extent, turbocharged/downsized engines. Indeed, the most fuel efficient hybrid models currently available have engine displacements of approximately two litres.

PURPOSE OF THIS REPORT AND CONTEXT

This report presents findings of an investigation undertaken by Change Energy Services and Pollution Probe to update knowledge and awareness about the applicability of emerging, advanced vehicle technologies (AVTs) to the reduction of greenhouse gas (GHG) emissions from light-duty vehicles – a classification comprising passenger automobiles and light trucks, as defined under federal regulation in Canada and the U.S. Transportation is the second-largest contributor of GHG emissions in Canada, and light-duty vehicles represent approximately half of total emissions from the sector.

Canada's Passenger Vehicle and Light Truck Greenhouse Gas Emissions Regulations are a key driver of technology development among automotive original equipment manufacturers (OEMs). The regulations establish a framework for emissions standards of progressively increasing stringency over time. The setting of these standards is informed by technical and economic assessments of new technologies or established technologies applied in new ways. Part of this assessment includes estimating the return-on-investment of identified technology applications, in which the incremental costs are compared to the value of the resulting reductions in emissions and fuel expense.

To inform the development of policies, strategies and future regulatory efforts in Canada that optimally promote the uptake of AVTs by automotive OEMs and consumers, thereby advancing GHG emissions reductions to an extent that is technologically feasible and economically practicable, the objectives of this review are to seek insight into the following questions:

- What is the potential of emerging AVTs (excluding fully electric powertrains) to reduce GHG emissions, considering Canadian operating conditions and market preferences?
- What are the estimated costs and payback times of AVTs for consumers?

Naturally, the potential costs and benefits of many emerging AVTs – recent in their development, by definition – have not been thoroughly benchmarked in official, public-domain studies and reports, such as the U.S. EPA's Draft Technical Assessment documents, or have only been notionally assessed to-date. The development of such AVTs can often be proprietary, advanced by only a small subset of automotive OEMs. A challenge, therefore, is not merely to identify emerging AVTs, but to extrapolate from the available research an assessment of how well they may align with diverse operating conditions and environments across Canada.

The scope of AVTs researched for this report includes:

- Advanced combustion and emissions control strategies – relating to improvements in engine thermal efficiency, often resulting from changes in compression ratio and reductions in pumping losses, and changes in combustion properties, involving more complete oxidation, lean fuel-air mixtures and changes to adiabatic flame temperature;
- Advanced powertrains – relating to improvements in the efficiency of power distribution throughout the vehicle system (i.e., propulsion and ancillaries), often achieved through advanced transmission design, high-voltage electric architecture, and mechanical and thermal energy recuperation; and
- Alternative fuels – relating to thermal efficiency and emissions performance benefits enabled through the use of fuel alternatives (to conventional reformulated gasoline and low-sulfur diesel), often due to higher compressibility and anti-knock characteristics.

Advanced materials and light-weight vehicle and component designs were out of scope but are referenced where thematically aligned with the categories described above and enabling of the improvements therein. As the focus is technologies applicable to combustion engine vehicle platforms, purely fuel cell or plug-in electric vehicle platform technologies are not in-scope.

Research and information-gathering methodology

The study team conducted a scan of literature available and accessible to the public, on AVT developments and estimated impacts. Literature sources included internet publications, technical journals, research papers, environmental studies and regulatory impact assessments from credible and authoritative sources, such as the Society of Automotive Engineers and academia. Only publications from 2014 onward were considered, with a bias toward more recent sources. From this literature scan, a shortlist of roughly 60 sources were identified for thorough review.

The literature scan also informed the development of a list of technical experts and automotive sector stakeholders from around the world to be interviewed directly by the study team. The interviews were intended to complement and enrich the information gathered through the literature review, and to help validate findings. This also provided an opportunity to appreciate the opinions and instincts of the expert interviewees regarding future applicability of identified AVTs.

An interview guide was developed and distributed to the prospective experts and stakeholders as an invitation to discussion. This guide was not a questionnaire; rather, it was a tool for narrowing the focus of discussion with interviewees to the relevant categories of technology. Drawing on first principles of heat engine and vehicle engineering, the study team proposed four such categories of technological improvement and design change within the interview guide; namely, innovations that:

- serve to reduce heat losses within an engine;
- facilitate an increase in compression ratio (to extract more work);
- serve to reduce ancillary loads (and associated losses) on an engine, including idling; and
- serve to reduce drivetrain losses (i.e., increase transmission efficiency).

In total, 13 individuals accepted invitations to be interviewed, broadly representing:

- original equipment and technology manufacturers,
- regulatory agencies with activities focused on AVTs, and
- independent experts or analysts from industry, academia and civil society organizations.

The information and insights gathered through the literature review and interview process were synthesized into this document, and presented within the following structure:

- Premises – An introductory overview of the fundamental factors influencing the efficiency of energy conversion and use within a vehicle and establishing a workable scope for the study.
- Baseline – A selection of the technologies in common use in new light-duty vehicles; technologies beyond this “fuzzy” baseline are considered “emerging” and thus in-scope.
- Opportunities – Describing the main technologies identified in the research (i.e., literature review and interviews) that are incremental to the baseline; what they are, how they work, what impact they could have.
- Discussion – Reflections on the findings and trends emerging from the research.
- Table summary – The literature review findings, tabulated.

INTRODUCTION: PREMISES

“Premises matter, only premises matter, now what was your question?”

Dr. David Greene, Senior Fellow, Howard H. Baker, Jr. Centre for Public Policy, presenting at the Pollution Probe Pathways Initiative Workshop in Toronto, March 2016, attributing the quote to the late Barry D. McNutt, Senior Policy Analyst, U.S. Department of Energy

At the most fundamental level, energy is required to move objects with mass. Most passenger automobiles and light trucks are propelled by energy in the form of heat produced by the combustion of hydrocarbon fuels, usually gasoline. This heat is harnessed mechanically, using piston-crank reciprocating engines – a broad category of heat engine design that is nearly ubiquitous in on-road vehicles, worldwide – to generate motive power. The majority of this power is channeled to the wheels of the vehicle for propulsion, and the remainder is used in the operation of various ancillary systems.

The products of fuel combustion in a vehicle engine are emitted through its exhaust system to the atmosphere. These emissions include (i) greenhouse gases (GHGs) that contribute to global warming and (ii) criteria air contaminants (CACs) that contribute to various types of air pollution, including photochemical smog. These categories of emissions are known to directly threaten human health and welfare through their effects, respectively, on (i) catastrophic climate change and (ii) respiratory illness-related public rates of morbidity and mortality (plus some minor contribution to acid rain). Consequently, emissions in vehicle exhaust are regulated under the law of many national and regional jurisdictions, including in Canada and the U.S., with automotive wholesalers as one of the principal, obligated parties.

Automakers are thus motivated to reduce the amount of fuel combustion required for vehicle operation. All else held equal, the less fuel burned, the fewer emissions produced. Furthermore, for that fuel consumption that is minimally required, the combustion emissions should be kept as benign as possible. Through the application of chemical engineering, some hazardous emissions, such as carbon monoxide, oxides of nitrogen and volatile organic compounds, can be converted into less hazardous forms, such as water, carbon dioxide and nitrogen, before release into the surrounding environment.

Minimizing fuel consumption (and, hence, emissions) implies maximizing the efficiency with which heat energy is converted into mechanical energy, and then distributing that energy throughout a vehicle’s system of components to meet the demand for propulsion and ancillary power. The amount of heat that can be converted to mechanical energy is subject to practical and theoretical limitations. Referred to as thermal efficiency, this can be represented as the ratio of useful work output to heat input, as follows.

$$\text{thermal efficiency} = \frac{W_{\text{out}}}{Q_{\text{in}}}$$

All heat input must be converted into some combination of work output and waste heat, as follows.

$$Q_{\text{in}} = W_{\text{out}} + Q_{\text{out}}$$

So, the thermal efficiency of an engine can also be represented as follows.

$$\text{thermal efficiency} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$$

From this equation, it becomes clear that minimizing heat losses is key to maximizing thermal efficiency and, hence, the amount of heat input that is converted into useful work output. A derivation of the above

equation represents the thermal efficiency of typical piston-crank internal combustion engines as a function of compression ratio (r) – a measure of the change in volume swept by the movement of the piston from the bottom of its stroke to the top – as follows.

$$\text{thermal efficiency} = 1 - \frac{1}{r^{Y-1}} ; \text{ where } Y \text{ is a ratio of heat coefficients}$$

This equation shows that the higher the compression ratio, the higher the thermal efficiency and, thus, the more useful work output for heat input. To be accurate, the above equation is specific to traditional gasoline-fueled, spark-ignited engines (i.e., Otto cycle engines), while a somewhat different equation represents diesel-fueled, compression-ignited engines (i.e., Diesel cycle engines). Notwithstanding the differences in their efficiency formulae, higher compression ratios are generally more fuel efficient. Under idealized scenarios, in which any practical losses in energy are disregarded, the above equations provide some theoretical boundaries to engine efficiency. Consider the thermal efficiency of an ideal heat engine using the ratio of Q_{out} to Q_{in} , and take as given that temperature is a consistent measure of heat in this example. The thermal efficiency thus becomes a function of the difference in temperatures outside the engine, T_C , to that inside the engine, T_H , as follows.

$$\text{thermal efficiency} = 1 - \frac{T_C}{T_H}$$

Assuming an ambient temperature outside the engine of 21°C or 294K, and a temperature inside the engine based on the combustion of gasoline – say, 800°C or 1,073K – the maximum thermal efficiency would be approximately 73%. Now consider an idealized gasoline-fueled, piston-crank engine operating on the Otto cycle with a compression ratio, r , of 8. Assuming gasoline has a Y value of 1.4, the thermal efficiency would be approximately 56%. Increasing r to 11 improves efficiency to 61%. This shows that even in an idealized engine, there are thermodynamic limitations to the amount of mechanical energy that can be harnessed from the heat energy liberated in the combustion of the fuel.

In reality, the measured thermal efficiency of engines in practical operation is much lower than the idealized models described above. Imperfections in combustion and fluid movements, friction forces and mechanical design limitations all contribute to energy losses that degrade thermal efficiency from its theoretical maximums. Typical gasoline engines often operate at only 25% to 30%, although some advanced, F1 motorsports powerplants approach 50% thermal efficiency or more.

The preceding theory is presented to establish premises for the technology review presented herein. Namely, that new technologies and design enhancements capable of increasing thermal efficiency towards the theoretical limits of engine design are in-scope, subject to potential for commercial deployment and, ultimately, widespread use in passenger cars and light trucks. Generally, this implies two groups of design change – those that:

- serve to reduce heat losses within an engine, and
- facilitate an increase in compression ratio (to extract more work).

The work output of the piston-crank engine is represented in the rotational energy of the crankshaft, to which the wheels and all auxiliary systems are connected mechanically, electrically or electromechanically. As within the engine, these systems are not perfectly efficient at converting and transmitting energy. Losses accumulate from friction forces, pumping losses and from imperfections in mechanical linkages and gearing. While each model is different, general abstractions of how energy and power are distributed throughout a vehicle system, including losses, can be visualized, as per Figure 1 below.

Why practical thermal efficiencies claims can appear to exceed theoretical limits

Theoretical heat engine efficiency formulae, as referenced in the text above, are usually introduced in thermodynamic course curriculum as closed cycles, in which a working fluid transfers heat energy from a hot reservoir to a cold reservoir. This serves to demonstrate the 2nd Law of Thermodynamics (i.e., total system entropy is constant), and it presumes that the cycle is reversible. But in reality, internal combustion engines operate under open cycle conditions, in which the working fluid enters the system fresh, as air, and is then exits the system as exhaust. Were it not for the need to transfer heat from the engine to prevent component failure, a situation can be envisioned where the thermal efficiency of the engine could theoretically reach 100%. Yet even here, practical limitations apply.

In respect of these limitations, the Transportation Combustion Engine Efficiency Colloquium, in 2010, concluded that "The maximum BTE [brake thermal efficiency] expected for slider-crank engines is about 60%, assuming that cost is not a constraint," and that "Achieving BTEs > 60% will require radical changes to present engines, including cycle compounding, new engine architectures, and more constrained combustion reactions."

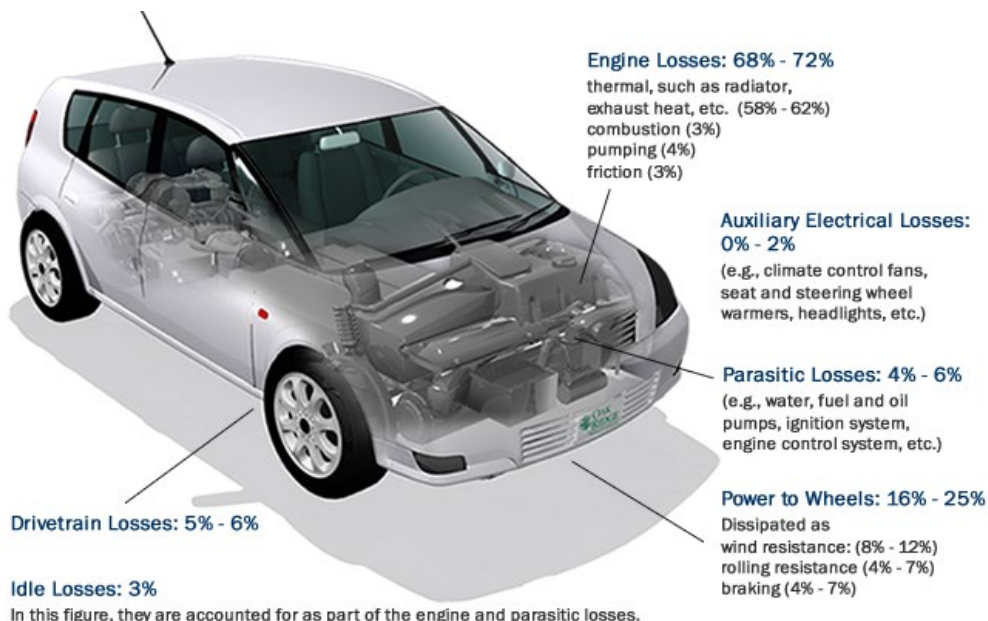
Claims of practical engine efficiency levels that appear to approximate the theoretical levels traditionally taught should, therefore, not necessarily be dismissed without scrutiny. Technically speaking, there remains substantial room for improving the thermal efficiency of internal combustion engines, and thus the overall fuel efficiency of vehicles (especially those with larger-cylinder engines).

Readers of this report are encouraged to consult the following resources:

U.S. Department of Energy, Office of Scientific and Technical Information. *Summary Report on the Transportation Combustion Engine Efficiency Colloquium Held at USCAR, March 3 and 4, 2010*. <https://www.osti.gov/biblio/993029-summary-report-transportation-combustion-engine-efficiency-colloquium-held-uscar-march>

Edwards, Wagner, Briggs, Theiss. Presentation: *Defining engine efficiency limits*. October 2011. Oak Ridge National Laboratory. https://www.energy.gov/sites/prod/files/2014/03/f8/deer11_edwards.pdf

Figure 1: Energy requirements for combined city/highway driving



Source: [US-EPA](#)

Beginning with the engine and ending at the wheel-road interface, the energy losses due to component operating efficiencies, as well as the demands for power to be met by the vehicle, can be approximately represented as follows (100 represents the total fuel energy input, which is distributed through the identified subsystems).

Table 1: Vehicle subsystem groupings and associated energy losses

Fuel energy input potential		100
Engine	heat loss through exhaust, coolant and radiator system, and radiated directly from engine	60
	losses due to imperfect combustion	3
	friction from moving surface interactions and airflow/fluid-flow restrictions (i.e., pumping losses)	7
	<i>total engine losses</i>	70
Ancillary	pumping for coolant, oil, fuel (also called <i>parasitic loads</i> , because these are powered by the engine crankshaft, which diverts power otherwise delivered to the drivetrain and draw power even when vehicle is still (i.e., idling losses))	5
Electrical	energy to power generator/alternator, which supplies electrical loads, such as lighting, cabin comfort systems, and battery charging	1
Drivetrain	losses to friction and imperfect mechanics in transmission, as well as other gears, connections from transmission output to wheels	5
Load at wheel-road interface	energy dissipated through air friction	9
	energy dissipated through wheel-road friction	5
	energy dissipated through braking	5
	<i>total external loads to be met by power to wheels</i>	19

The estimates for energy distribution above help to expand the premises for this technology review, to include changes that:

- serve to **reduce ancillary loads** (and associated losses) on an engine, including idling, and
- serve to **reduce drivetrain losses** (i.e., increase transmission efficiency).

A Fuzzy Baseline

The deployment of automotive technologies in new passenger cars and light trucks in Canada is comparable to that of the U.S. market, with some minor distinctions mainly resulting from vehicle safety regulations, such as daytime running lights, and consumer preferences, such as minivans with higher horsepower. By reviewing market data from both the U.S. and Canada, baseline vehicle conditions can be generalized. Although imprecise and very “fuzzy” in their representation of the state of technology use, a baseline vehicle provides a reference against which to assess the potential of various, emerging technologies to contribute meaningful reductions in fuel consumption and greenhouse gas emissions from future generations of vehicles sold and operated in Canada.

The degree of market penetration of broad categories of technology is reported in The 2019 EPA Automotive Trends Report,¹ as follows:

Model Year 2019, average use of emerging technologies across all automakers							
Turbo	Gasoline Direct Injection	Continuously Variable Transmission	7+ speed transmission (discrete gearing)	Cylinder Deactivation	Stop-Start (anti-idling)	Hybrid	Plug-in / Fuel Cell EV
34%	54%	24%	48%	13%	36%	6%	3%

The same datasets reported by the EPA are used in the Transportation Energy Data Book, a new edition of which is released by Oak Ridge National Laboratory annually,² but presented with a slightly different categorization:

Car technology penetration, cumulative to Model Year 2019							
Turbo	Gasoline Direct Injection	Continuously Variable Transmission (non-hybrid)	Continuously Variable Transmission (hybrid)	Cylinder Deactivation	Stop-Start (non-hybrid)	Stop-Start (hybrid)	Plug-in / Fuel Cell EV
39%	55%	30%	3%	3%	29%	4%	3%

This compares reasonably well to estimates of efficiency-enhancing technology adoption within Canada's vehicle fleet, as published by The International Council on Clean Transportation,³ providing a Canadian fleet overview based on a 2016 baseline year:

2016 Canadian fleetwide technology penetration – The ICCT							
Turbo	Gasoline Direct Injection	Continuously Variable Transmission (non-hybrid)	Continuously Variable Transmission (hybrid)	Cylinder Deactivation	Stop-Start (non-hybrid)	Stop-Start (hybrid)	Plug-in / Fuel Cell EV
25%	52%	2%	38%	11%	16%	0%	2%

Moreover, *The 2019 EPA Automotive Trends Report* shows that within the Port Fuel Injection (PFI) and Gasoline Direct Injection (GDI) categories of engines, which split the passenger car and light truck markets nearly evenly, multi-valve (i.e., >2 valves per cylinder) engines with Variable Valve Timing (VVT) are represented in the overwhelming majority of new vehicles sold. There is also an established trend from 6-cylinder to 4-cylinder engines. It is also notable that in the U.S. – and likely in Canada – interest in diesel engines has declined between 2014 and 2019, from a very small margin to an even less significant level.

In a recent analysis by the ICCT, the fleet-average greenhouse gas emissions rating for Model Year 2019 passenger cars was approximately 176 gCO₂/km, with light trucks at 254 gCO₂/km. Trucks outsell cars in Canada, leading the overall light-duty vehicle average to be **231 gCO₂/km**, according to The ICCT. This converts to roughly **10 L/100km**, reflecting an increasing trend among Canadian consumers towards larger vehicles, often choosing models classified as light trucks over passenger cars.

1 U.S. Environmental Protection Agency. *The 2019 EPA Automotive Trends Report*. 2020. <https://www.epa.gov/automotive-trends>

2 Davis, Boudny. *Transportation Energy Databook: Edition 38.2*. 2020. <https://tedb.ornl.gov/>

3 Posada, Isenstadt, Sharpe, German. *Assessing Canada's 2025 passenger vehicle greenhouse gas standards: Characteristics of the Canadian fleet*. 2018. The ICCT. <https://theicct.org/publications/canada-2025-cafe-standards-fleet>

Based on the information presented above, the following fuzzy baseline conditions can be ascertained:

Engine characteristics

- GDI, variable timed, multi-valve, gasoline engine OR PFI, variable timed, multi-valve, gasoline engine
- Some turbocharging to facilitate engine-downsizing
- Few occurrences of cylinder deactivation technology

Transmission characteristics

- 7+ speed automatic transmission, with early torque converter lock-up
- Continuously variable transmission (on non-hybrid powertrains)
- Start-stop functionality increasing from marginal levels
- Very low levels of adoption of hybrid powertrains

Scoping the opportunities for improvement

Relative to the baseline vehicle conditions, there are many automotive technologies and design enhancements that can improve the efficiency of energy conversion and distribution. A scan of available literature, including industry journals, academic studies, research papers and government regulatory reports, has yielded the categories of technology and design change explored in the pages that follow. These sources have also been summarized in the Annex tables that can be found at the end of the report.

The automotive innovations were further investigated through a series of interviews with leading experts in the field, as well as auto industry stakeholders. Their insights are also included in this report.

The study team was mindful to focus on developments in technology, adoptions of technology and new cost and benefits analyses that have emerged since the U.S. EPA's *Draft Technical Assessment Report* of 2016.⁴ AVTs identified and characterized in this report that were not part of the 2016 assessment include pre-chamber ignition, opposed piston engine design, 48-volt architecture, electrically actuated accessories and waste heat recovery systems.

4 U.S. Environmental Protection Agency. Draft Technical Assessment Report (TAR): Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025. 2016. <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF>

REDUCING HEAT LOSSES WITHIN AN ENGINE

Turbocharging (enabling engine downsizing)

Turbocharging can reduce heat loss by converting some of the heat energy in the combustion gases in the exhaust into useful work, via a turbine. The spinning turbine drives an impeller in the fresh air-intake manifold. This action pre-compresses the air before entering the combustion chamber. More air allows more air-fuel charge to mix in the combustion chamber, relative to the engine displacement volume. Thus, turbocharging a smaller engine (i.e., a “boosted” engine) allows it to generate the power of a larger, non-turbocharged engine (i.e., a naturally aspirated engine), generally speaking.

To an extent, smaller engines operating under higher loads tend to have lower pumping losses. The higher the boost pressure from the impeller relative to the back pressure on the turbine, the less work the piston must perform on the intake stroke to draw in the air-fuel charge. Also, the wider-open throttle conditions also reduce heat loss through the cylinder walls. The smaller engine size enabled by turbocharging also reduces friction within the engine’s moving parts. These factors contribute to a better thermal efficiency. However, there are limits past which downsizing introduces countering effects. For example, as the engine size is decreased, the surface-to-volume ratio of the cylinders increases, which increases heat loss to the cylinder block and coolant. Cost is also a barrier to downsizing, as it becomes increasingly expensive to manufacture smaller engines with sophisticated boosting systems.

Intercoolers are common on turbocharged engines. The compression work by impellers can significantly heat up the intake air (e.g., from 25oC to 160-170oC), which contributes to the likelihood of engine knock (i.e., premature ignition of the air-fuel charge due to over-heating). To mitigate this temperature rise, intercoolers draw heat out of the charge and expel it to the surrounding atmosphere. This introduces a new heat loss, unfortunately, and finding a way to recover and use this energy within the vehicle system is the focus of further technology development. Diluting the air-fuel charge with exhaust gases is one option, as is water injection (both discussed below).

Literature review findings: Engine downsizing enabled by turbocharging is widely identified as a trend that will continue and expand, especially when applied to light trucks due to a larger engine baseline. Estimated reductions in fuel consumption range from negligible to 8% (NRC, 2015). The market potential for downsized and turbocharged vehicles is quite large. EPA/NHTSA predict that up to 64% of new LDVs in North America will have some level of turbocharging and downsizing by MY 2021 (US EPA, 2020).

Insights from interviews: Turbocharging is expected to expand; indeed, some experts claim it may well be necessary to advance thermal efficiency into the 45-50% range. However, this will require improvements in turbine and compressor efficiency. Also, the heat extracted from the boosted charge, which is usually lost, should be recovered and put to work. It is unclear what technologies will emerge as effective options, although water injection has been trialed.

Variable turbine geometry

Most turbochargers currently use nozzle and blade designs that are fixed. VTG (variable turbine geometry) and VNT (variable nozzle turbines) can change to adapt to different conditions of fluid flow through the exhaust and intake manifolds. At low engine speeds, the angle of the blades align more with the flow to harness energy and reduce “turbo lag.” At higher speeds, the angle can be tuned to deliver optimal power to the impeller. VTG is reported as increasing boost pressure by up to 30%, improving compression, and reducing back pressure by 10%, reducing pumping losses.

Literature review findings: VGT has been used in diesel engine applications for some time, but its use in gasoline engines remains limited, due to the higher temperature of the exhaust. However, heat resistance designs have been advanced into some light-duty models (i.e., by Volkswagen and Porsche). Incorporating VGT into single-stage turbochargers leads to incremental costs of approximately \$150 (Blanco-Rodriguez, 2015; see Annex).

Insights from interviews: Current turbine and compressor efficiencies are approximately 60-65% and 75%, respectively. To achieve idealized efficiency levels in engine simulations (i.e., theoretically possible but not attainable with current engineering), turbine and compressor efficiencies at 80% are needed. Practically, current compressor designs could achieve this, but turbine designs require significant change that could take years to develop. VTG can improve boost efficiency at low speeds, but it is unlikely to increase peak efficiency. Tightening the fit of the turbine to prevent exhaust from passing around the outer edges of the blades is considered a more essential and practical improvement.

Cooled exhaust gas recirculation (EGR)

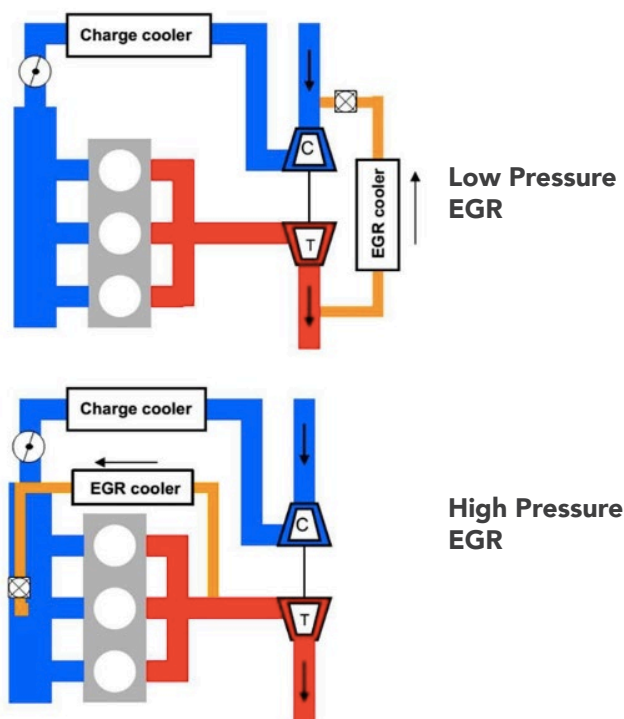
Some of the combustion gases exiting the combustion chamber can be recirculated back through the intake manifold. This effectively dilutes the fuel intake, thereby producing less heat for the volume of charge, which in turn lowers the temperature of combustion. This approach to cooling the combustion temperature has been used for many years to reduce the levels of oxides-of-nitrogen and other emissions in the exhaust stream. More aggressive EGR is now being used to reduce heat losses through the cylinder walls, given a lower ΔT to drive heat transfer. However, an additional heat exchanger is needed to reduce the heat of the exhaust gases prior to circulation back into the intake flow.

Additionally, the lower temperature conditions permit higher compression ratios. Effectively, as a mix of air, fuel and combustion products, the intake charge has a higher specific heat capacity, γ , and this allows greater compression, a longer power-stroke and improved thermal efficiency.

EGR works with naturally aspirated engines (i.e., engines in which compression takes place only in the cylinders – there is no pre-compression) but it complements turbocharging and supercharging especially well. The lower temperature conditions result in higher compression at the turbine, which enables further engine downsizing and slower speeds for a given power output. EGR can also help to reduce pumping losses. Valves can open further and for longer periods of time, which effectively minimizes throttling of the fluid flow through the engine.

Literature review findings: Cooled EGR is used in Toyota's 4th Generation hybrid models, such as the Lexus CT200h, which enables the Atkinson cycle engines (described later) to achieve compression ratios up to 13:1 and thermal efficiencies of 38.5%. In non-hybrid vehicles, such as those using Toyota's Dynamic Force engines (i.e., beginning with the 2018 Camry), thermal efficiency up to 41% is reported. Estimated reductions in fuel consumption range broadly, from 1.2 to 3.6% for low-pressure EGR, to up to 10% for high-pressure EGR (NRC, 2015).

Insights from interviews: Recirculating exhaust gases into the intake manifold can follow a high-pressure path, in which some of the exhaust is diverted prior to the turbine, or a low-pressure path, in which the diversion occurs downstream of the turbine. High-pressure EGR provides a higher thermal efficiency potential. As water is a major component of exhaust gases, cooled EGR designs must address the problems of possible condensation during cold operating conditions, which could limit the fuel efficiency potential and increase cost, potentially due to the addition of moisture traps. Cooled EGR is an increasingly common feature of turbocharged, down-sized engines, and based on interview findings it is a trend that is expected to continue. Discovering a way to use the heat expelled through the charge cooler would further improve overall system efficiency or contribute to catalyst temperature management.



Shown are two common cooled EGR system configurations tested by Mahle Behr on a 1.2-L gasoline engine, as reported by Bruce Morey for the SAE, 2014: *Cooled EGR shows benefits for gasoline engines*. <https://www.sae.org/news/2014/09/cooled-egr-shows-benefits-for-gasoline-engines>

The configurations shown also incorporate turbocharger systems with intercoolers (i.e., charge coolers).

Behr estimates that cooled EGR could improve the average fuel-economy from 2% to 5%, as measured on current drive cycles used by regulatory agencies.

Variable Valve Timing and Lift

The ability to vary the timing of valve actuation, as well as the degree of opening (i.e., valve lift), permits optimal fluid flow through the engine and the reduction of pumping losses over a range of operating conditions. As load and power output increases, valve overlap (the period during which intake and exhaust valves are both open towards the end of the exhaust stroke) is gradually increased.

First introduced in the early 1990s, VVTL is now ubiquitous – virtually all new models have some form of mechanically or hydraulically actuated valve control. Increasingly sophisticated and efficient actuation systems are enabling a wider range of improvements, including Atkinson and Miller cycle operation, as well as cylinder deactivation, which are described further below. Electrically-actuated VVTL is a more recent development and is seen as a way to simplify valvetrain design and reduce the parasitic load on the crankshaft that would otherwise power the camshafts and valves. However, most experts agree that the actual energy savings of this approach are insufficient, leaving mechanical or electro-mechanical systems as the dominant technologies. For example, Toyota has introduced a VVTL design that uses an electrical control to fast-switch between discrete phases of mechanical valve control.

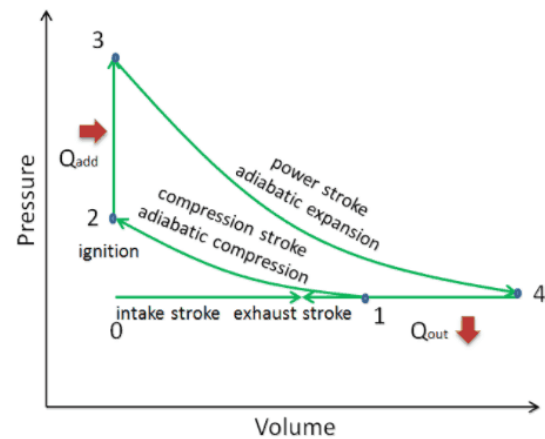
VVTL systems are either discrete, shifting between distinct stages of operation (usually two), or are continuously variable. In discrete systems, the valve control switches between discrete settings, determined by the load on the engine. In continuously variable systems, the timing, lift and dynamics of the valves can be set at any point within a range. Continuous VVTL is more complex, but it should enable greater reductions in pumping losses.

Atkinson / Miller cycle operation

Atkinson cycle operation is a special use of VVTL, in which an engine shifts from the traditional Otto cycle, in which the compression stroke and expansion stroke occur at the same ratio (that is, the compression ratio of the engine), to the Atkinson cycle, in which the expansion stroke has a higher ratio than the compression. This is achieved by timing the closing of the intake valve later than in an Otto cycle, resulting in a marginal increase in thermal efficiency that trades off against a marginal decrease in power and torque.

Variable valve control allows this effective separation of the compression and expansion strokes in an engine. By effectively increasing the expansion stroke, more work is extracted relative to a decreasing compression stroke, which reduces the potential for knocking. However, there is effectively less charge in the cylinder, reducing the potential power output.

Miller cycle engines restore the power otherwise lost to the shortened compression stroke by pre-compressing the air-fuel charge through turbocharging or supercharging.



Atkinson cycle PV diagram. Accessed from *Thermal Engineering*, <https://www.thermal-engineering.org/what-is-atkinson-cycle-atkinson-engine-definition/>

Atkinson cycle engines counter the same power loss (usually) in two ways: by increasing the size of the engine (measured by displacement) and by integrating the engine with an electric motor in a hybrid configuration. The electric motor manages the demand for peak power and torque, while the engine meets the demand for power at a lower level across a wide range of operating conditions. Thus, the Atkinson cycle is more typical of naturally aspirated engines, whereas the Miller cycle is more often coupled with turbocharged engines (including diesel). In both approaches, VVTL is used to reduce pumping losses.

Literature review findings: The use of VVTL specifically to reduce heat losses generates estimated reductions in fuel consumption from 1% to 6% (Blanco-Rodriguez, 2015; Isenstadt, 2016). When used more generally to enable other efficiency-enhancing designs, such as Atkinson and Miller cycle operation, the literature review reports a 3-10% fuel consumption reduction, or more (De Cesare, 2017). Discrete Variable Valve Lift results in 3.4-3.6% reduction in fuel consumption, and Continuously Variable Valve Lift leads to a 0.9-1% reduction (NRC, 2015). The Honda i-VTEC system uses constant VVT and discrete VVL control through cam profile switching. This cam switching concept can also be found in Chevrolet's intake valve lift control system (NRC, 2015).

Insights from interviews: All Toyota hybrid models use a dedicated Atkinson cycle engine design, in which the VVTL is more narrowly set for a greater Atkinson cycle efficiency. Whereas, some non-hybrid vehicle models use VVTL over a wider range of operation that allows the engine to effectively switch between Atkinson and Otto cycle operation. In the latter case, the thermal efficiency improvement tends to be limited in a trade-off for flexibility; nonetheless, it demonstrates the importance of VVTL to ongoing improvements in efficiency, and the range of changes in engine operation that it enables.

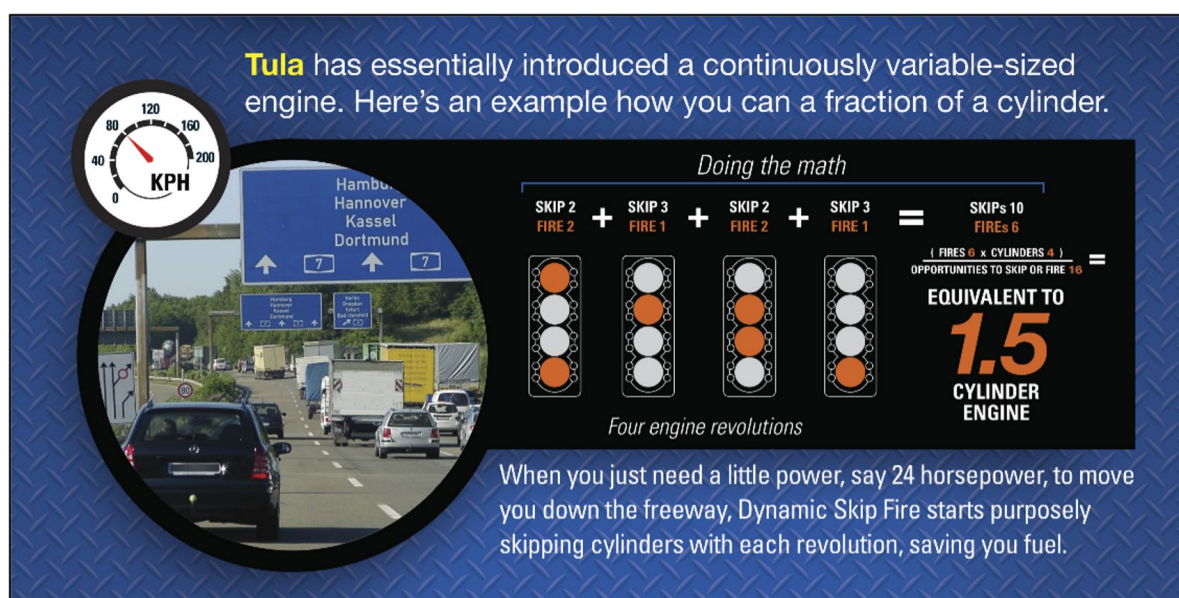
Cylinder deactivation / Dynamic cylinder deactivation

Cylinder deactivation (DEAC) effectively shrinks the size of the engine by closing the valves to some of the cylinders when their contribution of power and torque is not required, during periods of light-load operation. This "deactivates" the cylinder. The charge trapped within functions essentially as an air spring, until the cylinder is activated again. DEAC thus reduces heat and pumping losses.

Early deployments of this design were able to operate in only one of two modes: (1) all cylinders operating or (2) a predetermined number of cylinders operating. For example, an 8-cylinder engine could operate with only 4 cylinders, or a 6-cylinder engine with 3. With only one DEAC option, the efficiency gains are limited, and applicable only to some vehicle models. Also, certain cylinders always fire while others do not, leading to uneven heat distribution throughout the engine.

Recently, dynamic cylinder deactivation, or dynamic skip fire (DSF), has emerged as an “advanced” DEAC design. In this approach, the decision to fire a cylinder – or to skip firing a cylinder – is taking just prior to the opportunity. This has several advantages:

- more even distribution of heat, since the deactivation sequence can “roll” down the line of cylinders, such that each is more evenly used;
- more even distribution of crank force, meaning less vibration and an ability to operate DEAC at lower speeds;
- lower pumping losses (engine power is controlled by the firing of cylinders, meaning the throttle can remain more consistently open);
- can apply to smaller engines with an odd number of cylinders (e.g., 3-cylinders); and
- hypothetical enabling of a shift between four-stroke and two-stroke operation, which could yield further downsizing opportunities.



Dynamic Skip Fire: On-demand cylinder deactivation. Delphi website.

Literature review findings: Fuel consumption benefits of DEAC are estimated to range from 0.7-5.5%, with a 2-10% reduction in CO₂ emissions (NRC, 2015). The use of DEAC in passenger vehicles has been steadily increasing, with 15% of all vehicles using DEAC in MY 2019 (US EPA, 2020). Implementing DEAC in larger engines allows the cylinders to deactivate symmetrically to avoid intense torque fluctuations and vibrations (De Cesare et al, 2017). Incremental benefits of DSF over DEAC are estimated to range from 2-4% (MIT Sloan Lab, 2015).

Insights from interviews: DEAC has seen most success in larger engines with 6-8 cylinders, and its functionality has been surprisingly robust. Even so, the fuel consumption benefits have been modest in real-world operation. The potential for DSF continues to be explored, but the benefits of this design seem better suited to smaller engines with fewer cylinders (e.g., 4 or less), where it can address vibration issues. The issues of uneven heat distribution and wear, which were expected to be an issue with simple DEAC, have not emerged as major problems. Automakers seem to have found other engineering solutions to such concerns without resorting to DSF. The future of DEAC, including DSF, is considered by many experts and observers to be uncertain in the face of strong hybridization. In such hybrids, the engine is normally operating under light load, which obviates the benefit of reducing engine displacement via DEAC. However, its relative effectiveness may make it increasingly appealing in large-engine vehicle models, such as light trucks, for many years to come, where the value of the fuel savings are greater than in smaller-engine vehicles.

Thermo-swing

The thermo-swing concept aims to reduce heat transfer from the working gases in the combustion chamber, through the cylinder walls and into the coolants in the engine block, whereupon it is lost to the surrounding environment. Traditionally, the temperature of the cylinder walls remains relatively constant over the cycle of compression and expansion. During the combustion stroke, the higher temperature inside the cylinder relative to the surrounding walls results in a ΔT that drives heat transfer. To minimize this heat transfer, the ΔT must be minimized. This requires that the temperature of the cylinder walls “follow” the temperature of the working gases; in other words, the wall temperatures “swing.”

This is different than simply insulating the cylinder walls to prevent heat transfer, as this would increase the temperature of walls over successive cycles, thus preheating the intake charge. This reduces the volume of the charge and contributes to knock.

Thermo-swing has been a focus of ongoing R&D for decades, yet it has achieved very limited use in practical demonstration engines. Recently, there have been two approaches under development: material compounds with low thermal conductivity and low volumetric heat capacity that line the cylinder, and a dynamic, exchangeable fluid layer at the surface of the cylinder – in other words, an air gap of some sort.

Literature review findings: A lab-based analysis found that the fuel consumption improvement effect when silica reinforced porous anodizing aluminum (SiRPA) was coated on piston top surfaces, but not piston cavities, was much higher than SiRPA coatings which included piston cavities, at 1.9% and 0.4%, respectively (Kawaguchi, 2016).

Insights from interviews: Most experts and stakeholders consider thermo-swing coatings on cylinder walls to remain in the R&D stage and are not aware of any plans to deploy at commercial scale. Toyota has trialed a material in one of its diesel engine models (i.e., Thermo Swing Wall Insulation Technology, TSWIN), and, as per interview feedback, apparently Mazda is working to innovate a solution. There is a theoretical gain to be realized but the practical engineering has yet to emerge, especially in the context of material durability.

INCREASE IN COMPRESSION RATIO

Gasoline Direct Injection (GDI)

Distinct from PFI, in which fuel is injected onto the intake valves during the intake stroke, in GDI engines the fuel is injected directly into the combustion chamber under high pressure. The injection is designed to vaporize the fuel, which has a cooling effect on the air-fuel charge. This allows for a slightly higher compression ratio, which increases thermal efficiency and power output. Combined with engine downsizing, GDI engines can consume considerably less fuel.

GDI engines exist in more than half of all new light vehicles sold in Canada. However, there are concerns that GDI is associated with elevated levels of ultrafine particulate matter (UFP) in exhaust. Research from Ford indicates that UFP emissions from GDI engines are significantly higher, and can be several orders of magnitude greater, than those from traditional PFI engines.⁵ This may contribute to population health risks and represent a radiative forcing effect on global warming that counters a portion of the fuel efficiency benefit. Particulate matter in GDI engines may be the result of localized concentrations of fuel within the air-fuel charge when ignition occurs. This issue is being investigated and new particle number-based regulations have already been introduced in Europe and China to address increases in UFP emissions from GDI engines.

Mazda's SkyActiv-G engine format uses GDI to achieve a compression ratio of 13:1 in North America, and 14:1 in jurisdictions where higher octane gasolines are more prevalent. These high compression ratios are partly enabled by complementary engine enhancements, such as a tuned exhaust manifold that facilitates a more efficient fluid flow through the system, and some combustion chamber and piston head geometry that promotes more homogenous distribution of the air-fuel charge and rapid combustion. Depending on the drive cycle, fuel efficiency increases of 10-15% are reported on SkyActiv Mazda models.

HCCI and SPCCI

Homogeneous Charge Compression Ignition (HCCI) has also been announced by Mazda as part of its next-generation, SkyActiv-X engine format. In it, air-fuel charge is ignited by the heat of compression instead of a spark plug. Diesel engines are also considered compression-ignition engines, but ignition timing is controlled by the injection of diesel into the air charge at the end of the compression stroke. By contrast, the air-fuel charge is pre-mixed in a gasoline HCCI engine. HCCI promises the thermal efficiency performance of diesel engines but in a gasoline engine. In addition to leaner air-fuel burn and reduced pumping losses, HCCI enables higher compression ratios – upwards of 15:1. Mazda reports that this can deliver fuel efficiency improvements in the 20-30% range, over pre-SkyActiv engine formats.

However, the timing of compression ignition is highly sensitive to operating conditions and difficult to control. Explosive combustion often occurs under high engine loads, while misfires occurs during low loads. This restricts HCCI operation to a narrow band of power output levels. As a result, Mazda has delayed the introduction of the SkyActiv-X design in North America until the engine operating range can be suitably expanded to meet the expectations of customers.

Spark-Controlled Compression Ignition (SPCCI) is a modification to HCCI, in which the timing of ignition can be controlled by either compression or by spark-fire, according to the engine loading and speed conditions. Put simply and in very general terms, the SPCCI engine operates in lean-burn, compression-ignition mode at low-to-medium engine speeds, and spark-ignition mode at higher speeds. Mazda's SkyActiv-X engine is expected to work by drawing into the cylinder a very lean air-fuel charge – so lean

⁵ Maricq, Matti. Gasoline Engines: Ultrafine Particulate Emissions. Research & Innovation Center: Ford Motor Company. N.d. http://www.aqmd.gov/docs/default-source/technology-research/ultrafine-particles-conference/session6_5_mattimaricq.pdf

that it cannot ignite under normal compression – and then, at the right instant, an injection of additional fuel occurs while the piston nears the completion of its compression stroke. This injection is directed toward a spark plug that fires, thus igniting the rich concentration of fuel within the surrounding, lean air-fuel charge. As the flame front spreads outward, it creates a pressure wave that, adding to the pressure of the still-rising piston, is sufficient to ignite the lean air-fuel charge.

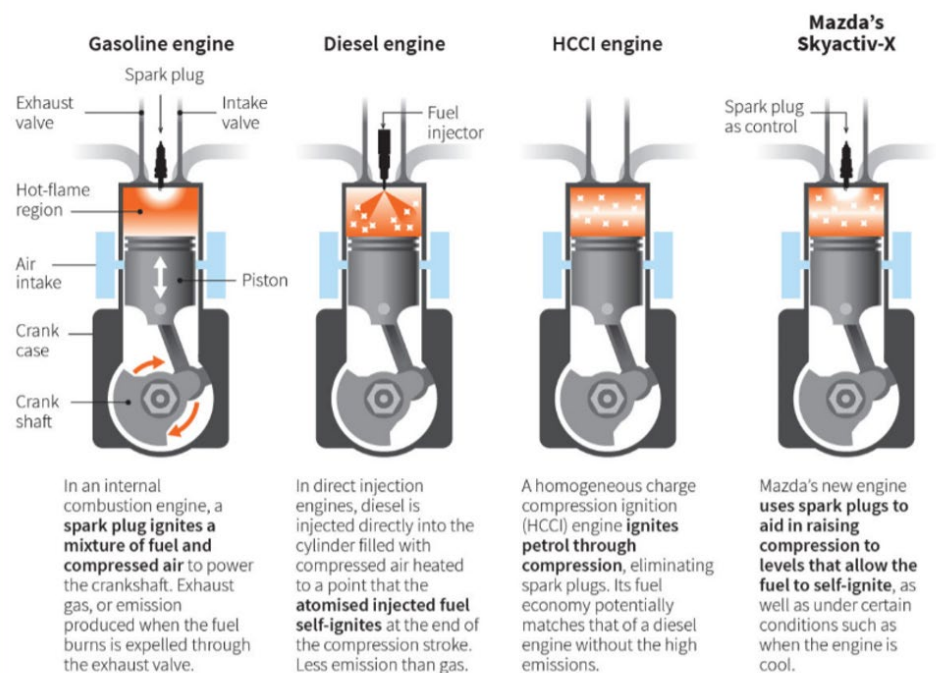
Indeed, by managing the timing and flow of the injection, an SPCCI engine can produce different effective compression – high and lower – according to the operating conditions of the engine. Effectively, this is a form of variable compression ratio.

The lean charge characteristics of the SkyActiv-X engine are assisted by a modest supercharger, which functions as a blower to add more air to the engine when needed.

Mazda's new engine

Mazda claims it has achieved a breakthrough in petrol engine technology that could cut fuel consumption by up to 30 percent compared to conventional gasoline engines. By introducing spark plugs on HCCI engine, a more complete combustion is attained, burning fuel air more cleanly and evenly.

COMPARISON OF ENGINE TECHNOLOGY:



Sources: Mazda; U.S. Department of Energy.

C. Inton, 09/08/2017

REUTERS

Literature review findings: The literature review reports that replacing a 1.6L PFI 4-cylinder engine with a GDI system reduces fuel consumption by 4% by increasing compression ratio from 10.5:1 to 11.8:1. In general, GDI is estimated to lead to a 1.5-2% reduction in fuel consumption and has a theoretical GHG reduction potential of up to 14% (Neyestani et al, 2020). It is a fast-growing technology, with a market penetration of 51% in MY 2018 in the U.S., estimated to increase to 93% by 2025 (Neyestani et al, 2020). Engines using GDI tend to be coupled with multi-valve and VVT technology (US EPA, 2020).

HCCI is shown to result in reductions in fuel consumption between 2.7 and 29% (Zhang & Zhao, 2014), while SPCCI has a GHG reduction potential of 20-30% (Johnson & Joshi, 2018).

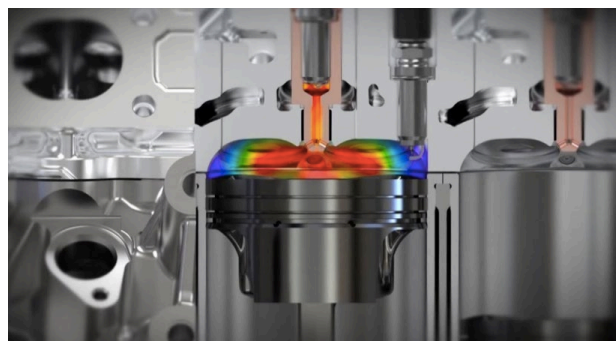
Compression ignition may limit the level of control with regard to scaling combustion processes with engine speed for SPCCI. SPCCI engines are also limited by load and speed rate over which they can operate. HCCI engines, on the other hand, have a key obstacle of controlling transients between low and high loads (Zhang & Zhao, 2014).

Insights from interviews: GDI has been shown to lead to the formation of fuel-rich regions on combustion chamber walls, which in turn can result in significantly increased emissions of UFPs relative to PFI engines. Some jurisdictions such as the EU and China use particle number (PN) rather than particle mass-based emissions standards, and as a result, gasoline particulate filters (GPFs) are typically required with the use of GDI engines. GPFs add roughly \$125 to total vehicle manufacturing costs and do not typically need to be replaced over vehicle lifetimes.

While experts interviewed are impressed with the recent efficiency achievements of Mazda's high compression ratio line of engines, there is a shared uncertainty about the future of HCCI and, more generally, about lean-burning engines. Particularly in North America, the stoichiometric ratio (i.e., $\lambda=1$) is key to complying with regulations on criteria air contaminants using three-way catalysts, which aren't effective under lean-burn conditions. It was noted that the most thermally efficient engines operating today are used in Formula One competition racing, operating at around 50%, which do not use HCCI. Moreover, the general view is there isn't much benefit to be realized in pushing compression ratios much beyond 14:1, as the gains diminish as the complexities and costs increase.

Pre-chamber combustion

Expected to be included in Maserati's MC20 supercar model, pre-chamber combustion enables higher compression ratios without necessarily relying on the lean-burn conditions of HCCI or SPCCI. It accomplishes this through speedier combustion. A pre-chamber is a separate, small volume above the main combustion chamber. It is usually shaped as a hemisphere at the bottom with a series of small holes positioned radially. These holes lead into a small cylindrical chamber that leads upwards to a spark plug. As the air-fuel charge in the cylinder is compressed, a small portion is forced through the holes up into the pre-chamber. Upon ignition, the combustion flames "squirt" out of the holes



Credit: Maserati. <https://www.roadandtrack.com/new-cars/a34054931/pre-chamber-ignition-system-explained/>

like jets into the main combustion chamber. This has the effect of rapidly distributing ignition throughout the combustion chamber and accelerating the completion of combustion. The faster the combustion event, the less likelihood of knocking. Also, Maserati's engine design includes PFI that introduces a stoichiometric air-fuel charge into the cylinder during the expansion stroke and a GDI to produce a high-pressure, evaporative cooling effect on the charge during the compression stroke. Combined, these features enable a modest increase in compression ratio and improved thermal efficiency.

The description above is known as *passive* pre-chamber combustion, and it is used in $\lambda=1$ engines. For lean-burn conditions, *active* pre-chamber combustion designs are used, in which the pre-chamber includes the fuel injector. However, passive pre-chamber is more likely to be embraced in North America, due the design of CAC emissions regulations.

During low-load operation, a second spark plug in the main combustion chamber is used to help stabilize combustion dynamics and slow the combustion event as needed. Complexity, cost and durability are the focus of current testing and development.

Literature review findings: Pre-chamber combustion allows for compression ratio increases of up to 15%. Despite a long history of research and applications, practical barriers to the implementation of these systems in light-duty engines remain. A historic key challenge for pre-chambers has been ensuring acceptable low load, idle, and cold start performance. Cold starts have proven particularly challenging with regard to compliance with modern emissions regulations (Institution of Mechanical Engineers, 2019).

Insights from interviews: Pre-combustion chamber design is not a new concept. It has been used in large diesel gensets for many years. But its use in small gasoline engines is viewed as a potentially promising innovation.

Water injection

Injecting water at different points in the engine cycle can enable increases in compression ratios. Like GDI, injecting water into the combustion chamber during compression can have an evaporative cooling effect that retards knock. It can also serve a similar function to cooled EGR, diluting the charge and increasing its effective density.

Indeed, water injection is not a new idea, having been used in combustion engines since the mid-20th century. However, a limitation has been the large amount of water required to be carried onboard the vehicle (perhaps as much as 30-50% the volume of the fuel). Other challenges include freezing and consistency of purity.

Solutions being investigated include water recovery and re-use systems. Ideally, the heat absorbed by the water could be used to enhance efficiency elsewhere in the engine or vehicle, instead of just discharging it to the surrounding environment.

Literature review findings: Water injection is estimated to provide a 5-10% reduction in CO₂ emissions. Water injection is shown to have great potential to extend knock limits without increasing turbine inlet temperatures and fuel enrichment, both of which are major limitations of current knock mitigation techniques (Zhu et al, 2019). It also has downsizing potential, as it may be used for employing turbochargers with VGTs (Zhu et al, 2019).

Insights from interviews: Water injection is generally considered moderately interesting to most experts and observers, but ingenious solutions will be needed to make it practical for widespread commercial use.

Variable compression ratio

Mechanically varying the degree of compression inside the combustion chamber can be achieved in many ways, including moving the cylinder heads, moving crankshaft axis or varying the length of the connecting rods through innovative linkages between the pistons and the crankshaft. The goal is to increase compression ratio during low engine loads for better efficiency, and decrease it during periods of heavy load and high-speed operation to avoid knock.

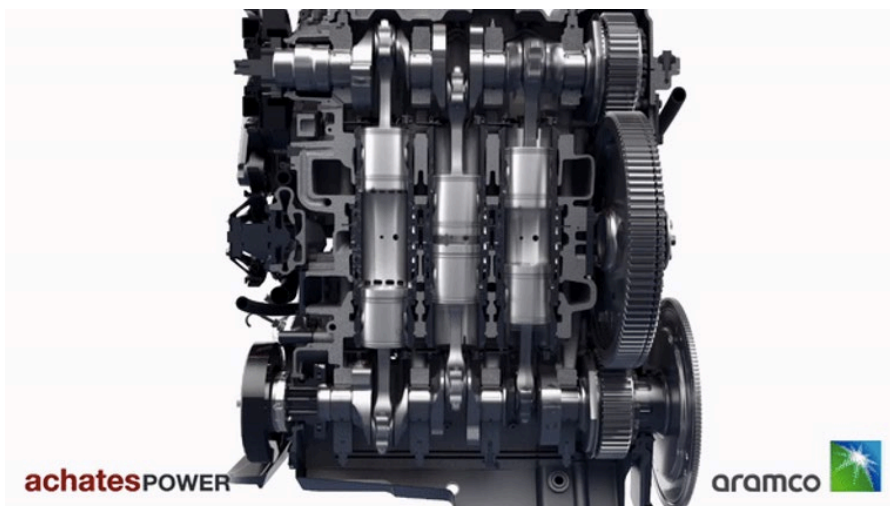
Nissan introduced a variable compression ratio (VCR) system into some 2018 and 2019 production models. The reach of the pistons was mechanically raised and lowered to vary combustion ratio continuously between 8:1 and 14:1. However, the performance was partly enabled by VVTL and turbo-downsizing, so the discrete effect of the VCR is unclear.

Literature review findings: Fuel consumption improvements of VCR engines are estimated at 3% in conventional powertrains and 8% in mild hybrids (Garcia et al, 2020). National Research Council estimated that VCR can yield CO₂ reductions between 3 and 9%, with up to a 5% reduction in fuel consumption after 2025 (NRC, 2015). FEV estimates that its two-stage VCR would reduce fuel use by 4.2%-6.2% (Xiao et al, 2018).

Insights from interviews: VCR is not generally viewed among the experts interviewed as a promising technology. Much of the benefit of VCR engine design can be achieved at less complexity and lower cost using other methods of managing knock. In particular, the proliferation of strong hybrid powertrains, in which the electric motor lightens the load on the engine, obviates the function of VCR. Beyond the compression ratios already being achieved, there is not much incremental gain expected from variable systems.

Opposed piston design

Opposed piston engines have been used for decades, mainly in large engines for industrial, marine and military applications. However, design work is recently being directed toward light-duty passenger vehicle applications using gasoline as fuel. Opposed piston engines are natively two-stroke engines, which generate exceptional low-end torque performance. From a cost-savings perspective, there are no valvetrains or cylinder heads. However, there are usually two crankshafts for each row of opposed pistons that must be mechanically linked to a single power output shaft, which adds complexity.



In addition to achieving very high compression ratios (up to 18:1), the absence of cylinder heads reduces heat loss, as there is less surface area relative to the volume of the cylinder (note that there are twice as many pistons as cylinders). This means that more of the heat performs work on the opposed pistons, improving thermal efficiency. Two pistons per cylinder also facilitates a higher stroke-to-bore hole ratio, further enhancing the potential for useful work to be extracted from the heat of combustion. Further, opposed piston engines use a low-pressure supercharger to increase gas exchange in the combustion chamber, which reduces pumping losses.

Importantly, currently proposed designs, such as Achates' 2.7-liter, three-cylinder design, are supposed to rely on compression ignition of the gasoline-fueled charge. Combined, these features are claimed to move thermal efficiency to beyond 40%.

Literature review findings: An engine OEM reported a 30% improvement in fuel economy over an efficiency optimized four-stroke diesel engine, and significant cost savings of 6% (approximately \$1,025), excluding exhaust aftertreatment hardware, compared to a current production four-stroke, inline six-cylinder engine (Fromm and Redon, 2017; Achates, 2020). Opposed Piston Design results in less heat loss due to higher wall temperatures of the two piston crowns and higher effective flow areas than a comparable four-stroke or a single-piston two-stroke uniflow or loop-scavenged engine (Johnson and Joshi, 2018).

Insights from interviews: Experts knew of no practical plans to bring an opposed piston engine design to market. The view was that the design was so radically different from existing engine designs, that the cost of implementation was too great compared to the potential efficiency gains. The unique attributes and performance characteristics of this engine design were thought to have value in specialized applications, but the prospect of mass market passenger car or light truck applications was considered to be very long-term.

REDUCE ANCILLARY LOADS (AND ASSOCIATED LOSSES)

High-voltage electric architecture

For decades, the basic electrical system in a light-duty vehicle operated at approximately 12-volts, supplying power to lights, instruments, wipers, the radio and various other electricity-using loads. The core of the system included a rechargeable lead acid battery, an alternator (to generate electrical power from the rotation of the engine), a starter-motor and the spark plug ignition subsystem. 12-volt electric architecture continues to be the standard for the majority of vehicles on the road today, but the advent of hybrid-electric powertrain technology has introduced new, higher-voltage systems to the North American market, from which new standards are evolving.

Higher voltage electrical architecture is attractive because it enables more of a vehicle's various subsystems to be powered electrically. In addition to the traditional electrically-powered accessories described above, higher-voltage systems can also power the various pumping and actuation subsystems that would otherwise be mechanically-driven by the engine crankshaft. Often referred to as ancillary loads, powering these subsystems with higher-voltage electricity allows for more energy-efficient operation, thus reducing the overall demand for fuel. Furthermore, the higher the voltage, the lower the current running through the electrical system, which facilitates the use of more compact motors for both the propulsion system and for ancillary devices.

Higher-voltage systems also enable the introduction of more robust battery systems, which make possible electrical motor-driven propulsion and, to the reverse, generator-driven recuperation of braking energy (i.e., regenerative braking). In this way, hybrid-electric vehicles are able to achieve dramatic reductions in fuel consumption – often in the range of 30% or more relative to a conventional baseline.

Some of the key innovations facilitated by higher-voltage architecture are listed below. Note that battery technology and purely electric propulsion systems are beyond the scope of this investigation.

12-24-volt

Mild hybrids, micro-hybrids and start-stop systems are enabled by this architecture. **Start-stop** functionality can operate on a 12-volt architecture, using a battery specially designed to support the shut-down of the engine at a stop, and its restart when the driver releases the brake pedal. This minimizes fuel consumption and emissions associated with idling. It represents a modest fuel savings at modest cost, and is increasingly a standard feature of many new light-duty vehicle models.

Micro-hybrids use 12-24-volt architecture to provide smoother, more responsive start-stop functionality, as well as some modest regenerative braking, relying on advanced lead-acid, NiMH or Li-ion batteries or, as in the case of Mazda's i-ELOOP system, an ultracapacitor. These energy storage systems supply power to the ancillaries and obviate the traditional alternator.

24-48-volt

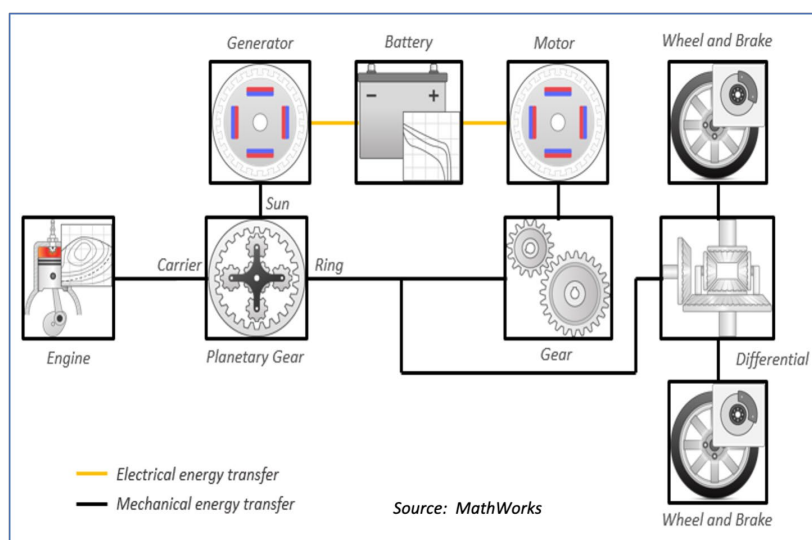
Mild hybrid is an informal term usually referring to vehicles that fall between micro- and full-hybrid systems. **Belt alternator-starter (BAS)** systems replace the conventional alternator with a higher-power electric motor-generator and a high-tension belt connected to the crankshaft, which can assist the engine with added propulsion power recovered and stored braking energy. Power-assist using regenerative braking boosts the overall system efficiency of a mild hybrid at modest cost. Such systems usually operate in the 24-48 volt range, enabling other electrical power enhancements, such as **e-boost**, in which the compressor on a boosted engine can be powered electrically. This eliminates turbo-lag, increasing the appeal of turbocharged engine downsizing.

The main advantage of mild and micro-hybrids is that they can be incorporated into existing vehicle models with minimal redesign of the engine and transmission system, delivering higher-voltage architecture efficiency benefits at minimal cost increments. However, these hybrid systems have limited regenerative braking capacity and remain a parasitic load on the engine, limiting the potential efficiency gains.

48-volt and higher

Parallel hybrid with two clutches is a design approach that Hyundai, Kia and others have introduced to some market success. A motor capable of generating propulsion power is positioned between two clutches – one connected to the engine and one connected to the transmission. This effectively decouples the motor from the engine, enabling all-electric propulsion. However, its speed is linked to the engine, which can set boundaries on the efficiency and cost potential of this hybrid arrangement. The advantage of this approach is its scalability, in that the motor can be sized for modest hybrid benefits up to fully electric drive.

Input power split hybrid design is used by Toyota and Ford to achieve the highest level of fuel efficiency improvements of any other hybrid architecture. In Toyota's Synergy Drive platform, a planetary gear system takes power from the engine and distributes it separately as mechanical energy to the drivetrain, and as electrical energy to a motor-generator, which in turn also powers the drivetrain. Effectively, the planetary gear system decouples the speed of the drivetrain from the speed of the engine. This allows the engine to generate power at its most efficient speed for much of the time, while the motor-generator meets the transient demand for power to the drivetrain. The battery state-of-charge is maintained by both a generator that runs off of the planetary gear system, and the motor-generator that captures braking energy.



Operating at 300 V, the Synergy Drive platform in current commercial use provides the highest level of fuel efficiency improvement of any competing hybrid system. By isolating the engine from the peak load of the drivetrain, it is able to operate on an Atkinson cycle for exceptional thermal efficiency. The use of two motor-generator units along with the planetary gear enables an optimal distribution of power throughout a vehicle's powertrain. The disadvantage of this system, however, is its cost and complexity.

Literature review findings: 48V architecture is estimated to reduce fuel consumption by 10-15%, or up to 21% with added technologies. It is also estimated to produce a 12-15% reduction in CO₂ emissions. The 48V system can be considered costly, as it increases the cost of a vehicle from \$1,010 to \$1,260 (Melaika et al, 2019). A major challenge to the 48V system identified in the literature is converting vehicle production to 48V systems when 12V systems have long been the industry standard (Kumawat & Thakur, 2017).

Dedicated hybrid engines (DHEs) have shown a wide range of fuel efficiency improvements (12-30%) depending on the level of hybridization. In simulations of different dedicated hybrid transmission (DHT) concepts, fuel consumption ranged from 4.4 to 4.7L/100 km. In these simulations, the power-split DHT produced the most powerful electric machine, with the best mechanical efficiency and lowest energy loss (Hengst et al, 2019).

12-24 volt hybrid architectures are expected to offer fuel consumption reductions of roughly 5-6% (Kumawat & Thakur, 2017).

Stop-start functionality has been estimated to provide a 2.1% fuel consumption reduction (NRC, 2015). It is also estimated to provide a 2-5% reduction in CO₂ emissions (Johnson & Joshi, 2018). In MY 2018, 29% of passenger vehicle models available in the US were equipped with engine idle stop/start systems (US EPA, 2020).

Insights from interviews: All experts and industry observers viewed hybrid-electric powertrains, which rely on higher-voltage architecture, as the leading technological advancement in reducing fuel consumption and emissions. No other powertrain innovation can compare with the double-digit percentage improvement. Indeed, higher-voltage electric architecture enables efficiency enhancements in other key categories of improvement, including reducing heat losses and increasing compression ratio, through hybridization. It is widely considered a cross-cutting development that will need to be embraced across all vehicle models if the pace of emissions reductions is to continue.

Experts also remarked that 48-volt architecture seemed to deliver the most “bang for the buck,” in that the majority of the benefits of hybrid-electric operation could be gained at much less cost than, for example, the 300-volt system used by Toyota. From a techno-economic perspective, the 48-volt system is expected to become a widely-adopted standard that would facilitate a rapid hybridization of the light-duty vehicle fleet during the next decade.

Reference was also made to a Dedicated Hybrid Engine (DHE) design approach, in which the combustion engine and the electric motor are closely integrated such that each operates only within its most fuel-efficient range. In other words, under light loads, such as constant speed highway travel, the engine provides most of the power to the wheels; whereas, under frequent acceleration (stop-and-go conditions), the torque demand is best met by the electric motor. Some simulations indicate that DHE designs could further extend the fuel consumption reduction potential of power-split hybrids to nearly 35%, relative to the current state-of-the-art combustion engine.

Notably, as hybrid systems become more optimized, the benefits of engine-downsizing diminish. Since the engine can be designed to produce power most efficiently within a narrow range of operating conditions, the benefits of cylinder deactivation, variable compression ratio and even turbocharging become increasingly marginal. Thus, high-voltage electric architecture appears to be synergistic with some efficiency-enhancing technologies, and divergent with others.

Friction reducing fluids, coatings

Friction between moving parts increases ancillary loads. Pumps to circulate working fluids, such as oils and coolants, camshafts and rocker arms to actuate valves, and air conditioner compressors are examples of moving-part devices that need power from the engine to operate (also called “parasitic loads,” as they consume power that would otherwise be delivered to the wheels). Reducing the friction among the moving parts in contact reduces the energy required by the ancillaries, as well as the energy lost in the system of belts and chains that distribute power from the engine to the devices. Engineered lubricants and advanced surface designs and coatings that reduce friction have shown surprising efficacy in minimizing losses and restoring efficiency to engines and powertrains.

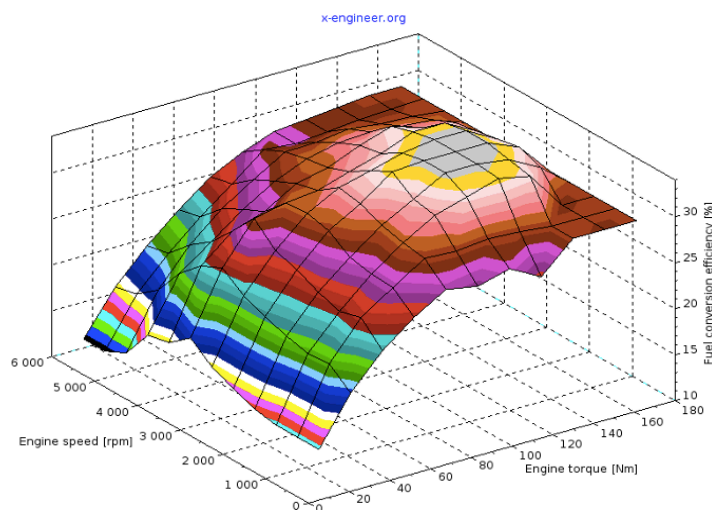
Literature review findings: Fuel consumption reductions from low friction lubricants were estimated to range from 1-3% (NRC, 2016; MIT Sloan Lab, 2015). It was noted that engine design changes could be required to provide compatibility with certain low-viscosity oils. These changes may include changes in oil pressure, bearing materials, and clearances, and other changes in

specifications for wear surfaces in the engine. However, the overall cost of switching to low-friction lubricants may be offset due to the need for less frequent oil changes.

Insights from interviews: Friction-reducing designs and synthetic lubricants continue to surprise experts and industry observers in their capacity to keep delivering reductions in fuel consumption. Whenever the friction reduction opportunity appears to have been fully realized, new breakthroughs, such as diamond-like carbon (DLC) that Nissan applied to its valve-lifters, expand the limits of what is considered possible. The recent introduction of low-viscosity, SAE 0W16 oil is expected to reduce engine friction by a greater degree than some previous transitions (e.g., 0W30 to 0W20). Incremental improvements are expected to continue at very modest cost.

REDUCE DRIVETRAIN LOSSES (I.E., INCREASE TRANSMISSION EFFICIENCY)

For as long as light-duty vehicles have been mass-produced, transmission systems composed of several discrete gears have been the standard means of converting the power output of the engine into the torque and speed needed at the wheels. Increasingly, continuously variable transmissions that do not rely on a set of discrete gear wheels are also being embraced within the North American market. Today, modern transmissions of all types are very efficient at transmitting mechanical power. Energy losses across a typical gearbox can be less than 5% and the rest of the drivetrain (i.e., rotating shafts and differentials) may accumulate another 5-10%. By reducing friction and distortion between and among and within these components, these losses are consistently moving toward the ultimate goal of zero. However, beyond 90% efficiency, the potential gains diminish while the costs escalate.



The following technology descriptions do not directly address the minimizing of losses within a transmission system. Rather, the focus is on the efficacy with which the various transmission designs keep the engine operating in its most fuel-efficient range, as this is the key factor driving the selection and innovation of transmission solutions within industry.

For a given level of power output, there is an optimally efficient combination of torque and speed in each engine. Usually, this point is at a mid-range speed and higher torque level (i.e., higher load), although it really depends on how the engine is designed.

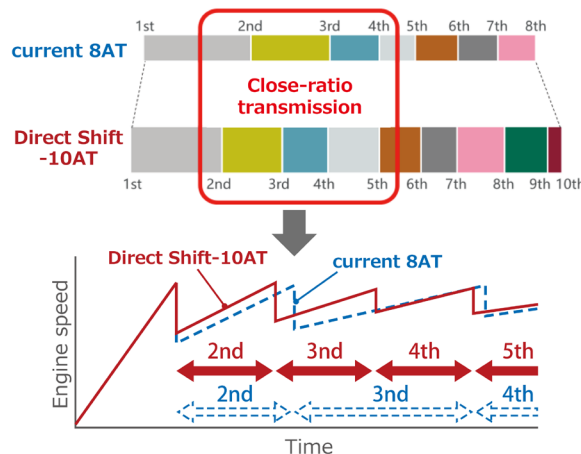
For example, the above image shows the “map” of a hypothetical engine’s measured energy conversion efficiency, as a function of engine speed and output torque. In this example, the engine produces power most efficiently near 2,500 rpm and 125 N·m. Transmission systems that work to maintain the engine at or near this optimal point of power output, while changing the speed and torque delivered to the wheels to meet a wide range of driving demands, are better able to manage vehicle fuel consumption to a minimal level.

Note that the power delivered to the wheels is the same as the power produced by the engine (ignoring losses), but as the product of speed and torque, this power can be delivered by the transmission to the wheels as either [high-speed x low-torque] or [low-speed x high-torque].

Automatic transmission (AT)

ATs are favoured by consumers in North America. An arrangement of gearwheels in a planetary mesh allows the engine input speed to the transmission to be converted into one of several discrete output speeds. The more speeds, the more opportunity to keep the engine operating at its most efficient state. So, there is a trend toward ever-higher numbers of speeds in new transmissions. However, this leads to larger and heavier transmissions, all else held equal. As well, cost and complexity increase, while the degree of fuel-savings benefit diminishes. So, the path of innovation leads to more ingenious use of planetary gearing architecture to produce more gear ratios (without necessarily adding more components) to produce more compact, lighter designs, and component refinements that continue to reduce power loss across the transmission.

Currently, ATs of up to 10-speeds are available on passenger car and light-truck models, with trucks having the greater prevalence in the market (possibly due to more availability of space). Transmissions tend to have long development lead times – roughly five years – before commercial introduction, in which an overriding risk is customer acceptance. Transmissions influence a driver's feel and perception of the vehicle during acceleration and cruising. Many gears can lead to frequent shifting events. If not smoothed out and shortened, the interruptive effect of unexpected gear shifting can be a confusing distraction for drivers.



Source: Toyota, comparing the shift logic in its Direct Shift-8AT and -10AT automatic transmissions. The close-ratio area depicts a similar gear-shift experience for the driver, while the expanded spread of gear ratios in the 10-speed provides great torque from stop, and lower rpm, vibration and noise at high-speed cruising. <https://global.toyota/en/powertrain/transmission/>

Aside from the speed-count, the scheduling of gearshifts has undergone significant refinement in recent years. Electronically-controlled “shift logic” can optimize for fuel efficiency or allow the driver to choose more aggressive performance-settings.

Literature review findings: MIT assessments found that transmissions with 7-9 gears can result in 10% reduction in fuel consumption (MIT Sloan Lab, 2015). EPA estimates around 18% reduction in CO₂ emissions, comparing 8-speed to 4-speed transmissions (US EPA, 2020). Recent introductions of 8-speed transmissions include the ZF 8HP45 transmission in a number of Chrysler/FCA products and several vehicles from European manufacturers. Ford Motor Company and General Motors have also developed 9- and 10-speed transmissions, particularly for smaller engines (MIT Sloan Lab, 2015).

Shift logic optimization is estimated to have a fuel consumption reduction of 0.5-1%, with fuel economy benefits of up to 5% (NRC, 2015). NHTSA sees shift optimization as a “no-cost technology,” due to its cost effectiveness, with a 2025 direct manufacturing cost of \$22 equal to the cost for ASL1 (NRC, 2015).

Insights from interviews: The efficiency-enhancing benefits of adding more gearing and speed-counts to ATs is seen as having a practical limit. Some observers are skeptical that the current highest speeds in A10 transmissions are engaged very often. The sense is that passenger car and light truck transmissions are unlikely to move past 8 and 10 speeds, respectively, for the purpose of reducing fuel consumption, and that the focus of innovation is increasingly on user “driveability.”

Dual clutch transmission (DCT)

A DCT can be considered an innovation on the traditional manual transmission in that it solidly engages with the engine using a clutch plate system and is relatively compact. There is no torque converter as in an AT, which relies on a fluid-based engagement with the engine when initially accelerating the vehicle from a stop. Nor does a DCT require numerous additional clutches and brakes, as is the case in ATs. Like manual transmissions, DCTs include a series of gears that engage and disengage by sliding along a set of shafts to achieve a discrete number of gear ratios. The result is lower losses of energy and power across the transmission, and a smaller, lightweight design.

Unlike a manual transmission, however, DCTs are not handled by the driver – gear shifting is computer-controlled. This has been a source of frustration for many drivers of DCTs, because sometimes the computer mis-predicts the next gearshift, resulting in occasional lag in responsiveness when the driver requires a boost in torque for acceleration. On the upside, when shifting is correctly guessed by the controller, it is executed very quickly (i.e., as little as hundredths of a second for a gearshift; much shorter than that of an AT), which helps to keep the engine at its most efficient point of operation. DCTs are expected to pair well with motors in a hybrid-electric arrangement, in which the motor supplements the torque requirements and addresses the lag conditions described above.

Literature review findings: DCTs are estimated to reduce fuel consumption by 0.5-1%. DCTs have been known to face acceptance issues because of consumers being accustomed to the feel of a torque converter during acceleration. As a result, OEMs are packaging DCTs with 7+ speed transmissions and implementing a wet-clutch version (NRC, 2015; Vaca et al, 2017). Unfortunately, in simulations, it has been shown that wet-clutch DCTs have energy losses caused by the wet clutch related components that exceed 40% of the total transmission energy dissipations (Vaca et al, 2017).

Insights from interviews: DCTs have been embraced more readily in markets where manual transmissions were dominant, such as in Europe. By contrast, in North America where the attributes of ATs are most appreciated, DCTs have faced resistance. Very few are showing up in passenger cars and there appear to be none planned for light trucks. Experts and observers say that the harsher, more jagged operation of the DCT will continue to keep the technology at the margins of the American and Canadian markets. This represents a missed opportunity for some marginal fuel savings, but that gap is being rapidly filled by continuously variable transmissions in North America.

Continuously variable transmission (CVT)

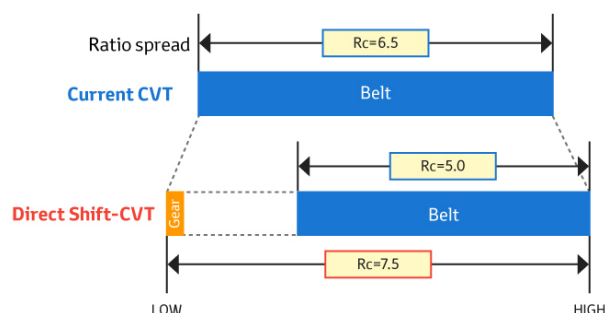
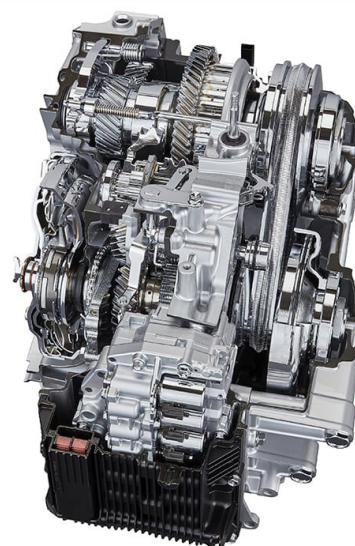
CVT are infinitely variable in their ratio of input-to-output speeds, within a certain range defined by an upper and lower bound. Within this range, the transmission can finely tune the torque-speed output to the ideal engine operating conditions at any power level, without discrete gear-shifting. The principles are simple and the design is compact, composed of two cone-shaped pulleys and a connecting belt. By moving the pulley halves along their axes, a continuous variation in the ratio of pulley speeds is achieved.

CVTs initially faced some market resistance relating to driver perceptions, due to a feeling of disconnect from the engine. There were also issues of lag in acceleration response to the driver's throttle input. Furthermore, friction losses due to slippage of the belt on the pulley was blamed for some earlier underperformance in real-world use. However, in recent generations of CVTs special calibrations have been made to address lag and slippage has been reduced. The inset image is of Toyota's Direct Shift-CVT, in which a traditional gear is used at low engine speed to deliver responsive torque. As speed increases, the gear is disengaged, and the belt-drive system takes over. This approach expands the effective upper and lower bounds on gear ratios.

Notably, there is a parasitic loss in the CVT relating to the fluid pressure that must be maintained to control the positioning of the pulleys. This will be a focus of ongoing innovation in technology and design.

Literature review findings: CVTs provide a 2.2-4.5% (3.5% average) reduction in fuel consumption relative to conventional automatic transmissions (NRC, 2015). As of MY 2020, CVTs are included in roughly 25% of new passenger vehicles in North America. By 2025 they are expected to have incremental costs of approximately \$150 relative to conventional 4-speed transmissions, down from roughly \$300 in 2015. Consumer preference for high torque vehicles poses a challenge for CVT uptake.

Insights from interviews: Some experts consider the CVT the most likely alternative to the AT in the North American market. Partly, this is due to the long-run estimates for cost and compact design, which are appealing to automakers. Customer who prefer ATs will need to come to accept CVTs, but this is considered a lesser barrier to overcome than that facing DCTs. Also, as drivers become more used to electric-propulsion systems, the synergies with CVTs will also propel adoption.

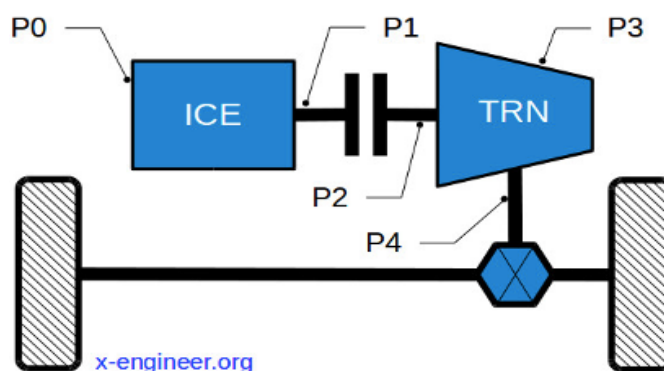


Source: Toyota. <https://global.toyota/en/mobility/tnga/powertrain2018/cvt/>

Innovations enabled by hybrid drivetrain architectures

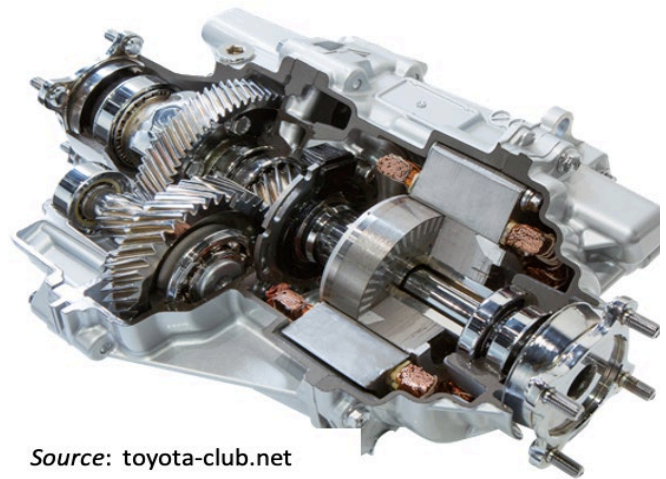
Earlier in this report, developments in electrical architecture were described in the context of enabling various hybrid-electric vehicle systems. An informal nomenclature has developed around the distinct types of hybrid architectures, which in turn enable new opportunities for transmission and drive power. These are explored below.

Referring to the inset diagram of an engine (ICE), connected to a transmission (TRN) via a clutch, we see power directed along a connecting shaft to a differential gear mesh that delivers power to the axle and wheels. An electric motor can be integrated into this vehicle system at several points with distinct effects, as follows:



- P0 The motor-generator connects to the engine. This can represent a mild hybrid or **belt alternator-starter (BAS)** system, which enables **idle-off** at stop and some regenerative braking. A disadvantage is that the BAS is a parasitic load on the engine.
- P1 The motor-generator is connected to the engine crankshaft. Similar to P0, the motor is linked to the speed of the engine.
- P2 The motor-generator is between the engine and the transmission; it may be side-attached to the transmission and decoupled from the engine, but it is directly linked to the speed of the engine. This can represent a **parallel hybrid with two clutches** design, based on a 48-volt system.
- P3 The motor-generator is integrated into the transmission; it is decoupled from the engine and its speed is now linked to the speed of the wheels. This can represent an **input-power split hybrid**, such as the Toyota Synergy Drive design operating at 300-volts.
- P4 The motor-generator is connected through a gear mesh on the rear axle of the vehicle; it can be located in the rear axle drive or in the wheels' hub. This is similar to P3 in terms of regenerative braking capacity, but it could also facilitate the **all-wheel electric-assist drive**. Torque-vectoring designs are also possible, in which the power delivered to each wheel can be independently varied.

For example, Toyota is currently introducing its latest "E-Four 4WD" platform in North America through its RAV4 and Highlander SUV hybrid models. The front axle is driven in typical Synergy Drive fashion, using the engine and two electric motors. The rear axle is driven electrically, using one motor integrated into a differential and speed-reducing gear box (see inset image). There is no driveshaft to mechanically connect the front and rear axles – the rear drive system is isolated from the engine. It provides power to the rear wheels when needed and can provide charging power to the battery during cruising and braking.



Source: toyota-club.net

Literature review findings: Dedicated hybrid engines (DHEs) have shown a wide range of fuel efficiency improvements (12-30%) depending on the level of hybridization. In simulations of different dedicated hybrid transmission (DHT) concepts, fuel consumption ranged from 4.4 to 4.7L/100 km. In these simulations, the power-split DHT had the most powerful electric machine, with the best mechanical efficiency and lowest energy loss (Hengst et al, 2019).

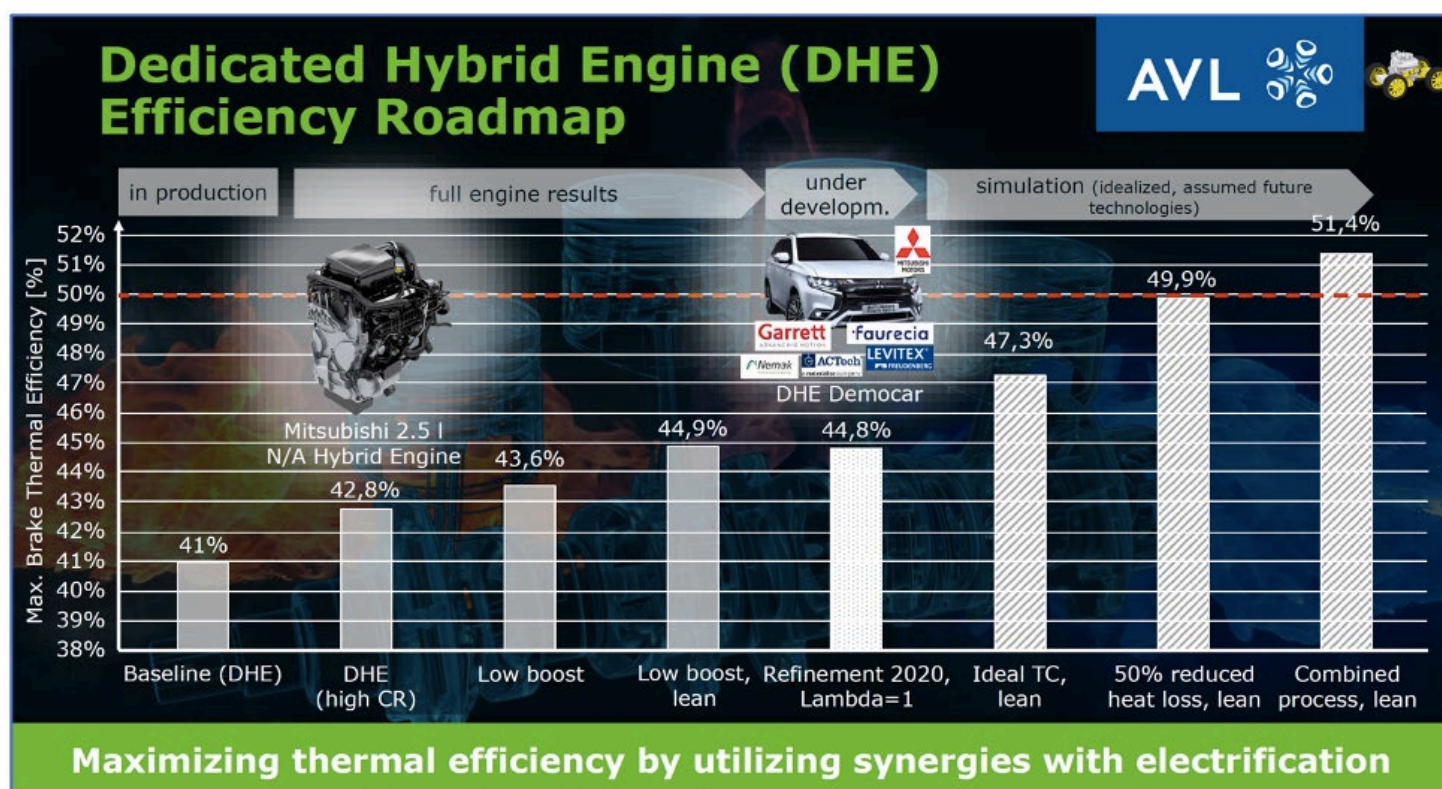
Insights from interviews: 48-volt architecture combined with P2 transmission designs were considered to be an attractive match, in terms of delivering the majority of the fuel consumption reduction achievable with hybridization at minimal cost. All-wheel electric assist drive was viewed as a well-understood design, but one that needs ongoing development to reduce costs and encourage market uptake.

DISCUSSION — REFLECTIONS ON THEMES EMERGING FROM INTERVIEWS

For North American markets, which represent a unique mix of consumer demand and regulatory frameworks, the benefits of stoichiometric engines are considered more compelling than the efficiency gains of lean-burning engines. Stoichiometric air-fuel ratio (i.e., $\lambda=1$) enables the use of three-way catalytic converters that are a very durable and cost-effective means of minimizing emissions of criteria air contaminants, which contribute to poor air quality and negative public health impacts. Fuel consumption can be reduced by lean burn which reduces carbon dioxide emissions, but managing the criteria air contaminants requires more elaborate and expensive emissions control systems. Most of the thermal efficiency improvements delivered by lean-burn can be achieved under stoichiometric operation through air-fuel charge dilution measures, such as cooled EGR.

Compression ratios in excess of 15:1 are considered unnecessary, as the thermal efficiency gains diminish as cost and complexity of managing pre-ignition/knock escalate significantly. Mazda's SkyActiv-X engines are 16:1, but achieve this compression using HCCI/SPCCI, which is proving to be difficult to operate in North America, given its fuel and emissions standards. Pre-chamber spark ignition is considered by some to be an easier approach to high compression ratios, as one example.

The following slide is from an AVL webinar delivered in mid-2020, showing their estimates of practically achievable levels of thermal efficiency in stoichiometric gasoline engines. Current performance is taken as 41%. By applying commercially-available technologies, including advanced turbocharging and hybridization, they estimate an additional 5% can be achieved. Beyond 45% thermal efficiency is the realm of simulation, where the theory is proven but the practical engineering and technological invention has not yet been developed.



Hybrid-electric powertrains were considered by far the most important development to support, according to all those interviewed. No other singular area of technology advancement comes close to the magnitude of reduction in fuel consumption delivered by aggressive hybridization – 20% at the low end and upwards of 30% for the most sophisticated (and expensive) systems.

However, engines deeply integrated into hybrid-electric systems are increasingly free to operate in a narrow, ideal range of operation where thermal efficiency is optimal, while the electric motors handle the transient loads at the very low and high ends of the speed spectrum. This effective isolation of the engine from where the “rubber meets the road” means that some technologies that were intended to enable better efficiency across a range of engine loads, no longer make much of a contribution. These include cylinder DEAC, variable compression ratio and, to some extent, turbocharged/downsized engines. Indeed, the most fuel-efficient hybrid models currently available have engine displacements of approximately 2 litres.

On the other hand, ongoing, incremental innovations in valvetrain actuation (VVTL), friction reducing lubricants and coatings, air-fuel charge cooling, and heat recovery and reuse are all expected to continue and will have practical application in future generations of combustion engines. Regarding fuels that enable better thermal efficiency (potentially through anti-knock qualities), higher-octane gasolines were considered marginally beneficial. On balance, a migration of the average octane rating from the current lowest level (i.e., roughly 87) would be expected to enable a net reduction in lifecycle GHG emissions, inclusive of both the refinery and the vehicle fleet. However, no breakthrough fuel alternatives were identified in the interviews, with two exceptions: first, the prospect of renewable gasoline synthesized from low-carbon feedstock; second, hydrogen from low-carbon feedstock for dedicated combustion engines. In both cases, the prospect of a low-carbon fuel supply chain led some interviewees to conclude that piston-crank internal combustion engines can be part of a low-carbon future.

ANNEX

Tabulated summary of findings

Through the literature review and the interviews with experts and stakeholders, the study team probed for information on improvements in efficiency, reductions in emissions and the associated costs of the enabling technologies. Where definitive estimates were found, the figures are included in the first table that follows, *Table 1: Aggregated Fuel Efficiency and Cost Data for Emerging LDV ICE Technologies*. Figures presented are taken directly from the associated publications identified in the table, accessible via the hyperlink (and in the Bibliography). The publications often describe differing procedures and analytical methodologies to generate results. In some cases, a percentage improvement in engine thermal efficiency is reported; in other cases, it may be an estimated reduction in fuel consumption for an entire vehicle. Therefore, the reader is encouraged to consult the publications identified directly for details. The value of the table is in providing at-a-glance assessments of technologies that the reader may wish to explore further.

The second table that follows, *Table 2: Available Fuel Efficiency and Cost Data for Emerging LDV ICE Technology Packages*, summarizes literature findings that relate to packages of vehicle technologies.

Table 1: Aggregated Fuel Efficiency and Cost Data for Emerging LDV ICE Technologies

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Theme: Reduce Engine Heat Losses							
Turbocharging to enable downsizing	<ul style="list-style-type: none"> • 0-6.5% in fuel consumption reduction • 3.1-8.3% in fuel consumption reduction 	<ul style="list-style-type: none"> • Turbocharging projected to reach 35-40% in MY 2020; 80% of gasoline turbocharged engines were 4-cylinder engines in MY 2019. • EPA/NHTSA predict 64% of the new car fleet will have some level of turbocharging & downsizing in 2021 (93% in 2025). 	<ul style="list-style-type: none"> • 2017 direct manufacturing cost of \$288 • Costs are reduced by 20% after 2 full years of implementation; followed by an estimated 3% reduction per year for 5 years; then 5 years at 2%/year, and then 5 years at 1%/year. • \$141-1106 in direct manufacturing cost for MY2025 • Turbocharged engines cost \$770-1,280 more than naturally-aspirated engines 	<ul style="list-style-type: none"> • Extra components required, i.e., heat exchanger, means less space under the hood • When tested with indolene, indicated that significant spark retard was required to avoid knock, in contrast to the higher octane E85 fuel. • Turbocharged engines typically experience exaggerated turbocharger lag at altitude because of the reduced exhaust mass flow available to accelerate the turbocharger. 	<ul style="list-style-type: none"> • Several key technologies enabling downsized and turbocharged engines were determined to be on the flat portion of the OEM learning curve from 2012-2025. These include GDI, turbocharging, cooled EGR, and VVT. 	<ul style="list-style-type: none"> • Turbocharging may be necessary to advance thermal efficiency into the 45-50% range. However, this will require improvements in turbine and compressor efficiency. Also, the heat extracted from the boosted charge, which is usually lost, should be recovered and put to work. 	Isenstadt et al. (2016) EPA (2021) MIT Sloan Lab (2015) NRC (2015)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Electric-boost turbochargers/superchargers	<ul style="list-style-type: none"> Electrically assisted, variable-speed supercharger results in 26% reduction in fuel consumption 48V e-boost turbos provide ~5% improved efficiency over regular turbo in 48V system Eaton states its EAVS e-boost supercharger can reduce fuel consumption by 14-32% 		<ul style="list-style-type: none"> Direct manufacturing cost for electrically assisted, variable-speed supercharger is \$1,000 - \$1,300 in 2025 MY 	<ul style="list-style-type: none"> Supercharged engine has greater BSFC than naturally aspirated unit because of parasitic losses and reduced compression ratio. To counter this, devices with internal compression have been developed but require a high cost for manufacturing precision requirements; efficiency improvements are rapidly eroded when the internal compression ratio of device doesn't match the overall required pressure ratio. 	<ul style="list-style-type: none"> Reduces turbo lag and supports compression in low-speed situations Saves energy in braking mode by slowing down the turbocharger Electric superchargers can lower emissions (with decreased turbo lag), even with stop-and-go utilization (urbanization). 12V e-boosting is possible, but only provides half the benefits of 48V system Delphi estimates 48V hybrids with e-boosting will achieve 60-70% of the CO₂ reduction benefits of higher voltage hybrid vehicles, but at 30% of the cost 	<ul style="list-style-type: none"> The heat extracted from the boosted charge, which is usually lost, should be recovered and put to work. It is unclear what technologies will emerge as effective options, although water injection has been trialed. 	Isenstadt et al., (2016) NRC (2015) Alshammari et al. (2019) Cornet et al. (2019)
Cooled exhaust gas recirculation (EGR)	<ul style="list-style-type: none"> Low pressure EGR 1.2-9% High pressure EGR 10-20% 1.2-3.6% reduction in fuel consumption Dedicated EGR results in 10% reduction in fuel consumption after 2025 Dedicated EGR results in 15-20% reduction in CO₂ emissions 		<ul style="list-style-type: none"> \$175-300 1-4 years; \$200 per % reduction in fuel consumption \$230-669 in direct manufacturing costs in 2025 MY Dedicated EGR \$853 in direct manufacturing costs after 2025 	<ul style="list-style-type: none"> Pumping losses could possibly increase due to the requirement for higher exhaust pressure to achieve the required EGR flow. High dilution rates with EGR might require upgraded ignition systems to achieve acceptable combustion stability. Such upgraded systems would add to engine costs. 	<ul style="list-style-type: none"> Often combined with turbocharging and intercooling to increase pressure and reduce temperature, since cooled EGR reduces fresh air for combustion Mitigates engine knocking Dedicated EGR may require use of hydrocarbon trap 	<ul style="list-style-type: none"> Cooled EGR is an increasingly common feature of turbocharged, down-sized engines – a trend that is expected to continue. Discovering a way to use the heat expelled through the charge cooler would further improve overall system efficiency or contribute to catalyst temperature management. 	MIT (2019) Fischer et al. (2017) Morey (2014) Conway et al. (2018) NRC (2015) Johnson & Joshi (2018)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Variable valve timing and lift, enabling Miller / Atkinson cycle operation	<ul style="list-style-type: none"> • 1.8 % CO₂ reduction in NEDC; Toyota's Valvematic system reported to improve fuel economy by 5% in 2014 MY Corolla • Discrete Variable Valve Lift results in 3.4-3.6% reduction in fuel consumption, and Continuously Variable Valve Lift leads to 0.9-1% reduction • Variable valve control at full and part load results in 5% reduction in fuel consumption • Atkinson cycle with VVT results in 3-5% reduction in CO₂ emissions • FEV estimates that Miller cycle reduces fuel consumption by 3.9-5.7% over baseline downsized turbocharged engine with VVT and lift 	<ul style="list-style-type: none"> • VVT has 80% penetration 	<ul style="list-style-type: none"> • \$170, or ~\$40-50 / gCO₂/km (cost ratio) • Direct manufacturing costs are \$126-210 for Discrete Variable Valve Lift; \$63-188 for Continuously Variable Valve Lift technology in 2025 MY 	<ul style="list-style-type: none"> • Limited by high peak cylinder pressures and temperatures, which affect powertrain design, as well as increasing knock tendency in gasoline engines 	<ul style="list-style-type: none"> • VVT advantages are increased torque at low engine speeds and higher maximum performance for less fuel consumption at high engine speeds. • Also, VVT increases scavenging and reduces part-load throttling losses. 	<ul style="list-style-type: none"> • VVT is now ubiquitous — virtually all new models have some form of mechanically or hydraulically actuated valve control. Electrically-actuated VVT is a more recent development and is seen as a way to simplify valvetrain design and reduce the parasitic load on the crankshaft that would otherwise power the camshafts and valves. However, most experts agree that the actual energy savings of this approach are insufficient, leaving mechanical or electro-mechanical systems as the dominant technologies. 	EPA (2021) NRC (2015) Johnson & Joshi (2018) MIT Sloan Lab (2015) Alshammari et al. (2019) Isenstadt et al., (2016) De Cesare et al (2017)
Dynamic Cylinder Deactivation/ Skip Fire	<ul style="list-style-type: none"> • 7.8% CO₂ reduction on US highway (8-11% in mild hybrids) • Cylinder cut out at lighter loads results in 4% reduction in fuel consumption • Cylinder Deactivation results in 0.7-5.5% reduction in fuel consumption, depending on engine size • 2-10% reduction in CO₂ emissions 	<ul style="list-style-type: none"> • 15% of MY 2019 LDVs will use some form of DEAC 	<ul style="list-style-type: none"> • \$60 in extra costs per % reduction • \$151-170 in direct manufacturing costs for cylinder deactivation in 2025 MY 	<ul style="list-style-type: none"> • Skip fire — need to be careful that fuel is not wasted while switching between cylinders firing. • Since other technologies (e.g. downsizing or VVT) can reduce pumping and friction losses, the coupling of CD with other technologies may not be as effective. 	<ul style="list-style-type: none"> • Improves fuel efficiency through reduced pumping work • Fuel efficiency improvement and CO₂ reduction levels tend to be at lower end of estimates in real-world applications 	<ul style="list-style-type: none"> • DEAC has seen most success in larger engines with 6-8 cylinders, and its functionality has been surprisingly robust. Even so, the fuel consumption benefits have been modest in real-world operation. The potential for DSF continues to be explored, but the benefits of this design seem better suited to smaller engines with fewer cylinders. 	MIT Sloan Lab (2015) NRC (2015) Johnson & Joshi (2018) Wilcutts et al. (2019) De Cesare et al (2017)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Combustion chamber wall insulation / thermo-swing	<ul style="list-style-type: none"> A lab-based analysis found that the fuel consumption improvement effect when a SiRPA compound was coated on piston top surfaces, but not piston cavities, was much higher than SiRPA coatings which included piston cavities, at 1.9% and 0.4%, respectively 			<ul style="list-style-type: none"> If the walls are insulated, the inside surface temperature, cylinder liner, cylinder head, and piston may become crowded, getting hotter and leading to less air getting in. 		<ul style="list-style-type: none"> Thermo-swing has been a focus of ongoing R&D for decades, yet it has achieved very limited use in practical demonstration engines. There is a theoretical gain to be realized but the practical engineering has yet to emerge, especially in the context of material durability. 	Kawaguchi (2016)
Theme: Increase Compression Ratio							
Gasoline Direct Injection	<ul style="list-style-type: none"> 1.5-2% reduction in fuel consumption (Stoichiometric GDI) 	<ul style="list-style-type: none"> GDI projected to be in 55% of vehicles in MY 2020, with market penetration in US estimated to increase to 93% by 2025 	<ul style="list-style-type: none"> \$210-378 in direct manufacturing costs for Stoichiometric GDI in 2025 MY 	<ul style="list-style-type: none"> Negative impacts could stem from fuel rich regions forming on combustion chamber walls, leading to an increase in ultrafine particle (UFP) emissions. Limited operating range of improved efficiency at low speeds and loads corresponding to the low lift cam 		<ul style="list-style-type: none"> GDI engines exist in more than half of all new light vehicles sold in Canada. However, there are concerns that GDI is associated with elevated levels of ultrafine particulate matter in exhaust. This may contribute to population health risks and represent a radiative forcing effect on global warming that counters a portion of the fuel efficiency benefit. GPFs can help to address UFP emissions, however. 	EPA (2021) MIT Sloan Lab (2015) NRC (2015) Middleton et al (2016)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
GDI: Lean burn	<ul style="list-style-type: none"> Stratified GDI engine operation & Lean NOx catalyst results in 6% reduction in fuel consumption 5% reduction in fuel consumption (Lean Burn with low sulfur fuel) 10-20% reduction in CO2 emissions 		<ul style="list-style-type: none"> \$590 \$1,026-1,334 in direct manufacturing costs for Stoichiometric GDI in 2025 MY 	<ul style="list-style-type: none"> Expensive exhaust aftertreatment may be necessary because the three-way catalyst cannot reduce NOx in case of excess of oxygen in the exhaust gas 	<ul style="list-style-type: none"> Requires expensive after-treatment because the three-way catalyst cannot reduce NOx in case of excess oxygen in the exhaust. Produces high compression ratios for improved thermal efficiency because of its charge cooling effects 		De Cesare et al. (2017) MIT Sloan Lab (2015) NRC (2015) Johnson & Joshi (2018) Alshammari et al. (2019)
Spark assisted homogeneous charge: Spark plug controlled compression ignition (SPCCI)	<ul style="list-style-type: none"> 20-30% CO2 reduction potential 	<ul style="list-style-type: none"> Production started in 2019; 60% of Mazda 3 orders have Skyactiv-X engine; 45% of Mazda CX-30 crossover orders 	<ul style="list-style-type: none"> Mazda's Skyactiv-X is >\$5,300 more expensive than 2-L gasoline version 	<ul style="list-style-type: none"> CI may limit the level of control with regard to scaling combustion processes with engine speed. SPCCI engines are limited by load and speed rate over which they can operate. More expensive, so not a strong candidate for hybridization 	<ul style="list-style-type: none"> Mazda has seen much higher uptake than expected in Europe for Skyactiv-X engine. 	<ul style="list-style-type: none"> There is a shared uncertainty about the future of HCCI and, more generally, about lean-burning engines. Particularly in North America, the stoichiometric ratio is key to complying with regulations on criteria air contaminants using three-way catalysts, which aren't effective under lean-burn conditions. 	Malan (2019) Elfalan (2018) Johnson & Joshi (2018)
Homogeneous charge compression ignition (HCCI)	<ul style="list-style-type: none"> 2-stroke controlled auto ignition operation results in up to 29% reduction in fuel consumption; other HCCI modes result in fuel consumption reduction between 2.7 and 11.9% 			<ul style="list-style-type: none"> Key obstacle of controlling transients between low and high loads. CAI modes (i.e., HCCI) have better fuel economy and lower NOx emissions than the conventional throttled 4-stroke SI operation. The coordination of the HCCI and SI engine modes with the exhaust aftertreatment system is an issue 	<ul style="list-style-type: none"> Study indicates potential synergy with highly downsized direct injection gasoline engines for much better fuel economy and performance. 	<ul style="list-style-type: none"> The general view is there isn't much benefit to be realized in pushing compression ratios much beyond 14:1, as the gains diminish as the complexities and costs increase. 	Zhang & Zhao (2014) NRC (2015) Johnson & Joshi (2018)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Variable compression ratio engines	<ul style="list-style-type: none"> Fuel efficiency improvements of 3% in conventional powertrains; 8% in mild hybrids CO₂ reduction between 3% and 9% up to 5% reduction in fuel consumption after 2025 10% reduction in CO₂ emissions 	<ul style="list-style-type: none"> FEV predicts VCR availability on a commercial scale by 2030. 	<ul style="list-style-type: none"> FEV estimates that the cost of a 2-step VCR system is significantly less than a fully, or continuous, VCR system, while still reaping more than 80% of the fuel consumption reduction potential of a fully variable system. \$763-1,146 in direct manufacturing costs after 2025 	<ul style="list-style-type: none"> High cost and complexity Complex handling during switching from high CR to low CR May never reach mass market 	<ul style="list-style-type: none"> Very effective coupling with Miller Higher efficiency at lower loads Tailpipe estimations are over Euro 6 requirements. Therefore, other technology needs to be applied to achieve 2021 CO₂ targets. VCR, relative to Miller cycle, allows performance to be completely maintained at lower engine speeds. 	<ul style="list-style-type: none"> VCR may be a competitor to Miller cycle concepts in the long run, offering manufacturers more options to improve efficiency while maintaining performance. However, VCR is not generally viewed as a promising technology. Much of the benefit of VCR engine design can be achieved at less complexity and lower cost using other methods of managing knock. 	Isenstadt et al., (2016) Garcia et al. (2020) De Cesare et al (2017) NRC (2015) Johnson & Joshi (2018)
Combustion chamber water injection	<ul style="list-style-type: none"> 5-10% reduction in CO₂ emissions 			<ul style="list-style-type: none"> The dilution of the mixture with water and the reduced temperature level in the combustion chamber have minor influences on losses due to unburned fuel and the losses due to heat transfer 	<ul style="list-style-type: none"> Fundamentals of both thermophysical and chemical kinetic effects of water addition on combustion phenomena and emissions need to be further investigated with respect to different water injection implementations and engine types. 	<ul style="list-style-type: none"> Water injection is still not a mature process for commercial vehicles. 	Zhu et al. (2019) Johnson & Joshi (2018) De Cesare et al (2017)
Opposed piston engine design	<ul style="list-style-type: none"> OEM reported 30% improvement in fuel economy over an efficiency-optimized, four-stroke diesel research engine 		<ul style="list-style-type: none"> 11% cost savings compared to a current production four stroke, inline six cylinder engine 6% cost savings excluding exhaust aftertreatment hardware (\$1,025 reduction) 	<ul style="list-style-type: none"> Ignition is trickier with pistons on two sides. Most are two-stroke engines, so there's an issue of lubrication oil entering the combustion chamber, and friction can go up. Cost and durability issues Unlikely to reach mass market 	<ul style="list-style-type: none"> Reduced heat losses; the Achates OP engine has two pistons facing each other in the same cylinder Leaner combustion / greater cylinder volume Quicker and earlier combustion at the same pressure rise rate Low load operation 	<ul style="list-style-type: none"> Experts knew of no practical plans to bring an opposed piston engine design to market. The view was that the design was so radically different from existing engine designs, that the cost of implementation was too great compared to the potential efficiency gains. 	Fromm & Redon (2017) Johnson & Joshi (2018)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Theme: Reduce Drivetrain Losses							
7+ speed transmissions	<ul style="list-style-type: none"> Fuel consumption reduction of 12% when comparing 8-speed to 4-speed EPA estimates 17.8-17.9% CO₂ reduction between 8 and 4-speed MIT estimates that more efficient transmissions with 7–9 gears result in up to 10% reduction in fuel consumption NRC estimates that 9-10 speed transmission results in 0.3% fuel consumption reduction (relative to 8 speed AT) 	<ul style="list-style-type: none"> 7+ speed transmissions at 47% of all vehicles in MY 2019 and projected to grow to 51% in MY 2020. 	<ul style="list-style-type: none"> For 8-speed, 2025 MY direct manufacturing costs ranging from \$47 to \$115 For 9-10 speed transmission, 2025 MY direct manufacturing costs are estimated at 83 CAD. 	<ul style="list-style-type: none"> New transmissions have high development costs and long design and validation phases. After a suitable layout is defined, a new transmission typically takes 5 years for design, development, and implementation in production. 	<ul style="list-style-type: none"> According to the NRC, moving to 8- and 9-speed transmissions would require a combination of high efficiency gearbox technologies, torque converter lockup, and aggressive shift logic. 	<ul style="list-style-type: none"> Minimal gains beyond 7 gear ratios; however, reducing parasitic losses within a transmission can offer an approximate 5% reduction in fuel consumption by 2025. Transmissions are unlikely to move past 8 and 10 speeds. Main focus now is on enhancing drivability rather than fuel consumption. 	NRC (2015) EPA (2021) MIT Sloan Lab (2015) Moskalik et al. (2016)
Dual clutch transmissions	<ul style="list-style-type: none"> 0.5-1% reduced fuel consumption 	<ul style="list-style-type: none"> EPA does not identify DCTs as a separate transmission category; some may still be reported as traditional automatic transmissions 	<ul style="list-style-type: none"> Dry-clutch DCTs provide 0.5 - 1% fuel consumption reduction at a direct manufacturing cost savings of approximately \$50 to \$60 relative to a wet clutch DCT. 	<ul style="list-style-type: none"> Have faced setback in U.S. market, due to users being accustomed to the smooth feel of a torque converter during acceleration. This is difficult to replicate with DCTs as they don't have the torque multiplication provided by a torque converter. Issues with cost, size, and packaging 	<ul style="list-style-type: none"> The two main advantages of DCTs are that they can shift very quickly, and they can avoid some of the internal resistance of a traditional automatic transmission by eliminating the torque converter. However, DCTs need wet clutches for effective heat dissipation (dry-clutch gets poor consumer ratings). Also, there's some issues with consumer acceptance in the US, who are more used to the feel of the torque converter. 	<ul style="list-style-type: none"> DCTs are viable alternatives to automated manual transmissions (AMTs), however uptake in North America is not expected to increase in the future. 	NRC (2015) Vacca et al. (2017) EPA (2021)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Continuously variable transmission	<ul style="list-style-type: none"> • 2.2-4.5% (3.5% average) reduction in fuel consumption relative to conventional automatic transmission 	<ul style="list-style-type: none"> • For MY 2020, the production of CVTs (including hybrids) has increased to almost 25% of all new vehicles. • In the near term, the belt-driven CVT is likely to remain the only type that will have any market penetration in the light-duty market as of 2020. 	<ul style="list-style-type: none"> • Estimated 2025 MY direct manufacturing cost of \$154 for the CVT relative to a four-speed automatic transmission (costs were ~\$300 in 2015) 	<ul style="list-style-type: none"> • Slow consumer acceptance due to non-traditional engine sounds and vibrations and concerns about the materials used in the manufacturing of the belt. • Consumer preference for high torque cars is a challenge for CVT; also need to have certain hydraulic pressure on pulley system so the steel belt or chain doesn't slip. 	<ul style="list-style-type: none"> • CVT fuel savings are due to the higher efficiency of controlling speed ratio, which reduces fuel consumption. • Toyota's TNGA powertrain will be in 80% of their vehicles sold in Japan, China, Europe, and North America by 2023. • However, parasitic losses can exceed those of a conventional automatic transmission. 	<ul style="list-style-type: none"> • Overall emissions when using CVT as a gearbox are less than manual or automatic transmissions. • Some experts consider the CVT the most likely alternative to the AT in the North American market. Synergies with hybrid powertrains may help future uptake levels. 	NRC (2015) Yamagata (2018) EPA (2021) Jawad & Ali (2020)
Shift logic optimization	<ul style="list-style-type: none"> • 0.5-1% fuel consumption reduction 		<ul style="list-style-type: none"> • \$22 in 2025 MY direct manufacturing costs 	<ul style="list-style-type: none"> • Shift optimization strategy can result in noise, vibration, and/or harshness (NVH) issues and driver discomfort as transmission undergoes frequent changes in gear ratios. 	<ul style="list-style-type: none"> • The cost estimated by NRC for shift optimization is primarily the result of NVH-related hardware necessary to allow the more aggressive shift strategy. 	<ul style="list-style-type: none"> • Some see shift optimization as a "no-cost technology," due to its very low costs yet modest fuel consumption benefits 	NRC (2015)
Anti-idle, start-stop functionality	<ul style="list-style-type: none"> • Up to 4% fuel consumption reduction • 2.1-2.2% fuel consumption reduction from Stop-Start (12V Micro-Hybrid) 	<ul style="list-style-type: none"> • Start Stop projected to increase to about 42% for MY 2020. 	<ul style="list-style-type: none"> • \$289-422 in 2025 MY direct manufacturing costs for Stop-Start (12V Micro-Hybrid) 	<ul style="list-style-type: none"> • Often disabled by users, negating benefits • In order to provide cooling during stops, an electrically driven air-conditioning compressor may have to be added, increasing cost. 	<ul style="list-style-type: none"> • Stop-start systems are typically used in engines with minimal electrification and therefore exhibit both lower costs and lower fuel consumption reductions than other hybrid (HEV) architectures. 	<ul style="list-style-type: none"> • Start-stop systems offer modest fuel savings at modest cost, and are increasingly a standard feature of many new light-duty vehicle models. 	MIT Sloan Lab (2015) NRC (2015) Johnson & Joshi (2018) EPA (2021)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Dedicated hybrid engine / transmission design	<ul style="list-style-type: none"> • Wide range of fuel efficiency improvements (12-30%) depending on level of hybridization • In simulations of different DHT concepts (multi-mode and powersplit) on WLTC drive cycle, fuel consumption ranged from 4.4 to 4.7 L/100 km. • Strong hybrids can reduce fuel consumption by 26.9-34.5% 	<ul style="list-style-type: none"> • 2025 market share projected to be worth \$3.6 billion 		<ul style="list-style-type: none"> • A challenge for parallel hybrid (P2) configurations is being able to maintain good drive quality because the clutch connects and disconnects the engine during operation. • An issue with the power split architecture is that when towing or driving under certain real-world conditions, performance is not optimum. 	<ul style="list-style-type: none"> • Fuel consumption for DHT concepts can be reduced by increasing the mechanical structure and reducing the size of the electric machine. • The two primary types of strong hybrids on the market are the parallel (P2) and the power split (PS). 	<ul style="list-style-type: none"> • In simulations, the power-split DHT had the most powerful electric machine, with the best mechanical efficiency and lowest energy loss. 	Hengst et al. (2019) Cornet et al. (2019) Johnson & Joshi (2018)
Theme: Reduce Ancillary Loads							
48-volt+ architecture	<ul style="list-style-type: none"> • P0 architecture had CO2 reduction of 9.7-10.1%; P1 had 10.7%-11.5%, P2 and P3 had 25% and 26% under various driving cycles • Reduced fuel consumption by 10-15%, up to 21% with added technologies • 12-15% reduction in CO2 emissions 	<ul style="list-style-type: none"> • 10% by 2025 	<ul style="list-style-type: none"> • Fuel savings of roughly 0.4 L/100 km • The 48V system increases the cost of a vehicle from \$1,010 to \$1,260 	<ul style="list-style-type: none"> • The 48V system requires additional space, meaning that vehicle design changes could be required for the additional system and electrical circuit. The components running on the 48V system also need to be designed accordingly. • Additional safety precautions are needed while designing the 48V electrical system. A malfunction between 48V and the 12V electrical system could lead to short circuit and this can damage the 12V system due to overvoltage. 	<ul style="list-style-type: none"> • Further improvements in fuel consumption and CO2 emissions could be achieved by engine downsizing. • 48V technologies can be installed in a vehicle along with conventional 12V systems, with slight variation in vehicle architecture. 48V systems can be used to power high load components, run additional electric components such as superchargers, etc., resulting in improved performance, efficiency and emission reductions. • A major challenge to the 48V system is converting vehicle production to them when the 12V system is the standard 	<ul style="list-style-type: none"> • Experts and industry observers uniformly viewed hybrid-electric powertrains as the leading technological advancement in reducing fuel consumption and emissions. No other powertrain innovation can compare with the fuel efficiency improvements that can be derived from hybridization. It is widely considered a cross-cutting development that will need to be embraced across all vehicle models if the pace of emissions reductions is to continue. 	Melaika et al. (2019) Kumawat & Thakur (2017)

Technology	Fuel Efficiency Improvement Potential	Market Penetration (North America)	Costs and Payback Period	Risks	Remarks	"Project Team's Judgement Call"	Links to Resources
Electrically-actuated accessories	<ul style="list-style-type: none"> • 0.8- 1.3% fuel consumption reduction from Electric Power Steering • 1-2.6% fuel consumption reduction from Improved Accessories 		<ul style="list-style-type: none"> • \$95 in direct manufacturing costs for Electric Power Steering in 2025 MY • \$47-77 in direct manufacturing costs for improved accessories in 2025 MY 	<ul style="list-style-type: none"> • Concerns were reported about failure modes with an electric water pump on turbocharged engines 	<ul style="list-style-type: none"> • Improved accessories include electric water pump, electric cooling fan, high efficiency alternator and mild alternator regenerative braking, and intelligent cooling 		NRC (2015)
Friction-reducing fluids, coatings	<ul style="list-style-type: none"> • 1% fuel consumption reduction from improved synthetic lubricants for lower friction; 3% from additional friction reduction opportunities • 0.7-0.8 % fuel consumption reduction from low friction lubricants • 1.2-1.4 % fuel consumption reduction from low friction lubricants and engine friction reduction, relative to previous tech 		<ul style="list-style-type: none"> • \$4 in direct manufacturing costs for low friction lubricants in 2025 MY • \$64-125 in direct manufacturing costs for low friction lubricants and engine friction reduction, (relative to previous tech) in 2025 MY 	<ul style="list-style-type: none"> • Some vehicles may be limited in changing to lower viscosity oils due to operating loads and temperature concerns. • Engine design changes could be required to provide compatibility with certain low-viscosity oils. These changes may include changes in oil pressure, bearing materials, and clearances, and other changes in specifications for wear surfaces in the engine. 	<ul style="list-style-type: none"> • The overall cost of switching to low-friction lubricants may be offset because fewer oil changes will be required 	<ul style="list-style-type: none"> • Modest benefits yet modest costs, which may warrant further research and development. Friction-reducing designs and synthetic lubricants continue to surprise experts and industry observers in their capacity to keep delivering reductions in fuel consumption. 	MIT Sloan Lab (2015) NRC (2015)
Smart cooling systems for managing heat losses better	<ul style="list-style-type: none"> • 2% reduction in fuel consumption 				<ul style="list-style-type: none"> • Cooling systems can be grouped into passive and active systems and use either air or liquids as a coolant. 		Cornet et al. (2019) MIT Sloan Lab (2015)
Waste Heat Recovery	<ul style="list-style-type: none"> • Up to 3% reduction in fuel consumption (after 2025) 	<ul style="list-style-type: none"> • Organic Rankine Cycle (ORC) systems are unlikely to reach production status for light-duty vehicles by 2025 as development of ORCs has slowed for LDV applications in recent years. 	<ul style="list-style-type: none"> • \$898-1,347 in direct manufacturing costs for 2025 MY 	<ul style="list-style-type: none"> • Using a thermoelectric generator (TEG) is challenging due to its low thermal efficiency (typically less than 4%), although materials to improve the conversion efficiency of TEGs are under development • An issue with TEGs is that the TEG unit in the exhaust increases back pressure, which lowers output and reduces efficiency. Materials costs are also high. 	<ul style="list-style-type: none"> • Includes waste heat recovery technologies other than turbocharging, such as thermoelectric generators (TEG) and organic Rankine cycle (ORC) systems. 	<ul style="list-style-type: none"> • Waste heat recovery systems rely on a low-grade heat source, which means the temperature differentials are not very large and thus tend to have low efficiency potential. 	NRC (2015)

Table 2: Available Fuel Efficiency and Cost Data for Emerging LDV ICE Technology Packages

Technology Package	Fuel Efficiency Improvement Potential	Costs and Payback Period	Remarks	Links to Resources
Turbocharging with downsizing and cooled EGR	<ul style="list-style-type: none"> Up to 30% 	<ul style="list-style-type: none"> \$700-800 0.5-2 years 	<ul style="list-style-type: none"> Offers higher torque at low RPM and greater towing capacity 	Isenstadt et al., (2016)
Turbocharged and downsized GDI engine	<ul style="list-style-type: none"> 8-12% reduction in fuel consumption 			MIT Sloan Lab (2015)
Cylinder deactivation with GDI and variable valve lift	<ul style="list-style-type: none"> 8.5% lower fuel consumption 		<ul style="list-style-type: none"> Direct injection and VVL contribute to higher engine peak torque and therefore improved engine performance. 	Lemazurier et al. (2015)
EIVC and LIVC, variable CR, external cooled EGR, and port WI, on a downsized VVA SI engine	<ul style="list-style-type: none"> Fuel consumption benefit of 6.9% (low load); 5.2% (medium load), 9% (high load) 		<ul style="list-style-type: none"> At the highest investigated load point, the fuel consumption gain is mainly due to the combination of VCR- and WI-related advantages. 	Teodosio et al. (2018)
Electric turbocharger with a 48 Volt BSG	<ul style="list-style-type: none"> Fuel economy improvement over 10% 			De Cesare et al (2017)
Turbocharged engine, GDI, LP-EGR, continuous VVL	<ul style="list-style-type: none"> CO₂ reduced by 3.2% with LP-EGR and another 2.5% by increasing the CR. 			Conway et al. (2018)
DSF with 48V (eDSF)	<ul style="list-style-type: none"> 15 % or better CO₂ reduction 	<ul style="list-style-type: none"> \$100 in extra costs per % reduction 	<ul style="list-style-type: none"> eDSF achieves three types of synergy in operating DSF in conjunction with a hybrid system: increased DSF operating range through torque smoothing, torque assist, and improved energy recovery during deceleration. 	Wilcutts et al. (2019)
Combined mDSF (i.e., DSF with Miller Cycle) -eDSF system	<ul style="list-style-type: none"> 18% CO₂ reduction 			Wilcutts et al. (2019)
mDSF	<ul style="list-style-type: none"> Reduces drive cycle CO₂ emissions by 10 to 12 % 	<ul style="list-style-type: none"> Cost-to-benefit ratio of \$46 per % 	<ul style="list-style-type: none"> Together with advanced engine technologies such as the Miller cycle, Dynamic Skip Fire can deliver a further synergistic fuel consumption reduction. 	Ortiz-Soto & Younkins (2019)
MAHLE powertrain (i.e. DHE, with port fuel injection, a single overhead camshaft (SOHC) without VVT, and two-valve per-cylinder technology)	<ul style="list-style-type: none"> 10-20% increase in thermal efficiency 			Green Congress (2019)
Homogeneous Charge Compression Ignition (HCCI) + Spark Assisted CI	<ul style="list-style-type: none"> Up to 5% reduction in fuel consumption (after 2025) 	<ul style="list-style-type: none"> \$577-706 in direct manufacturing costs for 2025 MY 		NRC (2015)

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