IJER Editorial – The Future of the Internal Combustion Engine

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Executive Summary

Internal combustion (IC) engines operating on fossil fuel oil provide about 25% of the world's power (about 3,000 out of 13,000 million tonnes oil equivalent per year – see Fig. 1), and in doing so, they produce about 10% of the world's greenhouse gas (GHG) emissions (Fig. 2). Reducing fuel consumption and emissions has been the goal of engine researchers and manufacturers for years, as can be seen in the two decades of ground-breaking peer-reviewed papers published in this International Journal of Engine Research. Indeed, major advances have been made, making today's IC engine a technological marvel. However, recently, the reputation of IC engines has been dealt a severe blow by emissions scandals that threaten the ability of this technology to make significant and further contributions to the reduction of transportation sector emissions. In response, there have been proposals to replace vehicle IC engines with electric-drives with the intended goals of further reducing fuel consumption and emissions, and to decrease vehicle GHG emissions.

Indeed, some potential students and researchers are being dissuaded from seeking careers in IC engine research due to disparaging statements made in the popular press and elsewhere that disproportionately blame IC engines for increasing atmospheric GHGs. Without a continuous influx of enthusiastic, well-trained engineers into the profession, the potential further benefits that improved IC engines can still provide will not be realized. As responsible automotive engineers and as stewards of the environment for future generations, it is up to our community to make an honest assessment of the progress made in the development of IC engines over the past century, with their almost universal adoption to meet the world's mobility and power generation needs. Considering that the maturity of IC engine technology is something that many other technologies / possibilities do not have, we also need to assess the potential for future progress, as well as to assess the benefits offered by competitor technologies, in order to make responsible recommendations for future directions.

Factors impacting that future are discussed in this editorial and include:
- the fact that affordable energy has been instrumental in raising the standard of living in the world dramatically, particularly in poor countries, and the fact that so far in the history of humanity the burning of fossil or bio-derived fuels has been the only reliable source of energy;
- the fact that the entire planet is linked by a massive transportation infrastructure that is largely based on the IC engine and that would require decades and tremendous expense to replace;
- the dramatic advancements in IC engine technology that have brought pollutant levels down a thousand-fold in past decades, and which now make particulate emissions from tire and brake wear a larger problem than engine emissions (in both IC engine powered and electric vehicles);
- the obstacles still faced by proposed alternatives, such as electric vehicles powered by batteries, which have tremendous cost, weight and other limitations, and which are hoped to be fuelled by renewables, such as wind and solar that currently represent only a miniscule fraction of the world's energy supply;
- and the fact that concerns about the impact of IC engines on climate change have become politically charged, even as they need to be assessed impartially. There is need for informed, data and science-driven government policies that promote a managed, realistic transition to sustainable future energy systems.

The vast majority of automotive engineers, including IJER editorial board members, are optimistic about the continuing importance of the IC engine to meet the world's mobility and power generation needs. Certainly, exploring new and competing engine technologies, as well as new fuels, is important for a sustainable future for our planet. The inescapable conclusion reached in this editorial is that, for the foreseeable future, road and off-road transport will be characterized by a mix of solutions involving internal combustion engines, battery and hybrid powertrains, as well as conventional vehicles powered by IC engines. Thus, there is a pressing need for recruiting the brightest young minds to engage in this effort.

Why the IC Engine?

The transport of goods and people is essential to modern society, and currently transport is almost entirely powered by internal combustion engines using liquid fuels due to their plentiful supply, convenience and affordability. In addition, stationary combustion engines (e.g., generators, not those for transport or off-road applications) are ubiquitous in our industries and in power generation facilities, which also promote the world's standard of living. Indeed, the demand for available and affordable energy is increasing with the increase in global population and prosperity, particularly in developing countries.

It is important to note that there are still no real alternatives that can compete with the IC engine over the entire range of applications that they cover and that, even today, IC engines are undergoing continuous further improvement [1, 2]. These developments make it even more challenging for competing technologies to gain advantage over the IC engine. Focusing on transport, the demand for energy is very large. There are around 1.2 billion light-duty vehicles (LDV) and around 380 million heavy-duty vehicles in the world, and these numbers are growing. The *daily* demand for liquid fuels exceeds 11 billion litres (~3,000 million tonnes oil equivalent per year, see Fig. 1). All alternatives, whether they are alternatives to IC engines or alternatives to petroleum-based liquid fuels, face very significant barriers to fast adoption. But, ill-informed mischaracterizations of combustion have led to a belief in many quarters that the death of the internal combustion engine (ICE) is both desirable and imminent. For example, many people believe that most of the world's greenhouse-gas emissions come from cars and trucks, a misconception that is grossly incorrect, as discussed later. It is therefore not surprising that some young people are dissuaded from, or feel guilty for undertaking ICE research, the primary interest of this journal.

There is still great scope for even further improvements in engines with advances in combustion technologies, especially when combined with electrification. This has been recognised by the major Original Equipment Manufacturers (OEMs) and Ref. [3] describes Toyota's release of its patents aimed at making hybrid technologies accessible to more manufacturers, which they believe will encourage production of electrified vehicles, including IC engine hybrids, plug-in hybrids, fuel cell and even fully electric vehicles. Indeed, it would be short-sighted if research and development on advanced power plant concepts slows, or is discontinued.

Engine Emissions and the Environment

Throughout the history of the IC engine – and decades before climate-change concerns became prominent – researchers have striven to improve its fuel efficiency, to reduce pollutant emissions and operating costs, and to ensure the optimal use of finite fuel resources for current and future generations. Over the last four decades, in response to air-quality concerns, research on engine combustion, exhaust after-treatment, and controls has led to a demonstrably cleaner environment thanks to a thousand-fold reduction in hazardous exhaust emissions (particulates, NOx, CO and unburned hydrocarbons). Many advances in these areas have been documented by technical papers in this journal [4]. Recently, however, major increases in concern about both air quality and the impact of greenhouse-gas (GHG) emissions on global warming have begun to drive local, national and international policy. Several initiatives are calling for drastic changes, and vehicle electrification is being heavily promoted. For example, the C40 Cities Climate Leadership Group, a group of 90 of the world's cities, which represents more than 650 million people and one quarter of the global economy, is focused on driving urban action to reduce greenhouse gas emissions and climate risks. Demands include eliminating combustion engines from inner city transport and the use of wind and solar as primary energy sources. However, as shown in Fig. 1, wind and solar supply only a very small fraction of current energy needs. Despite technical advances and cost reductions for wind and solar power, it appears very unlikely that most fossil-fuel energy sources will be replaced by alternative carbon-neutral sources over the next two or three decades [5].

Energy independence and energy security also play an important role in determining policy in many countries. Climate concerns must also be balanced by the observation that, by all objective/empirical measures of human development (e.g., absolute poverty levels, life expectancy, share of the world’s population that is undernourished, education ….), the world has been improving consistently, particularly in poorer countries, over the past decades due to the availability of affordable energy, and due to the combustion of fossil fuels in particular. The developing world will continue to focus on growth and on moving their populations out of poverty, and this simply cannot be achieved through wind and solar alone - most of the world’s electricity will still come from the combustion of coal or natural gas for decades. Climate justice must demand that the world’s poor (not just the elite in Western countries) have a right to a better life. This requires the availability of affordable energy, including from fossil fuels, until such time that proposed alternatives, such as wind and solar, and possibly as-yet-undiscovered technologies, become practical and affordable. But, for this to happen, significant obstacles will need to be overcome, including developing the means to store energy for use when there is no sun shining or wind blowing. The development of batteries capable of storing enough energy to meet needs is still a bottleneck, and was, in fact, even bemoaned by Thomas Edison to Henry Ford in their competition for control of transport engines over a 100 years ago!

IC Engine and Electrification

It is likely that future mobility will be characterized by a mix of solutions, involving battery electric and hybrid electric vehicles (BEV, HEV), fuel cell electric vehicles (FCEVs), and conventional vehicles, depending on consumer acceptance (e.g., cost), the country considered, and the specific application (city, country, personal, freight, etc.). Thus, the combustion engine will still play a central role, whether used for power generation or for powering the vehicle itself, even in strongly electrified powertrain configurations. Because of this, there is great interest in improving the thermal efficiency of IC engines without significant increases in purchase and operating costs in the short-to-medium term. These goals can be achieved through improvements in combustion, after-treatment and control systems, and by partial electrification in the form of hybridization, together with vehicle weight reduction and more efficient ancillary systems.

Although there is great current interest in the electrification of transport, only battery electric vehicles eliminate the need for an IC engine. However, life-cycle analyses [6] of the GHG impact of BEVs that consider the energy used in electricity generation and battery manufacture show that their true benefit is significantly less than is apparent at first sight. Many analyses ignore the upstream CO_2 in fuel extraction, refining and transportation, as well as in the production and distribution of electricity. Large amounts of energy are required to extract the critical raw materials needed for batteries and electric motors (cobalt, lithium, rare earths, etc.), together with huge amounts of water. End-of-life disposal -- toxicity in particular -- also needs to be factored into life-cycle analyses. (Many of these considerations also apply to equipment for wind and solar photovoltaic power generation.) Moreover, the construction of a new electricity infrastructure, capable of recharging millions of BEV's, will require further raw materials and energy consumption (with consequent CO_2 emission), and may be limited by the availability of critical materials.

The high cost of BEV's, as compared to IC-engine-powered vehicles (conventional or hybrid), is also driving the development of effective, but previously deemed uneconomical, methods to increase the IC engine's efficiency with advanced combustion modes, and to further reduce pollutant emissions. In this sense, the competition between electric motors and IC engines is stimulating beneficial evolution of the thermal engine itself.

"Zero Emissions"

It has been estimated that the fuel consumption in Spark-Ignition (SI) vehicles could be reduced by as much as 50% in the U.S. compared to the current average [2], and tailpipe CO_2 emitted will be reduced correspondingly. With existing catalysts and control systems - and these continue to be improved - particulates, NOx, unburned hydrocarbons (uHC) and CO could also be reduced to negligible levels from both SI and diesel engines. Frequently, pollutant emissions and CO_2 emissions from combustion are presented as being entirely equivalent, so that even engines with exceedingly low criteria pollutant emissions (NOx, CO, uHCs and particulates) are also regarded as polluting. Technically and practically, there is an important distinction. CO_2 emissions necessarily accompany any hydrocarbon combustion or chemical oxidation process, including human and animal life. The CO_2 emitted from an engine is directly proportional to the hydrocarbon fuel consumed, which is continually being reduced by technological improvements.

In terms of the criteria pollutants, the goal to achieve "zero impact emission vehicles" is very close, thanks to advanced combustion modes and innovative after-treatment systems, including extensive use of catalysts and high-filtration-efficiency Diesel and Gasoline Particulate Filters (D/GPF) in the after-treatment system, while the use of urea injections and Selective Catalytic Reduction (SCR) is leading to extremely low NOx emissions (e.g., 0.02 g/bhp-h or 15-20 mg/km). Indeed, there are even examples of vehicles having tailpipe unburned HC emissions below those in the ambient air at the engine's intake, so-called negative emission vehicles!

Indeed, the pollutant emissions discharged at the tailpipe outlet will be so low as to be hardly measurable, and their practical impact on air quality will be negligible. In terms of particulate matter emission, the impact of tire and brake wearing is already much higher than that due to the IC engine (tire wear produces around 50 mg/km of particulates), reaching values around ten times the emission from the engine (5 mg/km) [7]. This implies that today's conventional IC engine-powered-car is equivalent to fully electric and hybrid cars with regard to particulate emissions, when tire and brake and other contributions (e.g., road dust) are accounted for.

There are routes to short-term CO_2 reduction that are viable more quickly. First, a switch from gasoline to diesel internal combustion engine reduces CO_2 emissions by an estimated 11% at the tailpipe, and a diesel mild hybrid delivers a further 6% reduction. The final swap to full hybrid delivers another 16%. Note, however, that there is a public misconception, based on obsolete technologies and the recent emissions scandal, that the diesel engine is a high-pollution engine. As discussed above, this ignores the major advances that have been made in the last several decades in diesel engines and exhaust emission after-treatment.

Significant improvements to gasoline engines are also available with vehicle electrification. A direct switch from gasoline to gasoline-mild-hybrid can deliver 11%, and a further 23% in moving to full hybrid [2]. As these numbers demonstrate, there are immediate-term options for significant fuel efficiency improvement and hence CO_2 reduction of the order of 30% or more, for both gasoline and diesel.

It is also clear that “zero emissions” BEVs will not replace IC engines in commercial transport to any significant degree also because of the weight, size and cost of the batteries required [6]. Short of a major breakthrough in battery technologies, for the foreseeable future combustion engines, running on petroleum-based liquid fuels, will largely continue to power transport of the world’s goods and services. A transition from the gasoline or diesel internal combustion engine to a full gasoline/diesel hybrid can significantly reduce emissions [2]. But, due to the long turn-over and replacement time of vehicles, it will take a long time (decades) for full hybrids - even if they become common-place and affordable options - to become a major fraction of the world’s vehicle population. The sustainability of transport in terms of GHG and other environmental impacts, affordability and energy security can certainly be ensured by improving combustion engines, and this requires renewed emphasis on engine research and development.

Fuels

In the medium-to-long term, there is even greater scope for improving engines by co-designing fuel/engine systems for optimal performance [8]. Single- and dual-fuel technologies, such as HCCI, PCCI and RCCI [9, 10] offer significant promise for improving efficiency and reducing unwanted exhaust emissions. These advanced combustion modes can also benefit from available fuels or fuels whose composition is optimized for each application. To also reduce dependence on fossil fuels and for a decarbonization transition, progress is being made in the introduction of CO_2-neutral biofuels and synthetic fuels. Often, criticism of the internal combustion engine is not about the engine, but about the source of the fuel, and the use of bio or synthetic fuels can mitigate total carbon emissions. Indeed, some marketed biodiesels are more than 70% net-carbon neutral today. Some countries and states have even implemented a Low Carbon Fuel Standard (LCFS) and provide monetary incentives to encourage the biofuel market.

Hydro-treated Vegetable Oil (HVO) is a promising renewable drop-in fuel for diesel engines with very low CO_2 impact. Another emerging technology produces liquid transportation fuels from solid ligno-cellulosic, non-food biomass via fast pyrolysis, which is a thermal decomposition process that breaks down materials by heat in the absence of oxygen, producing syngas, bio-oil, and biochar. Bio-oil can be upgraded catalytically to liquid fuels. As a result, fast pyrolysis of waste biomass can produce biofuels and could enable a reduced carbon economy.

The use of alternative, synthetic fuels derived from waste bio-mass and renewable electric energy has also been proposed to produce an electrofuel (e-fuel) with net zero CO_2 emission (i.e., carbon neutral). This approach is currently being investigated as a smart way to store renewable electric energy when a production peak occurs, thanks to a chemical process to generate hydrocarbons from H_2 (produced by electrolysis of water) and CO_2 captured directly from the atmosphere or from other industrial- or bio-sources. Longer term, carbon capture technologies have been demonstrated to be able to collect and then dispose of or sequester CO_2 from vehicle tailpipes, and are projected to be cost effective [11].

Energy Sources and the Future

For electrification, electricity has to be produced, either by the IC engine (in the case of a hybrid vehicle), or from a power generating station and the grid. For the latter, it is currently mainly produced from non-renewable energy sources (with about ~40-50% losses, although these can be substantially higher for older coal-fired power plants which are still prominent in much of the world). In addition, the transport of electricity to the end user, together with corresponding charging/discharging losses at the battery, and the role of low or high operating temperatures in reducing battery performance accounts for another ~5-20% loss, resulting in an overall efficiency that is actually comparable to that of hybrid vehicles powered with IC engines and fossil fuels. Perhaps there is a political advantage to drawing power from the grid in that unwanted emissions are “not in my back yard.” The problem is flushed away to less visible areas, but with substantially less – and sometimes no – reduction in global carbon footprint. Indeed, a BEV charged from coal-fired electricity can easily have a larger carbon footprint than a comparably sized non-hybrid IC-engine-powered vehicle.

Renewable sources (including hydroelectricity) currently constitute about 10% of the global energy mix. The BP review of World Energy [5] forecasts that the fraction of total energy production from renewables will only reach about 14% by 2040, and in many regions, fossil fuels, including coal, will remain the greatest source of energy. It is therefore clear that in the medium term, the alternative of BEV transportation may modestly reduce, but will by no means eliminate, global CO_2 emissions. Of course, with a reduction of coal-fired electricity and transition CO_2-neutral technologies this situation could change.

Furthermore, much faster charging will be needed for broad market acceptance of plug-in and battery electric vehicles – note that essentially all scenarios currently involve substantial taxpayer or consumer subsidies for such chargers. In addition, mass electrification will require dramatic alterations to the entire electrical distribution system, from the power plant to the charging point. Given these issues, even the more aggressive mainstream market forecasts show IC engines still being in most cars in 2040 [12], and representing an even higher portion of the truck market.

Replacement of IC engines in heavy-duty transportation faces even greater difficulties in these respects. For example, a heavy-duty Class 8 truck in the U.S. with a 500-mile range, operating as an electric truck requires a battery with energy of ~1,000 kWh. Assuming a battery-to-motor efficiency of 95%, the appropriate battery weighs at least 5.5 metric tons (compared to about 1.3 metric tons for its diesel engine), and it consumes a significant part of the allowable payload. With the 120 kW Tesla Supercharger the battery takes around 12 hours to charge [6]. In addition, there is little discussion on replacing train and ship engines, a testimony to the extreme power requirements and unacceptably long battery charging times needed for these applications [6].

A sustainable mobility future will require a diverse portfolio to ensure the right technologies for the right applications, and it will span IC engines, fuel cells, pure EVs, and hybrid-driven propulsion systems. Like-for-like (“apples-to-apples”) comparisons are critical for accurate technology assessments of social, economic, and environmental impacts. More specifically, successful technologies must be market competitive in cost, user requirements, lifecycle emissions, and lifecycle efficiency; must ensure domestic energy security; and must consider societal impacts related to manufacturing and the acquisition and recycling of critical materials. To this end, the internal combustion engine and supporting infrastructure are well established, and innovations associated with technology developments continue to improve the overall efficiency and emissions signature of combustion-based technologies.

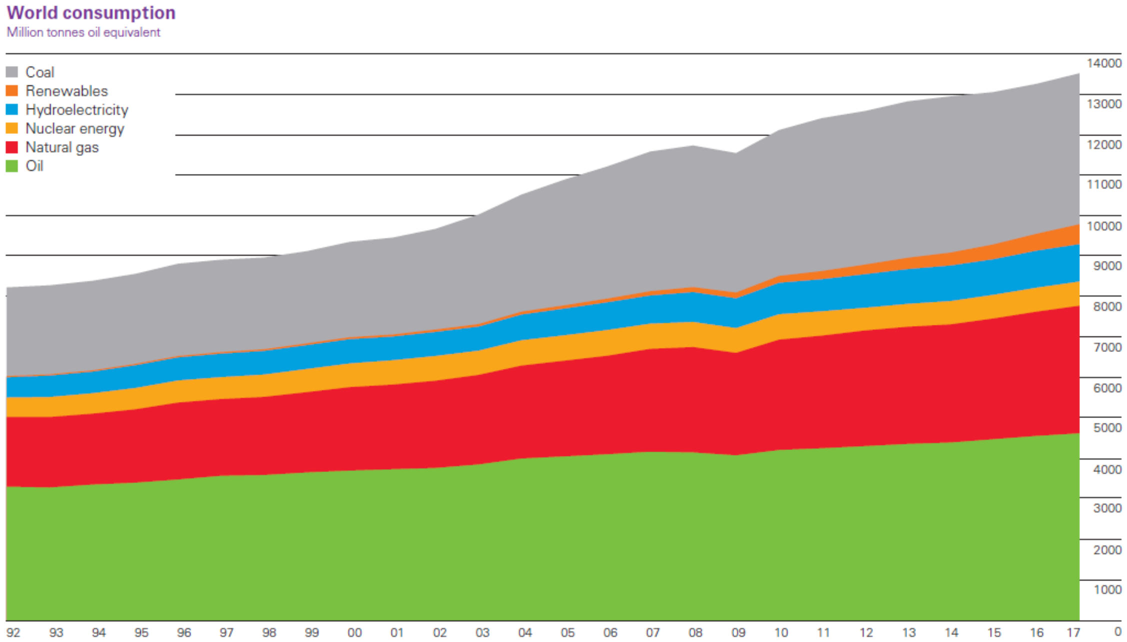

Figure 1: World energy consumption by source (millions of Petroleum equivalent) in the last 25 years [5]. About 70% of fossil oil (i.e., about 3,000 Mtoe) is consumed in IC engines.

The Climate Alarm

Popular and governmental response to predicted effects of anthropogenic global warming ranges from skepticism to alarm, with alarm dominating recent public perception, media content, and announced national and regional policies. The necessity for, and/or the role of engine combustion research and development in the race towards a CO_2-emission-free world is under debate, but we as the engine combustion research community, believe that the IC engine will continue to play an important role, if only for the reason that such an energy transition would undoubtedly take significant time. However, there is still controversy about the precise role of anthropogenic GHGs and CO_2, as well as the major greenhouse gas, water, on global climate change [13]. An overlooked fact is that, with hydrocarbon fuels, each molecule of CO_2 leaving the vehicle's tailpipe is accompanied by at least one molecule of H_2O. The actual balance between water vapor (as a GHG), and the clouds in the atmosphere, which reflect solar rays back into space and thus cause cooling, is still an active area of climate research [14].

Often, in the popular press, the debate is between those who quote unproven climate models that predict disastrous effects on our climate, and those who appreciate the catastrophic consequences, particularly on the poorest among us, in abandoning fossil-carbon-driven sources of energy (as well as the IC engine) that have driven the development of civilization so far. In any event, it should be clear that the practical consequences of societal action inspired by climate concerns could dramatically affect not only the long-term future of IC engines, but would also impact all aspects of energy and power use, as well as the standard of living on our planet. Major improvements of the combustion engine will be necessary to achieve dramatic reductions of GHG emissions in the coming decades.

With regard to greenhouse gas emissions, the contribution of transport to Global Warming Potential emissions has historically remained at 10%, as seen in Figure 2 [15]. Thus, a worldwide massive shift to electric vehicles could only result in a global (potential) reduction of about 10% of the equivalent tonnes of CO_2. (This also assumes that all electric vehicles would charge their batteries from energy sources without CO_2 emissions (i.e., renewable/nuclear).) Even for light-duty vehicles, as outlined in this editorial, an all-electric future will not arrive easily, quickly or cheaply, and IC-engine-driven transportation still has a major role to play for at least the next three decades [6]. It would be tragic if industry and governments were to abandon the very real near- to medium-term reductions in CO_2 and criteria emissions that are achievable with IC-engine-based propulsion because of over-optimism about the rate at which renewable or decarbonized sources can replace fossil-fuel energy for transportation.

(On the other hand, the rapidly expanding universe of consumer electronics is poised to outpace transportation as a source of global energy consumption. In 2015, Internet-connected devices, high-resolution video streaming, e-mails, surveillance cameras and smart TVs consumed 3% to 5% of the world's electricity. The growth of the Internet of Things, driverless cars, robots and artificial intelligence (AI) is adding significantly to this demand for power. It has been estimated that computers and communications could use as much as 20% of the world's electricity by 2025.)

We believe that public advocacy and educational programs, both in schools and in families, should focus not on instilling fear of global warming and climate change, but on how humanity can arrive at a hopeful future through increased efficiency of IC engines and other energy-consuming systems, development of renewable power sources, rational policy-making based on full-life-cycle analysis of alternatives, and systematic mitigation of the potential effects of global warming, as well as voluntary self-moderation of our consumer instincts.

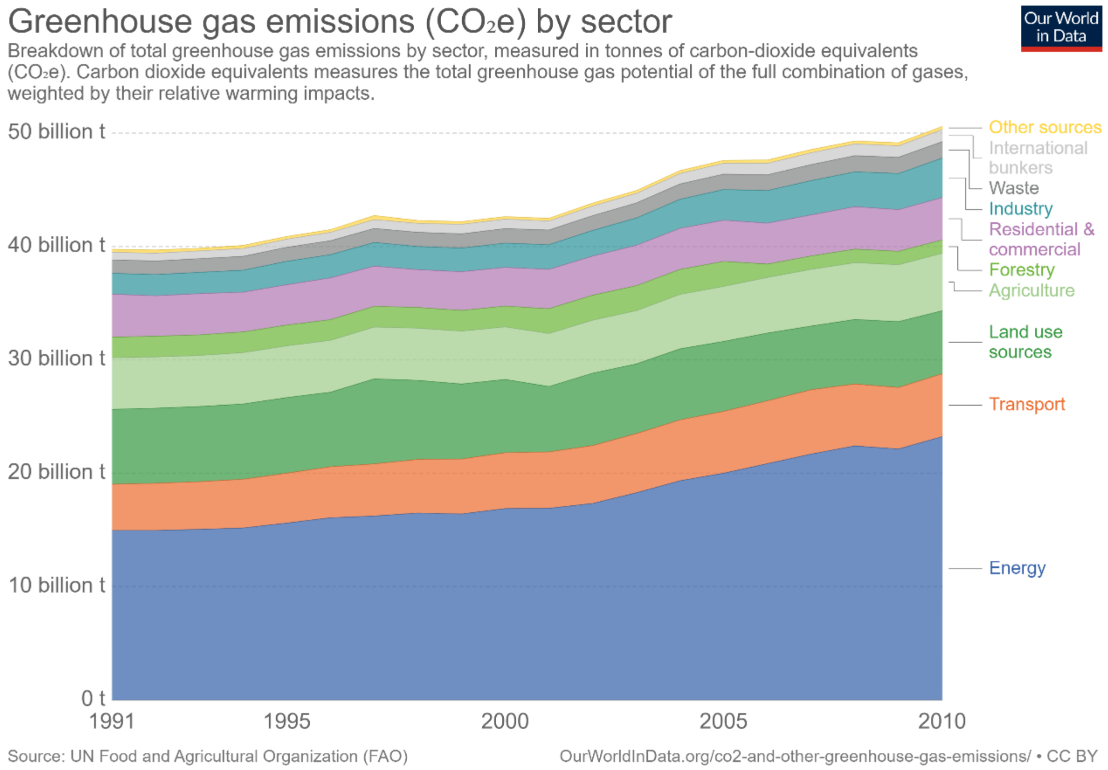

Figure 2: Global Warming Potential (GWP) in CO_2 equivalent tons by sector [15]. Transportation contributes about 10%.

Future research directions

Since its inception almost 20 years ago, this journal has chronicled advances in research in engines [4]. The journal's goal continues to be to provide a stimulating forum to encourage progress in IC engine R&D. In this spirit, the final section of this editorial provides a (possibly incomplete) list of potentially fruitful research topics that would be helpful to the field of engines. Advances in these areas would certainly benefit from worldwide collaborations between researchers in industries, government laboratories and academia.

Engine efficiency –

Combustion system: The development of novel combustion systems, including use of ultra-high fuel injection pressures, and new mechanical layouts, possibly beyond the slider crank, should be encouraged. This could be paired with combustion technologies with highly diluted combustion (stoichiometric with EGR as well as lean burn with excess-air ratios above 2). For this combustion improvement, mixture formation and charge motion, and ignition technologies including installation of pre-chambers need to be investigated.

Gas exchange: Improvements in engine breathing are of interest, potentially via exhaust gas turbochargers to realize fast response and low temperature combustion with ultra-high-pressure supercharging, large quantities of EGR, and further improvements in the Miller cycle with variable valve systems, while maintaining the required oxygen levels. Further development of exhaust gas energy recovery systems with turbo-compounding and possibly chemical reforming should be encouraged.

Electrification: offers significant improvements in system efficiencies, as well as GHG control, possibly leading to thermal efficiencies beyond 50%. The development of more efficient engines specifically for hybrid and range-extender systems (which enable the engine to run over a limited speed-load range) would also be helpful.

Engine lubrication: Reduction in mechanical loss should be achieved by improving lubrication systems with less oil consumption, especially for new engines with restricted operational areas in loads or speeds.

Engine thermal and energy management: is needed to comply with Real Driving Emissions (RDE) and to improve fuel economy. Not only reducing IC engine heat losses, but also improved thermal systems that include exhaust heat recovery systems, after-treatment systems, and their optimal control will be key technologies for the future.

Engine after-treatment –

Emissions-reduction technologies leading toward near zero emissions are required also by regulations. The establishment of improved and low-cost after-treatment systems to remove unburned hydrocarbon, particulate matter and NOx emissions under low temperature and excess oxygen exhaust gas conditions without sacrificing thermal efficiency is needed. Methods to reduce RDEs from gasoline engine vehicles at full load in enriched combustion or cold starting (which generate much particulate matter) with less expensive after-treatment devices should be explored.

Fuels –

The efficient utilization of dual-fuel combustion, and combustion of diesel/natural gas should be researched. In addition to ultra-dilute burn and development of direct gaseous fuel injection systems, research is needed to reduce methane slip and to improve thermal efficiency and exhaust gas emissions on natural gas engines, especially for large ships and co-generation. Analysis of global fuel usage suggests that the use of surplus low octane number fuels will become an important topic in the near future [16]. Also, intensified research on bio- and e-fuels for GHG mitigation would be helpful. “Designer” fuels offer the potential for efficiency improvements and near-zero pollutant emission [17]. These could include admixtures of variable H_2-quantities to hydrocarbons, oxygenated components and even quite new chemical components (e.g., NH_3).

Research tools needed for engine development include:

Engine simulations -

Supported by detailed experiments, there have been great advances in Computational Fluid Dynamics (CFD) modelling of combustion processes. Simulation tools are now heavily used by most engine OEMs to help design and optimize engines, benefitting from the vast computational power available to both industry and academia (e.g., [18]). Thanks to the rapid development of AI, various automatic predictions and optimizations are also being put into practical use. However, the optimization of engine combustion relies on accurate sub-models, many of which need further development to increase their predictive capability, as well as to reduce the need for empirical calibration. This is an active area of research utilizing Direct Numerical Simulations with an imminent introduction of machine learning and data science technologies. In addition, engine combustion includes transient phenomena such as cycle-to-cycle variations that are not well understood or analysed. Development of vehicle simulation models that include the power source together with its system components, transmission, peripheral devices, battery, motor, inverter and driving drag is needed.

Engine and vehicle control –

Real-time combustion control to reduce control margins and cycle-to-cycle variations requires calibration and control software innovation, possibly with on-board physical / statistical model-based control using AI. On-board optimization of multi-input / multi-output systems with model predictive control is needed. Control of efficient fuel injection systems to optimize mixture formation spatially and temporally in the combustion chamber, and methods to ensure stable ignition in very lean or dilute mixtures in SI engines, possibly using pre-chambers, and low-temperature plasmas would be of interest. Also, the use V2X to reduce fuel consumption of vehicles in real driving conditions needs to be analysed.

Closure

In summary, the Internal Combustion Engine, and IC engine research have a bright future, in contrast with some widely distributed media reports (e.g., [19]). The power generation and the vehicle and fuel industries are huge, representing trillions of dollars (US) per year in turnover, with a massive infrastructure. We are certainly in revolutionary times, but it is clear that power generation sources will not become fully renewable and transport will not become fully electric for several decades, if ever. However, research to improve efficiency and methods to reduce dependence on fossil fuels are exciting directions for future IC engine research. It is very likely that highly efficient "fully flexible" engines with hybridized solutions will be a big part of sought-after efficiency improvements, as well as emissions/GHG reductions [20]. Finally, it must be acknowledged that, in practice, people select their choice of powertrain based on numerous factors, including cost. Consumer preference is not decided by politicians, nor by car-makers, nor academia. Policy unilaterally favoring one technology solution may be deeply inefficient and perhaps even the wrong eventual solution. A better approach is to use real-world data to allow competing technologies to flourish if they evidence efficiency improvements and emissions reductions, and they then need to be delivered as soon as possible. Continued progress requires that we recruit the brightest young minds to engage in this effort to deliver a vibrant and sustainable future for the internal combustion engine.

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