CENTER FOR AUTOMOTIVE RESEARCH

Center for Automotive Research (CAR)

1000 Victors Way, Ste. 200
Ann Arbor, MI 48108
Phone: 734.662.1287
Fax: 734.662.5736

Advanced Power Technology Alliance
Advanced Internal Combustion Engine Survey
(Light Duty Vehicle Technology)

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Brett C. Smith
(bsmith@cargroup.org)
Director, Product and Technology Forecasting
Manager, Advanced Powertrain Programs
Center for Automotive Research

FOREWORD

The Advanced Power Technology Alliance is a program sponsored by the Michigan Economic Development Corporation and the Herbert H. and Grace A. Dow Foundation. The goal of the Alliance is to encourage the development of advanced power technologies and position the State of Michigan as a leader in this rapidly evolving sector.

The Advanced Internal Combustion Engine survey is based on the Delphi forecasting process and is highly dependent upon the quality of the small 'expert' panel. Great care was taken to identify experts in important areas of advanced internal combustion engine technology. These experts were then asked to respond to a questionnaire pertaining to advanced internal combustion engine technology. The survey had 16 carefully selected respondents, and each question had a response count of at least 10. The panel includes academics, automotive manufacturers and suppliers, non-government organizations, and energy representatives. While these numbers are low for a traditional survey, work done by the Rand Corporation for the U.S. Air Force in the late 1960s indicates that a small panel of experts with an interactive review of results can be a highly effective method of forecasting.

The survey data is presented in tables using arithmetic means for questions or a one through five scale. When the question calls for a response in the form of a number estimate, results are presented in medians with interquartile ranges (IQR)—that is, the point at which 25 percent of the answers are below the lower IQR and the point where 25 percent of the answers are above the upper IQR. The IQRs are useful to illustrate the relative consensus of the panel. Narrow IQRs indicate a strong consensus while a wider spread suggests a lack of agreement or relative uncertainty. Panelists' edited comments are included to give context and color to the numerical tables. These comments are particularly useful in understanding questions where there are large differences in opinion due to uncertainty or differing strategies.

A key point to keep in mind is that the expert panels' estimates represent their deep understanding of this very challenging technological issue. However, it is not a precise statement of the costs and efficiency potential of the investigated technologies. Instead, it presents a range of highly informed estimates and shared insights. We strongly urge the reader to consider spending time contemplating each of the selected comments. This document provides opportunity to benchmark opinion, test results, and strategies. In retrospect, some topics and issues will be more accurately predicted, others less so; but the data and comments presented in this survey offer a strong, shared experience-based description of advanced internal combustion engine technology.

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DEFINITIONS

Light Duty Vehicles: All questions pertain to light duty vehicles—passenger cars and light trucks up to 8,500 lbs. ETW.

Advanced Spark-Ignited Engine: Traditional gasoline spark-ignited engine that, through the addition of fuel efficiency designs and technologies, achieves 20 percent better fuel efficiency than the current spark-ignited internal combustion engine.

Fuel Efficiency Improvements: All questions requiring fuel efficiency percentage changes should be based on EPA Federal test cycle standards.

Tier 2 Regulations: (fully implemented 2009) for NO_X and particulate matter (PM).

	BIN 8	BIN 5	BIN 2
NO_x (PPM)	0.20	0.07	0.02
PARTICULATE MATTER (PPM)	0.02	0.01	0.01

EXECUTIVE SUMMARY

The internal combustion engine (ICE) has been the predominant powerplant in the automobile for nearly a century. Recent developments in alternatives to the ICE—especially gasoline/electric hybrid fuel cell power—have garnered significant media and public policy attention in recent years. However, the ICE remains a difficult and moving target. Although a century of development has lead to a highly refined technology, there is still some opportunity for further fuel efficiency gains. The Advanced Internal Combustion Survey addresses the opportunity and associated costs for the future development of the spark-ignited (gasoline) and compression-ignited (diesel) internal combustion engines.

The panel forecasts a moderate increase in fuel prices in the coming decade (approximately 35 percent). However, their forecast should be used, not necessarily to forecast the price of gasoline, but instead to put the remainder of the survey into context. A price of gasoline nearing the high end of the interquartile range may increase customer acceptance of more costly fuel efficiency technologies, while a real price nearer the lower end of the quartile may make such technologies a greater challenge to sell.

The spark-ignited gasoline engine has become the mainstay in the U.S. light duty vehicle market. The panel was asked to estimate cost and potential fuel efficiency improvements for eight engine technologies/strategies, and seven valvetrain technologies. Homogeneous charge compression ignition (HCCI) and direct injection were identified as engine strategies that offer significant opportunity for fuel economy improvement. Gasoline direct injection is a more developed technology than HCCI—which is still very much in the early developmental stage. However, both face significant hurdles in meeting future emission standards, especially NO_x. The panels' responses illustrate the opportunity, but also the cost and other challenges, associated with the additional technology. While panelists give valuable estimates for these technologies, they also indicate that these technologies are not additive. All too often, readers of reports such as this may assume that different technologies offer the opportunity to merely 'add-up' those technologies with the highest fuel economy gains (or the best cost-to fuel efficiency gains) and arrive at a, rather large, potential fuel economy improvement. The panelists present a strong case that the technologies highlighted are not additive. Yet, they indicate there are opportunities for synergy between selected engine technologies and other vehicle systems that may allow for significant fuel economy gains.

The panel also gives estimates for cost and fuel economy improvements for direct injection compression ignition (diesel) engines. Here too, the survey highlights opportunity—but also corresponding costs for further gains. The CIDI engine already offers significantly better fuel efficiency than the spark-ignited engine. The challenge for the diesel engine remains emissions, specifically particulates and NO_x. The panelists indicate a belief that after-treatment technologies may be technically viable to enable the CIDI to meet tier 2 Bin 5 requirements. However, they indicate it will take a comprehensive systems approach, including fuel injection, air management, combustion chamber design and after-treatment, for the diesel engine to meet the more stringent standards.

Although industry stake holders must work to develop alternatives to the current vehicle, it is essential to understand that the internal combustion engine is likely to be the dominant power source in the U.S. market for at least the next decade. The Advanced Internal Combustion Engine Survey presents an important piece in the discussion regarding emerging technologies that could enable the internal combustion engine to remain the dominant power source for the near future.

I. FUEL PRICES

ICE-1 Please estimate U.S. retail fuel prices per gallon for 2013, including fuel tax. Please use constant 2003 dollars. (Please consider government intervention and market forces.)

FUEL	ESTIMATED 2002*	MEDIAN RESPONSE 2013	INTERQUARTILE RANGE 2013
DIESEL	$1.32	$2.08	$1.76 / $2.43
GASOLINE, REGULAR	$1.36	$2.20	$1.79 / $2.50
GASOLINE, PREMIUM	$1.58	$2.54	$2.04 / $2.85

*U.S. D.O.E. 2002 weekly national average

COMMENTS

- Higher prices will be primarily caused by higher fuel quality requirements. Of course, prices will be volatile because oil prices will be volatile.
- Estimating the mean with +/- $0.30 variability.
- All of a sudden fuel taxation seems a popular concept. I expect some states to use this. I expect by 2013 global warming to be accepted by the United States government, and taxes are an obvious method to address the issue.
- The effect from Iraq oil production will have great impact.
- Estimating 50 percent increase in real price.
- Based on the expected increase in the cost of living. Other factors might contribute, such as political and international. Finally, it is the supply and demand that controls the price.
- Inflation is very low and should stay that way. No shortage of crude oil. Only unusual political problems could temporarily cause crude oil and refined products to rise faster than the underlying inflation rate.

STRATEGIC CONSIDERATIONS

The panel expects an increase in constant dollar gasoline prices in the coming decade. Given current global political instability—specifically in some important crude oil-producing regions—this forecast for higher fuel prices is understandable. However, it is important to note that the constant dollar price of gasoline in the United States continues to hover at times near historical lows. Another caveat with regard to this forecast: The panel was asked to base their estimates on the 2002 weekly average. The 2003 weekly average for regular gas was $1.56—a substantial year to year increase.

The price—or the expected price—of gasoline plays a very important role in the development and application of advanced powertrain technologies in the U.S. automotive market. Expectations for relatively low, stable fuel availability might suggest little consumer demand for more costly fuel economy technologies. Conversely, a forecast for significantly more expensive fuel would signal an opportunity for increased application of advanced technologies. The responses to this question should be used, not necessarily to forecast the price of gasoline, but instead to put the remainder of the survey into context. A price of gasoline nearing the high end of the interquartile range may increase customer acceptance of more costly fuel efficiency technologies, while a real price nearer the lower end of the quartile may make such technologies a greater challenge to sell.

II. SPARK-IGNITED ENGINE TECHNOLOGY

ICE-2a Please estimate component/system cost for the listed technologies currently and in 2013. Please base estimate for cost on a 6-cylinder DOHC (4 valves per cylinder) V-configuration engine.

SPARK-IGNITED ENGINE TECHNOLOGIES	COMPONENT COST AT MANUFACTURING VOLUMES OF 400,000 UNITS			
	2003		2013	
	MEDIAN RESPONSE	INTERQUARTILE RANGE	MEDIAN RESPONSE	INTERQUARTILE RANGE
COMPRESSION RATIO—VARIABLE	Not available	Not available	$300	$275 / $350
CYLINDER DISPLACEMENT—VARIABLE	$300	$275 / $350	$150	150 / 240
DIRECT INJECTION (DISI)—STOICHIOMETRIC	$250	$188/ $462	$200	$200 / $300
DIRECT INJECTION (DISI)—STRATIFIED CHARGE LEAN	$600	$300 / $700	$300	$200/400
HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI)—GASOLINE	Not available	Not available	$400	$238 / $525
LEAN BURN (PORT FUEL INJECTION)	$200	$100 / $350	$200	$100 / $200
SUPERCHARGER	$325	$269 / $425	$325	$225 / $400
TURBOCHARGER	$250	$200 / $350	$200	$175 / $325

OTHER

- Impulse charger: Current Cost $90; Cost in 2013, $30
- Cylinder-level mixture control: Current Cost, $100; Cost in 2013, $30

COMMENTS

- Costs are net costs (accounted for deleted or replaced content), costs do not account for exhaust treatment costs to meet regulatory compliance.
- Variable displacement will become as popular in North America as cam phasing is in Japan or diesel is in Europe. Long term HCCI is a must. It requires camless to enable it. Variable compression ratio is just a passing fad, you can have it for free with camless.
- I assumed variable displacement is cylinder deactivation
- The cost of supercharging and turbocharging depends very much on whether the engine is downsized to achieve the same power as a baseline North American engine (in that case the lower figure should be used), or it's based on the same displacement for significantly increased performance (higher figure).

ICE-2b Please estimate potential fuel economy improvements, as measured in percent change, for the listed technologies. Please base estimates for fuel efficiency gains on a 6-cylinder DOHC (4 valves per cylinder) V-configuration engine. Note: Your estimates should address each technology individually.

ENGINE TECHNOLOGIES	PERCENT FUEL EFFICIENCY GAIN	
	MEDIAN RESPONSE	INTERQUARTILE RANGE
COMPRESSION RATIO—VARIABLE	7%	5% / 9%
CYLINDER DISPLACEMENT—VARIABLE	8%	6% / 8%
DIRECT INJECTION (DISI)—STOICHIOMETRIC	7%	5% / 10%
DIRECT INJECTION (DISI)—STRATIFIED CHARGE LEAN	12%	10% / 15%
HOMOGENEOUS CHARGE COMPRESSION IGNITION—GASOLINE	14%	9% / 20%
LEAN BURN PFI	5%	4% / 8%
SUPERCHARGER	5%	5% / 9%
TURBOCHARGER	5%	4% / 11%

OTHER

- DaimlerChrysler magic engine technologies: 14%
- Boost/downsized displacement: 15%
- Miller-Atkinson: 10%
- Cylinder-level mixture control: 5%

COMMENTS

- I assume performance is held constant. It also depends a lot on what the reference engine is; lots of negative synergy at work here, e.g., the DaimlerChrysler 'Magic' technologies probably wouldn't give 14 percent if placed on a variable valve timing engine.
- Fuel economy gains from supercharger and turbocharger required downsized displacement to result in equal performance, but reduced fuel consumption.
- The American gasoline car market is the assumed application. It is not reasonable to separate out the compression ratio, expansion ratio, and pumping loop gains inherent in HCCI from its combustion efficiency gains. Camless wins out in fuel economy because many improvement strategies are possible.
- Assuming turbochargers and superchargers versus larger displacement. North American engine of same power rating.
- Not additive, of course. Estimates assume optimal use of each technology for fuel economy, incorporating any needed engine system re-optimizations, including displacement reduction at constant performance.

- I would place the benefit of direct injection stratified charge between10 to 12 percent. Most of the press for this technology has been for cars certified to the less stringent Japanese standards
- I expect HCCI will get close to a 20 percent improvement. The value of 5 percent fuel economy for supercharging is way too low. Values approaching 20 percent improvement for supercharging have been reported.
- I believe supercharging will not remain at the same cost in the next 10 years as the increased use of titanium will drop its cost considerably and is a material well suited for superchargers.

STRATEGIC CONSIDERATIONS (2A AND 2B)

It is important to note that the efficiency gains for the listed technologies are not necessarily additive. In fact, many of these technologies address the same inefficiency—that of internal pumping loss. Therefore, the reader must take great care when comparing and contrasting the tables. Also, the interquartile ranges are somewhat wide for several technologies. This is to be expected given the uncertainties surrounding many of these engine technologies. The cost and fuel efficiency estimates (median responses) as presented serve as realistic estimates, but certainly must be considered in the context of the interquartile ranges accompanying them.

The variable compression ratio—the ability to operate using differing compression ratios—presents an opportunity to optimize engine performance for the full driving cycle. The variable compression engine could increase efficiency at the lower power operating loads, while allowing for similar performance during higher load requirements such as those needed during acceleration. It is important to note that this technology is very much in the developmental stages, and much work remains.

Variable cylinder displacement—or cylinder shut-off—technology was offered in the U.S. market during the 1980s. However, due to the lack of effective control technology and other reasons, the mechanical system failed to meet consumer expectations. Improvements in electronic controls have created renewed interest in this technology. The panel estimates a potential fuel efficiency gain of 8 percent for cylinder shut-off. However, several caveats must be offered. First, cylinder shut off is more effective—in terms of efficiency and cost—for push-rod type engines than DOHC type engines. Adding cylinder shut-off to DOHC engines requires more components, and thus increased cost. Some of the efficiency gains achieved through cylinder shut-off with pushrod engines may already be partially achieved using the DOHC design. Second, the relatively wide interquartile range for fuel efficiency gains can be (in part) explained by the horsepower-to-weight ratio of a given vehicle. Vehicles that have a higher ratio—such as sports cars—may offer even higher efficiency gains due to their ability to run more often at cruising speeds with reduced cylinders. However, heavier vehicles using the same engine would likely operate using reduced cylinders less often—thus decreasing fuel economy improvements.

Direct injection engines offer some opportunity for increased efficiency, but present difficult emission hurdles. At least one manufacturer has offered gasoline direct injection (GDI) engines in other markets. However, there is much work to be done if they are to meet future emission regulations. There has also been much work done regarding lean burn strategies. The ability to operate an engine on a fuel-to-air mixture that is lower than stoichiometric, or varied (i.e., rich in an initial burn area and lean in other regions of the combustion chamber as in stratified charge)—offers potential for further fuel economy gains. Again, the challenge will be to assure effective combustion to reduce emissions.

HCCI offers great opportunity, but must be considered still in the early developmental stage. This technology may offer significant efficiency gains—approximating that of diesel engines—with extremely low emissions. However, the successful application of HCCI will require continued combustion chamber and controls research and development (to achieve more complete combustion and minimize hydrocarbons and carbon monoxide emissions). The ability to precisely control valve timing, cylinder temperature and fuel mixture will be required to achieve theoretical gains. The successful application of the HCCI engine will likely also require continued development of variable valvetrain technology. Several panelists indicate that they believe HCCI may only be achievable via electronic (camless) valve control. If such technology is required, the cost of HCCI may be cost prohibitive for some time. It is also possible that both spark-ignited and compression ignition engines may eventually add HCCI operation (i.e. mixed mode operation) during critical speed/load points.

Using supercharging or turbocharging to boost air pressure in the engine has been a viable fuel efficiency technique for decades. For boosting to be an effective fuel economy efficiency strategy, it must be used in combination with engine downsizing (i.e. reduced displacement). However, specifically in the U.S. market, boosting has more commonly been used as a performance-increasing strategy—holding displacement relatively constant while adding boost. It is also important to note the wide interquartile range for the efficiency gains for the two technologies. It is likely that efficiency gains may equal the higher end of the range if an associated reduction in displacement is included as horsepower is held constant or slightly reduced.

The panels' relatively flat cost forecasts for superchargers and turbochargers reflect a very mature market. However, it is important to note that there may be opportunity for materials and control developments to either increase performance and/or decrease cost for these two technologies.

ICE-3a Please estimate component/system cost for the listed valve train technologies currently and in 2013. Please base estimates for cost on a 6-cylinder DOHC (4 valves per cylinder) V-configuration engine.

SPARK-IGNITED ENGINE VALVETRAIN TECHNOLOGIES	COMPONENT COST AT MANUFACTURING VOLUMES OF 400,000 UNITS			
	2003		2013	
	MEDIAN RESPONSE	INTERQUARTILE RANGE	MEDIAN RESPONSE	INTERQUARTILE RANGE
CAMLESS ELECTRONIC VALVE ACTUATION	$700	$500 / $1200	$450	$300 / $680
CAMLESS HYDRAULIC VALVE ACTUATION	$700	$387 / $1025	$600	$340 / $939
VARIABLE VALVE LIFT AND DURATION (MECHANICAL)	$350	$263 / $688	$335	$150 / $400
INTAKE PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	$140	$80 / $163	$82.5	$69 / $117.5
EXHAUST PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	$150	$80 / $213	$90	$69 / $163
DUAL EQUAL PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	$180	$145 / $300	$144	$120 / $200
INTAKE VALVE THROTTLING (MECHANICAL)	$100	$65 / $175	$88	$55 / $115

OTHER

- Valve deactivation, dual displacement: Current Cost $200; Cost in 2013: $125

COMMENTS

- Estimates using learning curve variables (20-25 percent for camless, 15 percent for phasing, and 12 percent for mechanical dual equal systems). Costs are based on learning curve exponents and volume projections. Annual production volumes based on 60 million units per year in 2013 and my guess of 10 percent market penetration now growing to 15 percent by 2013 for all these technologies.
- Costs are net costs (accounted for deleted or replaced content), costs do not account for exhaust treatment cost to meet regulatory compliance.
- For the current cost, I assumed launch costs for those technologies not yet in production. For the intake and exhaust cam phasers, I assumed two phasers per engine, one for each camshaft. For dual equal phasing I assumed a single overhead camshaft, not the DOHC that you requested. If the engine has intake and exhaust camshafts then dual equal makes no sense. I entered the system costs for all, which includes changes to the engine, for example, light weight valves for the electronic camless.

ICE-3b Please estimate potential fuel economy improvements, as measured in percent change, for the listed valvetrain technologies. Please base estimates for fuel efficiency gains on a 6-cylinder DOHC (4 valves per cylinder) V-configuration engine.

SPARK-IGNITED ENGINE VALVETRAIN TECHNOLOGIES	PERCENT FUEL EFFICIENCY GAIN	
	MEDIAN RESPONSE	INTERQUARTILE RANGE
CAMLESS ELECTRONIC VALVE ACTUATION	10%	8% / 15%
CAMLESS HYDRAULIC VALVE ACTUATION	10%	5% / 12%
VARIABLE VALVE LIFT AND DURATION (MECHANICAL)	8%	5% / 8%
INTAKE PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	4%	2% / 5%
EXHAUST PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	2%	2% / 3%
DUAL EQUAL PHASING—I.E., VARIABLE VALVE TIMING (MECHANICAL)	4%	2% / 6%
INTAKE VALVE THROTTLING (MECHANICAL)	3%	2% / 5%

OTHER

- Valve Deactivation: 10%
- Supercharging: 20%

COMMENTS

- Reported fuel economy gains for electromechanical and electrohydraulic systems have been between 17 percent and 20 percent. I expect that once the significant control and system optimization issues are addressed (i.e. how to choose which of 1000 different valve events to use for either intake or exhaust, how to vary the events during startup, how to disable cylinders during part load), that the fuel economy improvement will be over 25 percent. Also the fuel economy gains for electrohydraulic will be higher than electromechanical, due to the ability to achieve variable lift.
- Most of these efficiency gains must be realized by delivering same torque / horsepower from a smaller displacement engine.
- Really depends on what other features are added to engine. That is to say, what are we enabling with camless? Are we enabling Miller-Atkinson strategies or merely getting rid of the friction in the cam followers.
- Some of the technologies are not offering significant fuel economy gains, but might be essential for meeting the emissions regulations with minimal fuel economy penalty. In other words, I see more VVT technologies of all types applied to SI engines even in cases where the “nominal” fuel economy benefit is small.

STRATEGIC CONSIDERATIONS (3A AND 3B)

The listed valvetrain technologies offer opportunity to reduce emission via a reduction in pumping—or air flow—losses. Several of the listed valvetrain technologies are currently in—at least limited—production. Therefore some care must be taken when discussing opportunity for added fuel efficiency gain to the vehicle fleet, and reduced cost due to ‘manufacturing learning curves.

Variable valve timing has seen increased penetration in the U.S. market in recent years. However, it has been often used to increase performance, and not necessarily focused on emission reduction. It is important to note that there is potential for gains if this technology is used to pursue emission gains. For example, one company has recently introduced a variable displacement system that leverages the variable valve timing technology already in place—offering solid increases in fuel economy over certain portions of the driving cycle. Such application of variable valve timing warrants close monitoring.

Another important consideration is that, in some instances, the valvetrain is an enabling technology. Camless—either electronic or hydraulic—valve actuation may be a necessary technology to achieve HCCI. However, some form of advanced mechanical lift and duration may be sufficient to achieve partial HCCI mode operation. It is also interesting to note the comments regarding potential limitations of electronic valve actuation. Due to the nature of the actuators, electronic valve actuation may not have the ability to vary lift on electronically actuated cam technology, whereas hydraulic actuation may allow for both lift and duration. Finally it is essential to not that the camless technologies, although offering some opportunity for increased fuel economy present significant cost barriers, and possibly even developmental barriers.

ICE-4 Please describe the important interactions that will affect efficiency gains from additional SI-ICE technologies. That is, are the gains additive (i.e. 1+1=2), or will they be diminishing as technologies are added (1+1 is less than 2)? And, what other vehicle systems (transmission, etc.) will affect the efficiency increases of these technologies?

COMMENTS

- Most of these technologies are aiming at the same small group of losses, so of course they aren't additive. I'm especially concerned about the interaction between engine map technologies and transmission technologies because I think they aren't paid much attention in the "grocery basket" approaches to estimating fuel economy. However, we need to avoid overplaying this; most of the technologies attack multiple losses, and there are some positive synergies as well. Actually, the few papers I've seen discussing these interactions appear to have a real axe to grind. We desperately need better discussion of these interactions in the literature.

- Sorry, this is a diminishing returns game. Benefits are not additive, but incremental. Transmission improvements will give the single highest boost to engine gains. Daimler-Chrysler is now introducing a 7-speed automatic (jumped from 5-speed to 7-speed). ZF and Aisin AW are coming out with 6-speed automatics.

- There are 'x percent' improvements to be had from changes to the powerplant which consists of the engine, transmission, and final drive. These improvements are: reduction in pumping losses, improvement in the expansion and compression work, improvement in duration of combustion, improvement in the efficiency, (i.e. completeness of combustion) and reduction in mechanical friction. Improvements to the transmission and final drive ratio have the same fuel economy benefit as reducing displacement. However these can also degrade driveability, which is why cylinder deactivation is being adopted. Any friction reduction technology will be completely additive to any other fuel economy improvement. Supercharging and turbocharging improve fuel economy in exactly the same way as cylinder deactivation, and so the two don't add. Camless won't add to any of the other engine airflow based technologies, as it can duplicate them all. Camless can combine partially with the fuel injection technologies.

- Most gains will not be additive. In fact some technologies cannot exist in the same engine. Continuously variable transmissions, automatic manual transmissions , 7 or 8 speed automatic transmissions combined with electric power steering, electric air conditioning, (allowing for beltless engines) all have an additive improvement in fuel efficiencies to the technology noted above.

- Gains have to be diminishing in returns. For example, how can you achieve same percentage gains with throttled-intake valves with cylinder deactivation as you would get without it? Transmissions will be significant contributors, but, gains for equal sized engines (e.g. 4-speed automatic transmissions versus 6-speed automatic transmissions will deliver better acceleration and modest fuel economy benefit. 6-speed automatic transmissions plus downsized engine can match acceleration of today's larger engine and 4-speed automatic transmissions, and give greater fuel economy benefit. What is the priority? Consumers always like more performance with no increase in fuel consumption, they don't get excited about same performance and lower fuel consumption.

- Camless, variable compression ratio and variable displacement are not additive. Neither is boosting on top of these. Parasitic auxiliaries can be improved to provide additional fuel economy gains in the near future.

- Gains will diminish as technologies are added. All of the above technologies rely on reducing pumping loss, higher indicated efficiencies due to dilute combustion and small reductions in engine friction. Total elimination of pumping loss would improve economy by 10-12 percent. Lean limit operation would contribute an additional 5 or 6 percent and further elimination of friction 1 or 2 percent. The most effective combined implementation is expected to yield 15-20 percent total improvement on the F.T.P. test.

- The gains are diminishing. A full benefit realization will require system re-optimization, including transmission. Improved transmission technologies can extend the benefits further but also with sub-additive interactions.

- Most of the fuel economy gains related to breathing and reduction of pumping loss are not additive, (e.g. if an engine already has a variable valve timing system, replacing this system with the camless will not result in the nominal improvement given in the table, but rather an incremental jump from the variable valve timing engine level). Novel combustion technologies like HCCI and stratified DISI eliminate throttling at low loads, hence the fuel economy gains from the technologies reducing pumping work would be diminished. Benefits of turbocharging will depend on the degree of downsizing of the engine, i.e., turbocharging for fuel economy rather than extremely high performance can provide significant gains. Transmission technologies will obviously have an impact. Automated manual or a six speed automatic would allow further improvements of vehicle fuel economy. A continuously variable transmission would improve vehicle fuel economy, but would diminish individual gains from some of the engine technologies aimed at reduced pumping work

- Integrated starter generators will contribute 2 to 6 percent incremental energy efficiency, depending on driving cycle, independent of other efficiency-related technologies. Turbocharging also allows downsizing engine and will result in fuel economy gain if turbo does not encourage driver to drive more aggressively just to experience the turbo. Lower viscosity engine oils can contribute perhaps 0.5 to 1.0 percent energy efficiency gain independent of other technologies. Engine friction reductions related to design may contribute 1 to 2 percent or more efficiency gain.

- All technologies described above are designed to reduce throttling losses. They are not additive. Therefore, it will be very difficult and expensive to exceed a 12 percent improvement in fuel efficiency.

STRATEGIC CONSIDERATIONS

The comments represent an outstanding elucidation of the challenges and opportunities regarding the combination of advanced powertrain technologies. Too often readers of reports such as this may assume that different technologies offer the opportunity to merely ‘add-up’ those technologies with the highest fuel economy gains, or the best cost-to-fuel efficiency gains and arrive at a potentially rather large fuel economy improvement. The panelists present a strong case that the technologies highlighted in previous questions are not additive. Yet they indicate that there are opportunities for synergy between selected engine technologies, and other vehicle systems, that may allow for significant fuel economy gains.

As indicated by the panelists, many of the technologies investigated in the previous questions address pumping—or air flow—losses. There is certainly a limit to the pumping efficiency improvements these technologies present. The comment regarding the replacement of a variable valve timing system with a camless system is indicative of the non-additive nature of these technologies. An important question that must be addressed by each manufacturer is the cost-benefit of such a change. It is entirely possible that the addition of camless technology does not add significantly to the fuel economy/performance of a vehicle that already has a very competent valve control strategy. That added cost may be better used to upgrade transmission capability or some other vehicle system. Yet, as many have indicated, the camless strategy may be an enabling technology for HCCI, therefore offer opportunity for other increases in efficiency

Due to resource constraint with this survey, we did not examine transmission technologies, nor the interaction between advanced internal combustion engine technologies and transmission options. However, it is important to note that there is opportunity for synergistic gains between the two systems. However, there are also situations where these two systems will in fact address the same issues. For example, because it allows the SI-ICE to operate at its most efficient load levels, the continuously variable transmission offers opportunity for significant opportunity for fuel efficiency gains. However, it may reduce the added benefit of “on-engine” technologies that address the same issue.

Finally, we concur with the final sentence of the first comment. There is a need to further the discussion, and understanding of the interactions between vehicle systems with regard to their effects on fuel economy and performance. Many, through such organizations as the Society of Automotive Engineers, have been active in this area and much work has been done. However, the industry could expedite the discussion regarding the tradeoffs and opportunities amongst the technologies and better communicate those tradeoffs to all industry stakeholders. Obviously, this need to better communicate the trade-offs must be balanced with competitive knowledge.

III. DIESEL/COMPRESSION IGNITION ENGINE TECHNOLOGY

ICE-5a Please estimate component/system cost for the listed technologies currently and in 2008. Please base estimates for costs on a 6-cylinder CIDI 4 valve engine.

COMPRESSION IGNITION ENGINE TECHNOLOGIES	COMPONENT COST AT MANUFACTURING VOLUMES OF 400,000 UNITS			
	CURRENTLY		2013	
	MEDIAN RESPONSE	INTERQUARTILE RANGE	MEDIAN RESPONSE	INTERQUARTILE RANGE
HYDRAULIC FUEL INJECTION	$600	$406 / $775	$500	$295 / $625
COOLED EXHAUST GAS RECIRCULATATION	$125	$100/ $262	NOT AVAILABLE	NOT AVAILABLE
TURBOCHARGER-ELECTRIC MOTOR BOOSTED	$425	$288 / $738	$270	$200 / $500
TURBOCHARGER-VARIABLE GEOMETRY TURBINE	$350	$200 / $350	$225	$150 / $306

OTHER

- In cylinder pressure sensor: Current Cost, $120; Cost in 2013, $60
- Intake-cam phaser: Current Cost, $40; Cost in 2013, $35

COMMENTS

- I'm assuming a 20% learning curve for these technologies and 400,000 average production volume. Now growing to 1,500,000 units in 2013. With this approximation, the 2013 costs are 0.459 times present cost.
- Component costs given on-costs may be less.

ICE-5b Please estimate potential fuel economy improvements, measured as a percent improvement, for the listed technologies. Please base estimates for fuel efficiency gains on a 6-cylinder CIDI 4 valve engine.

ENGINE TECHNOLOGIES	PERCENT FUEL EFFICIENCY GAIN	
	MEDIAN RESPONSE	INTERQUARTILE RANGE
HYDRAULIC ELECTRONIC FUEL INJECTION	5%	2% / 7%
COOLED EXHAUST GAS RECIRCULATATION	3%	0% / 3%
HOMOGENEOUS CHARGE COMPRESSION IGNITION	5%	1% / 15%
TURBOCHARGER-ELECTRIC MOTOR BOOSTED	9%	5% / 11%
TURBOCHARGER-VARIABLE GEOMETRY TURBINE	8%	4 % / 8%

OTHER

- Cam phaser: 3%
- Turbo-alternator: 4%
- Electric pumps: 4%

COMMENTS

- I think a variable manifold could offer a 3 percent fuel efficiency gain.
- Some of the technologies are not that attractive from the pure fuel economy stand point, but will be essential for controlling diesel emissions, and/or will help reduce the fuel economy penalty associated with emission control (e.g. common rail system).

STRATEGIC CONSIDERATIONS

The panel indicates that there is some opportunity for improvement in diesel engine efficiency. The list of technologies presented is certainly not a complete list, but offers some insight into future efficiency gains. The performance of diesel engines can be greatly improved through boosting inlet air pressure in the engine. Turbochargers, both electric motor and variable geometry, offer opportunity to improve the current technology, and thus warrant monitoring.

The maturity of the common rail fuel injection system has been a critical enabler for diesel engine technology in recent years. It is likely that future developments in this technology will continue to drive CIDI acceptance. Third generation fuel systems, with higher pressure injection, are currently moving into application phase. An important, but often overlooked, enabler for this technology has been the development of manufacturing technologies. The precision and pressure requirements of the new common rail system has been greatly enhanced by better, more capable processes.

The diesel engine is a highly efficient technology. However, the drawbacks of the compression ignition engine are the high levels of particulate and NO_x emissions and added cost vis-à-vis the spark-ignited engine. Although there is still opportunity for fuel economy gains, much developmental focus for the CIDI engine will be in emission reduction, in the coming years.

ICE-6 Please rate the likelihood that the following NO_x absorbers and particulate traps will be technically viable for meeting the Tier 2 bin 8 and bin 5 emissions limits. Where 1 = extremely likely and 5 = extremely unlikely. (Please base your response on application in a mid-size passenger car or similar cross-utility vehicle.)

SCALE	1	5
	EXTREMELY LIKELY	EXTREMELY UNLIKELY

TECHNOLOGIES	BIN 8	BIN 5
	MEAN RESPONSE	MEAN RESPONSE
NO_x CONTROLS:		
LEAN NO_x CATALYST	2.5	3.1
NO_X ABSORBERS	2.1	2.5
NON-THERMAL PLASMA	3.7	4.2
SELECTIVE CATALYTIC REDUCTION (SCR)	2.0	2.2
PARTICLATE FILTERS:		
CATALYTIC REGENERATIVE TRAPS	1.9	2.5
MICROWAVE REGENERATIVE TRAPS	3.6	4.0
NON-THERMAL PLASMA	3.7	4.3

OTHER

- NO_x Controls: Exhaust Gas recirculation, Variable Geometry Turbocharger and Common Rail - Bin 8=1; Bin 5=1
- Particulate Filters: Heated Metal Foam: Foam Bin 8=4; Bin 5=4

COMMENTS

- Low-sulfur fuel is a requirement for these to work.
- Technically viable does not automatically mean that it will be used, since that depends on multiple factors. As an example, urea SCR will be viable, but EPA might still be against its application due to urea concerns.

STRATEGIC CONSIDERATIONS

The panelists indicate that lean NO_x catalysts, NO_x absorbers and selective catalytic reduction (SCR) are likely to be technologically viable methods of meeting Tier 2 Bin 8 and Bin 5 for NO_x. They also indicate that catalytic regenerative traps (CRT) present one of most viable of the listed options to meet Tier 2 Bin 8 and 5 for particulate standards. There are several examples of CRT technology that are currently in use for heavy duty vehicles. Some form of CRT technology will likely be available for application in light duty vehicles in the coming years. However, cost will be a critical determinant of success. Several companies are also focusing on SCR technologies for

NO_x reduction. A common strategy for SCR is to periodically inject urea into the exhaust, thus neutralizing NO_x. However, this strategy relies on the user—the driver—to be responsible for assuring that there is adequate urea in the canister. The E.P.A. will likely only cautiously consider the implications of shifting responsibility from the manufacturer to the driver.

It is important to stress that each of the technologies will be highly dependant on the availability of ultra-low sulfur diesel fuel. It is likely that none of the listed technologies would be capable of functioning properly with the level of sulfur currently found in diesel fuel. Beginning in 2006, regulation will force sulfur levels down to 15 parts per million. However, it is possible that an even lower level will be required for these technologies to perform efficiently for extended periods. In order to assure that the technology can meet the long-term standards required by federal regulations, the technology must also be able to 'regenerate' reliably. This ability to regenerate consistently and reliably will continue to present a challenge.

The more stringent Tier 2 standards will require a systems approach, including fuel injection, air management, combustion chamber design and after-treatment. Certainly the first defense against NO_x and particulate will be a focus on minimizing the formation of NO_x in the combustion process. However, even given effective combustion management, there will likely be a need for after-treatment technologies to meet impending regulation. Finally, as the second comment suggests, technical viability is merely one element of the overall formula. There will be many factors (cost, reliability, material availability, etc.) which determine the success of the above technologies. Ultimately the key to the success of any of the technologies will depend on both effectiveness and cost. Economics will likely determine what wins and what loses.

ICE-7 Please describe what role diesel fuel additives will play in the reduction of particulates and NO_x for diesel engine technology in the coming decade.

COMMENTS

- Sulfur reduction is a major driver of PM/NO_x reduction.
- There are two additive candidates, bio-fuels such as esters added to petroleum derived Diesel fuel, and Cerium. The bio-fuel option permits reduction in net CO_2 emissions. There is a solid push for this in Europe, and I expect it will continue. The addition of Cerium to diesel fuel allows reduction of particulates with the right trap. I don't think it will expand outside of Renault.
- This issue will not be additives but sulfur content.
- Lower sulfur, cleaner diesels and bio-diesels will all play a role.
- Appears that only refinery additives (not onboard vehicle additives) will be acceptable to U.S. regulatory agencies.
- Fuel composition may be tailored to assist NO_x control. Not necessarily any additive. It is not likely that metallic additives will be accepted in United States.
- Additives will play, at most, an interim role—fuel formulation will be critical but largely through getting the correct hydrocarbon properties. In the long run, designs will have to rely on after-treatment (catalysts, controls) with a very clean, carefully formulated fuel. But, additives will probably drop out of the picture.
- Fuel quality has relatively minor effects on engine out emissions of PM and NO_x. I do not foresee additives being used for the sole purpose of reducing PM and NO_x emissions.
- Fuel additives are unlikely to meet political constraints.

STRATEGIC CONSIDERATIONS

There are several alternatives under investigation for use as diesel fuel additives for emissions control strategy. However, the panelists' do not offer strong support for such a strategy. Additives that have been used in Europe to treat particulate emissions (or are in consideration for use) include cerium and iron, among others. However, it is important to note that these additives have, for the most part, been used for heavy duty and/or off road applications. The comment regarding the acceptability of metallic-based additives is interesting. Certainly, secondary environmental impact of any additive will be closely monitored.

Fischer-Tropsch and biodiesels also present opportunity for fuel-based emission improvements. Although these alternatives will be capable of replacing only a small portion of the oil-based diesel feedstock, and may not be an energy efficient application, they do represent opportunity for reduced emissions for a portion of the fleet. The reduction of sulfur in diesel fuel will be the most important enabler for reduced emissions. There also may be some opportunity for additives to address lubricity issues as sulfur is removed, but any such additive would not likely effect emission controls.

IV. VEHICLE EFFICIENCY: TECHNOLOGY AND STRATEGY

ICE-8 Please rate the likelihood that the following types of internal combustion engines will be technically viable for meeting the Tier 2 bin 8 and bin 5 emissions limits by 2009. Where 1 = extremely likely and 5 = extremely unlikely.

SCALE	1	5
	EXTREMELY LIKELY	EXTREMELY UNLIKELY

TECHNOLOGIES	BIN 8	BIN 5
	MEAN RESPONSE	MEAN RESPONSE
SPARK-IGNITED ENGINE (DOHC, V6)	1.4	1.4
DIRECT INJECTION—DIESEL	1.8	3.0
DIRECT INJECTION—GASOLINE	1.5	2.1
HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE—GASOLINE	2.8	3.2
HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE—DIESEL	2.8	3.2
HYDROGEN SPARK-IGNITED ENGINE	1.9	1.9

OTHER

- Mixed Mode, homogeneous compression charge ignition, with either spark-ignited or compression ignited: Bin 8=1; Bin 5=2. Stand-alone homogeneous compression charge ignition not likely; mixed mode more likely.

COMMENTS

- Homogeneous compression charge ignition (CAI) will have good emissions performance except for NO_x.
- I believe that the current administration will work to relax the application of Tier 2 to diesel powered automobiles/SUVs. They will also work to relax the implementation of lower bin numbers.
- Homogeneous compression charge ignition is best considered as post-2010 technology. Hydrogen internal combustion engine is a non-starter in this time period. No serious development work will be undertaken. (And demonstration examples do not count!).
- The spark-ignited DOHC V6, hydrogen spark-ignited engine can meet Bin 2
- I believe the HCCI technologies will meet the most stringent standards.
- The spark-ignited engine, GDI homogeneous and hydrogen spark-ignited engines will be capable of meeting the Bin 2 standards
- I believe spark-ignited, homogeneous charge compression ignition gasoline, and hydrogen spark-ignited engines will be capable of meeting Tier 2, Bin 2 standards.

- At the least, the hydrogen spark-ignited and gasoline spark-ignited will meet Bin 2. But others may be capable.

- Spark-ignited with three-way catalyst and hydrogen spark-ignited. I think a mixed mode (spark-ignited and homogeneous charge compression ignition) might also meet the Bin 2 standards.

- Only spark-ignited, including stoichiometric direct injection spark-ignited will meet Bin 2.

- Spark-ignited port fuel injected, direct injection spark-ignited running in homogeneous mode, as well as dual mode (spark-ignited and homogeneous charge compression ignition) gasoline engines should be viable for Bin 2. Direct injection combustion engine will require a combination of significant advances in injection/combustion and after-treatment systems to meet the most stringent standards.

- Gasoline, gasoline direct injection and hydrogen should be viable for Bin 2.

- The spark-ignition engine with combined application of homogeneous charge compression ignition at low and after treatment devices. The direct injection diesel engine with advanced injection system, tight electronic controls and proper after treatment devices could meet Bin 2.

STRATEGIC CONSIDERATIONS

The panel expects that each of the listed technologies are at least somewhat likely to be technically viable for meeting the Tier 2 Bin 8 by 2009. They also indicate that the listed technologies may be capable of meeting Tier 2 Bin 5 standards by 2009. This, in a sense, highlights the challenge faced by manufacturers—and politicians. Each of these technologies offers potential, but also presents significant developmental cost. Manufacturers must allocate development resources using a market basket approach, assuring at least an understanding of each technology. However, because of limited resources, each manufacturer must select a limited number of technologies on which to concentrate development. The challenge is to invest in the 'winning' technologies''—in what is likely the very early stage of a long race. Concomitantly, those responsible for setting policy are faced by a plethora of (as of yet) mostly unproven technologies that are 'somewhat' likely to be useable in coming years.

The panel strongly expects SI-ICE to meet Bin 8 and Bin 5 standards. The comments suggest that panelists see little problem for the technology to meet the strict Bin 2 standards. Obviously the gasoline engine was used as the expected power source during the development of Tier 2 standards. However, there is some concern regarding the cost of added technology—if in fact there will be any additional cost—in meeting the standard.

The panel has shown great hope for HCCI throughout this survey. Although they indicate that the strategy may be early in the developmental stages, they also indicate that it has great potential. The HCCI operations presented in this question are viewed as slightly less than somewhat likely for 2009. However, many on the panel suggest a strong optimism for the strategy; thus it bears close monitoring. The panel also indicated that the diesel engine is somewhat likely to meet Bin 5 standards by 2009 (for further discussion, please see question 9).

Finally, the panel expects hydrogen internal combustion engines (H_2-ICE) to be technologically viable in meeting the standards. Many view the H_2-ICE as an initial stepping stone to the hydrogen economy and fuel cells for transportation applications. However, many also question the overall efficiency of the H_2-ICE. Although it is likely to be technologically viable by 2009, there is considerable doubt that it will represent a 'best alternative' for meeting the regulation. Hydrogen issues abound outside of the engine: where to get it, how to transport it, how to store it.

ICE-9 Will the compression ignition direct injection engine (with after-treatment technology and ultra-low sulfur fuel) be capable of meeting Tier 2 Bin 5 standards by 2009? Also, will CIDI be capable of meeting Tier 2 Bin 2 standards by 2009? Please discuss cost and most significant technological challenges for the diesel engine meeting Tier 2 regulation. (Please base your response on application in a mid-size passenger car or similar size cross-utility vehicle.)

COMMENTS

- From what I hear, bin 5 is likely. I haven't heard much about bin 2, but I wouldn't be shocked if that was possible—though I presume it would need super low sulfur fuel unless emissions technologies were perfected that weren't so sulfur sensitive (plasma-based?).

- Bin 5 - yes; Bin 2 will be difficult; challenges especially difficult will be the OBD2 and durability.

- Bin 5 is possible with significant investment in the engine and after treatment. Bin 2 is not. I believe that common rail, cooled EGR, variable geometry turbocharging, and hydraulic camless will be required, along with both NO_x and particulate traps. I would guess this to be about a $1,400 premium to the OEM over present diesels. The cost to the end user would be over $3,000, requiring significant tax breaks. A few years later, perhaps 2012, the camless can be adapted to get HCCI, which will eliminate the exhaust gas recirculation and the traps. That should save about $700 per engine.

- I think achieving Bin 5 by 2009 is possible. However, Bin 2 may be possible but very expensive.

- Tier 2 Bin 5 likely achievable by 2009. Bin 2 probably not practically achievable by 2009, and it appears no industry organization thinks that reaching Bin 2 is needed or has marketing value. Greatest technical challenge is getting NO_x absorber catalyst degradation under control.

- Yes for Bin 5, but it will be costly, especially relative to the fuel economy benefit achieved. Bin 2 is doubtful and, indeed, unlikely.

- Capable, yes. Costly, yes. How costly it is a guess

- CIDI engine with advanced injection system, ultra-low sulfur fuel and after-treatment should be able to meet Bin 5. Bin 2 poses significant additional challenges, and will require advances of the after-treatment technology combined with advanced injection/combustion systems allowing the CIDI engine to run “premixed”. Whether cost will be acceptable depends mostly on the fuel price and payback time. Mild-hybridization could reduce problems associated with most rapid transients

- Yes, I believe CIDI engines can meet Tier 2, Bin 5 by 2009. I do not believe that commercial CIDI engines will be able to meet the Bin 2 NO_x standard by 2009. The principle costs of meeting the Tier 2, Bin 5 standard will be an ultra high pressure fuel injection system 1,600-2,000 bar, a NO_x trap (selective catalytic reduction will not be a factor in the U.S. light duty diesel market), a particulate matter trap and electronic controls associated with managing all three systems.

- There is a good chance that this engine will be able to meet these standards.

STRATEGIC CONSIDERATIONS

The compression injection direct injection (diesel) engine has undergone drastic emission improvements in recent years. And although diesel is already gaining market acceptance in

Europe, its acceptance in the United States is far less certain. Diesel engines offer significant fuel economy improvements and CO_2 reductions vis-à-vis gasoline engines. However, particulates and NO_x remain significant barriers for diesel penetration in the United States. There is growing acceptance that, when combined with more efficient combustion design, the current oxidation catalyst may be capable of meeting tier 2 Bin 8 regulation.

While there may be general acceptance that the diesel engine will be capable of meeting the less stringent Tier 2 standards (Bin 8), for long-term market place viability, it is likely that diesel technology will need to achieve the more stringent Bin 5, or even the ultra-stringent Bin 2 levels. Panelist comments indicate a belief that the diesel engine will, in fact, be capable of meeting Bin 5, but likely not Bin 2. Several manufacturers have demonstrated technology that, if capable of meeting durability requirements, could likely meet the Bin 5 standards. In an effort to better assess the viability of diesel for tier 2 application, the Environmental Protection Agency (E.P.A.) has tested several diesel powered light duty vehicles over the past two years. Although each of these vehicles was either designed for other markets, or considered developmental, performance indicated strong progress toward meeting Bin 5 standards. However, such tests must be considered with caution. There is still great uncertainty regarding the future of diesel engines in the U.S. market.

A major concern raised by the panelists is the cost penalty associated with meeting the standard. The current diesel engine suffers a cost disadvantage to the gasoline SI-ICE engine. The addition of more expensive fuel delivery systems and after-treatment technologies required to meet the more stringent standards may make diesels not cost-competitive.