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NEW TECHNOLOGY IN LARGE BORE ENGINES

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NEW TECHNOLOGY IN LARGE BORE ENGINES

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THE ASME INTERNAL COMBUSTION ENGINE DIVISION
ROCKFORD, ILLINOIS
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edited by

B. CHRISMAN
COOPER INDUSTRIES, AJAX-SUPERIOR DIVISION

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FOREWORD

Themes for the Internal Combustion Engine Division Fall Technical Conferences are generally selected at least two years in advance. The Technical Committee recommends these themes based on issues which represent high concentrations of current technical activity for engineers involved in the engine industry. The theme for the 1990 Fall Technical Conference (FTC) is an update and re-investigation of the 1985 FTC theme. The 1985 FTC focused on "New Developments in Large Bore Engines." In the past five years, large bore engine technology advanced substantially and engine applications have undergone some changes. Therefore the 1990 FTC examines the latest "New Technology in Large Bore Engines." Most of the papers presented at this conference report accomplishments achieved with large bore engines, and a few of these papers describe work done with smaller engines, the results of which are directly applicable to large bore engines.

Technical papers received for the 1990 FTC theme fell into five specific topic categories, which resulted in the formation of five technical sessions. These sessions are: (1) Mechanical Design, (2) Engine Environmental Issues, (3) Fuels and Combustion, (4) Electronic Controls and Simulation, and (5) Engine Maintenance and Testing. This publication contains the 18 technical technical papers which were produced by 34 authors for the 1990 FTC. These papers were presented at Rockford, Illinois, October 8-10, 1990.

A major purpose of the Internal Combustion Engine is to promote the art and science of internal combustion engines through an exchange of technical information to benefit the engine industry and the engineering profession. This purpose is for the most part accomplished through activities defined in the ASME principal aims; i.e., "developing and disseminating technical information in order to provide a continuing education to mechanical engineers, the industries they serve, and mankind in general." Therefore it is imperative for our division to provide a forum for producing and presenting technical papers which extend the technology of the engine industry. Papers contained in this publication have been carefully reviewed by peers to assure that they are consistent with our goals to publish high quality, technically-sound information.

The technical papers represent an important part of this conference program. However the conference also features other technical content that is worthy of special mention:

1. An ASME Honda lecture by Professor John B. Heywood, dealing with a subject that encompasses much of the conference theme, "Future Engine Technology; Lessons from the '80's for 1990's."
2. An exhibition of old engines and their components, organized by Michael F. Marsh.
3. A tour through the Fairbanks-Morse engine manufacturing facility.
4. A free tutorial by F. Douglas Stover, presenting the latest technology in engine and compressor performance analyzers.

It requires many committed persons working together to produce a technical program of this nature. We gratefully acknowledge the efforts of major contributors, such as the session organizers; Carl McClung, James Wakenell, Jon Tice, Dave Ackerman, and Professors Reda Bata and Rameshwar Sharma. Our appreciation also goes to Professor John Heywood and the authors who presented their papers. The work of the paper reviewers and discussors is a key part of this publication. We thank our conference host, Fairbanks-Morse Division of Colt Industries, for their important contribution to the success of this conference. Our thanks also go to I.C. Engine Chairman, Albert Zagotta and the other members of the Executive Committee who provided their support.

Bruce Chrisman
Technical Program Chairman

1990 SOICHIRO HONDA LECTURER

Professor John B. Heywood
Director, Sloan Automotive Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

THE LECTURER:

Professor Heywood did his undergraduate work in Mechanical Engineering at Cambridge University and his graduate work at M.I.T. He then worked for the British Central Electricity Generating Board on magnetohydrodynamic power generation. Since 1968 he has been on the faculty in the Mechanical Engineering Department at M.I.T., where he is now Director of the Sloan Automotive Laboratory and Professor of Mechanical Engineering. His current research is focused on the operating, combustion and emissions characteristics of internal combustion engines and their fuels requirements. He is also involved in studies of automotive technology and the impact of regulation. He has published extensively in these areas of the technical literature and has won several awards for his research publications. He holds an Sc.D. degree from Cambridge University for his published research contributions. He is the author of a recently published text and professional reference "Internal Combustion Engine Fundamentals." In 1983 he was elected a Fellow of the Society of Automotive Engineers. He is a consultant to the U.S. Government and a number of industrial organizations.

THE HONDA LECTURE:

The Soichiro Honda Lecture has been established as a national lecture by the ASME to recognize achievement and significant contribution in the field of personal transportation. Past recipients are Dr. Helmut List, President of AVL, Dr. Phillip Myers, Emeritus Professor, University of Wisconsin and Dr. Horst Hardenberg, Director of Advanced Truck Engine R&D, Daimler-Benz.

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CONTENTS

FUTURE ENGINE TECHNOLOGY: LESSONS FROM THE 80's FOR THE 1990's

John B. Heywood
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

The past twenty years has seen an explosion in our knowledge of engine processes, steadily improving engine power density and efficiency, major reductions in exhaust emissions, and a substantial increase in engine sophistication and complexity. This paper explains how engineering analysis has played a major enabling role in realizing these improvements in spark-ignition engine performance. Examples are given of the many different types of analysis tools in areas such as combustion, emissions, stress analysis, system dynamics, and fluid flow that have been found useful in resolving different engine development and design problems and opportunities.

The significant improvements achieved in engine fuel consumption, power density and emissions control are then reviewed. It is argued, however, that the improvements in urban air quality do not correspond to the reductions achieved in vehicle exhaust emissions. Our current understanding of the link between vehicle emissions and air quality does not explain this discrepancy. What matters is low enough in-use emissions, and future regulations do not adequately focus on this essential requirement.

An available energy analysis of the four-stroke spark-ignition engine operating cycle is used to identify where opportunities for further increases in efficiency and power are to be found. Approaches that would improve combustion efficiency, reduce heat losses, increase expansion stroke work, reduce pumping work and decrease friction are discussed. It is concluded that many analysis tools are now available to identify more precisely how large these opportunities are, and how best they might be realized. The potential of various modifications to the four-stroke cycle SI engine cycle, and alternative spark-ignition and diesel cycles are reviewed. Finally, it is argued that relative to Europe and Japan, the United States lacks a sufficiently broad and organized research effort designed to support the exploration and development of these opportunities.

RATIONALE AND SCOPE

The past two decades have seen major changes in engine technology. These have come about due to the need to reduce vehicle emissions very substantially, improve fuel consumption due to market pressures and regulation, increase engine specific power to improve vehicle performance and reduce engine size and weight, and to improve vehicle driveability which had deteriorated significantly in the early years of emission control. For the spark-ignition engine, these improvements have come from many different areas; most important however, have been the development of much more sophisticated engine designs with electronic engine control, and the introduction and continued development of the catalytic converter.

You have generously honored me with the Honda Lectureship because of my research and writing on internal combustion engine technology over the past twenty or so years. So I thought it would be appropriate to use the opportunity this occasion provides to write a broader review of three topics in which I am much involved: (a) how engineering analysis has contributed to the engine improvements listed above; (b) how far we have progressed in our efforts to control air pollution; and (c) assess what potential remains for further improving current engine technology and examine some new engine options.

I will first discuss several areas of engine operation where the combination of analysis and extensive empirical data has led to significant gains. I will show that one essential feature of all these successful combinations of empirical and analytical (or computational) engineering is matching the type of analysis used to the specific problem. There are no universal analysis tools, though some are obviously more general than others. The major focus will be a spark-ignition engine performance, efficiency, and emissions, since this has received the greatest emphasis during the 1970s and 80s, will continue to be very important in the 1990s, and is my primary area of expertise. Diesel efforts are following this pattern too, but more slowly, because the problems of emission control and improved efficiency are more complex than in the SI engine, and the amount of resources available for diesel engine R & D is smaller.

I will then focus on passenger car emissions and urban air pollution. We will see that one success story of the 80s, the catalytic converter, has not apparently had the impact on the real problem--urban air quality--that it has had on spark-ignition engine exhaust emissions. A major reason is that the real problem--how all actual sources of emissions contribute to air pollution--has not received the same level of analysis as has the engineering "solution." Finally, I will discuss what I perceive to be the most important "engine" needs and opportunities for the 1990s.

THE ROLE OF ENGINEERING ANALYSIS

The Information Explosion and Escalating Complexity

Anyone who works with the technical literature on engines knows that it has been expanding at an enormous rate. As an illustration, I have plotted in Fig. 1 the number of technical papers published each year by SAE--which has become the largest source of such literature--over the past twenty-five years. Such literature records the expansion of our engine knowledge base, the analysis, computational, and diagnostic methods relevant to engine research and development and the successful resolution of engine problems and realization of new engine opportunities.

In parallel, the complexity of automobile spark-ignition engines has escalated enormously. As illustration, one recent production engine design (Inoue et al., 1989) incorporates a four-valve cylinder head, cam switching between low and high speed, a tuned intake and exhaust system, sophisticated electronic engine control and the sensors and actuators required to implement that control. Twenty years ago such geometric complexities would be the rare exception, and would only have been considered routine in special applications such as racing.

How Analysis Helps

Though many types of engineering activity have contributed to engine improvements over the past two decades, such developments would not have been possible without the contribution that has come from "engineering analysis." The 1970s and 80s have demanded rapid changes in technology; the next decade and beyond will require changes of comparable magnitude, at least. As I discuss a number of engine technology improvements, and the problems they were or are intended to overcome, I will show that there is always an "appropriate" engineering analysis methodology that substantially aids the development and design process. Usually this analysis methodology comes into use because a sufficiently quantitative understanding of the phenomena or processes involved has been developed, and techniques for measuring this behavior are available. The knowledge framework that results helps the practicing engineer organize his otherwise empirical data base and extract and use the information that it contains much more effectively.

This discussion, based on many years of experience in engine research and extensive contact with engine development and design, will show that our current knowledge of engine phenomena has two distinct sources: a vast experimentally derived data base--largely empirical--which has been developed over the past several decades (and continues to be developed at a rapid rate), and an ever broadening array of analysis tools based on our steadily increasing fundamental understanding of engine phenomena and processes. In this extremely detailed and complex engineering field, both are necessary for rapid progress, as I learned well during the ten years I worked on my recently published reference text on internal combustion engine fundamentals, Heywood (1988), and as I will illustrate in this paper.

How have engineers responded to this rapid increase in our knowledge of engine phenomena, the demands for improved performance (power, efficiency and emissions), and the availability of new technologies (such as sensors and computer controls)? My assessment is that the increasing use of analysis tools has enabled development and design engineers to apply this expanding knowledge base and realize in large measure the opportunities which more sophisticated and better optimized engine systems offer.

One of the clearest examples of the interplay between analysis and engine design is the development of fast-burn spark-ignition combustion systems. Developed in the late 1970s and brought into production in the early 1980s, the fast-burn approach to engine combustion has provided significant improvements in engine NO and HC emission control, and fuel consumption.

Figure 2 indicates how "fast burn" provides all these benefits, Kuroda et al. (1980). It compares the operating and emissions characteristics of a fast burn SI engine combustion system with those of the

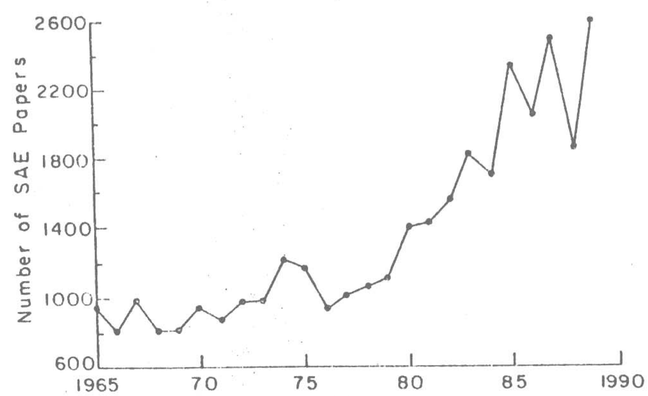

Fig. 1: Plot of number of papers presented at Society of Automotive Engineers technical meetings each year, 1965-1989.

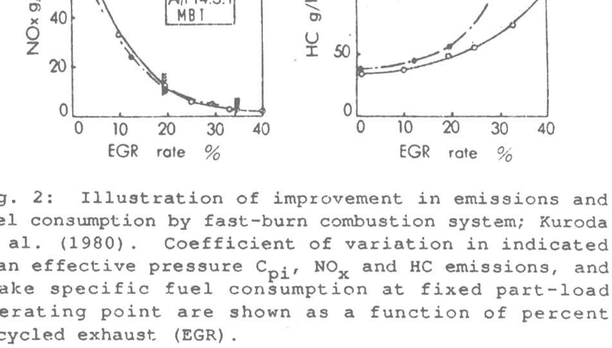

Fig. 2: Illustration of improvement in emissions and fuel consumption by fast-burn combustion system; Kuroda et al. (1980). Coefficient of variation in indicated mean effective pressure C_{pi}, NO_x and HC emissions, and brake specific fuel consumption at fixed part-load operating point are shown as a function of percent recycled exhaust (EGR).

Table 1

Series of Nissan Papers on Fast-Burn Engine Combustion Phenomena

Paper Title	Contribution
1. "Heat Capacity Changes Predict Nitrogen Oxides Reduction by Exhaust Gas Recirculation," S. Ohigashi, HJ. Kuroda, Y. Nakajima, Y. Hayashi, and K. Sugihara, SAE paper 710010, 1971.	1. Showed that engine data on changes in NO and fuel consumption (sfc) with EGR were well correlated by changes in heat capacity.
2. "Potentiality of the Modification of Engine Combustion Rate for NO_x Formation Control in the Premixed SI Engine," H. Kuroda, Y. Nakajima, K. Sugihara, and Y. Takagi, SAE paper 750353, 1975.	2. Used a computer simulation of SI engine cycle to calculate NO emissions and sfc as a function of burn profile. Showed that the trade-off between NO and sfc depended little on burn rate.
3. "The Fast Burn with Heavy EGR, New Approach for Low NO_x and Improved Fuel Economy," H. Kuroda, Y. Nakajima, K. Sugihara, Y. Takagi, and S. Muranaka, SAE paper 780006, 1978.	3. Used a detailed analysis of engine combustion patterns to show that faster burn rates allowed higher EGR rates (and therefore greater NO control and larger sfc gains) than slower burn rates.
4. "Lean Mixture or EGR - Which is Better for Fuel Economy and NO Reduction?" Y. Nakajima, K. Sugihara, and Y. Takagi, I.Mech. E., paper C94/79, Proceedings of Conference on "Fuel Economy and Emissions of Lean Burn Engines," Institution of Mechanical Engineers, London, June 12-14, 1979.	4. Used engine data and burn rate analysis to show that excess air (lean operation) and EGR has comparable effects on fuel consumption, though the engine will tolerate more excess air. However, EGR has much larger impact on NO.
5. "Effects of Exhaust Gas Recirculation on Fuel Consumption," Y. Nakajima, K. Sugihara, Y. Takagi, and S. Muranaka, Proceedings I.Mech.E., Automobile Division, Vol. 195, No. 30, pp. 369-376, 1981.	5. Used a thermodynamic model of the engine cycle, with engine data, to show that the fuel consumption gain with EGR and a fast burn was due to changes in heat capacity, heat losses to walls, and reduced pumping work.
6. "Nissan NAPS-Z Engine Realizes Better Fuel Economy and Low NO_x Emission," M. Harada, T. Kadota, and Y. Sugiyama, SAE paper 810010, 1981.	6. Showed how fast burn and high EGR tolerance could be achieved in practice by creating a swirling flow within the cylinder during the intake process.

"conventional" or slower burn that it replaced. The objective is a combustion process that is sufficiently fast and robust that it will tolerate a significant amount of dilution of the fresh fuel-air mixture with burned gases--residual plus recycled exhaust--to control NO_x. The figure shows that the reduction in NO emissions depends only on the amount of added EGR, but that the amount of EGR the engine will tolerate before its performance becomes too erratic (defined by the cycle to cycle variability in indicated mean effective pressure C_{pi}, for example, see Fig. 2 upper left) depends on the burn rate. The fuel consumption benefit from the faster burn is in part direct (faster release of the fuel's chemical energy does improve cycle efficiency), but in larger part is due to the dilution of the fuel-air mixture with additional EGR which changes the thermodynamic properties of the burned gases to produce more expansion stroke work, reduces heat losses, and (at a constant part load) reduces pumping work.

One of the first companies to implement fast-burn technology was Nissan, and a series of papers published through the 1970s by their Engine Research Department describes step by step how this technology was developed. Table 1 lists these papers and the key step each paper provided.

One sees within the engine R&D department a pattern of developing a sequence of "appropriate" analysis tools--often based on research done a few years earlier elsewhere, then using these analysis tools together with carefully structured engine tests to sort out what combustion approach would both reduce engine emissions, and improve efficiency and driveability. Interestingly, these analysis tools did not push the then available state of the art. They contained just enough complexity to do their intended job--the essence of "appropriate analysis."

A major problem with engine design throughout the past two decades of emission control has been finding the calibration that gives good control of emissions during engine transients and good vehicle response and driveability. A very different type of model has been developed and used to assist in the solution of these complex system-dynamic problems. The many components of the engine and vehicle, and the processes that link them, are modeled in whatever way most simply describes those aspects of that component's behavior that contribute directly or through its interactions with other parts of the total vehicle system to the vehicle phenomena of concern.

An example of such a vehicle system model is shown in Fig. 3 (DeLosh et al., 1981). It is designed to explore problems like those that arise on rapid accelerations or decelerations due to mismatches between the dynamic characteristics of the processes that take place in the many subsystems that make up the total engine system. Its power is in its "number crunching"; that is, its ability to deal quantitatively with all the interactions between the many subsystems that are involved in a change in engine conditions, when the total system complexity goes well beyond what the human mind can follow. Because even the subsystems are extremely complex, many component models are based largely on experimental data. For example, regression equations based on a measured engine performance map usually define the engine's response to changes in speed, inlet manifold pressure, air/fuel ratio, EGR, and spark timing; no analytic based engine model can yet do that with sufficient accuracy and economy. Process models are often physically based; e.g. the

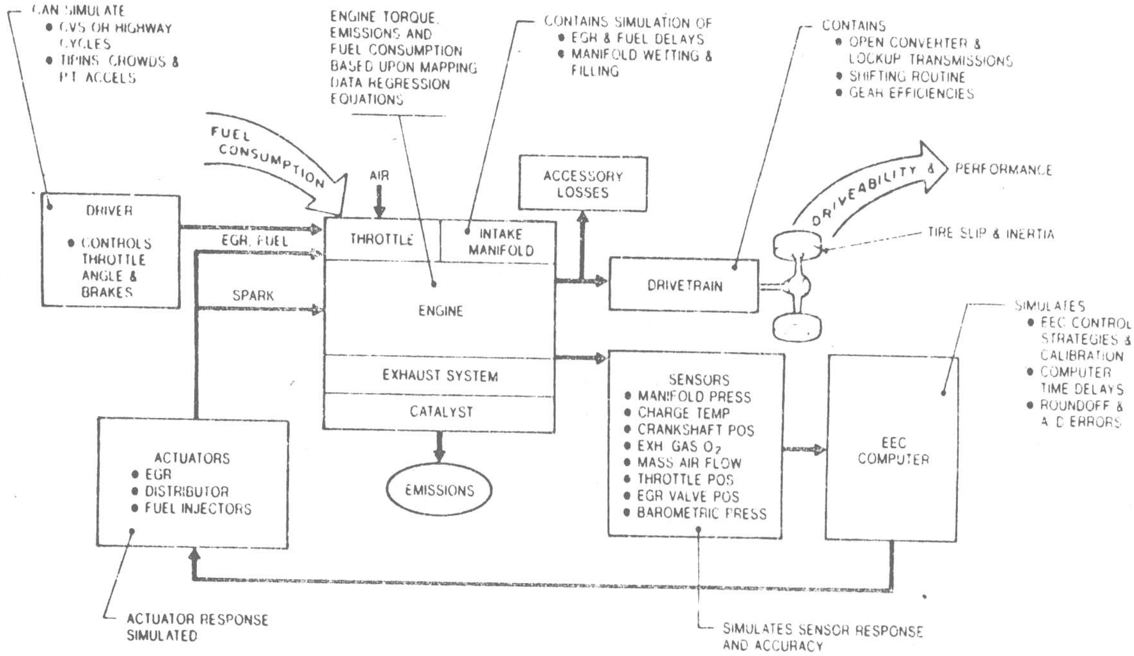

Fig. 3: Schematic diagram of vehicle system dynamic model use to examine problems like those that arise in rapid accelerations or decelerations due to mismatches in component dynamic characteristics; DeLosh et al. (1981).

flow of air and fuel into, within, and out of the inlet manifold is calculated from quasi-steady filling and emptying conservation equations.

Figure 4 shows an example of the type of results such analysis methodologies produce (DeLosh et al., 1981). Various engine and vehicle parameters are plotted versus time over a one second period during which the throttle on a 5-liter V8 throttle-body injection engine opens 25 degrees. In the example shown, the fuel metering has not been adjusted to compensate for the increase in airflow (the "airflow error") due to the manifold filling that occurs during throttle opening. The increasingly lean mixture in the cylinder at point "A" causes poor combustion, power is lost, and the vehicle stumbles. The continued rotation of the engine continues to drive the system, and at "B" the major portion of the lean transient has passed and the vehicle accelerates smoothly.

This is an example of an analysis methodology that organizes large amounts of data, combines it with theory where appropriate, and thereby follows a complex set of subsystem interactions as the vehicle is "driven" through those speed-time sequences where problems have been observed, or are anticipated. The potential for examining engine-caused vehicle transient problems is obvious. Such models are not fundamentally based; they usually cannot be because the amount of detail that must be incorporated for them to be useful is much too large for theory to deal with. They are, however, powerful diagnostic tools.

Fundamentals have provided an extremely valuable engine component analysis tool in the area of mechanical and thermal behavior of materials: stress, thermal expansion, deformation. Finite element analysis (FEA) techniques are well developed and have proved valuable in the design of geometrically complex components such as pistons which are heavily loaded, mechanically and thermally, where weight and geometric

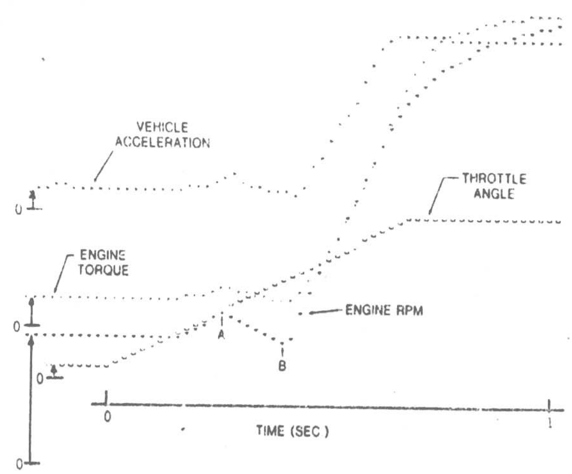

Fig. 4: Example of results from vehicle system dynamic model of Fig. 3. Shows engine speed, torque, and vehicle acceleration changes that occur during 25 degree throttle opening in 5-liter V8 engine. The increasingly lean mixture which the throttle opening produces in the cylinder at "A" causes the engine to misfire, and speed and torque fall. At B the engine recovers, torque and speed increase smoothly and the vehicle accelerates.

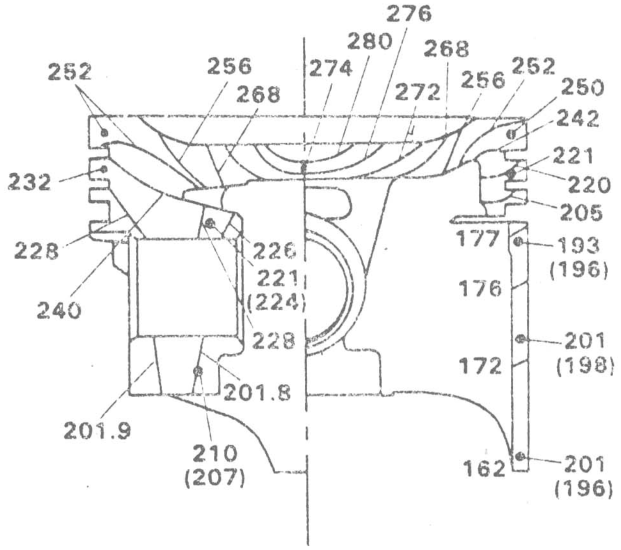

Fig. 5: Finite element analysis predictions of temperature (C) distribution in a spark-ignition engine piston at 4600 rev/min and wide-open-throttle. Dots show measured results. Li (1982).

details are especially important. Figure 5 illustrates the level of sophistication the results of such calculations can provide (Li, 1982). It shows the predicted and measured temperature distribution within the piston at high speed and load. The agreement between analysis and data is generally good. The one region where agreement is less good (the skirt) identifies where the major problems in FEA application remain--specifying the boundary conditions. In the calculation shown, the heat transfer coefficient between the skirt and liner has been overestimated. The complexity of and interrelations between engine phenomena are apparent: the successful resolution of one area of analysis then highlights the next related area where new knowledge needs to be developed--in this case the heat transfer processes that occur between the piston and the hot cylinder gases, the lubricant, and the liner.

Such finite-element based studies are now commonplace in the design of cylinder blocks, pistons, connecting rods, and crankshafts. However, since some of the important practical details still cannot be incorporated into the analysis methodology, due to lack of understanding or insufficient geometric detail, considerable skill is still required of the user to make simplifications in the problem and/or bridge these gaps with empirically based knowledge.

The equivalent methodology for the analysis of engine fluid flow phenomena rather than solid material phenomena--computational fluid dynamics (CFD)--though much more complex, is also proving useful in engine development. CFD codes for engine analysis have only recently reached the point where they can connect usefully with practical problems, though they have been important research tools for the past decade or so. These fluid-dynamic-based engine process analysis codes solve the partial differential equations for conservation of mass, momentum, energy, and species concentrations. The principal components of these "multidimensional" engine flow codes are the following: the models and equations used to describe the processes being analyzed (of which, for example, the turbulence model is critical); the procedures used to transform the differential equations into algebraic relations between discrete values of velocity, pressure, temperature, etc. at the grid points of the computing mesh which (ideally) matches the actual geometry: the algorithm for solving these algebraic equations; and the computer code that translates the numerical algorithm into computer language, and especially important, the interfaces for easy input and output of information (Heywood, 1988, Ch. 14).

Let me illustrate the power of these very sophisticated complex flow-analysis based codes, especially as engine development tools (they still lack the level of geometric detail required to aid engine design directly). At the current stage of development, their value lies in their ability to predict, with reasonable precision, the flow pattern within and around complex geometric shapes. Thus application areas include airflow under the hood around the engine and its associated components to predict underhood temperatures, flow through inlet ports, and flows within the cylinder. Figure 6 shows one recent example of predictions of the flow produced in the port and valve during the intake process (Naitok et al., 1990; the original figures, in color, show much greater detail). Such streamline predictions help the port and cylinder head designer achieve the desired in-cylinder flow field. Especially important currently is the level of swirl--rotation about the cylinder axis, or tumble--rotation about an axis perpendicular to the cylinder axis. While it is still difficult to relate the details of these in-cylinder flows to the flame development rate and its cycle-to-cycle variability, a quantitative analysis tool which relates the flow field to the geometric details is now available.

These CFD analysis tools are being used to help develop improved port and cylinder head geometries, as well as in areas such as improvement of coolant flows through the block and cylinder heads, and under-hood packaging of the engine, its auxiliaries, and other components.

This brief review illustrates the wide variety of analysis tools which now play a major role in engine development and design. The essential feature of these tools is that they are "appropriate" to the problem they are used on. Here, appropriate means they contain enough of the physics (through equations and/or through data) to describe adequately the phenomena in the problem under investigation and provide information that can be related to the practical problem. My

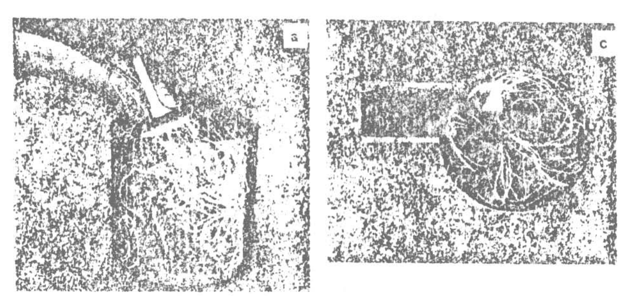

Fig. 6: Streamlines calculated with CFD engine code during the intake process, 160 degrees ATC, in the inlet port and cylinder of a spark-ignition engine. The complexity of the flow field and the value of a predictive code which describes the flow field are obvious. Niatoh et al. (1990).

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experience is that engine development and design practioners are much more astute at judging whether an available analysis meets their needs than they are usually given credit for. I have seen many instances where complex computer codes are now used extensively despite the time required to learn how to use them, because it is clear that they are "useful."

Impact on Efficiency and Performance

The oil price shocks of the 1970s and the Corporate Average Fuel Economy standards established in 1975 have forced significant improvements in part-load spark-ignition engine efficiency. The average fuel economy of the new U.S. passenger-car fleet in each model year has increased from 16 miles per gallon in 1975 to about 28 miles per gallon in 1989. About one-third of this increase has come about due to engine and drivetrain improvements. In addition, the poor performance of many vehicles in the late 70s and early 80s lead to a market demand for improved vehicle acceleration and driveability. How have engine designs responded to these challenges?

Increases in efficiency have come primarily from improvements in combustion and management of engine operation, modest increases in compression ratio, and reductions in engine friction (both in absolute magnitude and relative importance). The fast-burn combustion technology described previously in this paper raised engine efficiency at part load through more rapid completion of combustion, lower cycle-to-cycle combustion variability, and when used with increased EGR for NO_x control due to reduced heat losses, pumping work, and increased burned gas specific heat ratio. Friction has been lowered through careful attention to design details, through use of roller followers in the valve train, and because friction's relative importance decreased through use of higher output engine technology (see below).

Engine output has been increased significantly through use of highly tuned intake systems, and the introduction of multivalve technology. Figure 7 shows the torque improvements that have resulted. They are indeed large.

These efficiency and power density improvements have been achieved because the appropriate analysis tools were used to guide and support engine development and design. The role of analysis in the development of fast-burn technology has already been summarized. The development of tuned intake systems to increase the breathing capacity of engines over a surprisingly wide speed range would not have occurred without the use of unsteady gas dynamic models for flow in the intake system. Since the work of Benson in the early 1960s, one-dimensional computational fluid dynamic methods for predicting the wide-open-throttle pressure distribution and flow velocity in the intake system as a function of intake system geometry, in-cylinder engine processes, and speed, have been steadily developed and increasingly used to design intake systems (see for example Benson et al., 1964; Chapman et al., 1982; Morel et al., 1990).

Figure 8 shows a recent comparison of the predicted and measured intake manifold pressures in the inlet port of one cylinder of a 4-cylinder SI engine (Morel et al., 1990). The model predicts the airflow behavior in the manifold over the full speed range of the engine. Note that the tuned intake system provides a positive pressure pulse in the inlet port between bottom center at the end of the intake stroke and inlet valve closing. This is what increases the mass of air that enters the cylinder each cycle. As shown in Fig. 7, with well designed tuned intake systems, substantial increases in torque in the engine's mid- and high-speed ranges can be and are achieved.

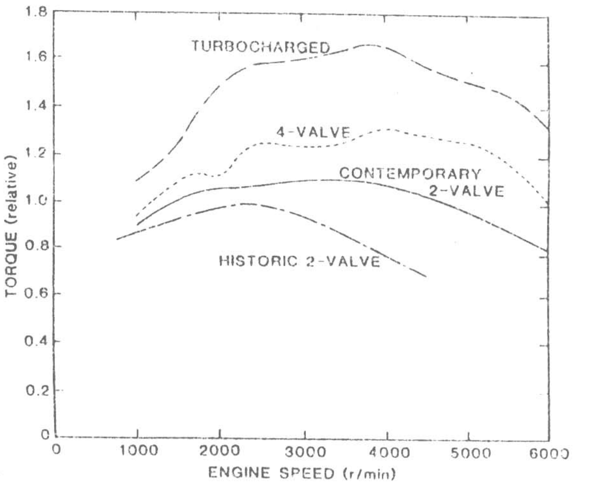

Fig. 7: Wide-open-throttle torque curves for modern 2- and 4-valve, and turbocharged spark-ignition engines, compared with standard design of two decades ago. Amann (1989).

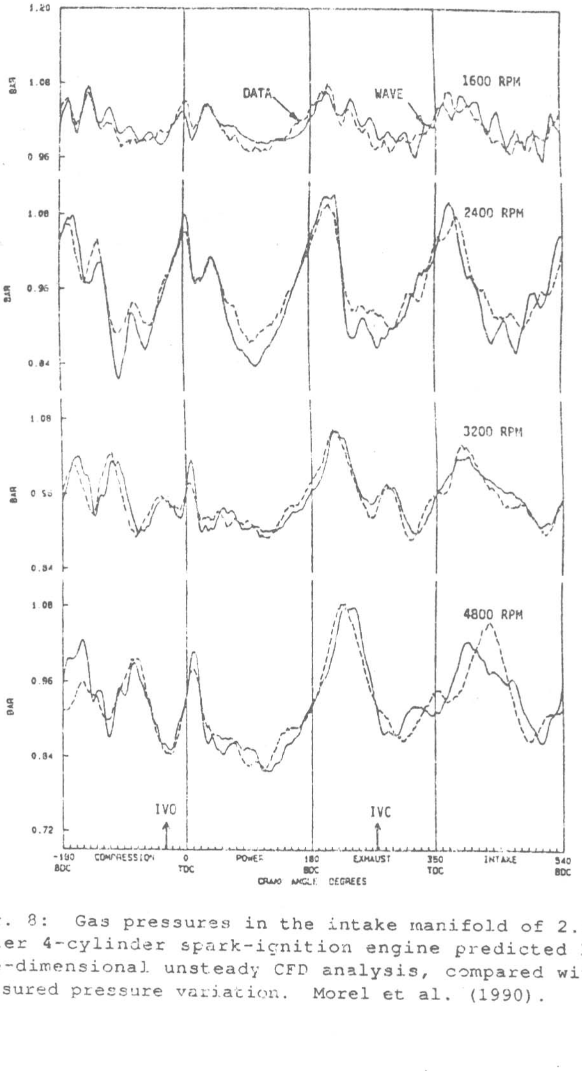

Fig. 8: Gas pressures in the intake manifold of 2.2-liter 4-cylinder spark-ignition engine predicted by one-dimensional unsteady CFD analysis, compared with measured pressure variation. Morel et al. (1990).

Summary

Will this trend of increasing use of analysis in engine engineering continue? Of course it will, because it is the best way to identify the opportunities for improving engine performance and target the necessarily empirical development required to realize these opportunities. However, support by industry and government in the U.S. may not be sufficient to ensure the steady expansion of new engine knowledge, and its encoding in appropriate analysis tools that the future will require. Relative to Europe and Japan, the United States lacks a sufficiently broad and organized research effort designed to support the exploration and development of these opportunities.

THE AUTOMOBILE AND URBAN AIR POLLUTION

Passenger Car Emissions

Exhaust emissions standards for unburned hydrocarbons, carbon monoxide, and oxides of nitrogen are now a small fraction (about one-twentieth for HC and CO; one-forth for NO_x) of the exhaust emissions levels of cars produced in the late 1960s; see Table 2. The current exhaust emission standards of 0.41 g/mile HC, 3.4 g/mile CO, and 1.0 g/mile NO_x, were implemented in 1981 and have therefore been in place for almost a decade. Over this period, spark-ignition engine exhaust emissions have been controlled with the three-way catalyst technology where the engine operates with a close-to-stoichiometric air/fuel ratio to provide both oxidizing species for HC and CO removal in the catalyst and reducing species for NO removal. An exhaust oxygen sensor and control system modulates the engine's air/fuel ratio about the stoichiometric point to take advantage of species storage on the catalyst surface. The difficult remaining engine problem is adequate control of HC and CO during engine starting and warm-up, before the catalyst is hot enough to be effective.

Of course exhaust emission control is not as simple as this brief description suggests, and many computer-based analysis tools from regression equations which smooth and correlate engine mapping data to define how an engine responds to changing operating conditions, to engine-in-vehicle simulations which are used to define the air/fuel ratio, spark timimg, and EGR strategy as a function of speed and load which maximizes vehicle fuel economy within the constraints of meeting the emissions requirements.

How well do these emission controls work? They do meet the requirements, since obviously all production models which are sold have been successfully certified. Recent EPA estimates based on vehicle emissions data, and a mobile source emissions model that adjusts for deterioration in emission control, mean vehicle speed, and ambient conditions (the latest version is "Mobil 4," EPA, 1990; see Attinson et al., 1990), suggest that in-use emissions are higher than the standards for exhaust HC and CO, and about equal to the standards for NO_x. HC emissions are predicted to be between 1 and 3.4 times the applicable standard with an average multiplying factor of 1.8. The higher factors have occurred the first year a significantly stricter standard was imposed: e.g. in 1980 when the HC exhaust standard went down from 1.5 to 0.41 g/mile actual HC emissions were estimated to decrease from 3 to 1.38 g/mile. Current production vehicles are estimated to have exhaust HC emissions of 0.66 g/mile. Actual CO emissions in g/mile are estimated by EPA to be consistently about a factor of 2 higher than the standards. NO_x emissions are estimated to be within about 10 percent of the applicable standard.

Complete Federal Test Procedure (FTP) emissions measurements by General Motors (Haskew and Gumbleton, 1986; Haskew et al., 1989) on in-use GM passenger cars from model years 1981 to 1986 show average 50,000 mile emission higher than the HC and CO standards for 1981 and 1982 (by about a factor of 2 for exhaust HC, and 1.5 (first year), 1.2 (second year), fo CO) while close to the NO_x standard. In-use cars from model years 1983 to 1986 matched the HC and NO standard, and exceeded the CO standard by some 50 percent in 83, 84 and 85.

Table 2
Automobile Exhaust Emission Standards
For HC, CO, and NO_x

Model Year	HC Emissions	CO Emissions	NO_x Emissions
Uncontrolled	8.2	89.5	3.4 - 4.4
1968	6.2	51	-
1970	4.1	34.0	-
1972	3.0	28.0	-
1973	3.0	28.0	3.1
1975	1.5	15.0	3.1
1977	1.5	15.0	2.0
1980	0.41	7.0	2.0
1981	0.41	3.4	1.0

Note: Standards g/mile.
Source: Grad et. al., 1975, EPA, 1990.

These studies have identified a number of very high emitting vehicles in the vehicle population: e.g. the GM study showed that a few percent (1-4 percent) of the cars have HC and CO emissions more than six standard deviations above the mean.

Before we interpret this information, we must add the results from attempts to measure on-the-road emission directly, a difficult and rarely attempted task. Measurements of pollutant concentrations in the air flowing out of the Van Nuys tunnel in Los Angeles have been converted to average car emissions rates based on measured traffic density. An inventory of vehicles entering the tunnel (over several periods of one hour) permitted an estimate to be made of expected emissions levels using the California Air Resources Board vehicle emissions factor program EMFAC7 (Ingalls, 1989). While the median vehicle speeds (usually about 40 mph) were higher than those of the FTP, and the driving patterns are different, measured emission rates were some 2 to 7 times higher than model estimates for HC, up to 3.6 times higher for CO, and between 0.6 and 2.5 times NO g/mile values. One contributing reason to these high HC measurements may be high evaporative HC emissions, so-called running losses, from the vehicle fuel system, which must be added to exhaust emissions to get total HC emissions, Halberstandt (1989).

A brief summary of the above would be (1) production vehicles meet the certific tion requirements; (2) in-use vehicles in the Federal Test Procedure have average emission levels (at 50,000 miles) that exceed the standards by factors of up to about 2 for HC and CO; (3) more recent model years do a better job of meeting the standards in practice; (4) a few percent of the in-use cars tested have very high HC and/or CO emissions (due to malfunctions and/or poor or no maintenance); (5) actual on-the-road emissions levels are difficult to determine, and one recent study suggests they may be much higher (at 40 mph, approximately constant speed) than the emissions levels which models used by regulators are predicting.

Urban Air Quality

Has urban air become cleaner during this 20 year period when exhaust emissions have been substantially reduced? The answer seems to be "yes," but neither as clean as Air Quality Standards require nor as clean as the achieved reduction in vehicle exhaust emission levels indicates should happen. Total U.S. CO emissions are estimated by EPA to have decreased by 30 percent, 1970 to 1987, and the transportation systems CO emissions contribution decreased by 43 percent. In 1970 transportation was estimated to be the source of 80 percent of the total CO; in 1987 it is estimated to be 65 percent of the total. Extrapolation of average ambient CO concentrations collected by EPA back to 1970 suggests that about a 50 percent reduction in ambient CO concentrations has been achieved over this same time period, 1970 to 1987. Yet CO emissions per average car mile in 1990 should be about one-third what they were in 1980 (Haskew and Gumbleton, 1988), and in 1980 average CO emission rates should have been about one-half of the peak emission rate in 1968 (Grad, et al. 1975): i.e., on a per car basis, CO emissions should be about one-sixth the peak 1968 value. Two obvious additional problems are growth in vehicle miles travelled, and the absolute increase (and larger relative importance), of non-transportation CO emissions. That vehicles exceed the standards in actual use has already been factored in, at least to the degree to which we understand it.

The hydrocarbon problem is more complex still. What matters is oxidant levels; composite average ozone concentrations have decreased by about 20 percent since 1978. Both HC and NO_x contribute to oxidant production, and the ratio of HC and NO_x concentrations in the atmosphere has a major impact on the amount of oxidant produced. Pre-emission control volatile organic compounds (circa 1968) came about equally from transportation and non-transportation sources. In 1987, EPA estimates suggest that non-transportation HC emissions are essentially the same as they were in 1970, and the transportation emission contribution has been halved (Atkinson et al., 1990). Passenger car exhaust HC emissions on an average car mile basis, have gone down by a much larger factor. However, there is concern that evaporative emissions from the vehicle fuel system are not adequately controlled, and have actually gone up as gasoline vapor pressure has risen, and HC reactivity may have increased due to the fuel composition trends of the past two decades. A major problem with volatile organic emissions is the large number of small stationary sources.

Summary

An important lesson from all this is that we do not adequately understand what is going on. While urban air pollution results from an extraordinarily complex set of processes, my own conclusion is that none of the players involved--auto industry, oil industry, regulators, politicians, and the public--have been willing to acknowledge the extent to which we cannot explain what is really going on (what progress we are making towards substantially cleaner air), nor willing to jointly commit the resources needed to understand the problems better.

I reach the conclusion that we have not cleaned up the air to the extent we should have, despite the very real engineering success of the catalytic converter and associated control equipment at reducing passenger car emissions. Though we can offer many possible explanations we really do not know what is not working the way we thought it would. Sources of discrepancy could be some or all of the following: (1) Average real-world vehicle exhaust emission levels may be substantially higher (by more than a factor of two) than the applicable standards; (2) Evaporative hydrocarbon emissions (running losses) are the major source of passenger HC emissions; (3) A significant number of vehicles (newer as well as older) may be really emitters due to component failures, malfunctions, and inadequate maintenance; (4) the growth rates for vehicle miles travelled in urban areas with major pollution problems may be significantly higher than the estimated growth rates; (5) The relative importance of mobile and stationary sources of emissions may have been incorrectly estimated: an error here could significantly change the expected reductions in emissions achieved to date; (6) The atmospheric chemistry that produces oxidants via photochemical smog may be much less sensitive to reductions in inputs (emission rates) than anticipated. Large questions, but a large and important problem! A much more extensive "engineering analysis" of this problem and its key components is required. Lower numbers for passenger car exhaust emission standards would not necessarily improve the situation as discussed below.

ENGINE TECHNOLOGY PROSPECTS FOR THE 1990s

What are the Needs?

Emissions. As explained above we need effective control of emissions in new cars at levels that are low compared to the emissions of old cars the new cars (largely) replace. Since cars last about 10 years, what is required is an incremental reduction in emissions every four or so years, until in-use transportation system emissions are sufficiently below stationary source emissions so that stationary sources become the primary focus for control. For HC it is total vehicle HC emissions that matter, exhaust and evaporative. This has always been the objective of vehicle emissions regulation; however, its realization in practice falls short of the objective. Just lowering the values of new car exhaust emission standards will not solve the problem, other measures are needed.

Engine size and weight. Under-hood space is at a premium; reductions in vehicle weight are attractive for many reasons. So higher specific power (power per unit engine weight or bulk engine volume) will continue to be an important objective.

Engine Efficiency. Stricter fuel economy standards are almost certain for many reasons: magnitude of our oil imports, the balance of trade problem they create, and their strategic impact; concern with rising CO_2 emissions and global warming; need to show the rest of the world we will moderate our high per capita energy consumption.

Reliability and Maintainability. Increasing engine complexity, market competitiveness, need for durable emission control, and the rising cost of vehicle service place a high premium on inherent engine reliability, and low and straightforward maintenance requirements.

Manufacturability. Need for shorter design cycles, and higher inherent quality to lower total manufacturing cost and increase flexibility. These requirements encourage fewer different size engines in each producers' line-up, more modular engine concepts to reduce development and design effort, and discourages use of more than one or two basic engine technologies.

What is the Potential for Improvement?

The concept of "available energy" is increasingly being used to analyze the energy conversion characteristics of engines. Internal combustion engines are devices that process a flow of fuel and air, and produce useful power: they release the chemical energy in our resource - the fuel, and from that energy produce a certain amount of mechanical work.

One can think of the fuel as "our system"; the key question is then how effectively can we produce useful work from this system, allowing it to interact with the atmosphere--our source of air, and also a constant pressure and temperature reservoir.

Application of the First and Second Laws of Thermodynamics to this system shows that the work producing potential of the fuel-air mixture as it goes through a device such as an engine which interacts with the atmosphere is given by the property availability or available energy, A, where

$$A = (U - U_0) + p_0(V - V_0) - T_0(S - S_0)$$

Here U is the internal energy of our system, p pressure, V system volume, S system entropy and the subscript zero denotes atmospheric values (e.g. $U_0 = U(T_0, p_0)$ where p_0 and T_0 are atmospheric pressure and temperature. One can understand the equation as follows. The first term $(U - U_0)$ is the change in internal energy of the system as it comes to equilibrium with the atmosphere. The last term $T_0(S - S_0)$ is the minimum heat transfer with the atmosphere required to bring the system and atmosphere to equilibrium. The $p_0(V - V_0)$ term is the work done by the atmosphere on the system as the system volume changes in this equilibrium process. The internal energy change less the minimum heat transfer less the work done on the atmosphere is clearly the maximum or available useful work. The final state of equilibrium with the atmosphere gives the maximum work. If the exhaust gases are not in equilibrium with the atmosphere, then additional work can, in principle, be produced.

An available energy balance through the engine cycle identifies where opportunities for producing useful work are lost through irreversibilities (such as friction) which destroy available energy, heat losses (which transfer energy and hence work producing potential out of the system) and flows (the hot exhaust gases transfer available energy out of the engine). See Heywood (1988), Primus et al. (1984), or Foster (1985) for a more complete explanation.

Table 3 shows typical numbers for the available energy losses and transfers for a spark-ignition engine at a part-load mid-speed operating condition. It is useful because it quantifies where opportunities for improving engine efficiency lie, and how large these opportunities are. The Table is based on 100 units of fuel available energy. Let us look at each of the terms in turn.

The combustion inefficiency is the HC, CO and hydrogen that exit the engine unburned in the exhaust. The unburned HC are about two of these five units, i.e. 2 percent of the fuel goes straight through the engine. In fact the impact on indicated work is greater than this. A larger fraction of the fuel, about twice as much, escapes the primary combustion process unburned in crevices, largely between the piston, rings and cylinder liner. A substantial fraction of this oxidizes during the expansion and exhaust strokes prior to exiting the cylinder (Namazian and Heywood, 1982). Emissions control requirements will require some reduction in this loss. If the 5 units are reduced to 4, and that extra fuel burns during the combustion process, indicated work would increase by 1 percent.

A major loss of available energy is the combustion process itself. Energy is conserved, but combustion is an irreversible entropy-generating process; the work producing potential of the hot combustion products immediately after combustion is lower than that of the fuel-air mixture just prior to combustion by some 19 percent. There is little we can do about this; burning our fossil fuels is the only practical method currently available for utilizing the fuel's chemical energy. Interestingly, stoichiometric combustion from a high temperature unburned mixture state minimizes this loss. Lean mixtures or EGR increase this loss modestly.

Heat losses from the hot burned gases to the combustion chamber walls remove about 20 percent of the fuel's available energy from the cylinder. (The actual heat loss is a slightly higher fraction of the fuel's energy.) Maximum heat loss rates occur right at the end of the combustion process. Reductions in heat loss would help, but are limited to modest amounts, see below. However, care should always be taken to hold heat losses to a minimum. A decrease in heat losses by x percent, results in an improvement in fuel consumption by about x/3 percent. The exhaust gas carries a comparable amount of available energy out of the cylinder. A greater expansion ratio would reduce this; otherwise exhaust gas energy recovery devices such as a turbine or exhaust-heat driven Rankine cycle system are required.

The indicated work--that transferred to the piston over the compression and expansion strokes--for this condition corresponds to about 36 percent of the fuel's available energy. This quantity, the indicated efficiency of a spark-ignition engine, is remarkably constant over the speed and load range, lying between about 35 and 39 percent at these conditions. It obviously depends on compression ratio and mixture composition (lean, rich, dilution with EGR). It also depends on burn rate and cyclic variability of the combustion process. This latter area has been exploited by the fast burn combustion technology.

Finally, at part load, friction decreases the brake output significantly below the indicated output. As indicated in Table 3 and Fig. 9, the cause is the pumping work requirement of the four-stroke cycle, and mechanical and auxiliary friction. This is, and has always been, a major problem for the four-stroke cycle. It is an area that is being actively worked on for the obvious reason that its leverage on brake output is large: a ten percent reduction in total friction at the conditions of Table 3 would yield a 4 to 5 percent improvement in brake efficiency.

In summary, based on this available energy analysis of the standard four-stroke spark-ignition engine cycle, I would rank the opportunities for improvement in this order: friction reduction (largest), expansion stroke work increase, heat loss reduction/combustion efficiency improvement (smallest).

Table 3
Typical Numbers for Available Energy Engine Analysis

Four-stroke cycle spark-ignition engine at 2000 rev/min, inlet pressure 0.5 atm, stoichiometric operation, compression ratio = 10.

	Indicated	Brake
Available energy of fuel	100	
Combustion inefficiency	5	
Combustion irreversibility	19	
Available energy loss due to heat loss	20	
Exhaust gas available energy (at cylinder exit)	20	
Indicated work	36	36
Pumping work loss		3.5
Mechanical friction and auxiliary loss		7.5
Brake work		25

What are the Opportunities?

Emissions Situation. Obviously all new cars produced must meet the emissions standards. There is an increasing trend towards worldwide uniformity in test procedures and levels of standards (though with different timetables). One appreciates the logic behind this trend. However, it underlines the need for reality (low in-use emissions), and the standards and test procedures that define them, to be closely coupled. Also, different urban areas in the U.S. as well as different parts of the world often have quite different air pollution problems and control needs.

In the U.S. we need an orderly progression towards lower total in-use emissions. This requires effective control of evaporative HC emissions as rapidly as possible, an understanding of the role and causes of very high emitting cars, and procedures (imposed on car producers and car owners) that reduce their impact significantly. It may well require significantly lower exhaust emissions levels significantly lower than current new car standards in some geographic areas in the future, evaluated at more demanding ambient conditions, but the rationale for that lacks adequate quantification. Current proposals in the Clean Air Act are pursuing some of these needs, though not all, and the politics of the situation unfortunately emphasizes the one option--much lower exhaust standards--which is probably not the most important need right now!

But, of course, all new engine options must show the potential of meeting the applicable standards. That gives a significant advantage to evolutionary developments of current production engine technology. Though we should remember that application of substantial engineering resources to the emissions control problem of the conventional spark-ignition engine and the diesel have proved remarkably effective at reducing their emission levels.

The Four-Stroke Cycle Spark-Ignition Engine. Let us look at combustion-related improvements, and then friction. We have already seen the efficiency advantages of fast-burn combustion technology with its rapid chemical energy release close to top center, lower cyclic combustion variability, and ability to absorb more EGR at part load for NO_x control. Some continued improvements here can be expected as the

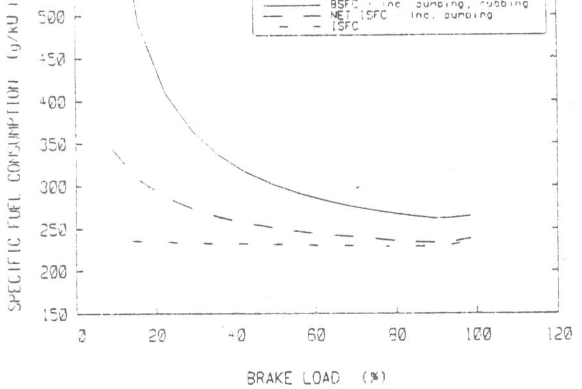

Fig. 9: Indicated (dash-dot line) and brake (solid line) specific fuel consumption of a standard spark-ignition engine over the full load range. Dashed line shows effect of pumping work. 1000 rev/min. Patton (1989).

technology spreads across all engines and is better optimized as it matures. Improved control of fuel metering via increasing use of more sophisticated port fuel injection systems aids this trend. One can also expect reductions in engine HC emissions and improved mixture control to result in some decrease in combustion inefficiency.

Increasing use of knock sensors will permit engine operation closer to the knock limit, and modest increases in compression ratio should result. Perhaps variable compression ratio concepts (e.g. the variable height piston crown concept of Wirbeleit et al., 1990) may prove feasible; use of a significantly higher compression ratio at part load where the engine is not knock limited improves part-load fuel consumption substantially.

There are no obvious ways to obtain substantial reductions in heat losses in spark-ignition engines. The engine is knock limited already with standard water cooled components. Use of significant thermal insulation is not therefore feasible, and even if it were the benefits are limited (Amann, 1989) because substantial heat "recycling" from the hot combustion gases to the incoming fresh charge via the walls then occurs. However, reductions in heat losses through careful optimization of combustion chamber shape to reduce the heat transfer surface area (Muranaha et al., 1984), improvements in surface finish (Tsutsumi et al., 1990) and surface coatings (Boehm and Harrer, 1990) offer useful incremental opportunities.

Friction is an extremely important opportunity. However, its many different components, and its link with wear and durability, make it a different engineering challenge. Here analysis can play an important role. A recently developed friction model (Patton and Heywood, 1989) predicts each significant engine friction component via fundamentally based scaling laws that have been calibrated against available friction component data. The model relates details of the engine's geometry and operating conditions to the magnitude and thus relative importance of each friction component. Figure 10 shows the friction breakdown by component at part load and wide-open-throttle over the full speed range of a modern spark-ignition engine. The model results show the importance of pumping work at part-load, and at high speed WOT, that piston, ring and connecting rod friction is especially important, and that valve train friction at low speed is a significant fraction of total fmep.

Mechanical rubbing friction and accessory drive reductions are already being partially exploited through use of roller followers in the valve train, smaller piston skirts, reduced ring tension, improved design and sizing of accessories. Additional opportunities exist in the friction area, and they will have a significant impact on brake specific fuel consumption.

Reductions in pumping work are harder to realize. Use of significant amounts of EGR, well controlled, helps here. Improved designs of inlet system, and especially ports and valves, helps at higher speeds and is especially important with fast-burn combustion technology since that requires intake flow control with special port and valve geometries.

Variable-valve-timing (VVT) is one option that is being explored. Many different VVT schemes are being considered for (a) improving the shape of the full-load torque curve as a function of engine speed, (b) improving idle combustion quality, and (c) reducing pumping work. Some cam shifting mechanisms are already in production (e.g. Inoue et al., 1989) for reasons (a) and (b), and significant benefits result. Here I will focus on pumping work reduction. Figure 11 illustrates

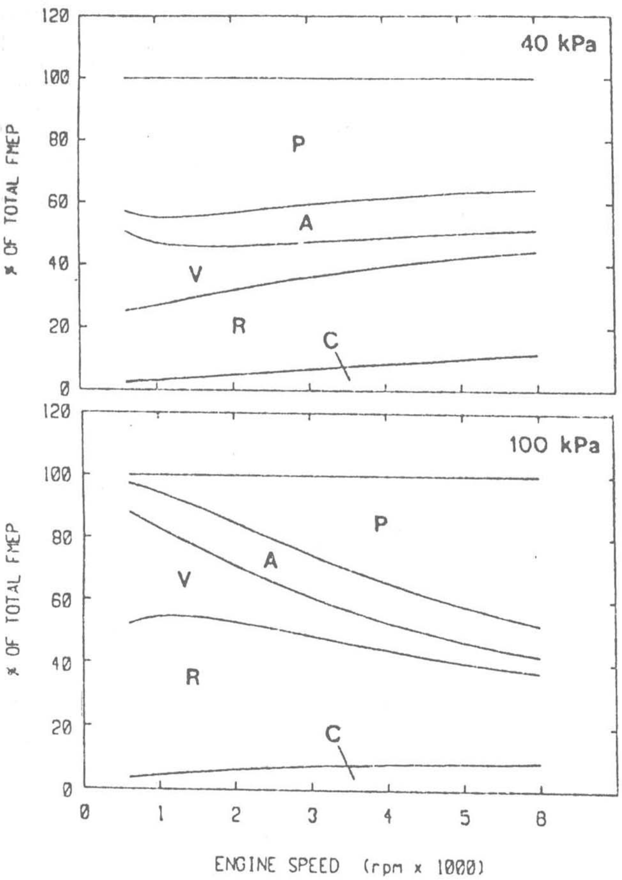

Fig. 10: The distribution of friction amongst its major components over the speed range of a 2-liter 4-cylinder modern spark-ignition engine, at part load (40 kPa inlet manifold pressure) and wide-open throttle. C = crankshaft and seals; R = reciprocating components; V = valvetrain components; A = auxiliary components; P = pumping work. Patton and Heywood (1989).

two variable valve timing concepts, later and earlier intake valve closing as load is decreased. Conventional load control by throttling reduces the mass of fuel and air in the cylinder by decreasing inlet manifold pressure. Late intake valve closing (LIVC) decreases the mass retained in the cylinder by progressively delaying intake valve closing until late in the compression stroke so the piston pushes a portion of the already inducted mixture back into the intake. The intake pressure remains close to atmospheric so pumping work is significantly reduced. However, the compression ratio is reduced, even though the expansion ratio remains unchanged. So the efficiency of the compression/expansion part of the cycle is reduced, somewhat decreasing the benefit. Early inlet valve closing (EIVC) is an alternative approach. Here the mass in the cylinder is reduced by closing the inlet valve earlier, during the intake stroke. Once the valve is closed, the trapped mass is expanded as the intake stroke continues and then compressed again during the compression stroke. The compression ratio is unchanged, but the pumping work benefits are not as large as with LIVC. Only limited data on the performance of these VVT concepts are available to date. Recent tests with late inlet valve closing load control showed part-load brake specific fuel consumption benefits of up to 13 percent (Saunders and Abdul-Waheb, 1989). A different study of early intake valve closing showed improvements in bsfc up to about 8 percent (Lenz et al., 1989).

When late intake valve closing is combined with a higher expansion ratio even larger efficiency gains have been demonstrated. This is the Atkinson cycle (Saunders and Abdul-Waheb, 1989). One major problem, however, is low specific power. This characteristic can be improved with the addition of a supercharger and intercooler to compress the air prior to entering the cylinder and still, in principle, avoid the problem of knock. This has been called the Miller cycle.

Many variable valve timing mechanisms have been proposed (see Ahmad and Theobald, 1989, for a review). Those that are sufficiently flexible to have a significant influence on fuel economy are usually complex, and the cost, durability, reliability, friction, and (if electromagnetically controlled) the power requirements are potentially major problem areas. Whether these are promising practical concepts is not yet clear.

Two-Stroke Cycle Spark-Ignition Engines. A recent modification to the two-stroke-cycle spark-ignition engine has brought this engine concept to the position of serious contender as a passenger car power plant. The most important innovation is fuel introduction into the cylinder after the air charge has been trapped. This prevents the large carry through (20-40 percent) of unburned fuel which occurs with conventional small two-stroke cycle engines and caused their poor fuel consumption and very high hydrocarbon emissions. Figure 12 shows one arrangement of this concept, the Orbital Engine Company's "Orbital Combustion Process." The key features are the air assist fuel injection system, the exhaust port control valve, and the low thermal inertia exhaust and oxidation catalyst system. Air is drawn into the crankcase past the reed valves, by the upward motion of the piston during the compression stroke. Fuel is injected into the cylinder after the piston has covered both inlet and exhaust

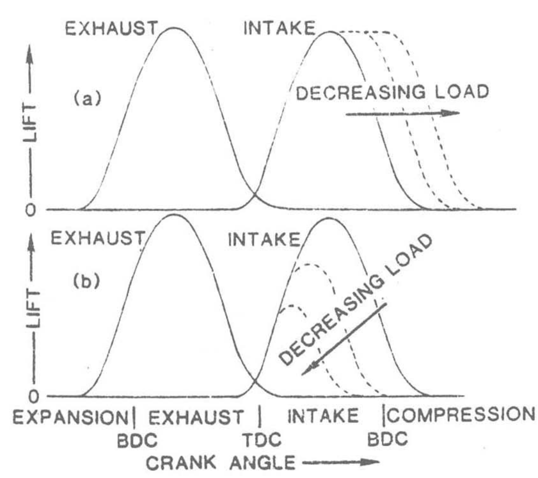

Fig. 11: Valve lift diagrams for (a) late intake valve closing, and (b) early intake valve closing as load is decreased. Both approaches reduce the pumping work at part load by changing the shape and enclosed area of the pumping loop on a p-V diagram. Amann (1989).

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