The Automotive Industry Needs Research

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There is now an increasing need for research to meet the objectives of vehicle energy conservation and the case for this is presented here. It illustrates the need for basic research in areas such as heat transfer and combustion in alternative engines, instrumentation, control, rheology and manufacturing processes for vehicle components and materials. Car manufacture needs research on thermo-mechanical treatments, application of optimisation theory, acoustic diagnostics and assembly of mechanical parts by robots. The best ways of attracting the attention of the university community to such research are also discussed, emphasizing the role of establishing good communication channels.

The automotive industry, in general, has not an out-standing record as a source of motivation and inspiration for basic and applied research. The situation is now changing; and one can forecast that more and more of the research activities of university scientists will be oriented towards problems derived from the automotive sector. In parallel with this, increased attention will be given to applied research and development programs carried out directly by industrial R and D laboratories.

Six major European automotive industries have recently set up a Joint Research Committee (JRC) to explore potential fields for communal long-term research. In the USA, government and industry have identified 12 research areas (see Table 1) for a possible joint support for basic research - the so-called CARP program (Co-operative Automotive Research Program).

Several working groups have been set up by the European JRC to develop program proposals in different areas; co-operation with universities and research institutions has already started in the combustion field, in aerodynamics, and in engine emissions. In the USA a team of approximately 100 scientists from university, industry and government laboratories have prepared advisory reports for CARP describing a range of research topics.

Table l. USA Co-operative Automotive Research Program (CARP). List of identified research areas (March 1980).

Combustion, thermal and fluid sciences
Structural mechanics
Electrochemistry
Aerodynamics
Materials science and processing
Control systems
Tribology
Acoustics and vibration
Surface science and catal0ysis
Environmental science
Biomedical science
Behavioural science

In Italy, the FIAT Research Centre, which is an active part of JRC, has for several years stimulated universities to focus research in the automobile field and has directly supported, through contracts, research in combustion; plastic and composite material properties; engine noise analysis; new techniques for quality controls; understanding material behaviour during rapid deformation for metal-forming; aerodynamic computation techniques and other topics. The growing need for research on vehicle energy conservation, together with the specific actions at national and international level indicated above, justify the forecasts of increasing involvement of university research in the automotive field.

Because of the resistance to change shown by any research body, including universities (resulting from internal inertia), it might be interesting to discuss how quickly and effectively opportunities to carry out research, motivated by and oriented to automotive needs, are likely to be accepted. One body might reject this appeal from the automotive sector, fearing an attempt to destroy the freedom of university research. Another could argue to the contrary, on general grounds, that such freedom of choice is purely nominal in the present highly specialized scientific world. In several fields of basic research the large size of research facilities and the need for team work make it essential to plan basic research for long periods ahead. Because of specialization, any free scientist will then find himself trapped in the strict planning needed to make long-term research possible.

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It seems therefore proper for an industrial sector, in urgent need of research, to present its own case to the research community, trying to orient basic research towards its own needs. The effort will be successful if more and more scientists, in planning their future work, freely decide to join in long-term research programs related to industrial fields. To contribute to this endeavour the present paper unveils such potential research programs without, however, seeking completeness or attempting any detailed analyses.

HEAT TRANSFER IN ENGINES

Although engineers have been successful in designing car engines for a long time, the actual details of the processes going on inside and outside the engine cylinders have only recently been subjected to careful study. This new trend has been prompted by general recognition of the inadequacy of the current design procedure to tackle and solve the large variety of complex problems posed by future engines. These will be expected to operate under quite unusual conditions requiring challenging optimisation among many conflicting variables.

Instead of the current design approach - namely, to try a new solution based on intuitive learning, then see what the results are and decide what to try next - the methodological design approach of numerical experimentation has appeared here, as in other engineering fields, to be far more satisfactory as well as time and money saving. Thus considerate emphasis is placed on the development of analytical and numerical capabilities.

For heat transfer science a turning point occurred around 1950, in conjunction with the evolution of nuclear power. During those years, for instance, research on two-phase heat transfer and fluid flow increased at an astonishing rate, mainly due to problems associated with water-cooled nuclear power plants.

Historically, the familiar process of boiling water has been of primary interest to engineers since the beginnings of steam technology for power production. However, research on heat transfer in boiling received a worldwide and unprecedented impetus for the development of pressurized water reactors: paradoxically, at their early development they were rigorously required not to allow boiling in the reactor core! In fact, before the feasibility of the boiling reactor principle was demonstrated, there was considerable concern about adverse conditions that might be caused by the initiation of vaporization in the core. Most of the initial difficulties originated from a lack of definite and adequate knowledge of basic mechanisms of the subtle and extremely complex processes of boiling heat transfer and two-phase flow. In order to relax the design constraints originally imposed and at the same time to be absolutely confident of safety margins against the occurrence of unexpected and unsafe events in the reactor, it was mandatory to solve formidable heat transfer problems.

This ambitious object was ultimately attained: during those years around 1950 tremendous strides were made in our basic understanding of two-phase pressure drop, critical heat flux or burnout, vapour voidage distribution, hydraulic stability of steam- water flow, heat transfer in superheated regions, transient behaviour of two-phase flow systems and so on. These advances required huge investments in research facilities all over the world, well co-ordinated programs and an unprecedented involvement of engineers and scientists in this field of research.

The present situation of the so-called mature car technology demands a new turning point in heat-transfer science to help us make the jump forward requested by the mandatory need for fuel economy and improved standards of exhaust emissions.

Some of the advances in heat transfer in water-cooled systems, gained in other fields, will turn out to be useful for the problems of heavy duty automotive engines; however, further investigation is required because no one has been able to master the case of water boiling in the tortuous ducts and irregular shapes usually present in the cylinder head of an internal combustion (IC) engine and its typical operating pressures and cooling needs (see Fig. 1). A further fact is that the cyclic characteristics of the heat source in the combustion chamber and the complex phase delay mechanisms make heat transfer dependent on engine speed. These aspects present a first set of topics for a research program: to improve heat removal capability in a cylinder head and thus improving automotive technology.

But there is more to it than the unknown factors of heat removal. Some of the heat transfer problems which exist for car engines are far more complex than those posed by nuclear reactors, as these arise essentially on the heat generation side. It is sufficient to note here that the process of instantaneous heat transfer at any point on the boundary of

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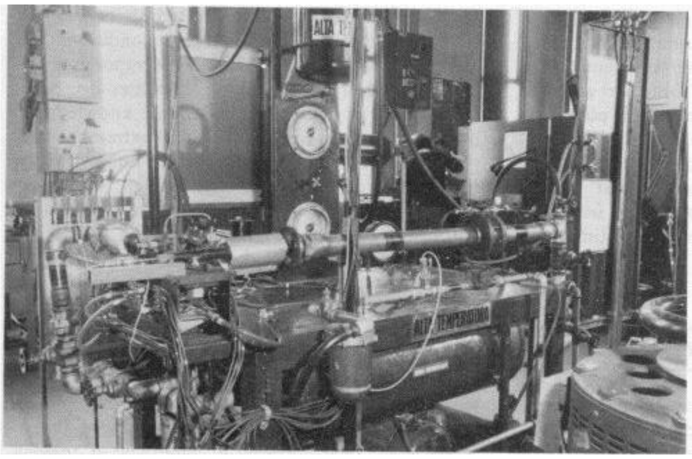

Figure l. General view of a test bench at the FIAT Research Centre for boiling water heat transfer experiments in internal combustion engine passages.

a fluid with variable volume, and reacting in unsteady conditions, has not yet been fully analysed. Even less is known about the heat exchange component resulting from flame radiation.

Most previous research refers to conditions in very large and slow marine diesel engines, but recent investigations have been carried out on spark ignition engines as well as on fast diesel engines. Several empirical correlations for heat transfer calculations have been proposed; but none of these formulae, empirical in nature, have been based on a clear-cut picture of the transfer of heat, mass and momentum actually taking place inside the combustion chamber. Even though suitable in some cases to evaluate instantaneous heat transfer rates, these relations fail to predict local values of heat fluxes because they are mainly based on mean values of gas physics and on engine operating parameters.

We are now witnessing an unbalanced progress in the state of the art of mathematical models and correlations of boundary conditions. On one side there are ever-increasing attempts to much closer mathematical simulation of time and space events within the combustion chamber; but on the other, the applied boundary constraints have only a global validity.

Outstanding progress is being made in developing the necessary instrumentation and analytical techniques for measurements inside the combustion space of an engine. By means of Raman spectroscopy, the gas composition and temperatures may be measured on a bench engine provided with suitable inspection windows. Velocity components can be measured by laser anemometry and local surface heat flux rates may be found from suitable film gauges and experimental transient techniques. Results thus obtained will constitute the necessary base for the development and validation of analytical models. In this context it is worth attempting to correlate surface heat flux rates measured in transient conditions with the relevant local process parameters (temperature and velocity) inasmuch as such phenomenological correlation would readily fit into mathematical simulation models.

A research agenda on heat generation for spark ignition engines could include measurements and analytical correlations of surface heat flux rates, gas temperatures, gas velocities, gas pressure and gas composition. Later on, the simulation of diesel engines should take advantage of experimental and analytical procedures developed for spark ignition engines. A higher degree of complexity exists for heat transfer in a diesel engine, where radiation represents a considerable portion of total heat transfer because much power is radiated from the clouds of soot particles populating the luminous flame and generated by the decomposition of hydrocarbons.

Spray droplet dynamics is another controlling factor affecting heat transfer through the phenomena of impact and evaporation. Separating radiant and evaporative components for the total rates of heat transfer is not an easy task. Furthermore, *in situ* measurement of radiant components is not easy to perform but some diagnostic techniques have already been developed for this purpose.

In the case of the diesel engine, in addition to the items suggested for the spark ignition engine, a research agenda on heat generation should include investigations on black-body and actual flame temperatures as well as fuel-droplet distribution.

ALTERNATIVE ENGINE COMBUSTION

The traditional approach to the design and optimisation of combustion chambers has relied heavily on integral experimentation on engine prototypes. This approach was the only one practicable in the absence of appropriate computational and experimental tools.

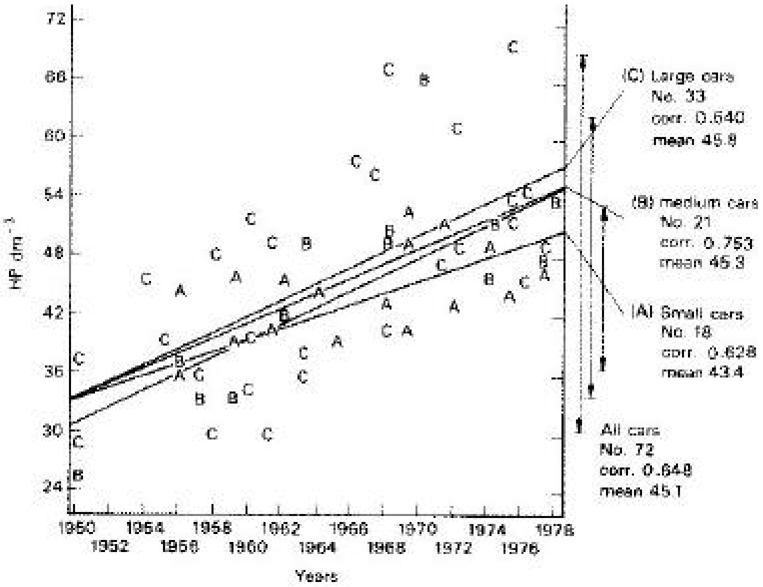

Figure 2. Trends in specific engine power for European cars, 1956-78

Combustion developed therefore more as an art than as a science. Apart from being costly and very lengthy, the integral approach was good enough for innovation of practical engines, especially if measured in terms of specific engine power (see Fig. 2).

The recent need to accelerate innovative changes, so as to deal more efficiently with noxious emissions and fuel consumption, has dramatically emphasized the need to change the design approach: in future the automotive engineer will need a fuller understanding of the underlying physical and chemical processes inside engine cylinders. Only then will a sound design compromise be achieved between fuel economy and emission performances as well as safety, comfort and cost.

There appears no hope of reaching these goals without resorting to mathematical computer simulation of engines. The first attempt in this direction occurred in the design and optimisation of the combustion chamber in gas turbines. These combustion processes, though complex, are relatively easy to model, because of their characteristics of axial symmetry, steadiness and completeness of the combustion chain reactions. The solution of these problems depends on gas diffusivity and complete chemical kinetics as well as on the conditions of air and fuel entering the combustion chamber. A further complication in vehicle application comes from dealing with liquid fuel, because atomisation and vaporization processes must be considered.

In reciprocating internal combustion engines, as distinct from gas turbines, the complexity of the problem grows dramatically. This is due to the basic structure of the combustion process unsteadiness of the flame, and its intermittency. Because of the wide range of operating speeds, this involves very different time intervals for the completion of the various processes and extremely variable boundary conditions.

The equations which describe the combustion process give a flame structure and speed which depend not only on diffusivity and chemical kinetics, but also on the entire time-and-space change in the flow field and furthermore on the boundary conditions depending on the heat-transfer coefficient between piston and cylinder wall as a function of position. The space in which these conservation equations have to be solved is typically three-dimensional. Unsteady single-phase, homogeneous charge, two-dimensional models are currently under development with heuristic-type boundary conditions.

The availability of a really effective model will depend firstly on considerable research to improve the basic understanding of the processes involved, such as chemical kinetics, turbulence, ignition, interaction between turbulence and kinetics, and so forth; secondly on the evaluation of the influence of boundary conditions and their behaviour as functions of the macroscopic operating conditions of the engine such as boundary-layer structure wall heat transfer, initial condition of large-scale fluid motion, and turbulence, as functions of intake system configuration and engine speed; and finally on the development of numerical techniques and pre-post processors for faster formulation, computation and analysis of the results.

The application of the existing models to a real case of a three-dimensional combustion chamber depends on the development of more efficient computation techniques and the definition of more precise boundary conditions. The complexity of the problem grows by another order of magnitude if the assumption of a single phase is given up and both liquid and gaseous phases are considered in the combustion chamber, as for instance in diesel and direct ignition gasoline engines. The development and optimisation of such combustion systems is particularly difficult for two basic reasons. First, the fuel-air mixing process required to sustain and control the combustion process is highly sensitive to the nature of the motion of the gas inside the cylinder, which in turn is strongly influenced by the geometry of both the induction system and the combustion chamber. Secondly, the fuel injected as a liquid must be atomised and the resulting spray dispersed and vaporized, before mixing and combustion can take place.

The factors which influence the process include, in addition to those governing the motion of the air, those affecting the configuration and location of the fuel injector, the injection timing, the fuel delivery characteristics and other factors. The complexity of the global combustion process is such that it is impracticable to consider studying it by basic research unless the global problem is broken down into well defined and simplified sub-problems. The experimental techniques above, by giving more insight into what happens cycle by cycle in the combustion chamber, will greatly help to identify and solve the sub-problems. The increasing complexity of engine testing can be grasped by looking at the ever increasing number of electronic apparatus in an engine test cell (Fig. 3).

The progressive availability of these experimental data will produce other important effects. First of all the number of data to be analysed (in one hour of an engine test run, say at 400 rpm, there are 240 000 combustion cycles) is such as to make new techniques for statistical analysis and pattern recognition mandatory. But even more important it will help to explain the engine behaviour in, transient conditions near the limits of good combustion, such as misfiring and knocking. It might well be that the vocabulary of combustion engineers will include in the near future such present day exotic terms as ergodism of the combustion system.

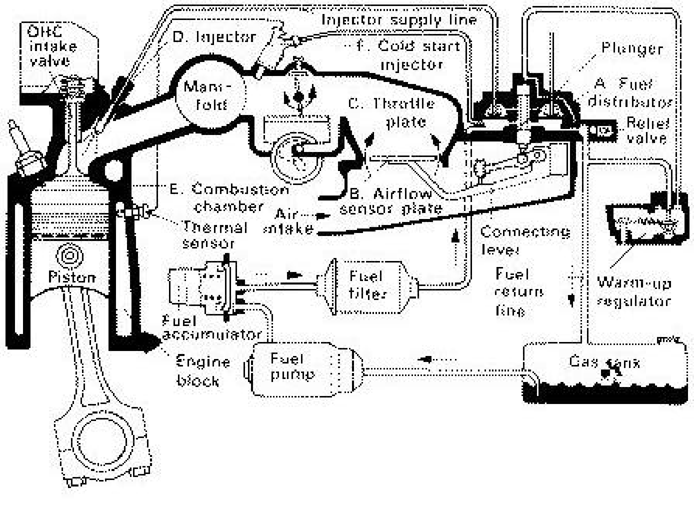

Figure 3. The complexities of a modern fuel injection system. (Courtesy: Volkswagen.)

ELECTRONIC INSTRUMENTATION AND CONTROL OF ENGINE AND VEHICLE

Notwithstanding our lack of theoretical simulation of the combustion process cycle by cycle, the need to control the combustion of the alternative engine is intrinsic in its very conception. Furthermore the required control function has in the past always been performed in the internal combustion engine by mechanical kinematics’ connections, such as the crankshaft and the camshaft. Now, within the last decade, the potential of electronic control, first using wired analogue systems and later digital systems, has been recognized and applied. Although electronic engine control is already marketed, the real challenge of such control is yet to be exploited-it will require the mechanical re-designing of the engine and of the combustion chambers.

When electronics have fully penetrated the mechanically-minded world of the designers of engines and of vehicles, the challenge of control systems research and of microelectronics will feed back to them. As applied to engine and vehicle control, the challenge of control theory derives from the complexity of the system behaviour as shown by the large variation in the time constants governing the dynamics of the vehicle sub-systems. These constants vary from less than a millisecond for the combustion kinetics, through approximately 1 s for the inertial response of the engine and vehicle, to 100 s for the engine's temperature change response.

The case is further complicated by the variability of the demands made on the vehicle by the multiplicity of the objectives of the control systems, some of which are contradictory (emission reduction against fuel consumption), and by the overriding importance of high reliability and low cost. Up to now, electronic control of engines has relied on static optimisation: the system response has been modelled in a deterministic way, correlating its parameters to a control variable, searching for an optimum in a steady-state condition. The weak points of this static optimisation arise because of the sensors' noise, the dispersion in engine-parameter values due to manufacturing tolerances, the degradation with time of the system parameters and sensor failures themselves; they have been ignored. To overcome at least some of these negative effects, feedback sensors (knock, exhaust-gas oxygen content and so on) have been added to improve the parameters of the stationary-control mode.

Major advances in engine and vehicle electronic control will come from the application of dynamic control and the development of suitable models of such systems, from the development of sensors and actuators, and from the development of a proper architecture of the electronic systems to ensure high reliability, resistance to the vehicle's harsh environment, and low cost.

The fundamental purpose of modelling must be a basic understanding of the process to be controlled. This will allow the identification of key variables controlling the process or system and will thereby provide guidelines for rational test procedures and make for a system design consistent with its specifications. A wide spectrum of modelling approaches exists from the detailed mathematically-complex models generally used for component design to the much simpler, liberalized models used for understanding dynamic interactions within a narrow range of conditions.

Parallel research for a better understanding of combustion, discussed above, will help the control engineers. However the challenge in system modelling is to derive as simple a model (structure and parameters) as possible, able to capture the physical behaviour which is important to system studies.

System reliability is dependent on the intrinsic reliability of the sensors and the actuators used in the instrumentation and control system. And here there is a large scope for the development of new sensors, reliable and of low cost and at the same time compatible with the harsh environmental conditions of the car's engine.

Systematic investigations of basic physical phenomena are now needed to identify sensor principles and to develop detailed models of the dynamic and stochastic characteristics of sensors. The problem of developing new actuators is much more complex as it is tied to the mechanical development of the engine and of the power transmission system itself. There is first of all the need for a better comprehension of the actions of today's systems.

Here one must separate often intermingled functions: for instance, the crankshaft performs the function of collecting power from the pistons and in parallel assures synchronization of the motions of the different pistons. Only after such separation can the related control variables be characterized.

Control system scientists should therefore look at the potential of proposed power plant systems where control functions and power transmission are separated. Examples are the electronic actuators of fuel injection in diesel engines and of valve opening in gasoline engines, the direct conversion of mechanical into electrical or hydraulic power in free-piston engines, and the electronic control of continuously variable transmission, as well as other possibilities.

Mandatory for automotive application of electronic control is an assurance that the system will work even with failed elements-fault-tolerance-as well as at low costs. Furthermore the electronic components in the automobile are part of a wider, more complex system whose functions will depend not only on the performance of the individual components and sub-systems, but largely on the architecture or hierarchy of the system. The system architecture should assure the integration of the control system with sensors and actuators and with the interface of the external world, be it the driver, the testing equipment or the maintenance garage. The type of architecture needed to assure these desirable functions in vehicle control is already the object of advanced research in computer science. A certain number of keywords such as hard real time, distributed fault- tolerance systems, graceful degradation, multiprocessor computer architecture and so on might be used as a guide in searching the relevant literature.

In general this type of research refers to general purpose systems. These have to be well-balanced for many different applications and are mostly produced in small quantities. In contrast, in the case of automobiles the spectrum of application is much narrower, while on the other hand, much more stringent requirements are imposed with regard to cost, mass-production, reliability and environment. All this makes it necessary to study specific architectures which might provide solutions, differing widely from conventional computer science applications in terms of both components and layouts.

Among the specific features of electronic car-control systems architecture are: sensors which must include logic components capable of managing communication roles; bus-bars to distribute electric power and information in parallel; components for the integration of analogue and digital logic; specific logic elements with internal redundancy to increase manufacturing yields; the use of optical fibres; and components with very large scale integration, together with new microchip design techniques. The real challenge to the electronic control systems designer and manufacturer can be grasped by looking at fig. 4, which

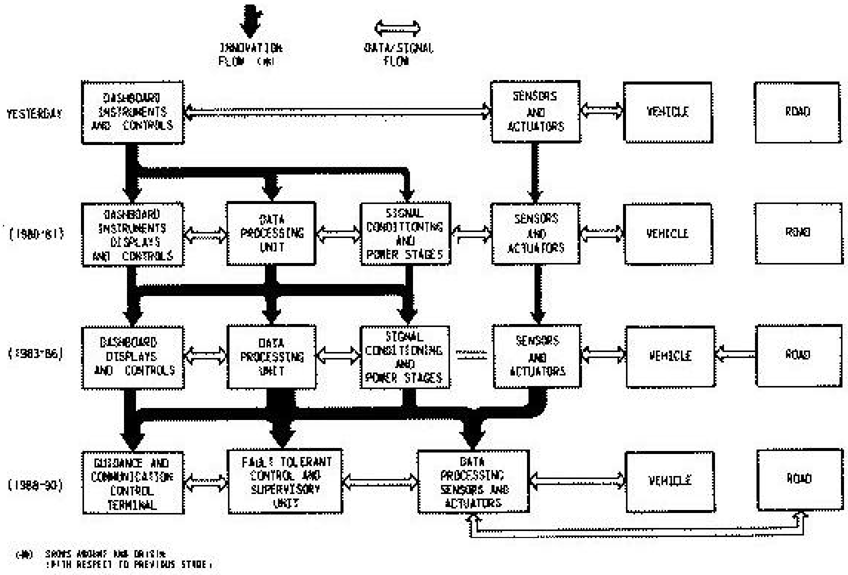

Figure 4. Electronic innovation in the control architecture of automobiles.

summarizes the different stages of integration of electronics in a car-control system.

RHEOLOGY IN VEHICLE DESIGN

Up to now rheology did not enter very deeply into the world of the vehicle engineers, with the exception perhaps of an occasional dialogue with wear and lubrication specialists. Over-simplifying, the vehicle is designed by using traditional linear mechanics of the continuum, namely elasticity theory (Hooke's Law) for solids and hydrodynamics (Newton's Law) for liquids. However, the recently-recognized need to evaluate the behaviour of a car in accidents and crashes has extended the analysis to large plastic deformations in solids.

In the future one can foresee that rheology will become more and more important in vehicle design. It may be defined as the science which extends the mechanics of the continuum to include non-linearity in a stress/strain relationship for solids and in a stress/shear-rate relationship for fluids. Rheology will be needed in car design for the better understanding of lubrication and to reduce friction losses, since at least a 5% improvement in fuel consumption is considered possible by better lubrication; for the development of new concepts in power transmission; and for the introduction of plastic and plastic-based composite materials for structural and mechanical components of cars. From such increasing interest in rheology for car design, basic scientific research will find new opportunities for work oriented towards specific car applications.

Up to now, the major thrust for rheology research has come from polymer development. The research workers, mainly chemists using rheology and rheometry, have tried to find relationships between macro-rheology and micro-rheology. Concepts of molecular weight and its distribution, cross-linking and entanglement, are only a few parameters of micro-rheology opening the way to apply rheology to wood, rubber, clay, cement, paper, paints and pitches. Furthermore, engineers rationalizing the transformation process have applied rheology to foods and cosmetics in addition to polymers and elastomers. Now rheology has entered medicine and biology with bio-rheology contributing to the study of blood and synovia flows as well as to microcirculation.

To return to car design. Rheologists, mathematicians and engineers have considered non-Newtonian fluid dynamics not only for tribological wear reduction, but also to minimize friction losses in automotive power transmission. Lubrication has usually been divided into boundary, hydrodynamic and elasto-hydrodynamic categories. In the transmission chain of car engines, from piston-cylinder and connecting rod to crankshaft, gears and bearings, all three are present.

Improvement in lubrication has been, up to now, mainly the concern of chemists by the introduction of additives, above all the so-called friction modifiers and viscosity index improvers. Friction modifiers act directly on the metal surfaces of the transmission elements, reducing friction by the addition of suspended solid particles such as graphite or molybdenum compounds or by adding soluble oil compounds. The viscosity index improvers, the so-called multigrade oils, are organic macromolecules which reduce the variation of viscosity with temperature, but also increase or decrease the friction coefficient. Great improvements in lubrication have arisen from research as measured by the increase in lubricant life-time in the engine.

Further progress is needed to reduce fuel consumption by an optimal combination of the lubricant base, mineral oil and/or synthetic fluid, friction modifier and viscosity index improver, as well as by metal surface treatment. The items of a possible research encompass: realistic models for boundary, hydrodynamic and elasto-hydrodynamic lubrication; rheometry of lubricants under real conditions, including high relative pressure and shear rates; and the development of lubricants with pressure-dependent viscosity decreasing with shear rate, which are thermally stable and show no degradation due to mechanical stress.

Mechanical power transmission by the transfer of forces across sliding surfaces pressed one against the other is an old idea. Recently the development, stemming from rheology research on lubricants, of a traction fluid has made continuous drive transmissions possible. The main characteristic of a traction fluid is a very high increase of viscosity with pressure: this is probably due to the occurrence in the lubricant film of a reduction of the free volume of special molecules and a hypothetical glass transition phase, elastically reversible.

Research to develop a better understanding of the traction fluid operating mechanisms can perhaps find an analogy in the approach of rheologists to an understanding of the synovial fluid, the lubricant of human joints. This fluid is a concentrated non-Newtonian solution whose viscosity markedly increases with pressure and decreases with shear rate. The increase of viscosity with pressure is related to an increase of concentration followed by gelation. Concentration increases because the less viscous parts of the fluid enter the sponge-like structure of the cartilage, the interface between the synovial fluids and the bones of the joint. Gels seem to be formed through the simultaneous action of free volume reduction and molecular re-orientation through the pores at higher load. The transformation is elastically reversible. Nature, in the case of the synovial fluid, has succeeded in mastering the interdisciplinary research needs mentioned above!

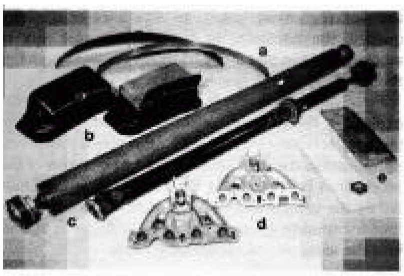

Figure 5.
Prototypes of composite and plastic fibre-reinforced components for vehicles compared with present metal components: (a) leaf-spring (weight reduction from 7 to 2.1 kg); (b) oil pan (weight reduction from 2.7 to 1.3 kg); (c) transmission drive-shaft (weight reduction from 18 to 10 **kg);** (d) inlet air manifold (weight reduction from 2.6 to 1.4 kg); (e) valve cover (weight reduction from 1.2 to 0.45 kg).

Applied research on composite materials has recently been sponsored by the aerospace industry. More challenging problems come from extending their use to the automobile industry because there are many mission utilizations with non-directional stresses in the structure and because of the importance of material choice compatible with large volume and low cost production. A wider use of these new materials in vehicles (see Fig. 5) will depend on research in the following areas: the mechanisms that influence the viscoelastic properties of the polymer base in composite materials (to be studied with simple structures, as for example amorphous polymers reinforced by inclusion of partially crystallized polymer and of mixtures of polymers, alloys of linear and branched polymers) and including the time dependency of the viscoelastic characteristics; the basic mechanism at the interface between the fibre and the plastic matrix, in terms of the ultimate properties of the composite material; developing a testing methodology to measure the mechanical-dynamical behaviour of composite materials-research to be aimed at phenomenological models equivalent to the linear elastic fracture mechanics used for metals; understanding the environmental effects on material properties including the appearance of crazing behaviour prior to rupture; and the development of tools for a computational structural analysis of composite materials.

PROBLEMS IN MANUFACTURE

The problems so far listed derive from the need of product innovation. Less emphasis is usually given to problem areas in manufacturing technology and processes. In spite of this, innovation has progressively produced dramatic changes if measured over a lengthy time. These innovations have almost been forced on to the car industry by the need to improve the working environment, an assurance of constant quality, the necessity to deal with a new mix of materials in the product and to accept the impact of the micro-electronic revolutions.

Four different areas need more basic research: exploiting thermo-mechanical treatment to improve the characteristics of metal components; applying optimisation theory to the logistics and layout of the production factory; using the analysis of noise emitted by the vehicle and its components as a diagnostic tool for quality control; and the diffusion of robots into the assembly of mechanical parts.

THERMOMECHANICAL TREATMENT OF METALS

Thermo-mechanical treatment, such as forming steel while in the austenitic state, developed around 1950 as a result of research to develop high-resistance steels with good formability. These requirements were in contradiction to the conventional technologies, but could be achieved by controlling the deformation process at medium temperature. The successes achieved in the laboratory were found to be difficult to transfer to an industrial scale, with the exception of aerospace applications, because of the high process costs due to the use of high purity steels and very precise control of process variables, such as temperature, time and deformation.

A new research effort came from the need to reduce vehicle weight in competition with other materials. It was found possible to develop new thermo-mechanical treatments by proper sequencing of the treatment steps, taking advantage of micro-defects produced by deformation.

It is therefore possible to design defects structures, provided one has a precise knowledge of the metallurgical phenomena and can accurately control the process variables. In other words, there is the need of a strict integration between physical metallurgy (crystal structure) and process metallurgy (deformation, temperature and time). Success in scaling-up these processes came through controlling the temperatures in sequential lamination, arriving at the so-called HSLA (high strength low alloy) steel.

Now the research challenge is to extend the thermo-mechanical treatment to produce during the deformation process more complex components which not only have the desired form but also have the local mechanical characteristics specified in the design. The research topics to underpin this desired extension are: Physical Metallurgy (work hardening limit state, recovery and re-crystallization phenomena, super-plasticity, and so on); Process Metallurgy (influence of alloying, at micro and trace level, in order to design strictly defined alloys); Science of Construction (design of preforms suitable for giving, through thermo-mechanical treatment operations, the required characteristics and shapes); Machine Design (extrusion and forging machines of suitable power, designed to give higher production rates through high-speed deformation and in *situ* heating and cooling systems); Tribology (tool-material interaction, lubricants for warm working operations, lubrication systems for complex geometries, and so forth).

APPLICATION OF OPTIMISATION THEORY

Operational research, such as the new system optimisation techniques of linear and non-linear programming, integral and dynamic programming, has led to new applications and novel motivation for further development in product distribution problems, aircraft scheduling, and similar sequential problems. Increase in computation speed now allows the use of mathematical algorithms in many new fields, for example chemical process control. Their application to the manufacture of cars is now being developed or at least considered theoretically. They are: economic layout of metalworking and/or assembling; optimal dimensioning of storage in a transport line; optimal work load distribution in a flexible manufacturing system; and dynamic control of batch flow in a conventional workshop and optimal management of the warehouse-workshop system. Research for these applications will be difficult as optimisation problems involve an extremely large number of variables, needing in turn a correspondingly large computer memory and long computer time. Moreover, the relationships among problem variables can seldom be summarized by simple analytical correlations but have to rely on simulation models of the entire manufacturing system under study.

A research agenda to develop more useful tools for such application would include the development of more efficient methods of breaking down large scale problems; the improvement of the efficiency of analytical tools such as the branch-and-bound method for reducing research space looking for possible solutions; and the development of methods which combine simulation models with optimisation techniques.

ACOUSTIC DIAGNOSTICS

The potential value of diagnostic tools based on the analysis of emitted waves, both acoustic and electromagnetic, was first exploited in aerospace, telecommunications and medical diagnosis. Aerospace research resulted, for example, in models to deal with aerial and structural noise propagation. Data transmission, mathematical image processing and identification of vocal characteristics are other examples.

The car industry started to apply these techniques to solve such problems as automatic diagnosis of gear couplings and gear boxes. An extension to more complex cases, such as complete engine diagnostic or vehicle comfort diagnostic, requires more complex techniques which are a challenge to more basic research.

The relevant research needs can be summarized as (1) the modelling of aerial and structural acoustical transmission for very complex systems with inherent interference. To give an idea of this complexity, consider the engine space under the bonnet, where interference from different sources and reflection from surfaces can contaminate the significant signals on which diagnosis must be based; (2) the development of experimental techniques together with appropriate transducers. In other fields, such as aircraft, it is possible to visualize an acoustic field using multiple detectors. For reasons of reduced speed and cost, the car industry must develop cheaper and simpler techniques. One interesting development might be represented by pressure transducers made of plastic material like polyvinyl fluoride; (3) the shortening of simulation and testing time to make it compatible with application in real time on the production line. The need here is to develop engine tests on the factory floor which will simulate all important effects without actually igniting the combustion or more generally replacing actual hot running conditions by cold testing, without impairing the diagnostic significance of the test.

ASSEMBLY OF MECHANICAL PARTS

Car assembly is probably the most labour intensive area in automotive productions, as the number of workers in this area is about 2.5 times greater than that in the mechanical workshops. Here the future of automation depends on the development of robotics. Robots programmed to perform simple operations an indefinite number of times could take advantage of a tayloristic organization of work. Then, human attendants would only have to supervise programming and maintenance without being bound to the assembly line.

The low level of automation on present assembly lines is practically due to the fact that work-places on an assembly line require a low capital investment; at the same time the operations that are performed, even when simple, are to a large extent undefined. The assembly line operator uses sight to pick up, inspect and orient the parts, he uses touch to feel insertion forces and thus is able to perform emergency procedures to accomplish his task even when minor deviations from the standard situation occur.

To replace a man for such apparently simple tasks requires not only a flexible operating machine such as a robot, but also some kind of artificial intelligence. Research topics, able to offer economically practicable solutions, are: robot vision; force and slip sensors; robot wrist compliance; special computer languages to teach assembly tasks to robots and special controllers capable of recognizing faulty situations and automatically able to recover standard performance.

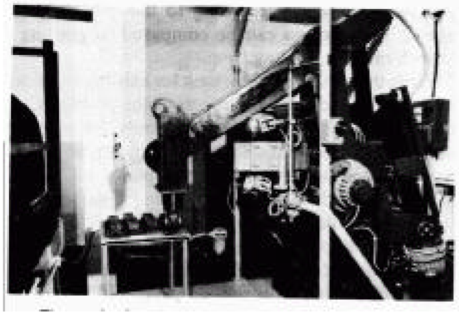

Figure 6. A robot-vision system developed at the FIAT Research Centre. The solid state TV camera (centre foreground) sends a picture of the vehicle's door frame to a computer which, in less than a second, processes it to determine the exact position of the holes. The robot's arm is then instructed to pick up a hinge and to bolt it onto the door frame.

There is room here for very challenging application research on artificial intelligence. In Fig. 6 the prototype of a robot is shown using vision and sensorial ability to decide where the holes on a door frame are onto which to bolt the hinges.

CONCLUSIONS

The case studies here presented show that challenging and long-lasting research problems can be found in a so-called mature industry. Because of this well- perceived need for research our industry is making the demand for research clear, meaningful and explicit. In the opening paragraphs of this review three cases were mentioned: the single company cooperating with universities, the group of companies joining together to refine research problems and cooperate in their solution and the large government-industries cooperative problem-definition program.

How will the research communities, especially the universities, react to match the research demand with their research offer? The risk is that any coupling between two so complex systems, research demand and research offer, will be very wasteful. The trick will be to induce an efficient organized response from the complex university research system by good communication. This we know from the theory of complex non-linear systems and their capability to show cooperative self-organizing behaviours. Communicating among complex systems is an iterative process. The first steps to match research demand with research offer can be from the industry side, to make the problem areas look familiar. From the stated objective of innovation leading to development, to applied research and to basic research, identifying the relevant disciplines; put the problems within well-established research paths. Show how research in different areas can be the basis for further progress in science according to the new research needs. This process can be compared to grafting a branch onto an existing tree.

From the university side: look for existing solutions in the perceived familiar aspects of the problems. At the beginning the problem will only be partially understood. Recognition of what is known and available in the different scientific disciplines will permit interaction with industry, proposing possible solutions that could be transferred. This will have the important effect of leading to an insight into the real complexities of the problem. Then make a general definition of the problems as perceived, since the university should not be passive by pretending to have only the role of problem solving: on the contrary, if the university made an effort and assumed also the task of defining the problem the results would lead to a first generalization, a great help for better understanding. Moreover this would help considerably in the thorough understanding of industrial problems in the research community.

The process should continue iteratively. In this review I have tried to demonstrate, if only in a very approximate way, the industrial research demands, quoting a few relevant examples from the car industry. The demands for innovation are very ambitious, both in effort and in time, and require such a major research investment that it is no longer possible to rely on a casual interaction between industrial and research community. Research must now be planned. To do this efficiently in the university industry must excite their internal capabilities through self-organization of seminars, conferences, informal communications between scientists and through academic recognition. Once the problem areas are well understood, the universities will succeed in developing a cooperative, coherent and resonant response to the research needs of industry.

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