RECENT DEVELOPMENTS AND TRENDS

By PETER KYROPOULOS

and CRAIG MARKS

WHAT IS THE status of automotive engines today? How do the various powerplants compare as to output. bulk. efficiency? What is the trend for future development?

This discussion will be limited to two basic classes of applications of automotive powerplants—passenger cars. with a power range from 100 to 200 hp; and highway trucks with a power range of 150 to 1100 hp.

For these vehicles. four types of powerplants are worth current consideration—the gasoline engine. the diesel engine, the gas turbine and the compounded powerplant (combinations of reciprocating engines and gas turbines).

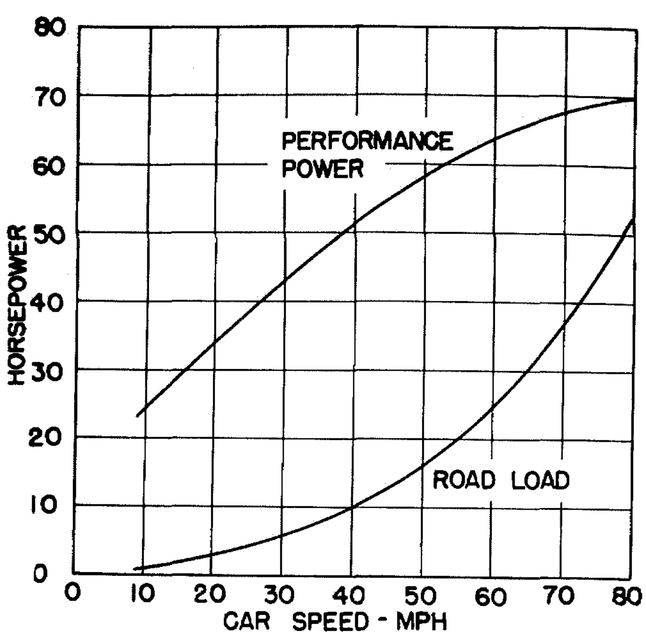
Passenger cars

A passenger car is expected to accelerate rapidly. to have good hill-climbing ability. to reach maximum speed quickly and to have reasonable fuel economy. In order to reconcile these conflicting requirements with each other it is necessary to consider the combination of engine and transmission. i. e., the whole power package. rather than each component separately.

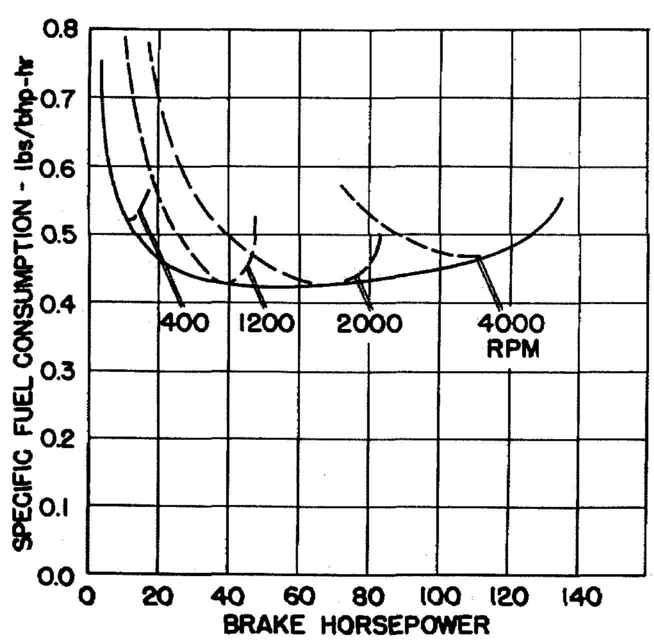
It is the aim of the transmission designer to produce a transmission which will take full advantage of the inherent economy of the engine while providing the necessary performance in acceleration and hill-climbing ability[1].

A design for given vehicle performance is based on power-required and power-available curves. Typical curves of road load horsepower for a passenger car[1] are shown in Chart A. The lower curve represents level road power required. the upper one shows power required for satisfactory acceleration and hill-climing ability.

The power delivered by the engine at any engine speed is shown in Chart B. plotted against values of specific fuel consumption. Operating the engine at constant speed and varying throttle settings results in one of the dashed curves of this chart. These curves are the so-called fish-hooks or consumption loops. For each speed there is *one* power of minimum fuel consumption. Especially at the lower engine speeds. fuel consumption increases rapidly if the power is changed ever so slightly in either direction away from the point of minimum consumption. The solid curve envelops all consumption loops. It represents, then. for all possible powers. the absolute minimum fuel consumption of this engine. Operation of a vehicle powerplant on this minimum curve would only be possible with an ideal transmission which would automatically adjust the engine



A. *Passenger car power requirements—for level roads (lower curve) and hill-climbing (upper curve).*



B. *Fuel consumption as a function of power and engine speed. Typical passenger car engine.*

This article has been adapted from a paper presented before the California Natural Gasoline Association. October 10. 1952.

speed to that required for any desired power output.

The efforts of engine designers are directed towards lowering this curve. Two steps are taken to accomplish this: (1) Increase in compression ratio; (2) Improvement in breathing.

The effect of *increased compression ratio,* both on power and fuel consumption, has been studied[2], as well as advertised extensively. Chart C shows the percent gain in power and decrease in fuel consumption for a typical modern V-8 engine, referred to 8:1 compression ratio as a base. The improvement is appreciable. No insurmountable design problems have arisen from increased compression ratios. Although octane requirements increase with compression ratio, this is an economic problem rather than one of engineering. If demand warrants production of such high octane motor fuels, they will be available.

Improved breathing can be brought about by supercharging as well as by proper manifolding[3]. This is illustrated in Chart D. Data represent production engines rather than experimental types and hence reflect realistically what can be expected.

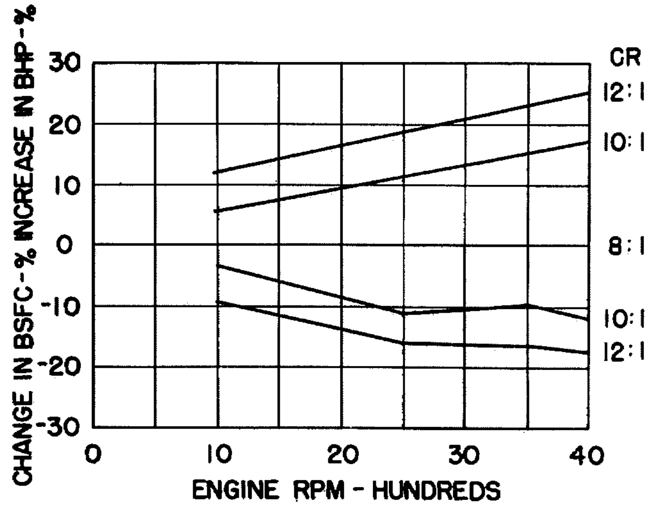
General problems arising in connection with the application of superchargers to reciprocating engines will be discussed later.

Engine-transmission relationships

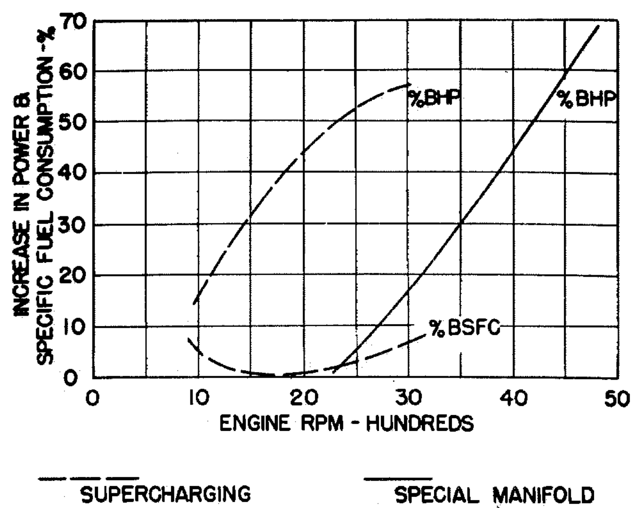
Returning to Charts A and B, it becomes apparent that the level road power-required is considerably smaller than the power-available. For example, at 25 mph approximately 5 hp are needed. In Chart B this corresponds to an engine speed of 400 rpm with a consumption of 0.6 lbs./bhp-hr; however, with present-day transmissions, the engine is rarely ever at its minimum fuel consumption. The ideal transmission would keep the engine operating on the solid (minimum) curve of Chart B at all times.

What this means in economy potential is shown in Chart E[1], in which the brake specific fuel consumption has been translated into the more tangible miles per gallon at road load. The ideal transmission curve represents the best obtainable mileage from the given engine. Comparison with the curve representing a typical stock car shows a possible improvement by a factor of two at around 30 miles per hour.

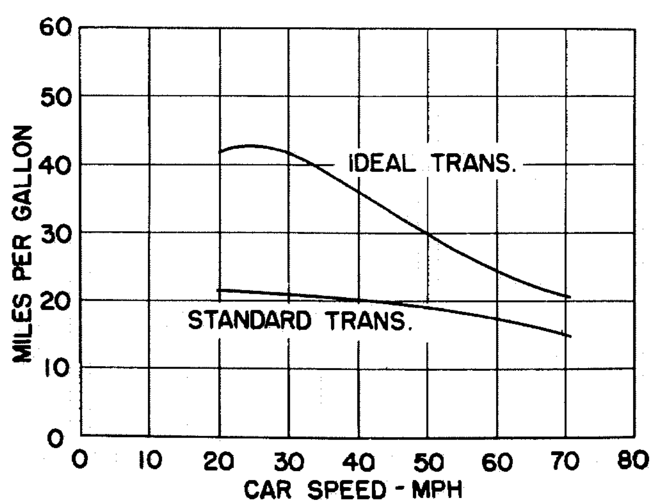
It should be emphasized that this gain is possible merely by developing a transmission which fully utilizes the potential of the engine. Any improvement in engine performance can be added to this gain. It is concluded that the proper matching of engine and transmission represents the most fundamental problem in vehicle development today. It is obviously not limited to the passenger car field.



C. *Change in fuel consumption and power with compression ration. (GM research engine.)*



D. *Change in power and fuel consumption for production engines with supercharger and special manifold.*



E. *Economy of passenger car with standard and ideal transmission. (GM research engine.)*

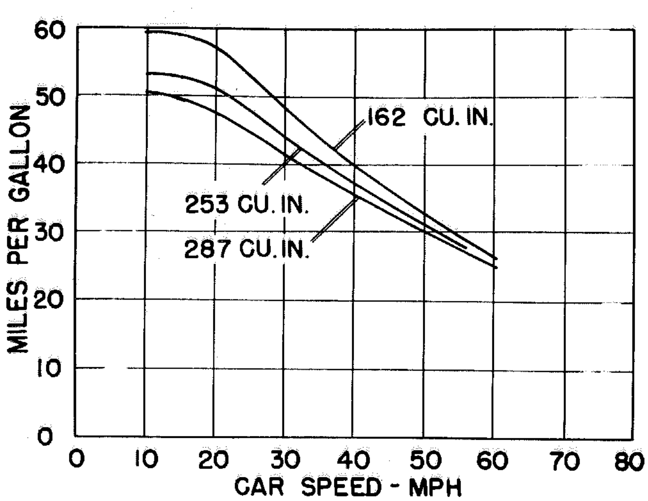
CADILLAC TEST CAR DATA

(1951 and 19XX cars are equipped with hydramatic transmissions).

	1915	1935	1951	19XX
Bore (inches)	$3\frac{1}{8}$	$3\frac{3}{8}$	$3\frac{13}{16}$	$3\frac{3}{4}$
Stroke (inches)	$5\frac{1}{8}$	$4\frac{15}{16}$	$3\frac{5}{8}$	$3\frac{1}{4}$
Displacement (cu. in.)	314	353	331	287
Compression Ratio	4.25	6.25	7.50	12.0
Brake specific fuel cons. lb/bph-hr		0.63	0.55	0.46
Miles per gallon at 50 mph	6.8	11.5	18.6	25.5
Max. Brake Torque (ft lb)	152	234	268	266
Max. bmep (psi)	73	100	122	140
Max. bhp	77 at 2600	108 at 3000	133 at 3600	148 at 4000
Hp/cu. in.	0.245	0.306	0.402	0.522
Wheelbase (inches)	122	128	126	126
Curb Weight (lbs)	4140	5050	4440	4440
Eng. rpm/mph	46.5	51.4	40.2	32.9
Axle Ratio	5.07	4.6	3.36	2.75

It is interesting to note, at this point, the effect of engine size (displacement) on economy, assuming the ideal transmission to be available. Chart F[1] shows a comparison of economy for three engine sizes. The advantage of the smaller engine is derived from the reduced throttling necessary for low power output; however, this advantage is not as great as might be expected, even at low speeds. At higher car speed it practically disappears. There is, on the other hand, no incentive to build engines with greater displacement volumes. The trend is towards smaller displacements with a possible optimum around 250 cu. in.

In order to put those minds at ease which might be alarmed by this discussion of a non-existent, hypothetical ideal transmission, Table 1[4] is shown above. It represents a comparison of Cadillac cars tested simultaneously, and illustrates the economy trend realized through engine development only. Even without the ideal transmission, the 19XX car manages to show an appreciable gain in economy over the 1951 model.



F. *Economy of passenger car with ideal transmission and engines of different displacement.*

The table further indicates the trend in displacement volumes. The brake horsepowers listed for the 19XX car seem to contradict the 1952 practice, which has become known as the "horsepower race." It is admitted among engine designers that much of this race has more advertising value than engineering merit.

For several reasons, there have been no attempts in the U. S. to utilize diesel engines in passenger cars. The small diesel has particularly poor part-load economy when compared with gasoline automotive engines. This, combined with such problems as smoking, the high cost of maintenance of injection systems, and poor starting in cold weather, makes this engine undesirable for passenger car service.

The gas turbine, likewise, is not particularly suited for passenger car service—a fact we will consider later on.

It must be borne in mind that the present gasoline engine has been developed until it is an extremely reliable powerplant, and production as well as servicing facilities are well established. To overcome this head start, any potential substitute must exhibit a real and present advantage, as well as promising future improvements to match those which are expected from the gasoline engine.

Trucks

Truck powerplants can be expected to undergo the most extensive development in the next ten years. Much of the incentive for this will come from the problems arising in highway trucking in the Rocky Mountains and on the West Coast. Let us formulate the requirements: a truck-trailer combination of 75,000 lbs. gross weight should be able to travel on grades from 3 to 7 percent at altitudes up to 8000 feet at speeds of not less than 45 miles per hour. These requirements demand powerplants of the order of 1100 hp; however, no such engine of reasonable size and price is now available for use in commercial vehicles.

Two primary requirements for this powerplant stand out: (1) High output per cubic foot of powerplant space; (2) Reasonable economy in cents per mile.

For the reciprocating engine this means high output per cubic inch of displacement and a strong advantage for the large diesel engine—which has a low fuel consumption, as well as being able to use a fuel that is inexpensive compared to high octane gasoline. This is the reason for the present predominance of diesel engines in large trucks.

It should be noted that attempts to utilize Bunker C fuel oil in conventional diesel engines have not so far been successful, because of excessive variation in its properties. Certainly it is worth bearing in mind that a powerplant which can be designed to utilize these low grade fuels is in a strong competitive position cost-wise.

High output per cubic inch displacement points to supercharging in both gasoline and diesel engine.

Supercharging

The four-stroke diesel is best suited for supercharging, and considerable development is under way in this direction. Since superchargers have been used extensively and successfully on reciprocating aircraft engines, we are often tempted to assume that application to vehicle engines should be a matter of course. This is by no means the case. The aircraft engine is basically a constant speed engine and transients are a minor part of its operation. The vehicle engine, on the other hand, seldom operates at one speed for extended periods. It is constantly accelerated and decelerated. Around this fact are centered the problems of supercharging vehicle engines.

Supercharging may be done either by means of a positive displacement pump (a Roots-type blower), or a centrifugal blower—driven mechanically, or by an exhaust gas turbine.

The mechanically driven Roots blower is well suited for variable speed operation but has relatively low efficiencies. The centrifugal blower is capable of high efficiencies but only over a limited range of flows. It is therefore not very adaptable to variable speed engine operation.

Axial flow compressors are not attractive for use on vehicle engines because of their excessive space requirements and cost, even though they promise high efficiencies.

The use of exhaust energy to drive the supercharger is thermodynamically highly desirable, since the power required to drive the blower is obtained from residual energy in the exhaust, whereas the mechanically driven supercharger uses engine power output directly. The turbocharger is not satisfactory, however, for applications which have stringent requirements for flexibility over a wide range of speeds and loads — such as are encountered constantly in vehicle powerplants.

It might be well to indicate at this point the order of magnitude of supercharge pressures and blower speeds. Typical pressures range from 37″ Hg absolute at 1200 engine rpm and 22,000 blower rpm to 49″ Hg absolute at 2100 engine rpm and 38,000 blower rpm. Roots blower speeds are lower and pressures higher at low engine speeds. The high speeds of the centrifugal blower indicate that the blower drive design problem is serious, especially if engine speeds vary rapidly. The high inertia of the rotating impeller imposes very high loads on the blower drive during changes in speed.

Considerable development work is needed before satisfactory powerplants will be produced which match in reliability the unsupercharged engines. High performance centrifugal superchargers for variable speed service must be produced.

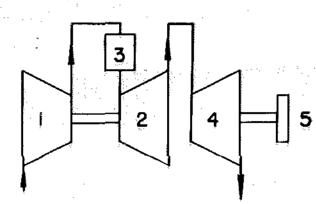
Octane requirements of supercharged gasoline engines are high, and present the same problems which the high compression engine presents. Anti-detonant injection for truck powerplants has been developed and is satisfactory. These facts notwithstanding, the advantage is with the diesel engine.

Weight and size of the reciprocating vehicle engine get rapidly out of hand as the power increases. The gas turbine then becomes at once an interesting possibility for vehicle (truck) applications in this high power range.

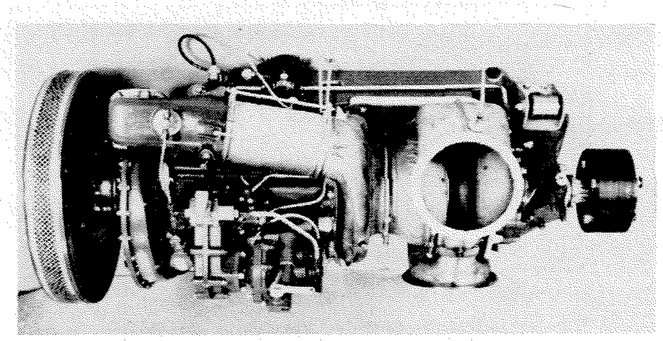
The gas turbine

The rapid development of gas turbines during the last 10 years has attracted considerable attention. Nevertheless, the basic theory was worked out and understood 45 years ago. Recent work has been directed towards making this powerplant reliable and competitive with other types. Applications have been made principally in the field of aircraft propulsion and power generation, both stationary and for rail service.

The Boeing truck gas turbine (below), with a schematic diagram of its components (right).



1 = COMPRESSOR
2 = COMPRESSOR TURBINE
3 = COMBUSTION CHAMBER
4 = POWER TURBINE
5 = POWER TAKE-OFF



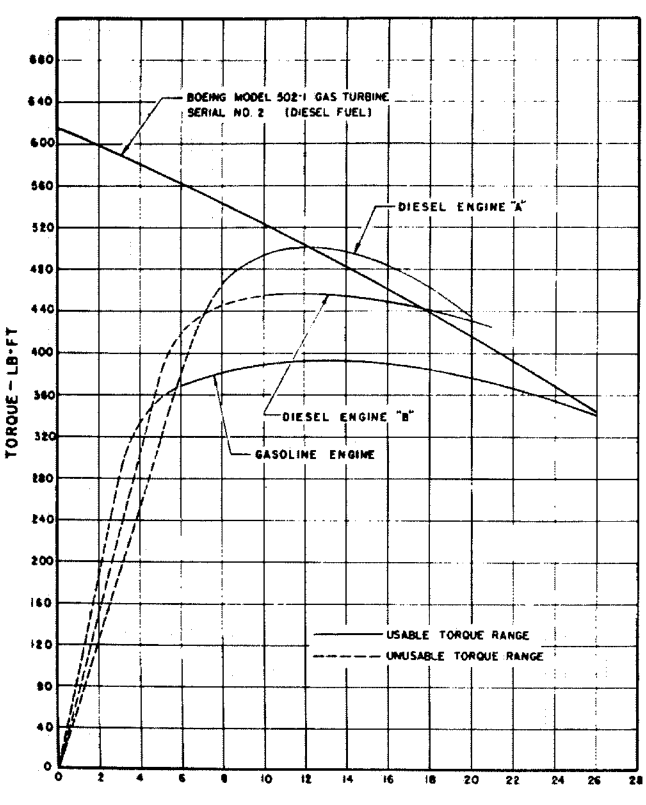
COMPARISON OF BOEING TRUCK TURBINE WITH OTHER POWERPLANTS

	Model 502	Aviation Gasoline	High Speed Diesel	Gasoline Industrial Automotive
*Part numbers in Engine	175	310	480	396
*Number of Parts in Engine	220	825	1400	881
Number of Close-Tolerance Running Fits	16	100	135	100
Max. Bhp	180	180	180	180
at rpm	36000	2700	1100	3600
Engine Weight—Pounds	200	395	2000	1500
Length—Inches	38	38	70	55
Width—Inches	22	32	30	26
Height—Inches	22	30	45	46
Installation Envelope—cu. ft.	12.7	25.2	66	46

*) Standard parts such as nuts, bolts, etc., not included.
"Part Numbers" counts only *once* any identical parts, i.e. 6 pistons = 1 part number but 6 parts.

It should be noted that these applications call for essentially constant speed service, for which turbo-machinery is most suited. Experimental vehicle powerplants have been designed and constructed and have demonstrated the potential of the gas turbine in this field.

The Boeing 502 truck gas turbine is shown on p. 21, along with a schematic diagram of its components. The unit consists of a centrifugal compressor driven by a gas turbine. The exhaust from the first turbine then enters the second or power turbine which, through a suitable reduction gear, drives the vehicle. This separation of compressor and power turbine is essential for vehicle applications since it allows speeding up of the compressor and gas flow, while the power turbine is at rest.



G. Comparison of gas turbine and other engines. Torque as a function of speed.

Table 2[5], above, is a comparison of the Boeing turbine with other powerplants of comparable output. The favorable weight-power ratio of the turbine is at once apparent: it is 1.1 lbs./bhp for the turbine, 11 lbs./bhp for the diesel engine and 8.3 lbs./bhp for the gasoline engine. The differences in space requirements and number of parts are similarly striking. Since present experimental vehicle turbines have been developed from aircraft applications (auxiliary powerplants) they have been designed with emphasis on weight reduction. Most likely this results in high cost. For vehicles, these extreme efforts to save weight may be a luxury so that a compromise may well be in order.

In Chart G[5] the torque characteristics of these powerplants are compared. The high stall torque characteristic of the turbomachine is highly desirable for vehicle application.

The fuel consumption curves, Chart H[5], reveal the most serious drawback of the turbine: high fuel consumption, or low thermal efficiency, especially at low speed. This difficulty arises in all gas turbine applications and is one of the most pressing assignments of research and development in this field.

It is well at this point to recall some of the fundamental facts concerning gas turbines in relation to the requirements of a vehicle powerplant.

(1) The turbine is basically a high speed machine. This is responsible for the small size per unit power.

(2) Maximum efficiency is obtained at *one* definite speed. The efficiency-speed relation is such that

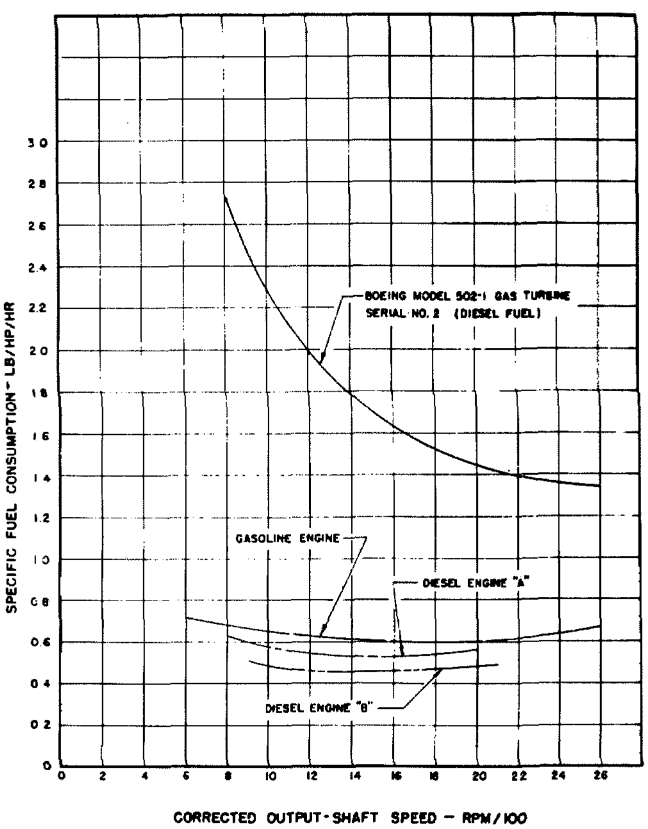
CONTINUED ON PAGE 24

good efficiency can be had only over a limited speed range. Below and above this range, very poor efficiencies are encountered. This is another way of saying that the turbine is basically a constant speed machine. The efficiencies we are talking about are thermal efficiencies. Their order of magnitude is 20 percent for the gas turbine, 30 percent for the gasoline engine and 35 percent for the diesel engine.

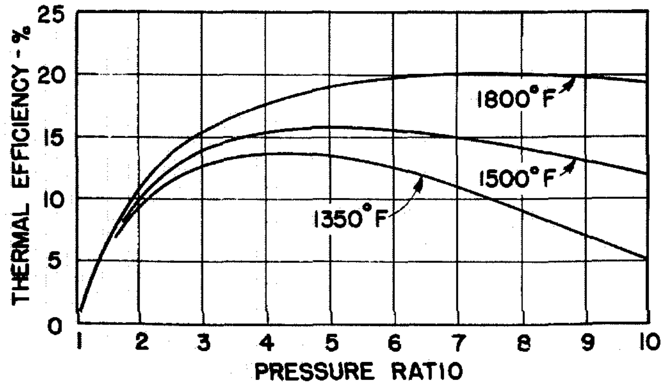
(3) The flow rates of the working medium are high compared to those of reciprocating engines. This presents problems of silencing, ducting, filtration and exhaust disposal. Not insurmountable in themselves, these items must be kept in mind where stringent requirements of shape and space must be satisfied, as well as human comfort.

(4) A definite lower limit of size exists below which a turbine with satisfactory efficiency cannot be built. To be sure, the small turbine will run, but it will have an excessive fuel consumption. On the other hand, the larger the turbine, the more rewarding will be attempts to improve efficiencies. Two hundred horsepower may well be considered the lower useful limit of gas turbines for vehicles. This is quite satisfactory, since in the class from 50 to 200 hp reciprocating engines are quite acceptable. The gas turbine thus takes over where the reciprocating engine becomes unwieldy.

In order to understand the problem of increasing thermal efficiencies and to visualize the approach to its solution, a closer look at the thermodynamics of the gas



H. *Comparison of gas turbine and other engines. Specific fuel consumption as a function of speed.*



I. *Simple gas turbine cycle. Effect of turbine inlet temperature on thermal efficiency.*

turbine is necessary. For the sake of simplicity we shall consider the simple gas turbine cycle. Here one turbine furnishes both the power necessary to drive the compressor and the useful work.

Several parameters vitally affect efficiency. These are pressure ratio (compressor inlet pressure over outlet pressure), turbine inlet temperature and component efficiencies (compressor and turbine efficiencies).

The temperature effect is shown in Chart I. At any one temperature, there is *one* pressure ratio for maximum efficiency. The need for high turbine inlet temperatures is obvious. This diagram points out two important prerequisites to gas turbine development: after thermodynamic theory, early in this century, indicated the potential capabilities, successful design had to wait for development of temperature-resistant materials and compressors with high efficiencies at high-pressure ratios. These two requirements, today, are still primary objectives of research and development.

Since the overall efficiency of the powerplant is a function of the product of the *component efficiencies*, it can be seen readily how important high compressor and turbine efficiencies are. Even though 80 percent for each component looks very good and, by present-day standards, *is* good (typical values are 77 and 71 per cent for compressor and turbine respectively), the product, 64 percent, is less attractive. The quest for high compressor efficiencies is the incentive for the vigorous development of axial flow compressors.

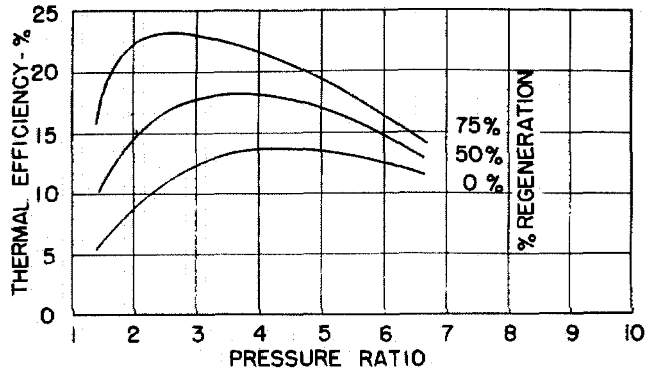
The exhaust from a gas turbine carries away considerable amounts of energy. Appreciable gains in efficiency can be had from *regeneration*. Regeneration takes place in a heat exchanger (called a regenerator) in which exhaust heat is used to preheat the air between compressor outlet and combustion chamber. Heat exchanger studies show that both space and weight requirements are such that the use of regenerators in vehicles is feasible.

The effect of regeneration on thermal efficiencies (Chart J), shows at once why regeneration must be considered. Fifty percent regeneration means that one half of the available thermal energy in the exhaust is put back into the cycle. For actual cycles the useful range

CONTINUED ON PAGE 26

of regeneration lies between 50 and 75 percent. It is possible, then, to raise the efficiency from around 13 percent to 22 percent by this means alone. Gains of this magnitude determine whether or not a gas turbine may be considered at all.

The question as to the importance of regenerator pressure drop must be answered. As with all heat exchangers, we have to pay a price for having them around. Pressure drops must be held to a minimum if the gains from regeneration are to be realized. For efficiency calculations the pressure drops are additive. This means that a drop of 1 percent of the inlet pressure on the air side and 2 percent on the gas side has the *composite effect of a 3 percent pressure drop on the cycle* efficiency. The detrimental effect of pressure drop is the more pronounced, the lower the turbine efficiency. This again emphasizes the need for high component efficiency.



J. *Effect of regeneration on thermal efficiency.*

The compounded powerplant

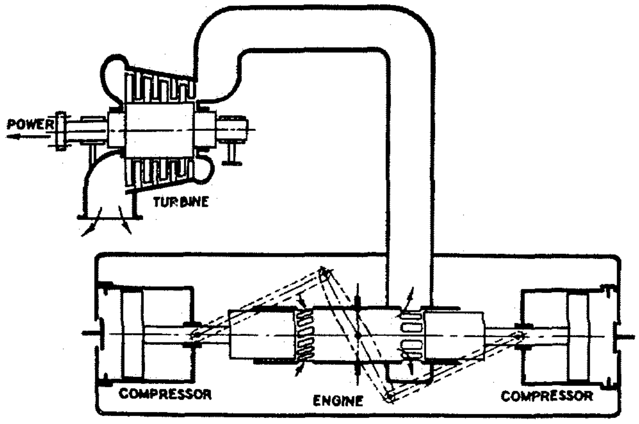
In the preceding discussion it has been tacitly assumed that the gas turbine is to be used by itself. This is by no means necessary. Since the power requirements of vehicles vary between great extremes—low speed cruising with an empty cargo space as compared with high speed climbing at full gross weight—it is entirely reasonable to think of a powerplant which uses a 200 hp gasoline or diesel engine for low power operation, and carries a turbine with about 800 hp capacity for high power operation. Such powerplants have not yet been built but are common practice in other fields. The cruising and high speed turbine combination in naval vessels is a typical example. The comparatively small weight and space requirement of a turbine makes it ideally suited for this type of standby service. The two powerplants may be entirely separate and operate independently, or they may be combined thermodynamically to a so-called compound powerplant. Such powerplant combinations have been investigated. A variety of combinations is possible.

The turbo supercharger is an example in which the exhaust turbine is an auxiliary power producer. If the size of the turbine is increased, reciprocating engine and turbine become of similar size. The order of size may also be reversed. The engine then becomes, so to speak, the combustion chamber of the turbine. This arrangement has definite advantages over the conventional turbine arrangement at part load.

In another variation the reciprocating engine may be used to drive a compressor. The engine exhaust is mixed with the compressed air, fuel is injected, and the resulting gas does work in the turbine. These are only a few of the possibilities. Actually about 100 variations are said to have been proposed.

For use in vehicles, one special compounded powerplant seems to offer particular promise. This is the so-called free piston gas generator. A schematic drawing of this powerplant is shown below. Such powerplants have been tested and are being built in Europe, and several companies in this country are engaged in development work in this direction.

As far as suitability for vehicle applications is concerned, the compound powerplant is basically a gas turbine plant, distinctly different from a dual powerplant using a gas turbine for high output operation only. There is, however, no reason why the latter could not be modified to operate as a compounded system.



Compounded powerplant: The free piston gas generator.

REFERENCES:

S.A.E. = Society of Automotive Engineers
A.S.M.E. = American Society of Mechanical Engineers

(1) Caris, D. F. and Richardson, R. A., "Engine Transmission Relationship for Higher Efficiency," SAE Preprint #779, Atlantic City, June 1952. (Excerpts: *Automotive Industries*, vol. 107, No. 3, 1 August 1952, p. 42.)

(2) Roensch, M. M., "Thermal Efficiency and Mechanical Losses of Automotive Engines," SAE Preprint #316, Detroit Meeting, March 1949.

(3) Zeder, J. C., "New Horizons in Engine Development," *SAE Journal*, vol. 60, No. 6, June 1952, p. 25.

(4) McCuen, C. L., "Economic Relationship of Engine-Fuel Research," *Proceedings, American Petroleum Institute*, 31M (III) 1951. (Excerpts: *Automotive Industries*, vol. 104, #11, June 1, 1951, p. 46.)

(5) Hill, H. C., "Progress of Gas Turbine Truck Testing," *SAE Transactions*, vol. 6, No. 3, July 1952, p. 395.