Note 89

TurboCharging background

Origin

The idea that the exhaust gas of an internal combustion piston engine could be led through a turbine which would use the otherwise-wasted energy to drive an inlet-charge compressor is as old as the Grand Prix car. The Swiss Alfred Buchi patented the basic separate turbocharger (TC) principle in 1905 (569,685).

Fundamental relation

The fundamental relation governing TC is:-

$$\left(1 - \frac{1}{RT^{1/4}}\right) = \left(\frac{(IVP)^{1/3.5} - 1}{\left(\frac{EGT}{250}\right) \times \left(\frac{MT}{MC}\right) \times eo}\right)$$

Where:- IVP = Inlet-charge absolute pressure ratio above ambient, atmospheres absolute (ATA);
RT = Turbine absolute expansion ratio to ambient necessary to drive the Compressor;
EGT = piston engine Exhaust Gas absolute Temperature at Turbine inlet;
MT = mass flow rate through the exhaust Turbine;
MC = mass flow rate through the Compressor;

MT is greater than MC by the fuel flow rate where the fuel is fed into the charge after the compressor.

eo = Overall TC Efficiency = (Mechanical x Turbine x Compressor Efficiencies).

This relation is derived in Sub-Note A.

For automotive use the fundamental problems of the turbocharger were :-

- To obtain a sufficiently high value of ‘eo’ at the necessarily small size of the Turbine and Compressor;
- To obtain Turbine materials which could withstand ‘EGT’ around 1,300K from a petrol engine for a sufficiently long life.

Early aero-engine research

In WW1 and the early 1920s the RAF/RAE did research into TC to restore aero-engine power at altitude. James Ellor of that establishment post-WW1 did the aerodynamic design of units to suit, firstly, the Napier “Lion” and then the Rolls-Royce “Condor”. In 1924 the Mark V of the latter type was built with an exhaust turbine driving a 2-stage centrifugal compressor and air-air intercooling before the engine intake , the fuel being petrol of low evaporative cooling capability. However, either the turbine flow capacity was insufficient or the component efficiencies were too low – both, probably – so that the back pressure ahead of the turbine actually reduced the ground-level power compared to the naturally-aspirated build. No flight testing was done and the TC project was abandoned (900,901). British piston aero-engines from then onward relied on mechanical supercharging (MSC).

Early racing-car TC

In 1925 Major Frank Halford, closely associated with both the aero-engine and racing-car scenes, designed from scratch for a racing car a 1.5 Litre IL6 engine with TC. Presumably the engine was intended to compete under the 1926-1927 1.5 L Grand Prix formula. This Halford engine had a centrifugal compressor with intercooler (although the fuel would certainly have been alcohol-based with high evaporative cooling capability; Halford, with Harry Ricardo, had been a pioneer of that type of fuel for naturally-aspirated racing engines a few years earlier) driven by an axial turbine (286). The blower on test was inefficient (904) and the turbine (with very short unshrouded blades) would certainly have been so. The engine never raced as designed and it was converted to Roots MSC.

Nothing further was heard of TC in the motor-racing world until 1952.

Successful aero-engine TC by General Electric (GE)

Led by Dr Sanford Moss, GE of the USA eventually developed by the late 1930s a TC unit suitable for altitude power boosting of military aero-engines built by Wright and Pratt & Whitney. Dr Moss had worked on centrifugal compressor research since before WW1 and in the 1920s was helpful to Duesenberg and Miller as these firms developed their US track-racing engines using that MSC approach (6). It seems very likely that the "*can-do, cut and try*" methods of the racing men also benefitted the GE work. The GE turbocharger found its 1st successful application with the Wright R1820-51 engine fitted to the prototype Boeing Y1B-17A in 1938. Compared to the MSC R1829-39 in the preceding service-trials B-17 batch this raised the operating ceiling by 10,000 feet (to 25,000 ft) (902) and so started the useful career of that aircraft as a day bomber. Subsequently GE applied their TC units to other US aero-engines which saw wide service in WW2. The basic GE design was an axial turbine driving a centrifugal compressor, (but with a size advantage on efficiencies compare to Halford's car TC). A large step forward was made in reliability by the use of "Vitallium" (Haynes Stellite 21) turbine blades (composition 62% Co, 28% Cr, 6% Mo, 2% Ni, 2% Fe + 0.2% C) which retained useful strength to 1,000C exhaust temperature (685). This GE TC experience led to the firm's selection by the USAAF to receive and develop the Whittle turbojet engine given to the USA under "Reverse Lend-Lease" in 1941.

Post-WW2 Diesel truck engine TC

The Diesel engine is a natural type to be TurboCharged since the exhaust is some 400C cooler than a petrol engine so turbine materials can be cheaper (although, of course, the heat energy to be exploited is also less).

By the early 1950s the TC design had been improved greatly for commercial Diesel engines by applying a radial-inflow turbine, more efficient at automotive sizes than the axial type, to drive the centrifugal compressor. Also the unit was sized to provide the desired boost pressure at medium engine speeds with an added wastegate to bypass surplus exhaust gas around the turbine at higher speeds so as to hold that pressure constant.

TC truck engine racing at Indianapolis

In 1950 the US Cummins truck engine company had entered unsuccessfully for the Indianapolis 500 mile race with a Roots MSC special racing version of their standard Diesel engine, taking up a 6.6 lItres option given for Diesels in the regulations where the pure racing spark-ignition engines were limited then to the alternative of 4.5 litres Naturally-Aspirated (NA) or 3 litres Pressure- Charged (PC).

Cummins re-entered the '500'race in 1952 with a TC Diesel engine. This provided about 400HP where the MSC engine had given 320HP, both at about 2 ATA IVP, i.e. + 25% (12,569). Despite the car being 1,000 lb heavier than its alcohol-fuelled rivals this power was sufficient (the engine horizontally mounted in a racing chassis) to take the Pole at 138 mph*. As the unit did not use the 'oversized TC + wastegate system' the basic centrifugal compressor relation of

$$\text{Pressure Rise proportional to } (\text{RPM})^2$$

meant that, even with the relatively small RPM drop in backing-off the throttle for each of the 4 large-radii slightly-banked Indianapolis corners, there was a substantial lag before full boost and power returned for the straights until the driver anticipated it and re-opened the throttle "early".

However, in the race the compressor suffered dirt ingestion clogging from the low intake of the flat engine and retired at 36% distance (569,905).

This was the 1st time that a TC engine had appeared in motor-racing and it would be the last for another 14 years.

---

*At Indianapolis the Pole is taken by the fastest car on the 1st day of official 4-lap Qualification, regardless of later higher speeds. Subsequently a 4.5 L NA car went 0.15% faster and then a 3 L MSC car went a record 0.74% faster. The rule-setters must have congratulated themselves on a job well done for three such completely different types of engine!

Successful Indianapolis TC

After 1946 the NA engine had reigned at Indianapolis in the shape of the Meyer-Drake Offenhauser (originally Miller) IL4 (of 4.5 L, reduced by the rules to 4.2 L in 1957).This was finally displaced after 18 straight wins by the Ford 4.2 L V8 NA in 1965. Louie Meyer then left the partnership and became the agent for the Ford engine. Dale Drake then asked Leo Goossen (the long-time sole American racing-engine designer) to redesign the NA ‘Offy’ very substantially into a short-stroke 2.8 L PC (the then alternative regulation pure-racing size).

A Roots MSC system was chosen by the maker for 1966 (716) but another solution was offered by Garrett AiResearch, using a commercial truck TC with wastegate (569,711). This contrasting pair therefore provided a very good illustration of the merits of TC v. MSC, as detailed below.

Data sources	(569,711,716,906,907,1046)	
Engine maker	Drake	
Bore (B)/Stroke (S)	4 1/8’’ (104.775mm) / 3 1/8’’ (79.375mm) = 1.32	
Swept Volume (V)	167.05 cubic inches (2,737 cc)	
	Mechanically Supercharged (MSC)	TurboCharged (TC)
Compression ratio (R)	8	8
Fuel	Methanol	
Pressure charging (PC) system	Commercial Roots type, made by Meihler-Dexter	Commercial Garrett AiResearch Type TE06
Fuel supply	2 Hilborn injectors at MSC entry	Hilborn injectors to each port, downstream of TC
Absolute pressure at inlet valve (IVP)	17 psi boost = 2.16 ATA Rising from 15 psi at 6,000 RPM	17 psi boost = 2.16 ATA limited by exhaust wastegate from 5,000 RPM
Intercooling	(Not needed with Methanol fuel)	
Peak Power (PP) HP	530	626*
@ NP RPM	8,500	8,500
Weight (W) kg	172	163
PP/W HP/kg	3.08	3.84

<u>Conclusion</u>: with all other things being equal, the TC engine therefore gave 18% more power than the MSC while being 5% lighter, a Power/Weight advantage of 25%.

The 96 extra HP of the former came from the shaft HP extracted from the crank to drive the MSC supercharger being that much greater than the power deducted pneumatically from the TC engine on the exhaust stroke by the increased back pressure (above the free exhaust expansion when NA) needed to drive the turbine.

The Roots supercharger required a gross 60HP @ 6,000 engine RPM and 15 psi boost (716) which can be extrapolated to at least 60 x (8,500/6,000) x (17/15) = gross 96 HP at full speed (642). Although this ‘envelope back’ calculation implies *zero* loss from the TC back pressure increase, which cannot be correct, it does illustrate how the TC advantage arises*.

---

*626 HP quoted from (711). Ref. (1046), equally authoritative, has 600 HP for the TC engine, i.e. 70 HP (13%) advantage. This accords better with the calculated 96 HP supercharger gross driving power, on the basis that 96 – (a deduced 26 HP extracted from IHP by back pressure in the TC engine) = 70 HP.

The difference of about 4% in quoted TC power, which may be just manufacturing repeatability, illustrates the problem of historical analysis described in the Foreword!

Further development of the TC engine at Indianapolis

Neither type of Drake engine could hold its power for long in 1966, but the TC version was clearly the '*Way to go*' and so it received more development for 1967 although still not a winner. However, success came in 1968. The TC innovation had prompted Ford that year also to produce a short-stroke 2.8 L adaptation of its original 4.2 L NA V8. From 1968 to 1996, after which date NA was imposed by Indianapolis rules, TC was supreme at that track whatever the engine maker (Cosworth and then Ilmor competed later) or the swept volume specified or the maximum IVP allowed.

Special conditions for TC at Indianapolis

Because the rules required methanol fuel (as a safety feature, it having a higher flash point than petrol (gasoline)), no Indy engine needed an intercooler because the high evaporative heat value of that fuel reduced the charge temperature entering the cylinder from the compressor delivery figure.

Indy racing, on a track with 4 large radii, slightly-banked corners, did not demand much attention to the lag in boost pressure recovery from the centrifugal compressor if the throttle was shut for any significant time, as would occur on European road circuits. Consequently only 1 turbocharger was fitted to Indy engines since its inertia was not a particular problem.

Sports-car TC

After 1968 TC was applied to several types of Sports-racing and Touring-racing engines by BMW, Porsche and Renault (all of whom went on to build TC Grand Prix engines). These engines ran on petrol (although Porsche did experiment with Toluene-based fuel once (608)). Despite this and having no intercooler and also being air-cooled, the Porsche Type 917/30 F12 produced 1,100 HP from 5.4 L with IVP = 2.3 ATA in 1973 to power the CanAm sports-racing Champion, repeating the previous year's success with a 5 L TC engine. This 1973 figure was then a record output for a road-racing car. These Porsche engines had coped with throttle lag by using small low-inertia turbochargers to each 6 cylinder bank and boost-sensitive fuel injection (569). Probably detonation was prevented by using a very-rich mixture. Certainly, when a fuel ration was imposed by rule in 1974, Porsche withdrew from the CanAm races.

Renault Grand Prix TC

In 1973 Renault produced in their "Amadée Gordini" specialist plant a pure-racing 90V6 2 L engine, NA, Bore (B)/ Stroke (S) of 86mm/57.3 = 1.5 for sports-car competition. This was Type CH1, designed under the direction of Francois Castaing (the 'CH' designation was in memory of Claude Hard, a former technical manager). After development this powered the winner of the 1974 European 2 Litre Sports-car Championship. The engine also powered the F2 Elf and Martini cars which won European F2 Championships, the former make in 1976 and the latter in 1977.

In 1975 a TC version was built and raced at Le Mans the following year but DNF. This had an intercooler to suit the petrol fuel. With Ken Tyrrell's advice (896) Renault had also since early 1975 been evaluating the 1.5 L PC rule option in the Grand Prix field, initially with a reduced-Bore/ short-Stroke (80mm/49.4 = 1.62) TC version of the CH1. While preparing in late 1976 for the 1977 Le Mans Renault senior management decided also to enter Grand Prix racing the same year. This dual-effort instruction showed the defect of "Big Firm Management" – an inability of 'mahogany-office-dwellers' to understand the load imposed by their decisions on 'coal-face-workers'! Le Mans was *not* won in 1977 but the GP car with Type EF1 engine *did* appear in July at the British race – a DNF. This was the 1st TC GP car since Halford's abortive design of 1925. In this case the initials 'EF' recognised financial help from Elf, the French national fuel company

Development of both the 2 L Le Mans and 1.5 L Grand Prix engines and cars continued in 1978 and this time a Le Mans victory was achieved. Afterwards all effort was put into the GP machines (909,910). A 1st win was gained in 1979, very fortuitously at the French GP, shortly after changing from a single TC to dual TC, one per bank of lower inertia, (amongst a vast number of reliability improvements).

The simple *destroking* of the CH1 decided upon finally for the 1977 Type EF1 GP 1.5 L engine (485) had led to the extreme B/S of 86mm/42.8 = 2.01, a ratio never seen before and which limited engine speed by reaching a Mean Valve Speed (MVS) limit for the steel coil-spring return system (CVRS) long before any bottom-end limit. Eventually, Renault accepted this and, in 1985, they revised the dimensions back to the original 80.1mm/49.4 = 1.62 for the type EF15.

The EF1 was the 1st Grand Prix PC engine to take a well-developed NA design having individually-tuned inlet and exhaust systems, a principle which had entered the GP arena originally in 1952 with the Ferrari Type 500 (q.v. Eg. 30), and simply increase the Manifold Density Ratio (MDR) by enclosing the inlet bells in a plenum chamber fed by the TurboCharger. The inlet tuning and, as far as possible to the TC entry, the exhaust tuning were preserved.

Bernard Dudot was the principal development engineer throughout the Renault unit’s TC life, assisted by Jean-Pierre Boudy and later Jean-Jacques His. It was Boudy, stimulated by the valve-gear problem of the EF1, who invented in 1984 the “Distribution Pneumatique” system with gas springs in place of steel springs which became the standard for Grand Prix engines after 1990 and permitted B/S ratio to be pushed well over 2 in the following decade (see Eg. 73 et seq). Honda later named it “Pneumatic Valve-Return System” (PVRS), which is more descriptive of its function.

Having pioneered TC in Grand Prix racing Renault saw itself copied in that sphere by all other racing engine makers, beginning with Ferrari in 1980. They never won either the Drivers’ or Constructors’ World Championships with their own TC cars (over 1977 – 1985) or as TC engine suppliers to other chassis makers (Ligier and Lotus in 1984 – 1986, plus Tyrrell 1985 – 1986). Partly this was because of another bad “Big Firm Management” decision which was to fire their No. 1 driver Alain Prost at the end of 1983, after he was just beaten by Piquet in a Brabham-BMW to the Drivers’ title, because he dared to criticise them – thereby losing a driver capable subsequently of winning 4 Championships!

Note 89

Sub-Note A

Derivation of fundamental TC relation

The power developed by a Turbine / required by a Compressor is:-

$$Cp \times \triangle T \times M$$

where:- Cp = Specific Heat of air at constant pressure appropriate to the Turbine / /Compressor temperatures;
$\triangle T$ = Total Head Temperature drop / rise of air passing through the machine;
M = Mass Flow rate through the machine component.

At equilibrium speed, where the Turbine supplies, with some rotor/bearing loss, just the power required by the Compressor:-

(1) $$em \times CpT \times \triangle TT \times MT = CpC \times \triangle TC \times MC$$

where T = Turbine; C = Compressor; and 'em' = Mechanical Efficiency of the rotor system.

Basic thermodynamic theory (e.g. (911)) also provides:-

(2) $$\triangle TT = et \times EGT \times \left(1 - \frac{1}{RT^{1/4}}\right)$$

(3) $$\triangle TC = \left(\frac{T1 \times (RC^{1/3.5} - 1)}{ec}\right)$$

Where 'et' and 'ec' are Turbine / Compressor Efficiencies;
RT = Turbine absolute total head expansion ratio to ambient necessary to drive the Compressor;
RC = Compressor absolute total head pressure ratio; if a small loss of pressure through an intercooler is neglected then RC = IVP = absolute Pressure ratio at the Inlet Valve above ambient;
EGT = Exhaust Gas absolute total-head Temperature at Turbine inlet;
T1 = ambient absolute total-head Temperature at Compressor inlet.

Combining equations (1), (2) and (3) :-

(4) $$\left(1 - \frac{1}{RT^{1/4}}\right) = \left(\frac{(IVP)^{1/3.5} - 1 \quad .}{\left(\frac{EGT}{T1}\right) \times \left(\frac{MT}{MC}\right) \times \left(\frac{CpT}{CpC}\right) \times em \times et \times ec}\right)$$

It is convenient to put

$$eo = (em \times et \times ec).$$

At the usual temperatures:- CpT = 0.276; CpC = 0.24;
and T1 = 288K (Standard ambient 15C).

Therefore (4) can be reduced to:-

(5) $$\left(1 - \frac{1}{RT^{1/4}}\right) = \left(\frac{(IVP)^{1/3.5} - 1 \quad .}{\left(\frac{EGT}{250}\right) \times \left(\frac{MT}{MC}\right) \times eo}\right)$$

Some actual data for the values of 'eo' and 'ec' are given on P.7, obtained from Porsche TC engines.

TurboCharger Efficiency figures from Porsche engines

Porsche/KKK data on ‘eo’

A typical value of ‘eo’ can be derived from data in ref.(241) for the 1974 Porsche 911/76 2.14 L engine with single KKK TC running at 90,000 RPM with a TurboCharger rotor rather less than 75mm diameter.

This reference gives EGT as 1,000C = 1,273K;

$$IVP = (1.4\ \text{Bar boost}) = \frac{(1.4 \times 14.5\text{psi}) + 14.7\text{psi}}{14.7\text{psi}} = 2.38\ \text{Atmospheres Absolute;}$$

$$RT = (1.2\ \text{Bar back pressure}) = \frac{(1.2 \times 14.5) + 14.7}{14.7} = 2.18.$$

It can be assumed that this is on 20% rich petrol mixture with the fuel injected after the Compressor, so

$$MT = MC + \left(\frac{MC}{14.7} \times 1.2\right) = 1.082 \times MC$$

Inserting EGT, IVP, RT and MT/MC into Equation (5) then gives:-

$$eo = 0.288$$

This can be regarded as em = 0.99; et = 0.58; ec = 0.5 (with pressure loss through the intercooler included against the Compressor efficiency). The turbine is expected to be more efficient than the compressor because its pressure drop helps to prevent boundary layer separation.

Porsche/KKK data on ‘ec’

Data in (571) for the 1983 1.5 L Grand Prix Porsche PO1 engine (aka TAG) gives the air exit temperature from the KKK TC compressor running at 120,000 RPM as

190C.

Assuming T1 = 15C (288K), this gives $\triangle TC = 175C$, for a boost pressure of 1.9 Bar.

$$\text{so } RC = \frac{(1.9 \times 14.5) + 14.7}{14.7} = 2.874$$

Inserting $\triangle TC$, T1 and RC into Equation (3) then gives :-

$$ec = 0.58$$

In this installation an air-air intercooler reduced the Compressor exit air temperature to 55C before fuel injection. Not counting here the loss through this component would explain partly the higher value of ‘ec’ compared to the speculation of 0.5 above but there was probably some development improvement as well.