Chapter 3.

Fueling Considerations.

An engine running at full power will almost invariably perform best with a rich mixture to ensure, firstly, that all the available air is consumed, secondly that detonation and other combustion maladies which might occur are avoided (excess fuel reduces internal surface temperatures and the likelihood of detonation) and, thirdly, that by having a slight cooling effect through evaporation it will increase charge density and resultant power.

On the other hand best fuel efficiency will be achieved with a slightly weak mixture thereby ensuring, through having excess air present, that all available fuel is consumed, yet excessive weakness beyond this point causes fuel consumption to actually increase. Detonation and similar misbehaviour is rarely troublesome except near to full throttle and volumetric efficiency is irrelevant during throttled operation. To find the ideal fueling requirement of an engine it is necessary to find out how the torque and specific fuel consumption (fuel consumed per unit of power in unit time) change as the air/fuel ratio is varied from rich to weak limits. This data can be plotted out graphically to create what is called a fuel loop.

The Fuel Consumption Loop.

A fuel loop is a basic method of analysis that conveys a lot of information. Quite simply the engine is held in a constant condition on a dynamometer, starting with very rich fueling then gradually weakened off until the point is reached where the engine can hardly run. The diagram (Fig. 3.1) shows what a fuel loop might look like plotted from a constant speed / full throttle condition.

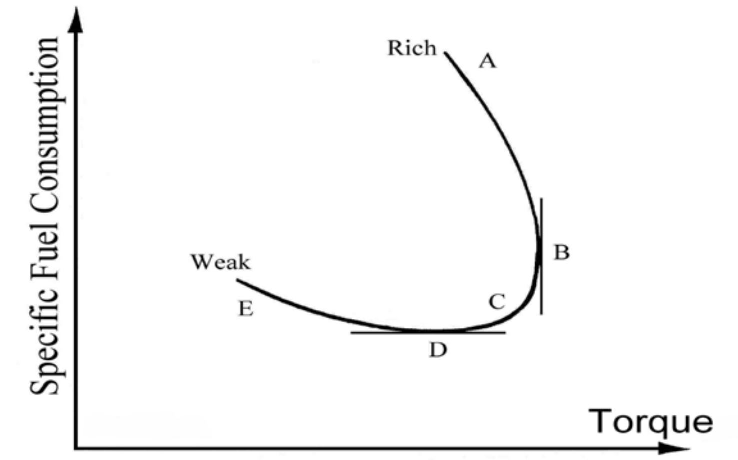

Fig. 3.1 A fuel consumption loop.

Starting from the excessively rich point A, which might equate to having 8 or 10% carbon monoxide (CO) in the exhaust, it will be seen that torque increases to a maximum at point B where CO might be down to about 4%. This point defines the optimum full load fueling requirement. Further weakening takes the curve to point C where fueling is at the perfect mixture for complete combustion – the stoichiometric point. Torque will have fallen slightly and CO will be very low, around 0.1% or so.

The curve then continues with falling torque to point D which is where thermal efficiency reaches a maximum – this being the point of minimum specific fuel consumption (best economy). With further weakening combustion becomes slow and unstable causing the specific fuel consumption to rise and torque to fall away towards point E whilst unburnt or partially burnt fuel will be discharged in the exhaust stream so HC emissions rise dramatically. Eventually combustion will be taking place too slowly to effectively drive the piston and may continue after the exhaust valve opens and perhaps even until the inlet valve opens – causing a characteristic ‘spit-back’. A lean burn spark ignition engine differs in its ability to extend the minimum specific area further before the curve starts to rise up towards E.

Of course when measurements like this are being taken it is vital that the test conditions are stable and consistent and that correction is applied for ambient conditions – barometric pressure, temperature and humidity. For instance, raised air temperature can have several effects which together can extend the weak limit and shift the minimum specific point slightly to the left. In the part throttle condition the reduced density of heated air will permit the throttle to be further opened for a given load condition thereby reducing pumping losses. Exhaust scavenging will also improve as will mixture quality. This is why manufacturers often modulate air temperature so that cool air is provided for maximum volumetric efficiency at full throttle but heated air may be used to improve economy in the cruise condition.

A fuel consumption loop indicates clearly what fueling will produce best power and what will produce best economy for that particular engine specification in that particular operating condition. It is necessary to plot a whole family of loops at different speeds and loads to get the full picture and although engineers had been able to obtain this sort of information for many years it could only really be fully exploited by engines that ran at constant speed, such as those used in aircraft where the pilot would be trained how to trim engine settings for maximum range. It was only when electronic fuel injection arrived that it became possible to achieve fuel settings that approached the ideal for all conditions.

One has to be aware of a possible trap for the unwary. A part throttle loop at constant vacuum produces valid information but does not clearly define the minimum specific condition because a different vacuum setting at the same load might be better. It is therefore often more convenient to plot for changing vacuum at constant load to deal with the part throttle conditions. Some people might have trouble grasping this point, which may need some contemplation and several constant vacuum loops to be plotted and a line drawn through their respective minimum specific consumption points for it to become clear.

Another point which is illustrated by the fuel loop is that the torque (or power) changes only gradually either side of optimum fueling point B, but the minimum specific consumption point D is much more critical with regard to exact fueling. Fortunately part throttle operation is far less sensitive to volumetric efficiency variables between individual engines and the minimum specific point is often only of academic interest anyway because most engines will be running at the stoichiometric point C to achieve optimum catalyst efficiency. These factors make it possible for a manufacturer to arrive at a standard fueling specification that will work satisfactorily with all the variables among individual samples of mass produced engines.

This may be enlightening to those enthusiasts who dream about fitting an aftermarket EFI system so that they can then adjust the fueling on a rolling road (chassis dynamometer) to find some sort of ‘sweet spot’ that is the optimum for power, or for economy. Sadly it doesn’t often work like that – there is usually quite a wide range of settings where nothing much seems to change and meanwhile air, coolant and drive train temperatures may be changing and having more effect than any fine adjustment. The loop makes it easy to see the exact points to aim for, bearing in mind that the respective optimum air/fuel ratios may change at different loads and speeds and the curve itself will usually not be so perfectly formed as the example.

These days the fundamental method of plotting out loops on a succession of graphs can be replaced by a computer link between the dynamometer and all the engine inputs and ambient conditions, enabling the minimum specific point to be identified almost instantly as the fueling is swept from rich to weak. However this is probably impossible to achieve with much precision on a chassis dynamometer because of all the variables associated with the transmission and tyres. Modern fuel injection control units have what is called adaptive memory, the ability to trim out the settings according to usage patterns, and with the addition of a wide band Lambda sensor it is possible for a system to set itself up to some predetermined air/fuel ratios whilst being driven around. A manufacturer will know the exact fuel requirement of a particular engine design and a production ECU (Electronic Control Unit) will be pre-programmed to aim for the most appropriate air/fuel ratios when applying adaptive corrections.

The technology has obvious attractions for a specialist aftermarket system but it still cannot find the optimum points without the characteristics of the engine being defined in the way that can be seen from the fuel loop. However the loop also tells us that for most applications absolute exactitude is not required anyway, and when it is there should be ample budget to not have to rely on self-tuning.

Specific Fuel Consumption.

Many people mistakenly believe that best fuel efficiency will be obtained at the maximum torque condition. In fact there is no reason at all why this should be so. Maximum torque is largely a function of maximum volumetric efficiency, whereas minimum fuel consumption is very much dependent on losses associated with friction and pumping work. A specific fuel consumption map can be derived from a family of fuel loops to show the pattern for a particular engine type (Fig. 3.2).

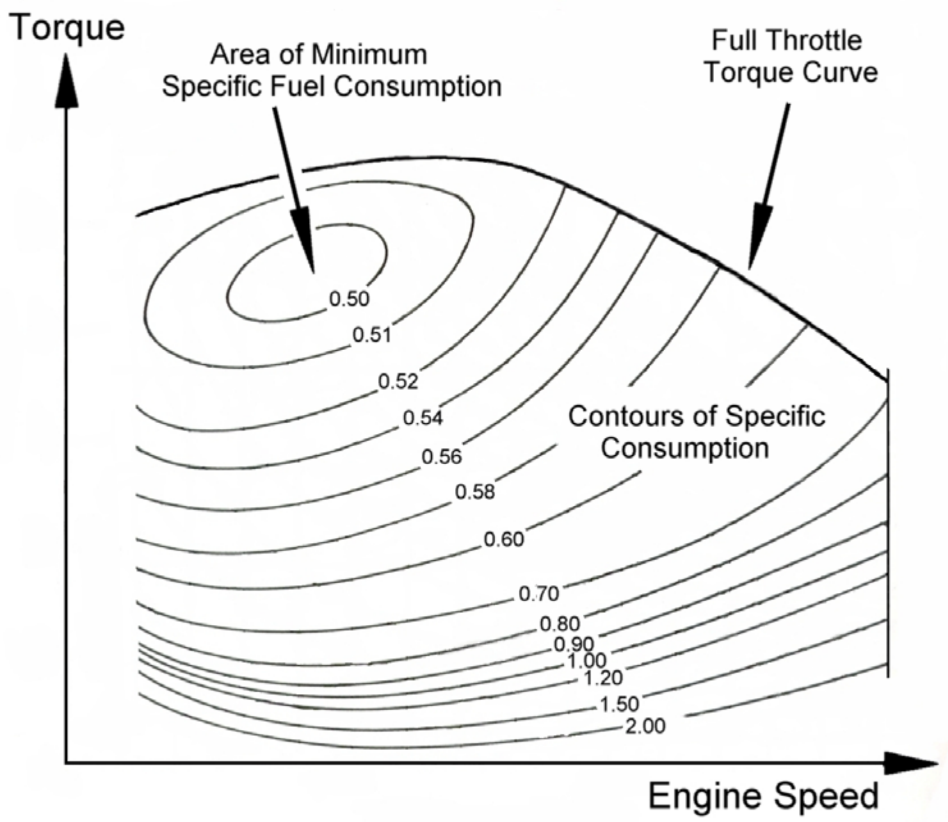

Fig. 3.2 Specific fuel consumption map (C. F. Taylor).

In terms of speed the minimum consumption is very much affected by friction so is closely related to piston speed. Generally, for all engines from the smallest portable to the largest ship engine, two stroke or four stroke, minimum specific consumption falls around a mean piston speed of about 7 metres/sec (1250 ft/minute), which on an engine of 70 mm stroke equates to about 2500 r.p.m. Below this speed there is more time for heat to be lost from the charge to the structure and coolant, and above it friction and windage losses (turbulence within the crankcase) become more significant. In racing engines with extreme camshafts low speed efficiency may be so reduced that the minimum consumption point can only occur higher up the speed range.

21 pages follow.