Rotax Carburettor Jetting
Prometheus 1.1

Ventimore (UK)

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Nomenclature

C_d	Discharge coefficient.
C_{da}	Venturi discharge coefficient.
C_{df}	Fuel nozzle discharge coefficient.
C_p	Molar specific heat at constant pressure.
C_v	Molar specific heat at constant volume.
D	Diameter of jet/tube.
ρ	Density.
g	Gravitational acceleration ($g = 9.8 m/s^2$).
γ	Ratio of specific heats, $\gamma = \frac{Cp}{Cv}$.
j	Jet size ($\frac{j}{100}$ = diameter of jet in millimeters).
P	Air pressure.
P_a	Atmospheric pressure.
P_m	Air pressure at the mouth of the carburettor
P_v	Air pressure at throttle slide, Vapour pressue.
Q	Mass flow
R	Gas constant (Ideal Gas Law).
T	Temperature.
τ	Throttle position (0=fully closed, 1=WOT)
ω	Engine speed (RPM).

1 Usage Advice

You should not use the recommended settings provided by Prometheus until you have some experience selecting carburettor jets.You are advised to consult a karting professional for help. Once you have calibrated the software, you should be able to reliably use the jetting recommendations. Note that you always use Prometheus at your own risk.

2 Synopsis

This document presents the mathematical model behind the Prometheus jetting application for Dellorto VHSB 34 carburettors used by Rotax kart engines. The software can be downloaded from http://www.bowmain.com/Karting/default.html.

3 The Rotax Engine

The Rotax engine comes in 4 variants: Senior, Junior, Mini and Micro. Engine power varies considerably between engines. This is achieved by use of a "power value" on the Senior engine, and restrictors on the Mini and Micro engines. This document will not consider the Micro engine.

The Rotax engine has a 54 mm bore and 54.5 mm stroke.

Junior motors produce, according to Rotax, 15kW at 8,500 RPM at Rotax standard reference conditions (25C, 990 mb and 0% humidity, air density = 1.157 kg/m^3)

Compression rate is 7.9:1 so maximum theoretical thermal efficiency is 56%. The author was unable to locate any documentation regarding the actual thermal efficiency of the Rotax engine, so a guesstimate thermal efficiency of 23% is assumed.

Table (1) shows the implied volumetric efficiencies for each Rotax engine type at standard reference conditions assuming the fore-mentioned thermal efficiency. It shows Mini-max engines operate at less than $^2/_3$ volumetric efficiency.

The accuracy of the thermal efficiency figure could be improved with precise fuel consumption figures. In the absence of further measurements, the values in the table above will be used for calculations in the rest of the document.

	RPM	Air flow (m^3/sec)	Air flow (kg/sec)	Fuel flow (kg/sec)	Therm eff. (%)	Vol. eff. (%)	Calc. Power (kW)	Act. Power (kW)
Mini	8,500	0.01768	0.0205	0.00162	23	58	9.96	10
Junior	8,500	0.01768	0.0205	0.00162	23	87	14.95	15
Senior	11,500	0.02392	0.0277	0.00220	23	91	21.15	21

Table 1: Theoretical power vs. actual power at standard conditions

4 The Dellorto Carburettor

4.1 The Purpose of a Carburettor

Carburettors are designed to maintain a consistent air/fuel mixture over a wide range of conditions and throttle openings.

Carburettors rely on Bernoulli's law: the air flowing through the carburettor at speed creates a vacuum which sucks fuel from the carburettor into the airflow. The faster the airflow, the greater the vacuum will be, and the greater the amount of fuel drawn from the carburettor.

A stoichiometric mixture occurs if the air/fuel ratio (AFR) is 14.7:1 by weight. It is the theoretical point where there are sufficient oxygen molecules present to consume every molecule of (reference) fuel. In practice, fuel does not burn completely at the stoichiometric ratio – the oxygen is not able to "get at" all the fuel in the limited time available during combustion. Maximum power occurs when there is enough fuel to use all the oxygen molecules in the air, usually at an air/fuel ratio of about 12.6:1.

There is some ambiguity in the terms lean and rich. Technical documents adhere to the convention that any air/fuel ratio less than the stoichiometric ratio is rich, and any air/fuel ratio greater than the stoichiometric ratio is lean. However engine tuners frequently refer to any air/fuel ratio less than maximum power ratio as rich, and any air/fuel ratio greater than the maximum power ratio as lean. Nearly all engines in the real world run with air/fuel ratios between the maximum power ratio and the stoichiometric ratio.

It is less ambiguous to use λ = the air/fuel ratio divided by stoichiometric air/fuel ratio. Maximum power then occurs at a lambda of about 0.86.

If the λ is less than 0.86, the exhaust gas will contain unburnt fuel and unused oxygen; conditions in the hot exhaust may produce combustion resulting in "popping".

4.2 Air and Fuel Delivery

The carburettor delivers fuel to the venturi via a number of pathways (often referred to as circuits).

- The main circuit delivers the bulk of the fuel when the engine is operating normally.

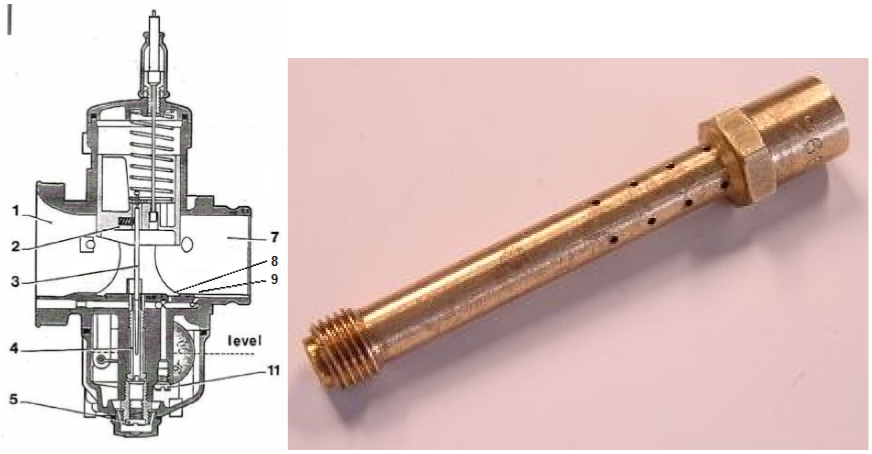

Figure 1: Carburettor and Emulsion Tube

- The idle/progression circuit supplies fuel at low speed. The main circuit is non functional at low speeds, typically below $1/8$ to $\frac{1}{4}$ throttle.
- The starting circuit ensure that the mixture is sufficiently rich that it will start.

The starting circuit does not deliver fuel during racing and will not be discussed further.

4.3 The Main Circuit

The venturi is shaped so that it is at its narrowest above the main fuel nozzle. Fuel is drawn from the bowl at the bottom of the carburettor, through the emulsion tube (4) and into the venturi (1,7) before entering the engine. The emulsion tube sits in a fuel well which is connected via passages to holes at the front of the carburettor venturi. The emulsion tube (4) contains a number of holes along its side that allows air from the fuel well to enter the main flow of fuel to the venturi. The level of fuel in the bowl is maintained by a float system and the amount of fuel drawn up into the emulsion tube is controlled by the main jet (5) which is immersed in the fuel in the bowl. A tapered needle (3) move up and down with the throttle slide and restricts the flow fuel flowing out of the top of emulsion tube into the venturi. The sudden decrease in pressure as the fuel/air mixture enters the venturi causes the fuel to atomise.

The main jet is “dominant” in controlling the amount of fuel flowing into the venturi if the slide is between $\frac{3}{4}$ and fully open. The tapered needle is “dominant” in controlling the amount of fuel flowing into the venturi if the throttle is between $\frac{1}{4}$ and $\frac{3}{4}$ open.

If the throttle is less than $1/8$ open, the main fuel nozzle is largely shielded from the air flow and the main circuit does not supply any fuel to the engine.

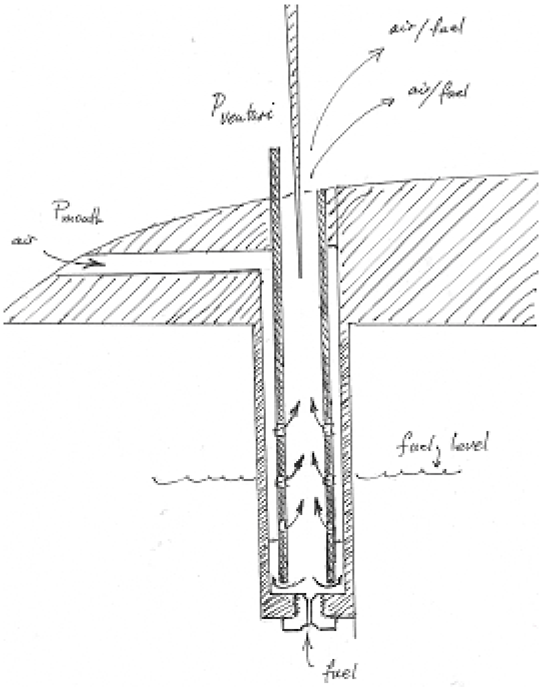

Figure 2: Carburettor - Main Circuit

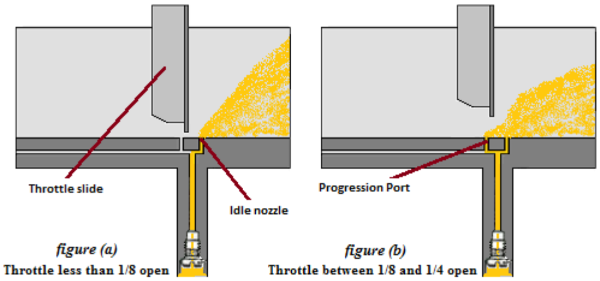

figure (a)
Throttle less than 1/8 open

figure (b)
Throttle between 1/8 and 1/4 open

Figure 3: Flow from Idle circuit

Somewhere between $^1/_8$ and $\frac{1}{4}$ throttle, the pressure differential becomes sufficient to draw fuel/air mixture up into the venturi and into the engine.

4.4 Idle and Progression Circuits

The idle jets and emulsion tubes are miniature versions of those found in the main circuit, without the presence of a needle The “stacked” idle jets limit total fuel flow through the circuit. Holes in the side of the emulsion tube draw in air from the carburettor mouth which mixes with the fuel and exits into the venturi. However no needle is present in the emulation tube to regulate flow.

The idle/progression circuit has two exits into the venturi. The first hole (closest to the carburettor mouth) is the larger of the two and is called the progression port. The second exit is referred to in this document as the idle nozzle.

The VHSB carburettor comes with 12.5 and 8.5 “progression ports”. The 12.5 carburettor has a progression hole of 1.2 mm and a rear idle nozzle of 0.5 mm. The 8.5 carburettor has a progression hole of 8.5 mm and a rear idle nozzle of 0.5 mm.

If the throttle is almost closed, the airflow is diverted into the progression hole by the geometry of the carburettor throttle slide. Air enters the tube connecting the bleed holes with the front of the carburettor and then re-emerge from the rear idle nozzle. As the throttle is open further, the momentum of the diverted air flow is insufficient to force air into the progression hole; instead the flow through the progression hole reverses and air/fuel mixture from the idle system exits from both ports.

What effect do the different “progression ports” have? The 12.5 carburettor will have a greater increase in the richness of the mixture progressing from a fully closed throttle to a partially open throttle. The progression port should not have any effect on the operation of the carburettor once the main fuel circuit dominates (i.e. above about $\frac{1}{4}$ throttle) since the carburettor tuning process will compensate for any increase/decrease in flow from the progression hole.

It would appear that the 12.5 progression is intended to provide extra fuel to the progression circuit in conditions of low temperatures and high atmospheric pressures.

The rear idle hole is slanted towards the engine, reducing the Bernoulli effect drawing air/fuel from the hole. The Dellorto manual says that

> “When the valve is lifted slightly (up to about $\frac{1}{4}$ throttle) the vacuum generated by the inducted airflow begins to be consistent, and stops drawing fuel from the idle nozzle. Under these conditions, the vacuum is sufficient; however, to draw fuel from the progression port, which is always fed by the idle jet placed in the float chamber”.

5 Air Density

Air density varies with temperature and pressure. Ideal gases (including air) obey the Ideal Gas law at normal temperatures and pressures.

$$PV = nRT \tag{1}$$

where P is the pressure, V is the volume occupied by the gas, n is the number of moles of gas, R is gas constant for the specific gas, and T is the absolute temperature (Kelvin).

The equation assumes that gas particles do not interact with one another except for perfectly elastic collisions. The air pressure has 2 components: the pressure due to collisions with water molecules, P_v, called the vapour pressure, and the pressure, P_d, due to collisions with non-water molecules that make up “dry” air. I.e.

$$P = P_v + P_d \tag{2}$$

The air can only hold a specific amount of water vapour dependent on its temperature, at which point it becomes saturated. The saturated vapour pressure, P_s, is found experimentally to be described by the following formula [1].

$$P_s = e_s/p^8 \tag{3}$$

$$p = c_0 + c_1T + c_2T^2 + c_3T^3 + c_4T^4 + c_5T^5 + c_6T^6 + c_7T^7 + c_8T^8 + c_9T^9 \tag{4}$$

where

$e_s = 6.1078$

$T=$ temperature (Centigrade)

$c_0 = 0.99999683$

$c_1 = -0.90826951 * 10^{-2}$

$c_2 = 0.78736169 * 10^{-4}$

$c_3 = -0.61117958 * 10^{-6}$

$c_4 = 0.43884187 * 10^{-8}$

$c_5 = -0.29883885 * 10^{-10}$

$c_6 = 0.21874425 * 10^{-12}$

$c_7 = -0.17892321 * 10^{-14}$

$c_8 = 0.11112018 * 10^{-16}$

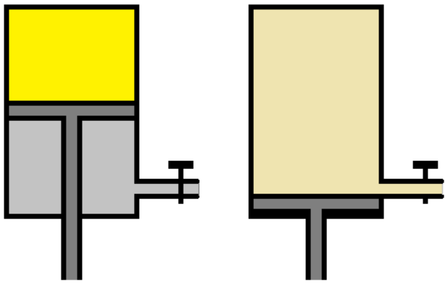

Figure 4: Simplified model of induction

$c_9 = -0.30994571 * 10^{-19}$

The actual vapour pressure, P_v, can be found by the following formula.

$$P_v = (relative\, humidity) * P_s \tag{5}$$

Rearranging

$$\rho = \left(\frac{P}{R_d T}\right)\left(1 - \frac{0.378 P_w}{P}\right) \tag{6}$$

where $\rho =$ density (kg/m^3), $P =$ air pressure (Pascals), $P_w =$ vapour pressure (Pascals), $R_d =$ gas constant for dry air = 287.05 J/(kg*Kelvin), $T =$ temperature (Kelvin).

5.1 The Effect of Atmospheric Conditions

How do changing atmospheric conditions affect the airflow to the engine? How does it affect volumetric efficiency? If the air becomes less dense, does the engine draw in proportionally less air, or is the engine response non-linear?

The hypothetical experimental device shown in figure (4) can be used to model induction. It consists of a piston and a cylinder, and at the bottom of the cylinder is a tube of constant radius and length leading to the outside atmosphere. There is a tap in the tube that prevents any flow through the tube until the tap is opened. Initially the piston is half way down a cylinder, the air in the cylinder is at atmospheric pressure and the tap closed. The cylinder is then drawn down so that the volume inside the cylinder is doubled. When the piston reaches the bottom of the cylinder, the tap is open and air from outside at atmospheric is allowed in.

Assume the airflow is not choked. Assume also that the gas expansion is adiabatic, then $PV^\gamma = constant$ where P is the pressure in the cylinder and V is the internal volume. During the expansion phase, $V \rightarrow 2V$ and $P_{atmos} \rightarrow P_2$, so $P_{atmos}V^{\gamma} = P_2(2V)^{\gamma}$. Solving yields $P_2 = \left(\frac{1}{2}\right)^{\gamma} P_{atmos}$ so

$$\Delta P = \left(1 - \left(\frac{1}{2}\right)^{\gamma}\right) P_{atmos} \tag{7}$$

The model suggests that for a naturally aspirated engine the draw ΔP is proportional to the outside atmospheric pressure P_{atmos}. I.e.

$$\Delta P \propto P_{atmos} \tag{8}$$

If the pressure Patmos is kept constant and assuming non-choked isentropic flow, then (see Appendix)

$$flow_{mass} = C_d \rho_1 A_2 \sqrt{2C_p T_1} \phi \left(\frac{P_2}{P_1}\right)$$

For an ideal gas,$\rho = P/RT$ so

$$flow_{mass} = C_d \left(\frac{P_1}{RT_1}\right) A_2 \sqrt{2C_p T_1} \phi \left(\frac{P_2}{P_1}\right)$$

I.e. if the pressure is keep constant, then the mass flow is inversely proportional to the square root of the temperature.

$$flow_{mass} \propto \frac{1}{\sqrt{T_1}} \tag{9}$$

The result is also consistent with published formulas for dyno correction factors. (See Appendix). Combining (8) and (9) gives

$$flow_{mass} = \mathrm{K}. \frac{P}{\sqrt{T}} \tag{10}$$

where K is a constant. For a ideal gas, $T = \frac{P}{R_{air}\rho}$ so (10) gives

$$flow_{mass} = \mathrm{K}\sqrt{\rho P} \tag{11}$$

If the atmospheric conditions changes so that the outside pressure $P_1 \rightarrow P_2$, and $\rho_1 \rightarrow \rho_2$ then, all other considerations unchanged, (17) implies

$$flow\, rate_1(kg/sec) \rightarrow flow\, rate_2(kg/sec) = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)}(flow\, rate_1) \tag{12}$$

6 The Airbox and Filter

All the air that enters the engine must pass through the airbox. The presence of a gauze air filter causes a drop in pressure downstream from the filter. The gauze should be cleaned regularly to ensure that it does not restrict air flow resulting in reduced power and inconsistent jetting behaviour.

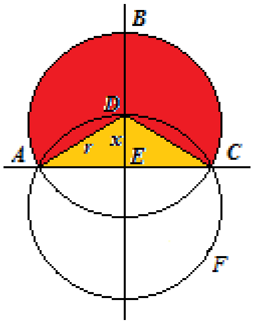

Figure 5: Venturi cross section. Height = 36mm, radius = 30 mm

The drop in pressure due to the air filter is typically

$$\Delta P = k.v^2$$

where$v$ is the volicity of the air flow and$k$ is a constant. However for the moment we shall ignore the effects of he airbox and filter.

7 Venturi Airflow

7.1 Venturi Size

The 34 in the VHSB 34 indicates the venturi size is 34 mm. But what does this mean? The carburettor is not circular; its shape is shown in figure 5.

The height of the venturi BG is 36 mm, the radius r of the offset circles is 30 mm. The area A of the truncated circle ABCEA is equal to sum of the area of the circle section ABCDA and area of the triangles ADE and CDE and is given by the formula

$$A = 2\left(\pi - cos^{-1}\left(\frac{x}{r}\right)\right)r^2 + 2x\sqrt{r^2 - x^2} \tag{13}$$

where x is the offset of the centre of the circles from line AC.

Substituting the measured numbers into the equation yields an area of 886 mm^2 for the whole venturi, which is the same as a circular venturi of diameter 33.6 mm.

The cross-sectional area of the venturi $A = A(\tau)$ is almost a linear function of the throttle position τ, as shown in the figure (6), where $\tau = 0$ means the throttle is fully closed, and $\tau = 1$ means the throttle is fully open

7.2 Venturi Pressure - Initial Flow Estimate

7.2.1 Estimates using Bernoulli

The venturi pressure can be estimated by assuming the air in incompressible and using Bernoulli's Principle:

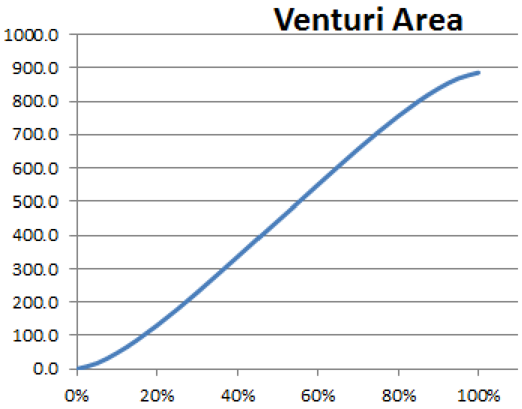

Figure 6: Venturi area (mm^2) vs. throttle opening (percent)

$$P_{venturi} = P_{atmos} - \rho_{air}\frac{v^2}{2} \tag{14}$$

where v is the venturi air speed ($\mathrm{m}^2/\mathrm{sec}$), $P_{venturi}$ is the venturi pressure (Pascals), P_{atmos} is the outside atmospheric pressure (Pascals), ρ_{air} is the air density (kg/m^3).

The air speed at wide-open throttle (WOT) and maximum revs can be calculated from the engine swept volume (125cc) and engine speed (RPM) using the formula

$$v = eff_{vol}\left(\frac{0.000125}{A(\tau)}\right)\left(\frac{\omega}{60}\right) \tag{15}$$

where $A(\tau)$ is the venturi cross-sectional area (m^2), ω is the engine RPM, eff_{vol} is the volumetric efficiency.

The pressure drop at the mouth of the carburettor, ΔP, is then

$$\Delta P = \frac{\rho}{2}\left[eff_{vol}\left(\frac{0.000125}{A(\tau)}\right)\left(\frac{\omega}{60}\right)\right]^2 \tag{16}$$

For a Junior engine running at 11,000 rpm and assumed 87% volumetric efficiency, the pressure is in the order of only a 25 millibars (0.02 atmospheres). The weakness of the vacuum is not surprising to anyone who has held their hand across a working carburettor - the airflow is quite gentle, even if noisy. If the carburettor created a perfect vacuum, it would take about 9 kg of force to remove a hand.

Induction is an extremely complex process. Air is not drawn steadily into the engine. Instead the air is first drawn into the engine by the decreased pressure in the crank, the port is then closed as the crank rotates, and the inertia of the air moving towards the closed port creates a compression wave that moves back through the carburettor. The results is that the air pressure in the venturi pulsates. At low flow levels, pulsation effects are small, however at high flow levels the fuel flow is known to be greater than it would be for the same average airflow at steady state [9].

It is known that for real carburettors the favourable pressure gradient keeps the boundary layer attached until the airflow reaches the fuel tube [10] (i.e. flow is not turbulent).

7.2.2 Estimates using flow equation

It is possible to estimate the pressure at the venturi using our original estimate of flow.

where the flow is measured in m^3/s, R is the tube radius (m), η is the fluid viscosity (m/sec), ΔP is the pressure differential between the ends of the tube (Pascals), L is the tube length (m).

However this formula is inconsistent with the published Rotax jet

The mass flow (kg/sec) through the tube is then

$$flow_{(mass)cylinder} = C_d \frac{\pi \rho R^4}{8 \eta L} \Delta P \tag{17}$$

If the atmospheric conditions changes so that the outside pressure $P_1 \rightarrow P_2$, and $\rho_1 \rightarrow \rho_2$ then (17) implies

$$flow\, rate_1 (kg/sec) \rightarrow flow\, rate_2 (kg/sec) = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)} (flow\, rate_1) \tag{18}$$

If the pressure P_{atmos} is kept constant and assuming isentropic flow, then (see Appendix)

$$flow_{mass} = C_d \rho_1 A_2 \sqrt{2 C_p T_1} \phi \left(\frac{P_2}{P_1}\right) \tag{19}$$

For an ideal gas $\rho = \frac{P}{RT}$ so

$$flow_{mass} = C_d \left(\frac{P_1}{R T_1}\right) A_2 \sqrt{2 C_p T_1} \phi \left(\frac{P_2}{P_1}\right) \tag{20}$$

Figure (7) illustrates the complexity of a potential surface representing the average airflow past the throttle slide as a function of both engine speed and throttle position.

As the throttle begins to close, the pressure at the throttle drops and the air speed increases. The increased air speed mitigates against the decreased cross sectional area so that there is only a minimal decrease in flow. As the throttle continues to close, the airflow becomes choked and the airflow is described by equation (62). This suggests that the airflow then becomes proportional to the cross sectional area and hence proportional to the throttle position, however C_d

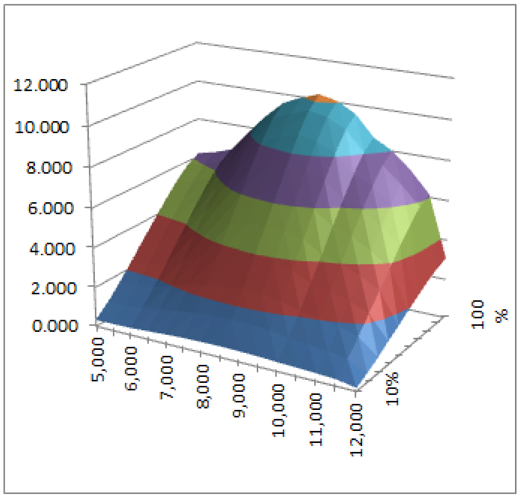

Figure 7: Average airflow volume (relative) as a function of engine speed (RPM) and throttle position (percent).

is also a function of throttle position so the flow actually decreases even more quickly than that.

When does the flow become choked? Ignoring the effects of the airbox intakes and air filter, substituting values for Senior Rotax at STP and 11,500 RPM into equation (61) indicates that flow becomes choked when the venturi area is approximately 520 mm^2or about 60% throttle.

There does not seem to be much published material on the flow past a slide throttle (this may be a failing of the author to locate such literature). There is literature on the flow past a butterfly throttle. Even though the geometry of a slide throttle appears very different to that of a butterfly throttle on first glance, in both cases the diverted flow is used in the same way to control idle and progression holes.

In the absence of evidence to the contrary, we use values consistent with the published literature and assume that the flow discharge coefficient $C_d(z)$ is a function of throttle position and varies from about 0.6 when the throttle is almost closed, to about 0.95 when the throttle is fully open.

8 The Main Jet

8.1 Compensating for Atmospheric Conditions

Suppose that the optimal jet for air density $\rho_{air,1}$ and atmospheric pressure P_1 is j_1, what is the correct jet when the air density is $\rho_{air,2}$ and pressure P_2?

The first step is to establish how the mass flow through the varies with jet size (diameter). Several possibilities present themselves but ... don't know how to do this...only one is consistent with the published Rotax jetting formula. No dependency on density!

$$flow_{(mass)} = kC_d \frac{R^2}{\eta}\sqrt{\Delta P} \tag{21}$$

If the atmospheric conditions change, then

$$flow\, rate_1(kg/sec) \rightarrow flow\, rate_2(kg/sec) = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)}(flow\, rate_1) \tag{22}$$

$$flow_2 = kC_d \frac{(R_2)^2}{\eta}\sqrt{P_2} = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)} flow_1 = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)} kC_d \frac{(R_1)^2}{\eta}\sqrt{P_1} \tag{23}$$

where P is the pressure across the main jet, R is the radius of the jet oriface. Simplifying gives

$$(R_2)^2\sqrt{P_2} = \sqrt{\left(\frac{\rho_2 P_2}{\rho_1 P_1}\right)}(R_1)^2\sqrt{P_1} \tag{24}$$

$$(R_2)^2 = \sqrt{\left(\frac{\rho_2}{\rho_1}\right)}(R_1)^2 \tag{25}$$

$$R_2 = \left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{4}} R_1 \tag{26}$$

Equation (23) contains a number of variables that are not easily observable but are expected to be relatively constant over the operational range of the model so (23) can be rewritten as

$$flow_{main-jet} = K_{main-jet} j^4 \Delta P \tag{27}$$

where the constant $K_{main-jet}$ can be inferred from experiment. Note that it is assumed ρ_{fuel} is constant.

The radius R of the jet is related to the jet size j by $R = \frac{j}{2}.10^{-5}$.

If conditions change, then

$$flow_{main-jet,2} = \left(\frac{j_2^4 \Delta P_2}{j_1^4 \Delta P_1}\right) flow_{main-jet,1} \tag{28}$$

The pressure differential is given by $\Delta P = P_{below-jet} - P_{above-jet}$ with $P_{below} = P_{atmos} + \rho g h$ since the fuel bowl is directly connected to the outside atmosphere (see Figure(2)) and $\rho g h$ is the pressure due to the weight of the fuel in the fuel bowl.

The calculation of P_{above} is more problematic. The region directly above the main jet is extremely complex to model. It is directly connected to the carburettor mouth however there is no guarantee that the pressure at the bottom of the fuel well in the emulsion tube, directly over the main jet, will be the same as pressure as that at the mouth. The best we can say is that P_{above} is somewhere between P_{mouth} and $P_{venturi}$.

The statement $P_{above} \approx \alpha P_{mouth} + \beta P_{venturi} + \rho g h_{well}$ and $\alpha P_{mouth} + \beta P_{venturi} \propto P_{atmos}$ is made without proof. It is also assumed that height of the fuel in the fuel well is roughly the same as that in the fuel bowl (cancelling out the effects of the weight of the fuel).

///

which yields the Rotax jetting formula.(See Appendix)

$$j_2 = j_1 \left(\frac{\rho_{air,2}}{\rho_{air,1}} \right)^{\frac{1}{4}} \tag{29}$$

9 The Emulsion Tube and Needle

The emulsion tube and needle is considerable more complex than it appears. The literature makes it clear that the air holes in the emulsion tube and air bleed system play a significant and complex role in maintaining the AFR over a wide range of conditions. The holes in the emulsion tube have a number of effects:

- The injection of air into the emulsion tube lowers the density of the fuel, and increases the overall flow.
- The air bleed to the front of the venturi lowers the pressure inside the fuel well so that, apart from minor losses, the fuel well and the bottom of the emulsion tube are at the same pressure as the mouth of the carburettor.
- The added air in the fuel promotes explosive atomisation of the fuel as it leaves the emulsion tube

The fuel flow from the emulsion tube into the venturi is modelled by (Bernoulli)

$$flow_{tube} = C_{df} A_{orifice} \sqrt{2\rho_{fuel}(\Delta P_{tube} - gh\rho_{fuel})} \tag{30}$$

where $\Delta P_{tube} = \Delta P_{mouth} - \Delta P_{venturi}$. The fuel flow ceases if $\Delta P_{tube} - gh\rho_{fuel} < 0$ which Dellorto states happens when the throttle is between $^1\!/_8$ and than $\frac{1}{4}$ open.

9.1 Orifice Area

The clip position affects the gap between the throttle needle and nozzle at the top of the emulsion tube by raising or lowering the needle relative to the throttle slide.

The approved needles for Rotax engines are K27 and K98 whose characteristics are shown in table (2).

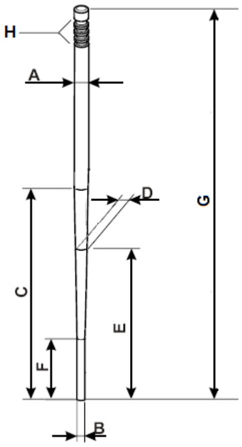

Figure 8: Dellorto Needle Measures

	A(mm)	B(mm)	C(mm)	D(mm)	E(mm)	F(mm)
K27	2.50	1.80	40.0	0	0	0
K98	2.52	1.80	44.0	0	0	0

Table 2: Dellorto Needle Specifications

The radius of the needle at the top of the emulsion tube is a function of the distance the needle protrudes into the tube and the needle specification.

Define x so that it corresponds the pin position. I.e. $x = 1$ when the clip is in the first (topmost) slot, $x = 2$ when the clip is in the second slot, etc. The distance the needle protrudes into the tube is then given by

$$z(mm) = z_1 + (1 - \tau)h_v–(x - 1) \tag{31}$$

where τ is the throttle position (0 → fully closed, 100% → fully open) , z_1 is the needle depth at WOT (mm), h_v is the venturi height (mm)

Suppose the needle protrudes 12 mm into the emulsion tube at WOT when the clip is in slot 1. Put the venturi height h_v = 36mm. If the throttle is 50% open and the clip is in position 3, then the needle protrudes into the emulsion tube by an amount z (mm) = 12 + (1 - 0.5) 36 - (3 - 1) = 20.5 mm

The cross-sectional area of the annular orifice between the emulsion tube and needle is

$$A_{oriface} = \pi[R^2–r^2(x, \tau)] \tag{32}$$

Substitution into (30) yields

$$flow_{tube} = C_{df}\pi[R^2–r^2(x, \tau)]\sqrt{2\rho_{fuel}(\Delta P_{tube} - gh\rho_{fuel})} \tag{33}$$

9.2 Compensating for Atmospheric Conditions

If the atmospheric conditions change so that the temperature $T_1 \rightarrow T_2$, the pressure $P_1 \rightarrow P_2$, and density $\rho_1 \rightarrow \rho_2$, then the to maintain the same AFR, the fuel flow through the emulsion tube must increase by a factor. Substituting (32) into (33) yields

$$[R^2–r^2(x_2, \tau)]\sqrt{2\rho_{fuel,2}(\Delta P_2 - gh_2\rho_{fuel,2})}$$

$$= \sqrt{\left(\frac{\rho_{air,2}P_1}{\rho_{air,1}P_2}\right)}\left\{[R^2–r^2(x_1, \tau)]\sqrt{2\rho_{fuel,1}(\Delta P_1 - gh_1\rho_{fuel,1})}\right\} \tag{34}$$

10 The Idle and Progression Circuit

Dellorto suggests “The operation of the independent circuit starting device can be divided into two parts: Initially when starting, during the first few turns of the crankshaft on the kick-starter or the starter motor, the device delivers a very rich mixture. Figure 16 (not reproduced) shows the mixture ratio depends entirely on the variety of drillings in the emulsion tube, because air passing through holes (2) draws up fuel which is standing in the jet well (1). In this period, the mixture strength is not determined by the starter jet size but only by the amount of fuel contained in the well above the holes located below the float-chamber fuel level. After this, a mixture leaner than previously is delivered and this mixture reaching the combustion chamber produces the first proper running of the engine.

Figure 15 (not reproduced) shows the mixture strength delivered through the emulsion tube depends on the size of the starter jet (6) and on the size of the air duct (10).

The channel size (4) is such that it creates an optimum vacuum in the starter valve chamber, at the emulsion tube outlet both for starting up and for the mixture required by the engine for its running and warming up. Therefore, varying the position or the size of the starter emulsion tube holes will change the amount of fuel delivered; the mixture ratio is controlled by the starter jet size and therefore a larger jet causes enrichment and vice-versa. Difficulties in starting the engine can occur when this mixture is too rich or too lean and you can see this from the spark plugs. After some starting attempts, remove the spark plugs and, if these are wet, the mixture is too rich and you will therefore need an emulsion tube with holes higher up. Conversely, if the spark plugs are found to be dry, the mixture is too lean and an emulsion tube with holes lower down is therefore needed. If the engine stalls when the engine is first started from cold before it has been running for at least a minute with the starting device on, you will need to reduce the starter jet size because of an over-rich mixture or increase it if the engine stalls because of a lean mixture..."

The Dellorto advice illustrates just how important the idle jets can be to overall performance.

The flow through the idle jets is described by essentially the same equation as the main jet

$$flow_{idle-jet} = A_{idle-jet}.j^4(\Delta P + gh\rho_{fuel}) \tag{35}$$

where $\Delta P = P_{atmos} - P_{mouth}$.

The flow through the idle jets should ideally change by the same factor as the flow through the main jets to compensate for changes in atmospheric conditions (see equation 18). The required change is too small to be prompt a change of idle jet size, instead the flow can be increased or decreased by changing the float height.

If the atmospheric conditions change so that the pressure $P_1 \rightarrow P_2$, density $\rho_1 \rightarrow \rho_2$, then the to maintain the same AFR the following relationship must hold.

$$\Delta P_2 + gh_2\rho_{fuel,2} = \sqrt{\left(\frac{\rho_{air,2}P_2}{\rho_{air,1}P_1}\right)}\{\Delta P_1 + gh_1\rho_{fuel,1}\} \tag{36}$$

where h_1 is the initial height of the venturi above the top of the fuel in the fuel bowl, and h_2 is the height of the venturi to compensate for the atmospheric conditions.

10.1 Comparison of idle jets

Rotax karts are permitted in the UK to run either 30/30 idles jets or 60/60 idle jets. The 30/30 idle jets provide a wide cover of atmospheric conditions, however under some circumstances it is possible that the configuration cannot provide the necessary fuel flow. In this case, the 60/60 idle jets provides an alternative. If the software detects that the standard 30/30 idle jets are not adequate, it will issue a warning recommending the larger jets.

If you choose to changes idle jets (or needles) you should always save the data under a different “engine”. For example, if your favourite engine is called “Brutus”, then it is recommended that you create multiple engine entries with the software, possibly using names such as “Brutus-K98-30/30” and “Brutus-K27-60/60”. Prometheus however does not enforce this requirement.

How much does the idle jet affect the AFR at WOT? If the main jet is 165, and the idle jets are 30/30, then the percentage additional flow from the idle circuit at WOT can be estimated to be

$$\frac{flow_{idle-jet}}{flow_{main-jet}} = \frac{(30)^4}{(165)^4} = 0.001 = 0.1\% \tag{37}$$

which is not significant.

If the main jet is 165, and the idle jets are 60/60, then the percentage additional flow at WOT can be estimated to be

$$\frac{flow_{idle-jet}}{flow_{main-jet}} = \frac{(60)^4}{(165)^4} = 0.017 = 1.7\% \tag{38}$$

which is sufficient to change the optimal settings for the main jet and needle.

11 Fuel density and viscosity

Fuel density and viscosity vary with temperature and pressure. It turns out that the density and viscosity variation can have a very significant effect on jetting. Figure (11) shows jetting recommendations using the Rotax rule (47). Figure (12) shows the jetting recommendations using the Rotax rule incorporating varying density and viscosity. In the first figure the range is covered by just 6 jets (150 → 162). In the second jet the range is covered by 11 jets (140 → 165). Not only does the density/viscosity variation result in more frequent jet transitions, the transitions become much more dependent on temperature than pressure (the slope of the boundary between jet regions is steeper than in the simple model).

Why would Rotax recommend a rule that is sub-optimal? The answer is two-fold. The Rotax rule is a the recommendation for pilots; fuel calculations need to be simple and do-able with simple equipment such as a calculator. The second reason is that once an engine “warms up”, the fuel is no longer at air temperature. Rather it appears from published jet settings, the fuel sits somewhere between the engine operating temperature and the engine operating temperature.

The corollary of this is that careful control of engine temperature must be maintained during track testing - not only because the engine performs inherently performs better within certain temperature limits (talk to your engine builder) but also that engine temperature affects the optimal mixture.

12 The Software

12.1 The Algorithm

The software optimises

1. Idle and progression circuit performance by solving for the fuel float height h in the equation $flow_{idle} = Aj_{idle}^4(\Delta P_{idle} - gh\rho_f)$ for the required flow with $\Delta P_{idle} = k_1 P_{atmos}$. The user selects the idle jet (30/30 or 60/60).

2. Top-end performance by solving for the jet j in the equation $flow_{main-jet} = A_2 j_{main-jet}^4 \Delta P_{main-jet} + Aj_{idle}^4(\Delta P_{idle} - gh\rho_f)$ for the required flow with $\Delta P_{main-jet} = k_2 P_{atmos}$. Note the flow includes flow from the idle and progression circuits and assumes the recommended fuel float height from the previous step.

3. Mid-range performance by solving for the needle slot x in the equation $flow_{tube} = A_3[R^2 - r^2(x,\tau)]\sqrt{\rho_{fuel}(\Delta P_{tube} - gh\rho_{fuel})} + Aj_{idle}^4(\Delta P_{idle} - gh\rho_f)$ for the required flow with $\Delta P_{main-jet} = k_3 P_{atmos}$. Again the calculation includes the flow from the idle and progression circuits using the recommended fuel float height.

The temperature of the fuel is calculated by $T_{fuel} = T_{engine} + \alpha(T_{engine} - T_{atmos})$ where α is an adjustable constant. T_{engine} is also an adjustable constant - the default value is 55C.

12.2 Warnings

The software issues warnings if

- The atmospheric temperature is within a few degrees of dew point. There is a real possibility that water can come out of the air in these conditions and block the jets. This leads to a very characteristic behaviour: a water droplet forms in the fuel bowl. Initially the kart runs well, but the water droplet is suddenly sucked up into the main jet and the engine stutters or stops. The kart is then brought back from the track by which time the water droplet has fallen back into the bottom of the fuel bowl and the engine runs fine again.
  Water condensation can also appear in the petrol can. It is a good idea in cold conditions to keep the fuel well above dew point, use a fuel funnel

with a water filter and check the fuel bowl for water after each run (any water droplet will be visible).

- The recommended carburettor settings cannot be physically achieved.

13 Jetting Track-side

The following algorithm can be used track-side to initially calibrate Prometheus, or to check it's correctness. The following discussion is focused on Rotax-Max karting, but is also be relevant to other classes of karting and 2-stroke motorcycles. The tuning process consists of the following steps:

1. The float level is adjusted.
2. The idle is adjusted.
3. The main jet is selected.
4. The clip position is selected.

13.1 Selecting the float height

The best way to select the float height is to use Prometheus. It may take considerable testing to find a configuration that optimises both main jet, clip position and float height. If you do not have Prometheus and cannot perform the required testing, set the float at the standard height. Experiment with the float height after performing the other steps.

13.2 Adjusting the idle.

The idle adjustment is described in detail in the Dellorto documentation [4] as follows.

> The beginning setting is mixture screw 1-1/2 turns out from lightly seated, and idle-speed screw set one full turn inwards from point it JUST begins to lift the slide.
>
> Always adjust the idle setting with the engine fully warm.
>
> Screw in the idle-speed screw to obtain a slightly-higher idling speed than normal (about 1200 RPM for a four-stroke engine or about 1400 RPM for a two-stroke); Then adjust the air-adjusting screw to obtain the most even running.
>
> Then unscrew the idle-speed screw again until you obtain the normal idling speed. Finally, to obtain the best engine running, it is worth rechecking by very carefully readjusting the air-adjusting screw

In the UK, noise restrictions means that it is not possible to run a kart at a track for more than 10 seconds - not enough to warm up the kart and adjust the idle and idle fuel screws. It probably makes more sense to run the kart in practice and adjust the idle immediately afterwards. It would also makes sense to mark the air and fuel screws so these can be adjusted without needing to actually run the engine.

13.3 Selecting the main jet

The main jet is selected to optimise AFR at high RPM. There are a number of ways to do this:

1. Make sure the engine is "warn" and listen for "popping" on the straight. Start rich and select a smaller main jet every time the kart goes out on the track. When the kart makes popping noises on the straights, go back one jet. (If you cannot make your engine "pop" by reducing the jet size, the needle in the fuel bowl may not be sealing properly. It is probably a good idea to have the carburettor inspected by someone who knows what they are doing)
2. Use GPS, which can display the calculated engine power at different RPM. Select the best jet by finding the one that creates the best top-end power. Great if you can afford it.
3. Experience. If you have been to the same track literally hundreds of times, which is the case for some team managers, then you should be able to rely on your past experience to select jets. Saying that, even karting professionals do not always get it right.

You should always record as much information as you can from your track session, including at least the temperature, pressure, humidity, main jet, pin position, idle jet (and float weight), float level and notes on the engine performance (e.g. too lean - pops at end of straight)

You can record your session information in Prometheus.

13.4 Selecting the pin configuration

The pin configuration is selected to optimise AFR at medium and low RPM. There are a number of ways to do this:

1. Driver feel. Selecting the pin position by driver feel is more difficult than selecting the main jet. There is no clear indicator, such as engine popping, that signals the AFR is right or wrong. In general, if the AFR is not right then the driver will simply report that he is slow out of corners, or that the engine hesitates in some corners. If your driver is not experienced or sure of himself, then any slowness can be put down to other factors.

2. Select the clip position that is “equivalent” to the main jet. The idea is that the engines requirement for fuel is determined (amongst other things) by the air density. If a change in air-density implies the main jet flow needs to be reduced/increase by a specific factor, then the flow through the idle circuit should be reduced/increased by the same factor.
   Unfortunately the “equivalence factor” can only be found by testing.
3. GPS. Select the best clip position by finding the one that creates the best low and mid-range-end power.
4. Experience. Most teams rely on past experience when choosing the pin configuration, in combination with driver feel and observation. Saying that, there a lots of "rules of thumb" in use out there that simply don’t work. E.g. "Add a bit more fuel" to make an engine go faster.

13.5 Things to always do

To create a database that you can use to make accurate jetting predictions, you should (if possible):

- Always record everything you do, preferably in Prometheus.
- Always use the same fuel.
- Always use the same oil.
- Always keep the exhaust matting and air cleaner gauze fresh.
- Always keep the engine operating at its optimal temperature.

Be aware that you may need to recalibrate the software each time you mix and match exhausts, engines and carburettors.

13.6 Don’t Worry, Be Happy

Provided that your settings are in the correct ballpark, the performance of your kart will sufficient to win races. In practice, the biggest variable is the driver.

14 Model Limitations

14.1 Operational Range

The model and software are intended for use within the following limits:
$910 \text{ mb} \leq \text{Pressure} \leq 1050 \text{ mb}$
$0^\circ\text{C} \leq \text{Temperature} \leq 45^\circ\text{C}$
$0 \leq \text{Humidity} \leq 100\%$
$140 \leq$ Rotax jet size ≤ 165 (configurable)

14.2 Model Considerations

The models presented above have a number of limitations. These include:

1. The model is crude and only a rough approximation to the real world. The trick to generate a good model is to determine which inputs "matter" and which do not, and to produce a good approximation for those that do.
2. At this stage, Prometheus suffers from a lack of experimental data to confirm the accuracy of the model. Although track data is helpful, information such as accurate pressure, flow and discharge coefficients make it possible to confirm the model is correct and extrapolate to conditions where no testing has been done.
3. The models are hard to calibrate. It is necessary to establish the value of a number of constants before the models can be used reliably. For most people this will means building up a sizeable amount of on-track data. Even with large amounts of data it may still not be possible to calibrate the model correctly since jet sizes and pin positions represent discrete data; an engine may operate best using a single jet over a reasonable large range of changing conditions before there is a sudden transition with the engine operating better with a jet one size larger or smaller. It is the transition points that convey most information. To make matters worse, small changes to the exhaust or carburettor may have a significant effect.
4. The model inputs and constants may contain significant error. For example, 1% change in temperature = 3C. Poor quality thermometers are only accurate to this order of magnitude. If you choose to exclusively use software to select jets, you should invest in top quality barometers and thermometers. The air temperature in shaded sections of a track may be different from that directly exposed to the sun; which should be used in the model? It has been pointed out that even the jet sizes are only approximately correct.
5. The implementation of the model can have a noticeable effect. There are, for example, several formulas for air density which give slightly different numbers.

It is for these reasons and others that most professional teams do not rely solely on software for jetting. They tend to draw on a wealth of experience that is not available to those new to karting. Teams also have the ability to use strategies that are not available to individuals. For example, it is not uncommon for teams to send out drivers on different settings to determine which is best. It should also be noted that those making the calls about which jet to use, even in large teams, do not always get it right.

14.2.1 Inputs and Likely Error

It is almost impossible to quantify the amount of error present in the model. It is certainly not 0.299%[1] (not 0.3%?). The following is a list of variables that can affect carburettor jetting.

- Atmospheric Temperature - Temperature calculations are in Kelvin. 1% error $\approx$ 3K. A variation of 3K (3C) in the measured temperature can frequently be seen by simply moving around a race track.
- Fuel/Engine Temperature - Engine temperature is generally controlled by movable flaps or by strips of gaffer tape or not at all. Engine temperature is typically monitored by devices on the steering-wheel but the fuel temperature is unknown.
- Atmospheric Pressure - 1% error $\approx$ 10mb. The likely error in the recorded pressure is expected to be $<$ 0.3% given that commercial quality barometers should measure the atmospheric pressure accurately to within a few millibars. Pressure changes slowly, so this input is unlikely to change over the time taken to prepare a kart and race.

  If you have any concerns over the accuracy of your barometer, then do a tour of the paddock asking those with weather stations what they believe the atmospheric pressure to be. Ask them if they have calibrated their barometer – if they have, discard their readings. The remaining readings should cluster around the true value and be near the reading on your own barometer.
- Humidity - The valid range is 0-100%. A 1% change in humidity has smaller effect than a 1% change in pressure or temperature. Quality barometers should measure the humidity to a high degree of accuracy ($<$5%).
- Jets - A single increase or decrease in jet size typically represents a change in flow of approx. 6-7%. The jets themselves are mass-produced items so there is some variation in the actual flow rates of the jet.
- Fuel composition - This can effect both the optimal AFR and the energy content of the fuel.
- Fuel specific gravity (density) - A change in the specific gravity indicates a change in the fuel chemical composition, which will affect the maximum power and stoichiometric AFR [12] as well as the flow though the jets.
- Fuel viscosity - The viscosity of the fuel/oil mixture changes with temperature and choice of oil. To achieve the best possible results with the software, you should always use the same oil.

---

[1] JetTech advertising claim

- Oil - Another component of the fuel. You should always use the same oil and mix the oil and fuel in the same ratio. The oil only represents a small percentage of the combined fuel-oil mixture (2%) so the overall mixture is relatively insensitive to poor oil measurement (thankfully – since very few people take care doing this). The effect of the oil is to slightly change the stoichiometric air-fuel ratio, the fuel viscosity and to a lesser degree, its density.
- Gravity - The gravitation constant varies across the world by as much as 0.6%! It does however vary very slowly over the planet's surface.
- Altitude - This has no direct effect on the jetting. The effect of attitude is covered by the effect of atmospheric pressure. Ignore

To achieve the best possible results with the software, you should always attempt to use fuel from the same source - if you can afford it, use racing fuel. The supply chain in the UK and many other countries is such that there can be no guarantee that fuel purchased from any same petrol station will be consistent. The best that can be said is that petrol in the UK should comply with the BSEN 228 standard, however that leaves considerable scope for variation. It is probably best to purchase fuel from a petrol station owned by a big-name petroleum company like BP, Shell or Esso which has a high turnover. The composition of fuel also changes to minimise emissions at different times of the year - Winter fuel, for example, will contain more short chained hydrocarbons such as pentanes which are removed in Summer.

14.2.2 Measurement of Density and Viscosity

It is possible to purchase the instruments that measure fuel density and viscosity. They are very expensive and hard to justify for Lad and Dad operations. They also do not reveal the changes to the maximum power AFR which can be significant. The Prometheus website contains a link to an Australian BP Fuel News showing the different maximum power AFR for BP Regular Unleaded and BP Premium Unleaded.

14.3 Impossibility of Accurate Non-Calibrated Models

The limitations of the model and likely error in model inputs (typically $\approx 1\%$) mean that it is impossible to produce a model which works best straight out-of-the-box. Even gravity varies from place to place. It is necessary to calibrate the model to get the best fit with reality

14.4 Sea-level Atmospheric Pressure and Altitude

Probably nothing is so poorly understood as the effect of Altitude. Measured atmospheric pressure is related to sea-level atmospheric pressure by the formula [7]

$$P = P_{sea-level}\left(1 - \frac{6.5}{T}\right)^{5.2558} \tag{39}$$

Sea-level atmospheric pressure is supplied by the Department of Meteorology. It is a theoretical number generated from a slew of temperature, humidity and pressure data; it cannot be a "real" number since it purports to show what the sea-level air pressure would be if the ground above sea-level was taken away and replaced by a column of air.

Sea-level atmospheric pressure is notoriously unreliable. The temperature used in the formula is typically an average of temperature over several hours. Any calculation that uses pressure supplied by the Department of Meteorology must be regarded as containing significant error, particularly at altitude. Don't worry if your barometer varies from the official figure.

In short, ignore altitude. Do not "recalibrate" your barometer - this is a procedure designed to ensure that planes don't fly into each other, and/or weather stations report an (inaccurate) figure close to the sea-level figure. It is not recommended for racing. Directly measuring atmospheric pressure is the way to go. Fortunately many of the calculations are sensitive to ΔP.

15 Next Steps

Works is under-way to confirm the model's by direct measurement. CFD is also being explored. It has the potential to provide detailed flow information that it not available in any other way. For example, it has the potential to give a definitive answer to questions such as "what is the difference in performance between 8.5 and 12.5 progression jets?" Unfortunately time considerations mean that this work will probably not be available in the near future.

Please note that this document is under continuous development and will be updated as often as time allows. It is intended to accompany Prometheus software but can be downloaded from the Prometheus website.

16 The Need for Data

Theoretical models are nice but without good data, they are not usable. Prometheus are always seeking partners with jetting and other data to further develop the model.

17 A Personal Note

There is a flourishing market in "good" carburettors; the author has heard of prices well beyond that affordable by Lad and Dad. Unlike engines, every part of a carburettor can be replaced or adjusted. It is hoped that Prometheus will help to render any difference in carburettor performance inconsequential.

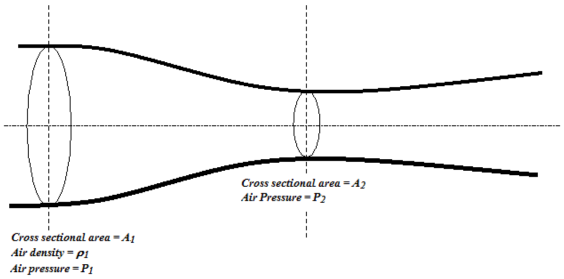

Figure 9: Venturi

18 Appendix A - Rotax Jetting Advice

The Rotax Service Information (Bulletin 8 UL 87E) [2] says

> "In practical operation an exchange of the main jet according to a correction factor is carried out. This correction factor f_D can be calculated from the denity ration or taken directly from the table
> $f_D = \sqrt[4]{\rho/\rho_0}$"

19 Appendix B - Flow Equations for a perfect gas

There are multiple formulas for turbulent and non-trubulent flow, each with their own assumptions and applicable situations. All the equations below refer to the venturi shown in figure 9.

The following equation assumes a large cross section A_1 such that that the initial air velocity $c_1 \approx 0$. The pressure P_1 is usually taken to be $P_{atmosphere}$ (and $A_1 \to \infty$).

$$flow_{air} = C_d(z)\rho_1 A_2 \sqrt{2C_p \left(\frac{P_1}{R\rho_1}\right)} \phi \left(\frac{P_2}{P_1}\right) \tag{40}$$

where

$$\phi(x) = \left[x^{\left(\frac{2}{\gamma}\right)} - x^{\left(\frac{\gamma+1}{\gamma}\right)}\right]^{\frac{1}{2}} \tag{41}$$

If the flow is choked, then it is no longer described by (40), rather it is described by

$$flow_{choked} = C_d A \sqrt{\gamma \rho_1 P_1 \left(\frac{2}{1+\gamma}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}} \tag{42}$$

where A is the cross-sectional area. Once the flow becomes choked, the fluid velocity becomes unresponsive to the pressure differential along the tube (the air/fuel velocity becomes unresponsive to the engine vacuum).

19.1 Bernoulli's Equation

Incompressible flow along a streamline:

$$\frac{P_1 - P_2}{\rho g} = \Delta Z + \frac{(c_2)^2 - (c_1)^2}{2g} \tag{43}$$

Compressible flow along a streamline:

$$\frac{P_1}{\rho_1 g} + \frac{(c_1)^2}{2g} = \Delta Z + \frac{P_2}{\rho_2 g} + \frac{(c_2)^2}{2g} \tag{44}$$

Flow using Bernoulli

$$Q_{vol} = A_1 \sqrt{\frac{2\left(\Delta Z + \left(\frac{P2}{\rho 2} - \frac{P1}{\rho 1}\right)\right)}{1 - \left(\frac{A1}{A2}\right)^2}} \tag{45}$$

19.2 Darcy Equation

Loss of pressure due to friction (applies to both laminar and turbulent flow):

$$\Delta p = \frac{\rho f L c^2}{2D} \tag{46}$$

20 Appendix C - Derivation of non-choked flow equation

$$j_2 = j_1 \left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{4}} \tag{47}$$

Air flows through the venturi shown in figure 9. The flow is assumed to be isentropic. As a result P, T and ρ and are not independent; they are related by equations (51) and (52). It is possible to express any two of the quantities in terms of the third.

For a volume of gas flowing through the venturi:

$$q - w = (h_2 - h_1) + \frac{1}{2}\left[{c_2}^2 - {c_1}^2\right] \tag{48}$$

where q is the heat transferred to the gas per unit mass while in the volume, w is the work done by the gas per unit mass of gas, h is the gas enthalpy, c_1 is the velocity of the gas entering the volume and c_2 is the velocity of the gas exiting the volume. For a carburettor, the volume under consideration typically consists of a region immediately outside the air intake through the venturi to just past the fuel jets. In that case $c_1 \approx 0$. The flow is assumed to be adiabatic so $q = w = 0$. (48) reduces to $0 = (h_2 - h_1) + \frac{1}{2}{c_2}^2$. Rearranging gives

$$c_2 = \sqrt{2\left(h_1 - h_2\right)} \tag{49}$$

Air is an ideal gas so $h = C_p T$ where C_p is the heat capacity at constant pressure and T is the temperature (Kelvin). (49) can therefore be written as

$$c_2 = \sqrt{2C_p\left(T_1 - T_2\right)} \tag{50}$$

The airflow is isentropic so

$$PV^{\gamma} = const \tag{51}$$

and

$$P^{\left(\frac{1-\gamma}{\gamma}\right)}T = const \tag{52}$$

It follows that

$$\frac{T_2}{T_1} = \left(\frac{P_1}{P_2}\right)^{\left(\frac{1-\gamma}{\gamma}\right)} \tag{53}$$

Substituting (53) into (50) gives

$$c_2 = \sqrt{2C_p T_1\left[1 - \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]} \tag{54}$$

The mass flow though the carburettor is conserved, so

$$flow_{air} = \rho_1 A_1 c_1 = \rho_2 A_2 c_2 \tag{55}$$

Note that

$$\rho_2 = \left(\frac{P_2}{P_1}\right)^{\left(\frac{1}{\gamma}\right)}\rho_1 \tag{56}$$

Substituting (54) and (56) into (55) and introducing the ubiquitous C_d factor gives

$$flow_{air} = C_d(z)\rho_1 A_2\sqrt{2C_p T_1}\phi\left(\frac{P_2}{P_1}\right) \tag{57}$$

For a perfect gas $P = \rho R_{specfic}T$ so (57) can be rewritten as

$$flow_{air} = C_d(z)\rho_1 A_2\sqrt{2C_p\left(\frac{P_1}{R\rho_1}\right)}\phi\left(\frac{P_2}{P_1}\right) \tag{58}$$

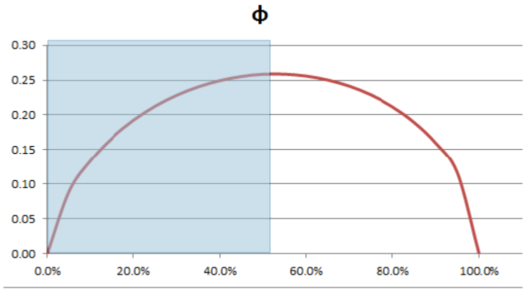

Figure 10: ϕ

Some manipulation using the relationships $\gamma = \frac{C_p}{C_v}$ and $C_p - C_v = R$ yields a version of the equation that is quite common in the literature and does not depend on C_p or C_v:

$$flow_{air} = C_d(z) A_2 \sqrt{2\rho_1 (P_1 - P_2)} \left\{ \frac{\left(\frac{\gamma}{\gamma-1}\right) \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma+1}{\gamma}\right)} \right]}{1 - \left(\frac{P_2}{P_1}\right)} \right\}^{\frac{1}{2}} \tag{59}$$

In both (58) and (59) the flow is a function of ρ_1, P_1, P_2, A_2 and C_d:

$$flow_{air} = f\left(\rho_1, P_1, P_2, A_2, C_d\right) \tag{60}$$

Equation (57) is only valid if the flow is not choked. Figure (10) shows the value of ϕ over the interval from 0 to 1. The flow increases with increased pressure differential but begins to taper off .ϕ has maximum value at $x_{max}$where

$$x_{max} = \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \tag{61}$$

For air, $x_{max} = \left(\frac{P_2}{P_1}\right)_{max}$ is approx 0.5283. At $\left(\frac{P_2}{P_1}\right)$ ratios below this value, flow becomes choked and is described by (62)

$$flow_{air} = C_d A_2 \sqrt{\gamma \rho_1 P_1 \left(\frac{2}{1+\gamma}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}} \tag{62}$$

Choked flow is a function of ρ_1, P_1, A_2 and C_d, but no longer sensitive to P_2:

$$flow_{air} = g\left(\rho_1, P_1, A_2, C_d\right) \tag{63}$$

21 Appendix C - Dyno Correction Factor

The SAE J1349 (Revised AUG2004) Dyno Correction Factor relates the indicated Power developed by an engine at a specified temperature and pressure to that indicated at STP of 25C and 990 millibars. I.e.

$$\frac{Power^{ref}_{at-wheels}}{Power^{T,P}_{at-wheels}} = CA \tag{64}$$

The Dyno Correction Factor CA varies inversely with the power, so as temperature increases, the developed power decreases but the Dyno Correction Factor increases.

The formula assumes that the internal engine friction is constant and consumes 15% of the power at STP. I.e

$$Power_{friction} = 0.15.Power^{ref}_{Actual} \tag{65}$$

$$Power^{ref}_{at-wheels} = Power^{ref}_{Actual} - Power_{friction} \tag{66}$$

$$Power^{T,P}_{at-wheels} = Power^{T,P}_{Actual} - Power_{friction} \tag{67}$$

Equations (8) and (9) indicate that mass flow and therefore power is proportional to the dry atmospheric pressure P_d and inversely proportional to $\sqrt{T}$. I.e

$$Power^{T,P}_{Actual} = \left[\left(\frac{P_d}{P_{ref}}\right)\sqrt{\frac{T_{ref}}{T}}\right] Power^{ref}_{Actual} \tag{68}$$

Substituting (65) into (67) and (66) yields

$$Power^{ref}_{at-wheels} = (1 - 0.15).Power^{ref}_{Actual} \tag{69}$$

$$Power^{T,P}_{at-wheels} = \left\{\left[\left(\frac{P_d}{P_{reference}}\right)\sqrt{\frac{T_{reference}}{T}}\right] - 0.15\right\}.Power^{ref}_{Actual} \tag{70}$$

Combining (69) and (70) gives

$$CA = \frac{0.85}{\left\{\left[\left(\frac{P_d}{P_{ref}}\right)\sqrt{\frac{T_{ref}}{T}}\right] - 0.15\right\}} \tag{71}$$

The published formula is

$$CA = 1.176\left[\left(\frac{P_{ref}}{P_d}\right)\sqrt{\frac{T}{T_{ref}}}\right] - 0.176 \tag{72}$$

Note (72) is of the form $CA = 1.176x - 0.176$ while (71) is of the form $CA = \frac{0.85}{\frac{1}{x}-0.15}$ where $x = \left[\left(\frac{P_{ref}}{P_d}\right)\sqrt{\frac{T}{T_{ref}}}\right]$.

Equation (72) is a linear approximation of the form$CA = mx + c$ of (71). To see this, note that at $x = 1$ (STP), $m = \frac{dCA}{dx} = \frac{-0.85}{(1-0.15)^2}.\frac{-1}{1} = 1.176$. At $x = 1$, $CA = 1 = 1.176 - c$ so $c = 0.176$.

The SAE documentation says that the approximation is good at WOT in the range 15C - 35C however testing indicates that it is actually remarkably good over a much wider range of temperatures.

The mechanical losses due to friction will vary considerably from engine to engine dependent on such things as the camshaft configuration, oil pumps, number of cylinders and the like. The engine friction also varies with engine operating temperature (Pit lore says the Rotax 125 works best 45C-55C). The SAE formula does not take any of this into consideration, however a survey of the web suggests that it is good enough to be in widespread use by engine builders.

22 Appendix D - Jetting Recommendations

The following heat maps were generated in Excel and show recommended jetting assuming a 158 reference jet at 20C, 1015 mb and 50% humidity. Note that the variation of fuel density and viscosity has a significant impact on jetting.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
1050	162	162	162	162	162	162	162	162	162	160	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155
1045	162	162	162	162	162	162	162	162	160	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155
1040	162	162	162	162	162	162	162	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155
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1030	162	162	162	162	160	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155
1025	162	162	162	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155
1020	162	160	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155
1015	160	160	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155
1010	160	160	160	160	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155
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995	160	160	160	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152
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985	160	160	160	160	160	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152
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950	158	158	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152
945	158	158	158	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152	152
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935	158	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152
930	158	158	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	150
925	158	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	150	150	150
920	158	158	158	158	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	152	150	150	150	150
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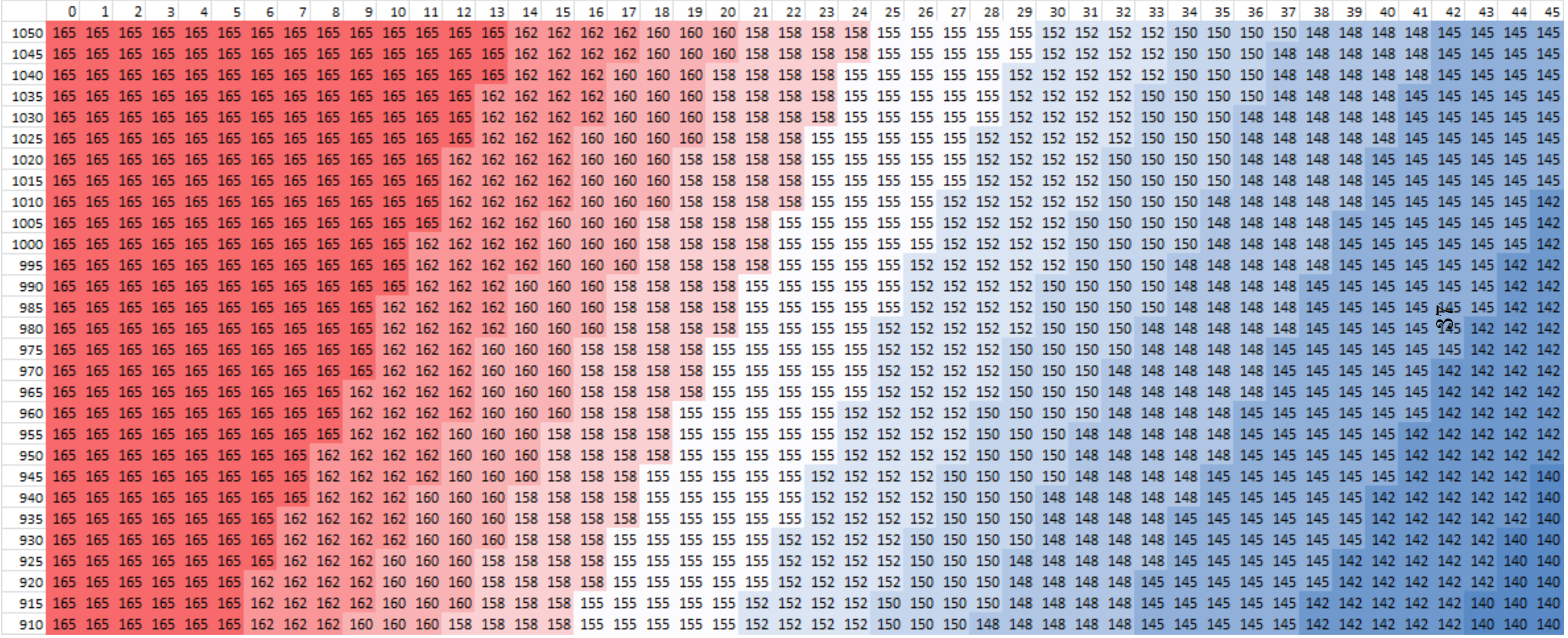
Figure 11: Jetting - Rotax formula



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
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1020	165	165	165	165	165	165	165	165	165	165	165	165	162	162	162	162	160	160	160	158	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	150	148	148	148	148	145	145	145	145	145	145
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985	165	165	165	165	165	165	165	165	165	165	162	162	162	162	160	160	160	158	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	150	148	148	148	148	145	145	145	145	145	145	142	142
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940	165	165	165	165	165	165	165	165	162	162	162	160	160	160	158	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	148	148	148	148	148	145	145	145	145	145	142	142	142	142	142	140
935	165	165	165	165	165	165	165	162	162	162	162	160	160	160	158	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	148	148	148	148	145	145	145	145	145	145	142	142	142	142	142	140
930	165	165	165	165	165	165	165	162	162	162	162	160	160	160	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	150	148	148	148	148	145	145	145	145	145	145	142	142	142	142	140	140
925	165	165	165	165	165	165	165	162	162	162	160	160	160	158	158	158	158	155	155	155	155	155	152	152	152	152	150	150	150	148	148	148	148	148	145	145	145	145	145	142	142	142	142	142	140	140
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Figure 12: Jetting - Rotax formula inincorporating adjustment for changing density and viscosity.

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[1] http://wahiduddin.net/calc/density_altitude.htm

[2] Rotax Service Bulletin, June 1990.

[3] Section 2.2 of the Dellorto Motorcycle Carburettor Tuning Guide (http://www.ducatimeccanica.com/dellorto_guide/dellorto.html).

[4] Section 3.4 of the Dellorto Motorcycle Carburettor Tuning Guide

[5] Section 3.6.5 of the Dellorto Motorcycle Carburettor Tuning Guide.

[6] Section 4.1 of the Rotax FR 125 Owner Manual, BRP-ROTAX GmbH & Co. KG, 2006 Edition.

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