Problems Encountered When Scaling Plans.

When building scale models as well as scaling a design up there are certain scaling and strength of materials rules you need to keep in mind.

Firstly you would generally you keep everything the same for appearances sake.

However you should keep in mind that scaling up or down introduces problems.

Problems Caused By Squared and Cubed Numbers:

Areas increase/decrease to the square of the scale, volumes and mass to the cube of the scale and polar and mass moments to the 4th power - this last item is the most trouble (see later).

Example:- If you take a 2 litre motor and double its dimensions - the volume / mass is 2x2x2 = 8 times bigger - so if the original engine was 2 litre and weighed 200kgs - your scaled up engine to twice as big (dimensionally) will become 16 litres and weigh 1.6 tonnes !

By the same token if you scaled it down 2:1 (half size) it would become 250cc and weigh 25kg.

In the case of the 2 litre - if it made 200 Horsepower (a hundred horsepower per litre - high performance) - scaling is going to have a strange effect - the double size engine is going to have the same mean effective pressure applied to 4 times the area and twice the stroke so the torque is going to be 8 times greater - however the mean piston speed cannot be increased (limits of lubrication capability were already at maximum on the 2 litre engine) so if our 2 litre motor was capable of 6000rpm our 16 litre motor will only be capable of 3000rpm so overall our power only increases 4 times to 800 horsepower not 1600 as you might have expected. So it achieves only half the specific horsepower - 50 horsepower per litre.

By the same token our half size 250cc model can do 12000 rpm and generate 50 horsepower or 200 horsepower per litre - that is why high performance engines have more smaller cylinders.

O.K. I'm talking theoretically here - in practice I don't think the 250cc would be that good or the 16 litre that bad - but always have these ratios in your mind. (Because of aspiration and carburation issues - atoms don't scale ! Flame speed and flame propagation in the engine remain the same regardless of its size etc. etc.)

4th Power Problems:

Now we come to the tricky bit - the polar moment - the ability of a shaft to resist torque - is to the 4th power - so in the case of our 2 litre scaled up to 16 litre the torque increased by 8 times but the ability of the crank to resist the torque went up 2x2x2x2 = 16 times - so the crank becomes over-designed for the application and the journals could be reduced.

The opposite is going to happen with our 250cc scaled down engine - the torque is going to be 1/8th but the ability of the rotating parts to handle it is going to be 1/16th and therefore be much more highly stressed (double in this case) and more prone to failure.

You can see this on large cranks from marine engines - they look relatively "skinny" when compared to our normal frame of reference - a crankshaft from a car engine. If you radically scale down such an engine - say 1/10th scale you are going to end up with a crank that is effectively only 10% of the original torsional design strength relative to its new size.

We generally don't want to actually derive extreme performance from a model - so you can get away with it - but be careful.

Assuming you want to make allowance - lets say the 2 litre's main crank bearings were Ø60mm and the big end journals Ø40mm then our scale sizes would be Ø30mm and Ø20mm which is actually too small for the design.
The true (compensated) scale for the Ø60 should be the 4th root of (60^4)/8 which scales down to Ø35.67 (not Ø30 as you might presume).and the Ø40 scales down to Ø23.8 (not Ø20 as you might presume). So we would round up to Ø36 & Ø24

(A simple way to calculate the 4th root is to take the square root twice.)

So torsionally stressed parts need to be slightly larger than scale on scaled down motors.

What you can also see is that a small change in diameter makes a big difference to polar moment - so if you scale down a shaft to say Ø6.9 then round it up to Ø8 - or apply the calculation - never round down. (The Ø8 shaft would be 80% torsionally stronger than Ø6.9).

You don't have to slavishly follow such "Strength Of Materials" type calculations but you should always have these rules at the back of your mind. Also bear in mind the actual strength of the materials you have chosen etc. etc.

In most cases, scaling down works to your favour in terms of strength in everything except torsionally loaded parts.

The inertia of a flywheel is also to the fourth power problem (its “Mass-Moment” or its inertia) - so scaled down flywheels have considerably less inertia relative to the scaled down engine - err upwards on diameter and thickness when scaling down flywheels.

Whilst a flywheel's inertia is a 4th power, the energy it contains is multiplied by the rotating speed squared – so since most scaled down models turn faster than the original, this reduces the effect – but we normally want display models to turn as slowly as possible – so be aware of the rules.

Some Things Can't Be Scaled:

A final comment - atoms don't scale - so things like lubrication clearances remain the same and effectively scale up leakage, by-pass etc. in a model that has been scaled down. Hence frequent problems with compression and carburation etc. on small scale motors.

Again following our 2:1 scale 2 Litre engine: Our airflow is 1/8th of the original but the area of the throttle bodies will be ¼ in other words – they will be too big for the required venturi effect etc.

Example: The original Venturi was Ø38 = an area of 1134mm^2 so our scale Venturi needs to be 1/8th of that (in order to retain the same airflow velocity through the Venturi) or 141.7mm^2 = Ø13.4 rather than Ø19 from its simple scale value.

Spark plug gaps and ignition voltage and power required to ignite a petrol engine remain the same regardless of scale (atoms don't scale) – so you may have problems with insulation on H.T. cables and distributor caps built to scale.

Appearance Of Scale:

Sometimes models "just don't look right" – this is especially true of model cars – if you look down on a car from a tall building it will look longer and narrower than you normally perceive it to be.

Consequently model cars built to scale tend to look "wrong" when held in your hand or viewed from above simply because it is via a perspective that we do not usually see cars from.

In modelling this is called the "scale effect" so it is fairly common to deliberately shorten and slightly widen the body scales of model cars to get them to "look right" even though not true to scale.

Scaling In The Real World: A Caveat.

If you were to scale down a house for a model, you would simply scale it. But if you scaled the plans up with the intention of creating a bigger house, you would not increase the height of the walls – you would also not increase the thickness of the walls while the loading on them might increase significantly and the roof structure would become much more highly stressed etc. etc.

A supporting beam or lintel structure over a wider aperture cannot be simply scaled up.

When scaling up for real-world practical applications be sure that all the necessary safety calculations are performed by competent persons.
There have been many examples of scaling failures in structural, marine and aero applications – don't do it without consulting structural engineers etc.

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Ken Irwin – Cape Town - 14th September 2020

To contact me send a personal message to "Ken I" via the HMEM Website.

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