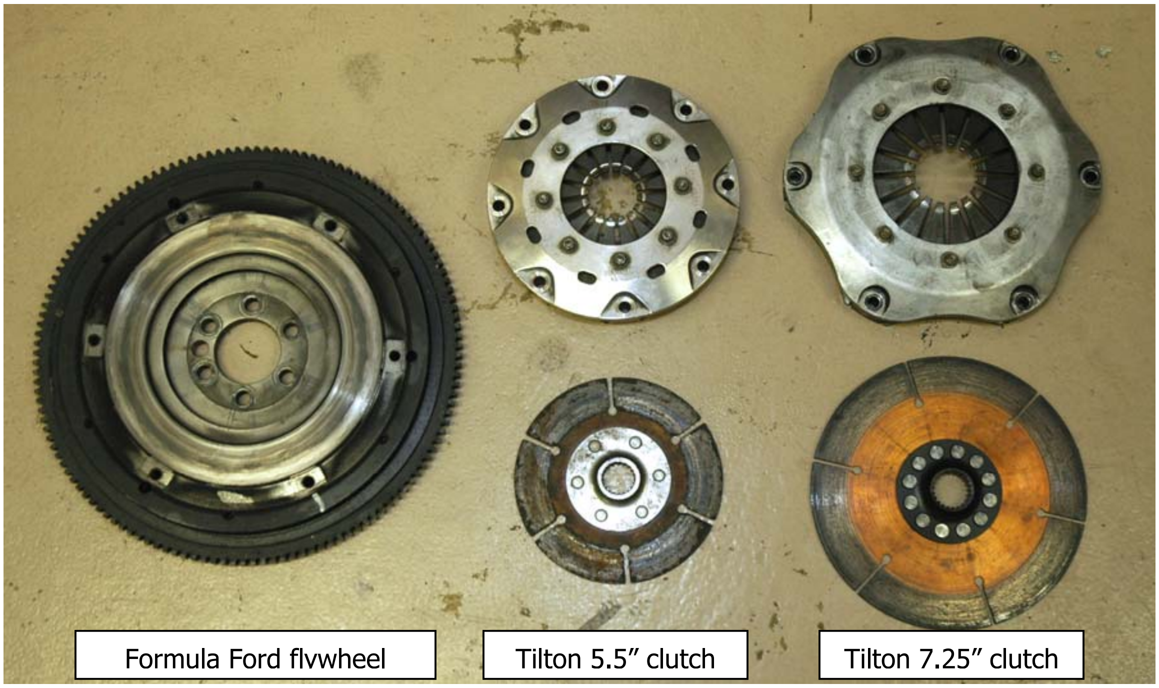
Flywheel and clutch choices



Acceleration is vitally important in every type of racing, and Formula Ford (FF) is no exception. One of the many choices available to the FF racer in the USA is the type of clutch to use. In some parts of the world, a stock Ford clutch and clutch cover is required – however for SCCA Formula Ford in the USA, no such restriction applies:

> D.5. Clutch
> The use of any single plate clutch is permitted provided no modification is made to the flywheel other than changing the points of attachment of the clutch to the flywheel, and provided that it shall have an operable clutch system. Carbon Fiber clutches are not permitted.

A minimum weight is specified for the flywheel of 15.5lbs. This rule changed in recent years from 19.4lbs for the ‘uprated engine’ used in almost all cars:

> l. Flywheel
> Weight with ring gear:
> 15.5 lbs minimum for the original and uprated engine.
> The flywheel may be machined provided the machining to reduce weight to the above minimum weight retains the standard profile. Flywheel locating dowels are permitted.
> An alternate flywheel from JAE, part # JAE1600 is also allowed to the above weight of 15.5 lbs.

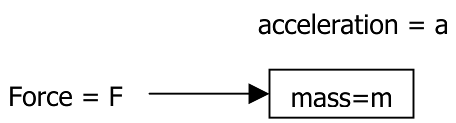
Flywheels are rarely machined to the absolute minimum weight; some margin is left to allow for resurfacing as the flywheel is worn down by clutch slippage.

At the time of the rule change, the primary reason given for reducing the weight of the flywheel was to improve reliability by reducing the number of crankshaft breakages.

However, a lighter flywheel and clutch assembly will surely have a performance advantage over a heavier one – but by how much?

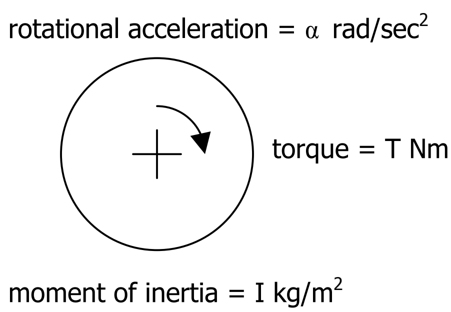
Overcoming inertia

Newton's Second Law describes the straight-line (linear) acceleration of a body from rest in free space; the net force applied and the mass of the object determine the acceleration at any given point in time:



$$F = ma \qquad a = \frac{F}{m}$$

A similar equation applies when a torque is applied to make an object spin – a rotational acceleration. In this case the rotation acceleration is determined not only by the torque applied (force times distance) and the mass of the object – but also by the distribution of mass about the axis. This is measured using a term called the mass moment of inertia (MMI). This is also often referred to just as the 'moment of inertia' or MOI.



$$T = I\alpha \qquad \alpha = \frac{T}{I}$$

Different shapes of the same mass have different moments of inertia, for example:

Flat disc or cylinder of radius r, mass m	Thin ring of radius r, mass m	Solid sphere of radius r, mass m
$I = \frac{1}{2}mr^2$	$I = \frac{2}{5}mr^2$	$I = \frac{2}{5}mr^2$

A shape where the mass is concentrated at the outside (e.g. a ring) has a higher moment of inertia than a shape where the mass is concentrated around the axis (e.g. a sphere). With a higher moment of inertia, slower acceleration/deceleration is possible for the same torque.

The flywheel in an internal combustion engine is essentially an energy-storage device. The power from the engine is delivered in many small bursts – as each spark ignites the mixture and forces down a piston. The flywheel resists rapid changes in rotational speed and thus allows this pulsating energy input to be smoothed out.

We can see that for a more general form of the equation, we can say $I = Dmr^2$ where D is a constant representing the distribution of mass.

For the change in weight of Formula Ford flywheel, and assuming the distribution of mass remains the same (the rules say that the profile cannot be altered), the change in moment of inertia will be directly related to the change in mass.

A flywheel weight reduction of 20.1% from 19.4lbs to 15.5lbs would result in a 20.1% reduction in flywheel moment of inertia – assuming that the distribution of the mass remains the same.

Therefore – for a given torque, the lighter flywheel will accelerate 20.1% faster. However, this is not the end of the story – the flywheel is only one part of the total moment of inertia of the drivetrain that is resisting the torque from the engine.

This change will not show up as an increase in horsepower on a traditional braked engine dyno, since for each hp reading, the engine is being run at a constant speed. On the track, a benefit will be seen since the engine is always accelerating or decelerating, and never run at constant speed!

As a side point, an increase in measured horsepower would likely be seen on a drum-style ('inertia') chassis dyno. These devices estimate engine power output by measuring engine RPM against the corresponding acceleration of a large drum. The MMI of the drum is known, and the MMI of the vehicle drivetrain is estimated. Hence for a fixed engine power output, if the MMI of the vehicle drivetrain is reduced, the measured 'engine power output' will appear to increase – this could be achieved by fitting a lighter flywheel, wheels with lower MMI, etc etc..

In order to understand the effect on overall vehicle performance, we need to get an idea of the total moment of inertia of the rotating/reciprocating masses in the drivetrain:

- Crankshaft
- Pistons/connecting rods
- Flywheel
- Clutch
- Transaxle
    - Shafts
    - Gears
    - Dog rings
    - Bearings
    - Differential
- CV/Tripod joints
- Driveshafts
- Hubs
- Brake discs
- Wheels and tires

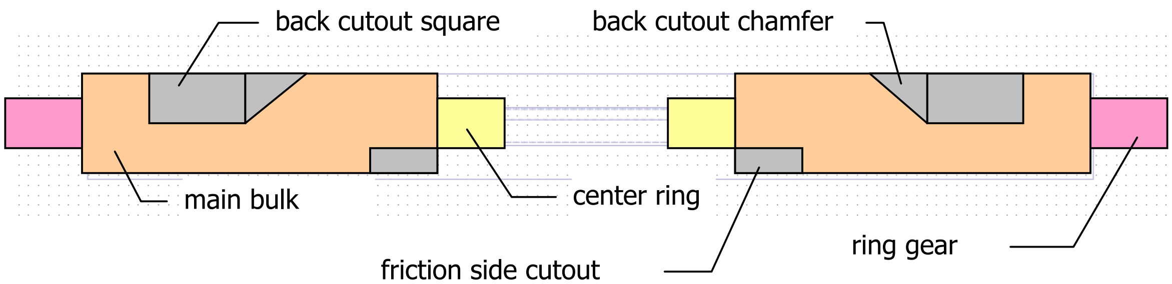
Since that all seems very complicated, before getting into that, we can consider the behavior of the two different types of flywheel and the two clutches under consideration.

Flywheel and clutch

The Tilton and Quartermaster catalogs helpfully list the moment of inertia of clutches:

- Tilton OT-II 7.25" single plate racing clutch MMI = 0.0130 kg/m^2
- Tilton OT-III 5.5" single plate racing clutch MMI = 0.0061 kg/m^2
- Quartermaster Pro Series 5.5" single plate MMI = 0.0066 kg/m^2
- Quartermaster Pro Series 7.25" single plate MMI = 0.0160 kg/m^2

Moment of inertia figures for the FF flywheel are rather harder to come by. It would be possible to measure MMI directly, however in this case it is relatively easy to produce an approximate number using a simplified 3d model of the stock Ford flywheel.



The MMI figure for the flywheel can be calculated as follows. First, three main components are considered, each as a thick-walled ring – the main bulk of the flywheel, the ring gear and the section in the center. Yet more rings can then subtracted from the flywheel to complete the model. The total volume of the flywheel can then be calculated.

At this point, a little bit of trickery takes place. If we assume that the heavy and light flywheels really do have an identical profile, the only way that the weight can be different is if the density of the material changes. So we work out the density for each flywheel as volume divided by weight.

Now, we can work out the weight and MMI for each thick-cylinder component being used to make up the flywheel model – summarized in the table below. The equation for MMI of a thick cylinder is shown to the right, where r_1 is the inside radius, r_2 is the outside radius, and m is the mass.

$$I_Z = \frac{1}{2} m(r_1^{\,2} + r2^2)$$

The table below shows the numbers for the 19.4lb flywheel.

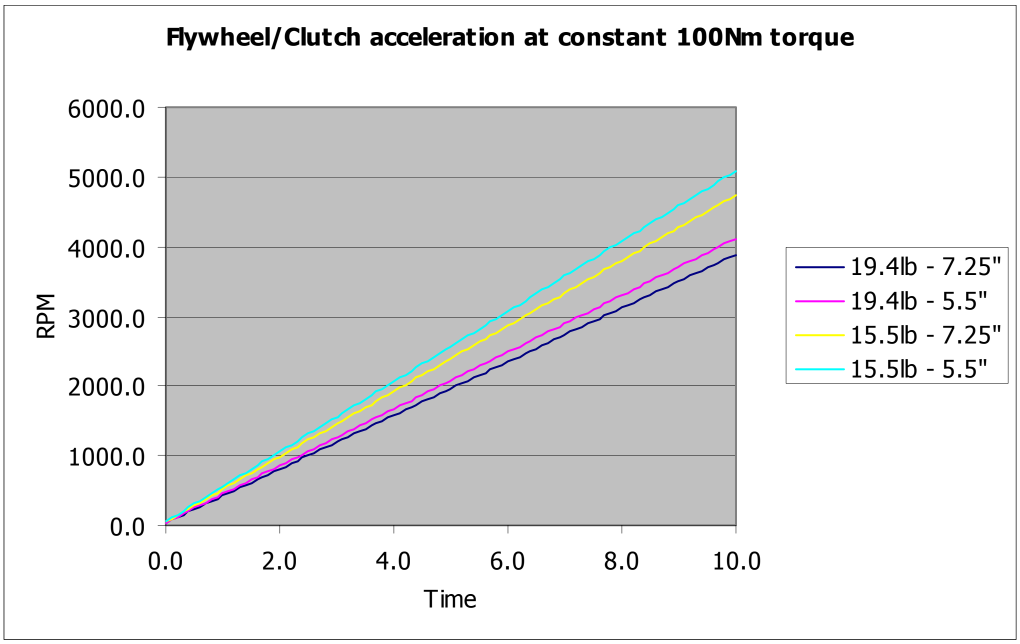
Item	OD mm	ID mm	Thickness mm	Effect on MMI	Volume m^3	Weight kg	MMI kg.m^2
Ring gear	286.0	256.0	9.7	1	0.0001	0.925	0.017
Main bulk	256.0	79.4	26.9	1	0.0013	9.373	0.084
Center ring	79.4	44.4	10.5	1	0.0000	0.269	0.000
Friction side cutout	108.3	79.4	9.1	-1	0.0000	-0.291	-0.001
Back cutout square	194.0	147.0	11.7	-1	-0.0001	-1.104	-0.008
Back cutout chamfer	147.0	106.4	11.7	-0.5	0.0000	-0.354	-0.001
Sum					0.0012	8.818	0.091

Repeating the calculation for the 15.5lb flywheel, we can come up with the two figures:

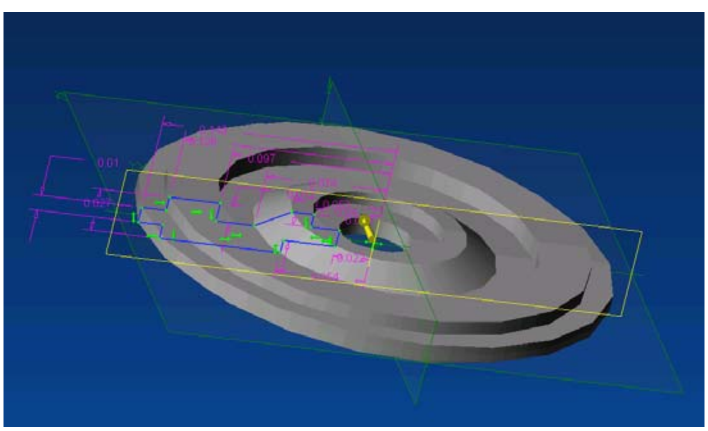
- 19.4lb flywheel
  MMI = 0.091 kg/m^2

- 15.5lb flywheel
  MMI = 0.073 kg/m^2

With the figures for clutch and flywheel combinations above, we can calculate the rotation speed of each possible flywheel/clutch assembly for a fixed torque of 100Nm (~74 foot-pounds), assuming no friction or other losses. The combined MMI is calculated simply by adding together the moments of inertia of the two parts – the clutch and flywheel.



From the graph we can see that there is a significant difference in acceleration between the light and heavy flywheels, but that the difference made by changing clutches is smaller.



Frankly, life is too short to be working out moments of inertia by hand, so we can fall back on some high-techery in the form of 3D-CAD, in this case Alibre Design Xpress.

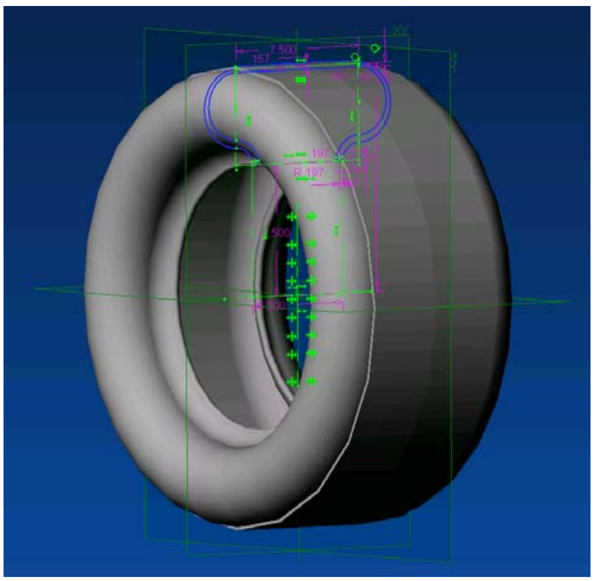
The same flywheel model described above was entered, and the tool used to calculate moment of inertia using the densities for the 15.5 and 19.4lb flywheels. Happily, the same answers were obtained.

Tires

Having calculated the beneficial effects of the lighter flywheel and smaller clutch, we now need to put these in context – to see how much of a difference it will make to real acceleration.

In order to do this, we still need to know the moment of inertia of the complete drivetrain. This remains rather complicated, so we will next consider the tires – on account of them being the largest and heaviest rotating objects attached to the car.

More simplified models can be built, for the front and rear tires. The pictures below show a Formula Ford rear tire – a 22.5″ x 7.5″ cantilever rear to be fitted to a 5.5″ wide 13″ diameter rim.

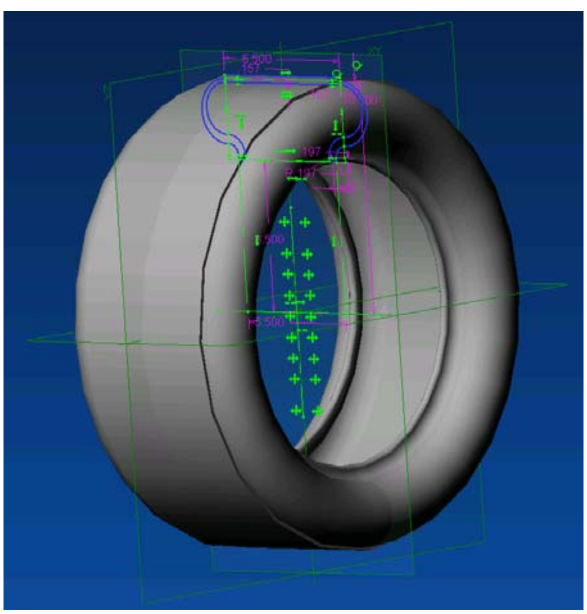


The CAD tool is first used to calculate the total volume of the tire model – in this case 0.00650m³. The weight quoted by Goodyear is 15.2 lbs (6.99kg). If we assume constant density, we can enter the density figure as 1061.166 kg/m³. The tool can then be used to calculate mass moment of inertia for the tire around the axis of rotation - 0.4354 kg.m².

The process can be repeated for a front tire, a 20.0 x 6.5 to be fitted to the same 5.5″ x 13″ rim, the tire weighing 8.5lbs (3.86 kg).

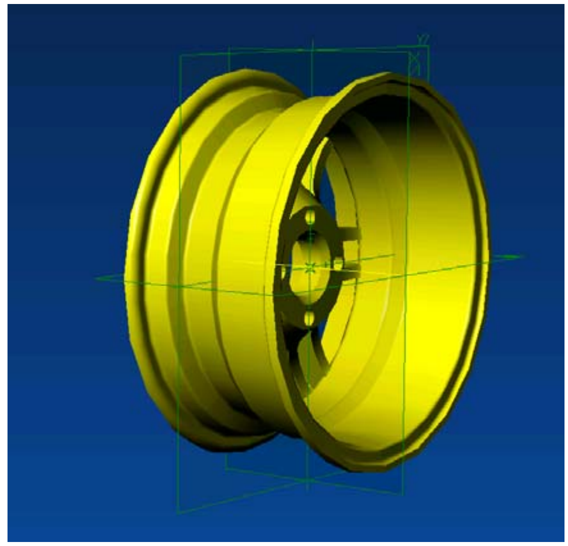
Volume is 0.00471m³, making the density 817.81 kg/m³.

The mass moment of inertia of the front tire is calculated to be 0.2026 kg.m².



Wheels

After the tires, the next largest set of rotating objects in the drivetrain must surely be the wheels. The car of interest is a modern Van Diemen, so a simplified model of one of the beautiful (but heavy) Van Diemen/O.Z. 12-spoke 5.5" x 13" wheels has been produced.



Using the same strategy as before, the volume was calculated to be $0.001910m^3$, which for an 8lb (3.63kg) wheel, would make the density 1899.6 kg/m^3.

The mass moment of inertia of an O.Z. 12-spoke wheel is calculated to be 0.0607 $kg.m^2$.

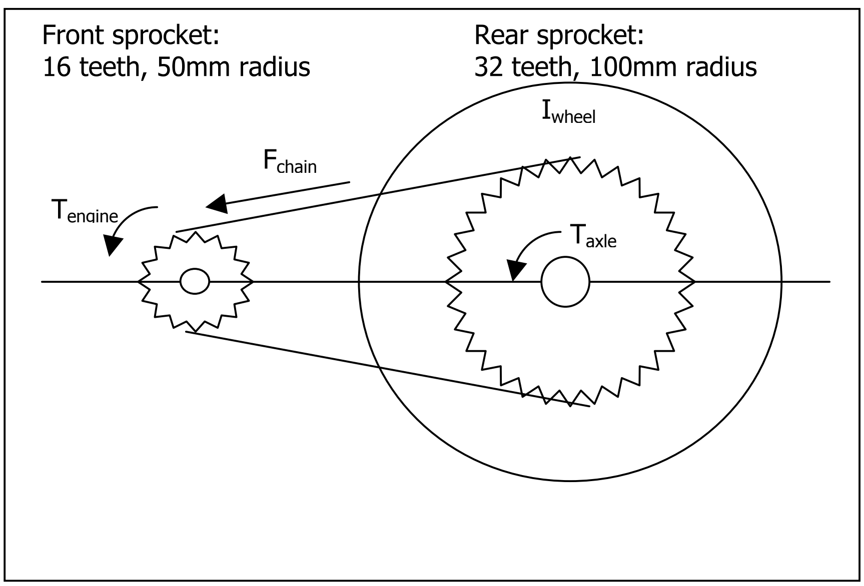
Inertia and gearing

The table below summarizes what we have learned so far about the inertia of various objects:

Item	Weight (kg)	Density (kg/m3)	MMI (kg.m2)
Flywheel - 19.4 lb	8.80	7463.7	0.0908
Flywheel - 15.5lb	7.03	5963.2	0.0725
QM 5.5" clutch	-	-	0.0130
QM 7.25" clutch	-	-	0.0061
Tilton 5.5" clutch	-	-	0.0066
Tilton 7.25" clutch	-	-	0.0160
Front Tire	3.86	817.8	0.2026
Rear Tire	6.89	1061.2	0.4354
OZ wheel	3.63	1899.6	0.0607

Now that we have some numbers for some major components of the drivetrain, it's time to start thinking about acceleration. This isn't going to be actual vehicle acceleration just yet – first we will work out free acceleration of the drivetrain, for which we need to consider the effect of gearing.

The combined effect of the gearbox and differential is to reduce the rotational speed of the engine to a lower speed at the wheels. The effect is also to multiply the torque provided by the engine to allow for acceleration. This can be visualized by thinking about a go-kart driveline.



The diagram shows a 16-tooth front sprocket and a 32-tooth rear sprocket.

For every turn of the front (engine) sprocket, the rear (axle) sprocket will go half a turn. Hence the gear ratio is 0.5.

If the engine supplies a torque of 100Nm, and the front sprocket has a radius of 50mm (0.05m), the force in the chain will be:

$$Force = \frac{Torque}{Dist} = \frac{100}{0.05} = 2000N$$

The radius of the rear sprocket can be found from the front sprocket radius and the gear ratio – The circumference of the rear sprocket is twice that of the front – as circumference $= 2\pi r$, a doubling of circumference can only come from a doubling of radius – from 50mm to 100mm.

Since the force in the chain will be the same at both sprockets, the torque at the rear axle will be:

$$Torque = Force \times Dist = 2000 \times 0.1 = 200Nm$$

Or we could say:

$$T_{axle} = \frac{T_{engine}}{GearRatio} = 100 \times \frac{32}{16} = 200Nm$$

Now we are able to work out acceleration of the rear wheel– for which we will assume that the rear wheels are the only part of the system with any inertia – in this case I_{wheels}.

Using the equation for rotational acceleration, we can work out the acceleration α at the axle by using the torque at the axle and the mass moment of inertia of the wheel:

$\alpha_{axle} = \frac{T_{axle}}{I_{wheels}}$ and then move on to the acceleration at the engine $\alpha_{engine} = \frac{\alpha_{axle}}{GearRatio}$

Substituting some of the equations above, we can get the acceleration at the engine in terms of engine torque, the moment of inertia of the wheel and the gear ratio.

$$\alpha_{engine} = \frac{\alpha_{axle}}{GearRatio} = \frac{T_{axle}}{I_{wheels} \times GearRatio} = \frac{T_{engine}}{I_{wheels} \times GearRatio^2}$$

Which is all well and good, but what happens when we want to consider inertia of some object connected to the engine – a flywheel or clutch for example, or even the engine itself? It would be necessary to consider different accelerations and torques for different objects based on the gear ratio.

Life can be made easier by considering together all the moments of inertia in the system as they appear to the engine. We can then simply sum all the inertia figures to get the total inertia as seen by the engine – which will change as the gear ratio changes. The moment of inertia seen at the engine of a system with a clutch, flywheel and wheels connected via a gearbox, would then be as follows:

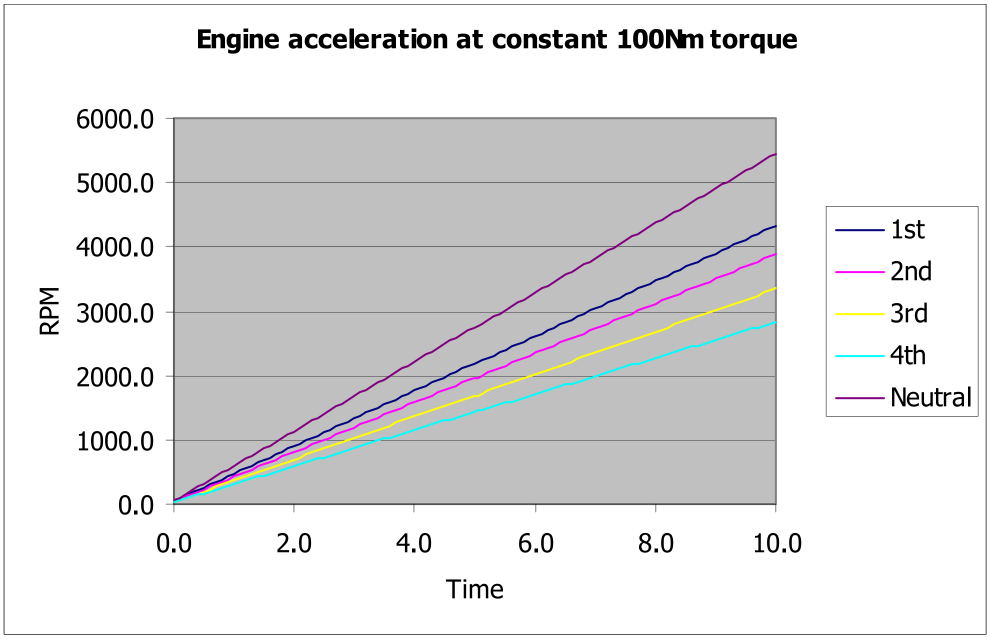
$$I_{drivetrain} = I_{clutch} + I_{flywheel} + \left(I_{wheels} \times GearRatio^2\right)$$

Sample Formula Ford gears are shown in the table below, along with the calculated total mass moment of inertia of the drivetrain in each gear.

			Ratio	Overall
Diff	10	31	0.323	-
First	16	34	0.471	0.152
Second	17	29	0.586	0.189
Third	22	30	0.733	0.237
Fourth	24	27	0.889	0.287

Clutch/Flywheel	Wheels/Tires	Total kg.m2
0.0885	0.0229	0.1114
0.0885	0.0355	0.1240
0.0885	0.0555	0.1440
0.0885	0.0816	0.1701

The table assumes the 15.5lb flywheel with the Tilton 7.25” clutch, and a pair of OZ wheels and rear tires. Notice how the effect of the wheels becomes more pronounced in higher gears. Also note that despite the rear wheels and tires having a much higher MMI than the flywheel, the effect of gearing gives the flywheel a large influence on the overall figure.



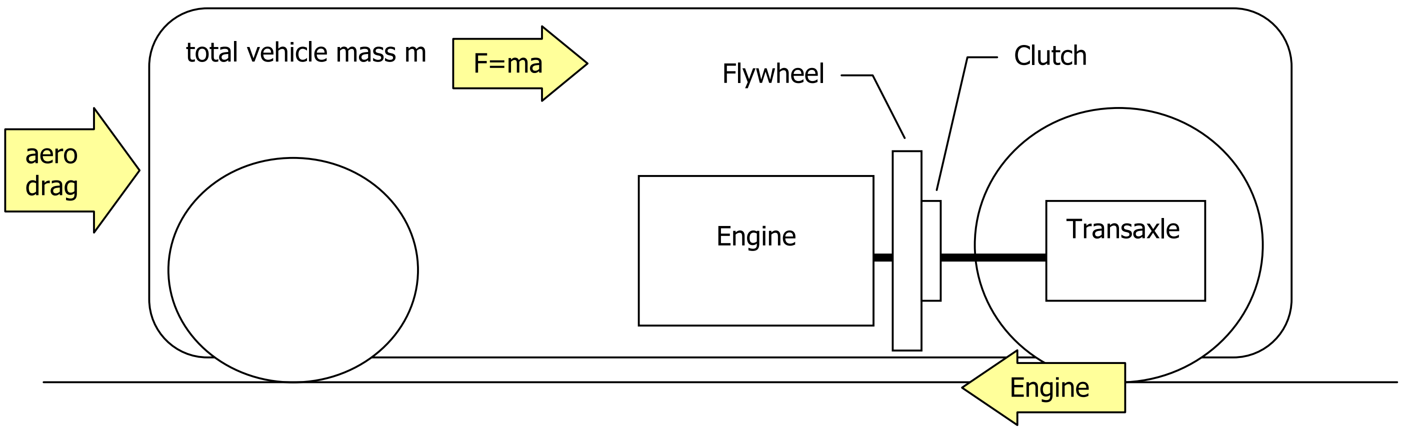
The chart shows free acceleration of the drivetrain in each gear, for a constant 100Nm torque.

Straight-line acceleration

To be a useful vehicle, the car needs to move along rather than just spinning its wheels in the air – so next we must consider straight-line acceleration.

Once the car is a moving object we need to consider more forces – the force required to accelerate the mass of the vehicle in a straight line, and aerodynamic drag. These must be considered along with the inertia of the drivetrain, and the various torques and forces resolved into a single figure for acceleration.

We can also throw in the complication that the engine power output varies with rotational speed (i.e. RPM) – and hence with the gear ratio and the size of the driven wheel.



Vehicle mass

All the forces in the system can be resolved to torques at the crankshaft. The force required to accelerate the mass of the vehicle can be converted to a torque at the rear axle by using the radius r of the driven wheel, then to a torque at the crank by factoring in the gear ratio.

$$T_{linear} = F \times Dist \times GearRatio = m \times a \times r \times GearRatio$$

However, this is not all that helpful since we would like to calculate the a single value for acceleration of the vehicle based on the known torque of the engine – and not have to deal with separate figures for linear acceleration of the vehicle and rotational acceleration of the engine.

So we can cheat a little by making the mass of the car appear to be yet another inertia figure at the crankshaft.

Just considering the torque at the axle first of all:

$T_{axle} = F \times Dist = m \times a \times r$ and it is also moment of inertia times rotational acceleration

$T_{axle} = m \times a \times r = I \times \alpha$, and we can say that the rotational acceleration of the axle will be related to linear acceleration of the vehicle based on the radius of the tire, so

$\alpha = \dfrac{a}{r}$ and as a result this can be substituted into the above equation to get

$$m \times a \times r = I \times \alpha$$

$$m \times a \times r = I \times \frac{a}{r}$$

$$m \times r = \frac{I}{r}$$

$$I = m \times r^2$$

Considering the effect of the gear ratio we then get $I_{linear} = m \times r^2 \times GearRatio^2$

For a 500kg (1100lb) Formula Ford with a 0.286m radius rear tire (22.5" diameter), in first gear (0.152) the result would be:

$I_{linear} = 500 \times 0.286^2 \times 0.152^2 = 0.944$ kg.m^2

Which is around an order of magnitude larger than the mass moment of inertia of the clutch, flywheel and road wheels combined.

Note that the rotating parts of the vehicle, such as the wheels, are included twice:

- Once for being accelerated in a straight line
- Once for being made to spin

Aerodynamic drag

The aerodynamic drag on the vehicle is dependent on the square of speed (v), the frontal area (A) and coefficent of drag (C_d), and the air density (greek letter rho - ρ).

$$F_{drag} = \frac{1}{2}\rho v^2 C_d A$$

For a modern Formula Ford, a figure for C_d.A of around 0.4 - 0.5 would be reasonable.

This can be considered as a force acting on the body of the vehicle, or converted to a torque seen at the engine. It is useful to consider as a torque at the engine, since it can be used to calculate the net torque available from the engine:

$$T_{drag} = F_{drag} \times r \times GearRatio \qquad \text{and} \qquad T_{net} = T_{engine} - T_{drag}$$

Now it is possible to calculate rotational acceleration at the crankshaft as the car accelerates, including:

- Inertia of the engine, flywheel and clutch (I_{engine})
- Inertia of the drivetrain, transaxle, rear wheels and tires ($I_{drivetrain}$)
- Inertia of the front wheels and tires (I_{front})

For any given vehicle speed, the rotational acceleration of the crankshaft at the engine would be:

$$\alpha_{engine} = \frac{Torque}{Inertia} = \frac{T_{engine} - T_{drag}}{I_{engine} + \left(\left(I_{front} + I_{drivetrain} + mr^2\right) \times GearRatio^2\right)}$$

We can convert rotational acceleration at the crankshaft to linear acceleration of the vehicle by using the gear ratio and the radius of the driven wheel, to give:

$$a_{vehicle} = \alpha_{engine} \times r \times GearRatio$$

With the formula for acceleration at any given speed in place, we now need to know the engine torque at that same speed.

Engine Power and Torque

Torque and Power and related by the following formula:

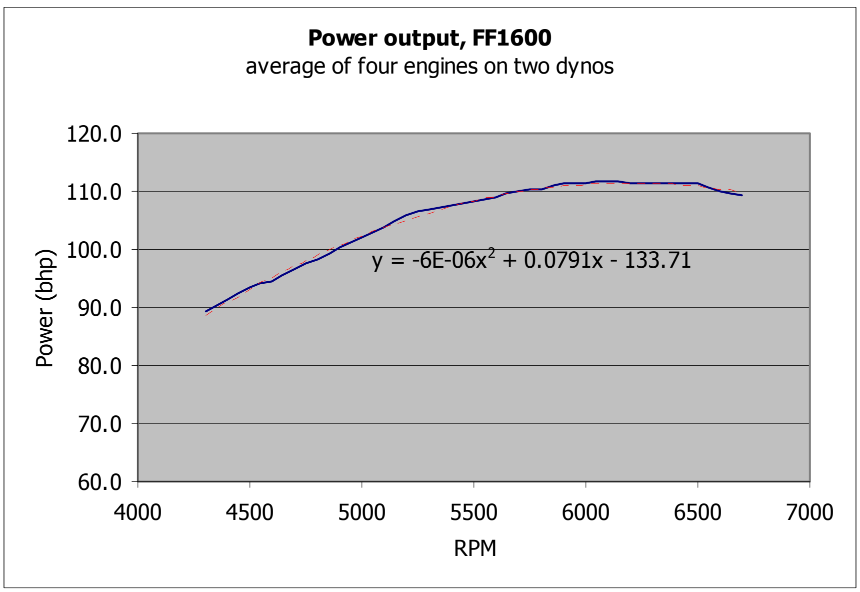
$$Power = Torque \times AngularSpeed = T.\omega$$

Where torque is in Newton-meters (Nm), angular speed (Greek letter omega) in radians/sec (rad/s), and power in Watts.

For automotive purposes in the USA, the various conversion factors can be use to say that:

$$Power = \frac{Torque \times RPM}{5252}$$ where power is in horsepower, and torque in foot-pounds (lbf.ft)

Since we can discover the engine torque directly from the power curve, it is useful to have an equation for that power curve.



The chart shows a power curve obtained by averaging the dyno data from four different Formula Ford 1600 engines, from two different engine builders.

A handy feature of Microsoft Excel can be used to add a trendline to the chart – in this case a second-order polynomial. From this we can discover an equation that can be used to re-create the power curve using from the RPM. This is also useful as a math channel for data logging.

For the average of the four engines used, the formula for Power (hp) would be:

$$Power = -6.3871 \times 10^{-6} \times RPM^2 + 0.079143 \times RPM - 133.71$$

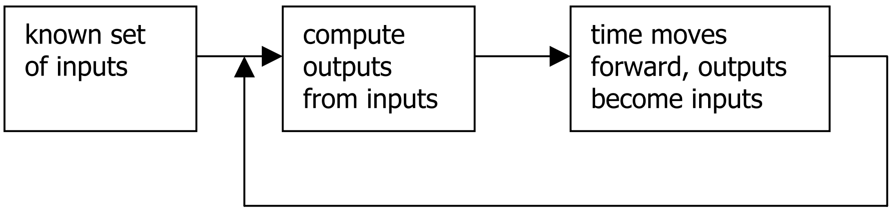
To match reality, the power output should be scaled to take account of losses in the gearbox and transmission – conventional wisdom says that the gearbox can suck up 10%-20% of the engine power output.

By using conversion factors from horsepower to Watts (1 hp = 745.699872 Watts) and from RPM to radians/sec (1 rpm = $\frac{2\pi}{60}$ rad/sec), we can readily calculate the available torque for any given angular speed.

At this point, we would be able to construct a large equation for acceleration at any given speed, if the gear ratio was fixed – and hence the RPM of the engine directly related to engine speed. Since the driver will be making gear changes, everything suddenly gets all non-linear. In order to move forward, the next step is to create a stepwise simulation of acceleration.

Stepwise simulation

The stepwise approach is a simple but powerful technique for simulating complex systems. It allows complicated systems to be broken down into manageable chunks, allows for feedback, and allows non-linearities to be introduced.



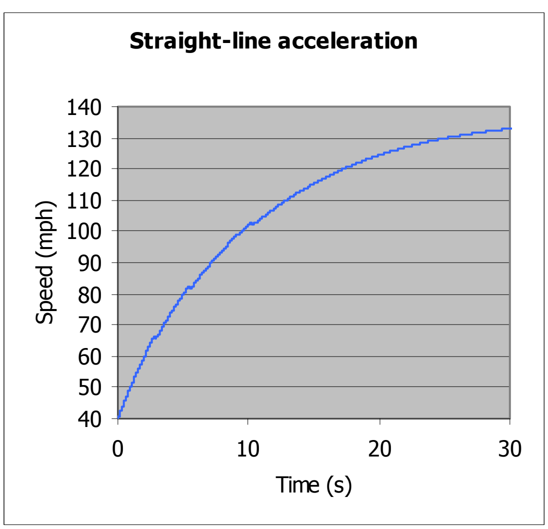
For a simulation over a fixed period of time, that time is broken down into small chunks, known as steps or deltas. The big assumption is that the state of the system at the end of one step can be computed by the inputs at the beginning.

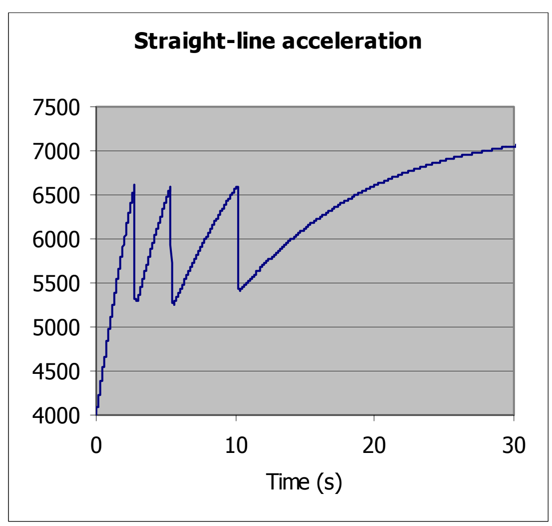
This technique allows gearshifts to be simulated – if the RPM passes a given shift point, the next gear will be selected. Furthermore, the engine power output can be cut for a fixed time to model the effect of the time that the car is out of gear.

In the case of straight-line acceleration, we can do the following

Inputs	Calculations	From
Speed	Speed at end of step	Starting speed, calculated linear acceleration
Gear	Gear at end of step	Upshift when RPM passes shift point
Throttle position	Throttle position	Time passed since last upshift

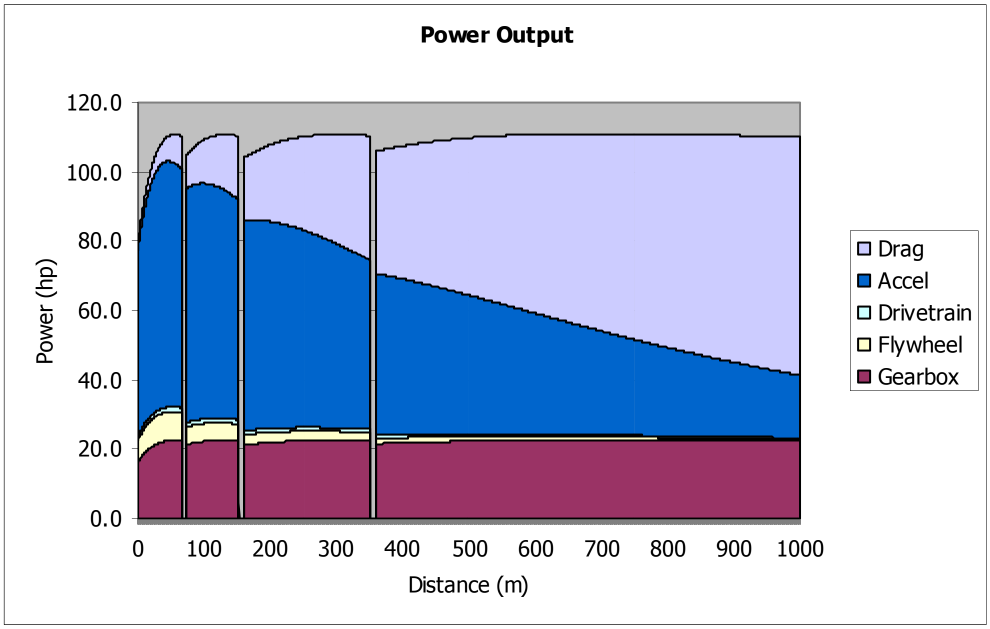
Putting everything together, we can produce a spreadsheet to calculate straight-line acceleration over time for a given set of inputs – the graphs below show speed and RPM.





Where does all the energy go?

The chart below shows engine power output from a Formula Ford 1600 during straight-line acceleration – and how that power is consumed.



The engine power is consumed by:

- Linear acceleration of the vehicle mass – the desired result
- Aerodynamic drag – moving the air out of the way as the vehicle passes.
- Gearbox – friction between gears, bearing drag, heating up the oil, gears, case etc
- Rotational acceleration of the mass moment of inertia of the engine, clutch and flywheel
- Rotational acceleration of the drivetrain mass moment of inertia (gearbox, wheels, tires, driveshafts etc)

Each area in the chart is a direct measure of energy. Power multiplied by distance is 'Work' – which is a measure of energy, measured in Joules. Clearly the energy spent accelerating the engine flywheel is significant – particularly in the lower gears, but not nearly of the same order as the energy spent fighting drag and overcoming losses in the transmission.

Note that a flat figure of 80% has been used for transmission efficiency, however it is not clear how accurate this figure is, or even how the figure might vary - with road speed and load for example.

The effect of the wheels and tires is not as great as might have been expected – the effect of the gear ratio being that the flywheel is asked to both rotate faster and accelerate faster than the wheels and tires. Since the power consumed overcoming rotational inertia is proportional to both angular speed and angular acceleration, the flywheel takes a lot more power than all four wheels and tires combined.

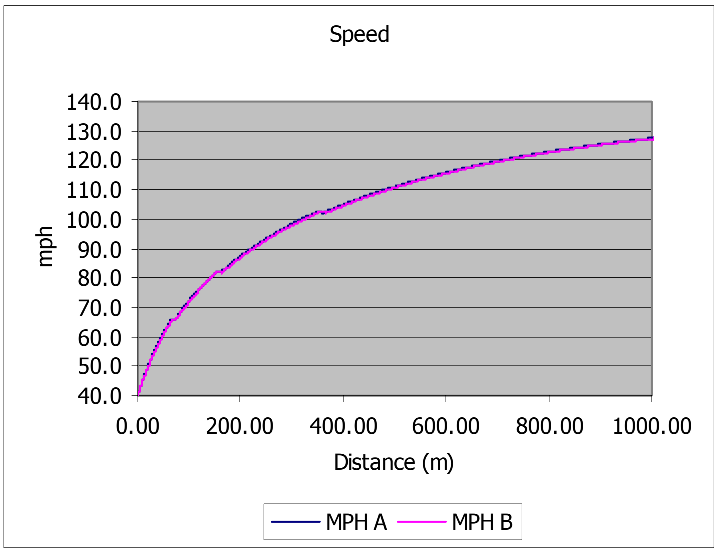
Comparisons of straight-line acceleration

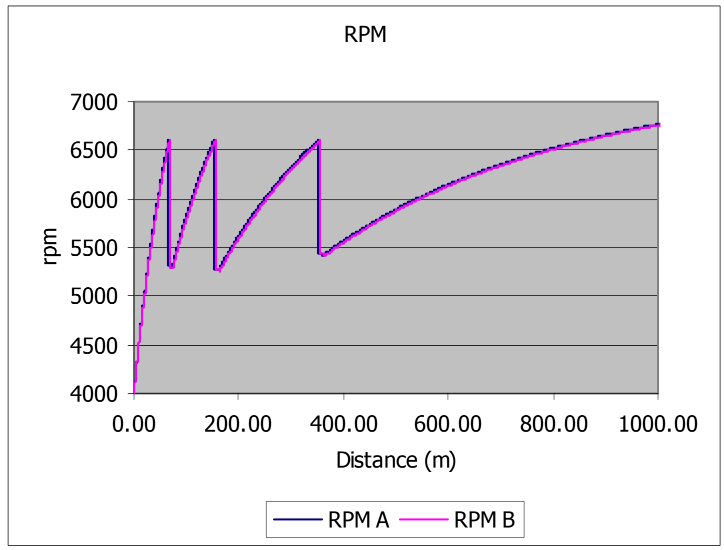
With a straight-line acceleration model in place, it is possible to start making comparisons, given all the assumptions accumulated so far.

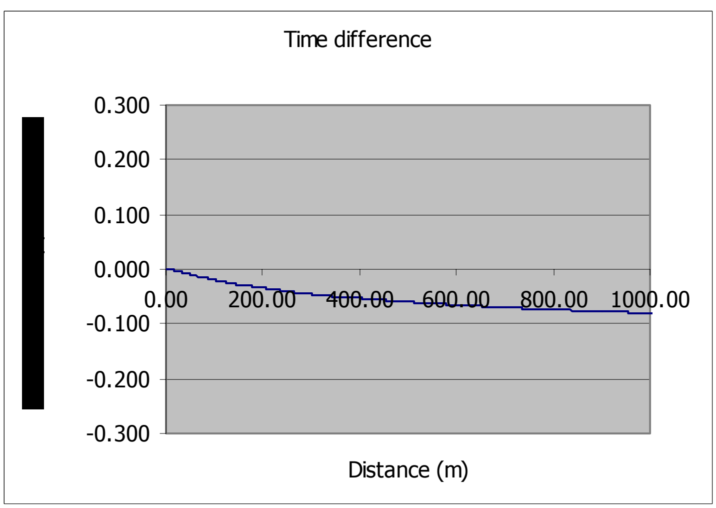
The charts below show two scenarios:

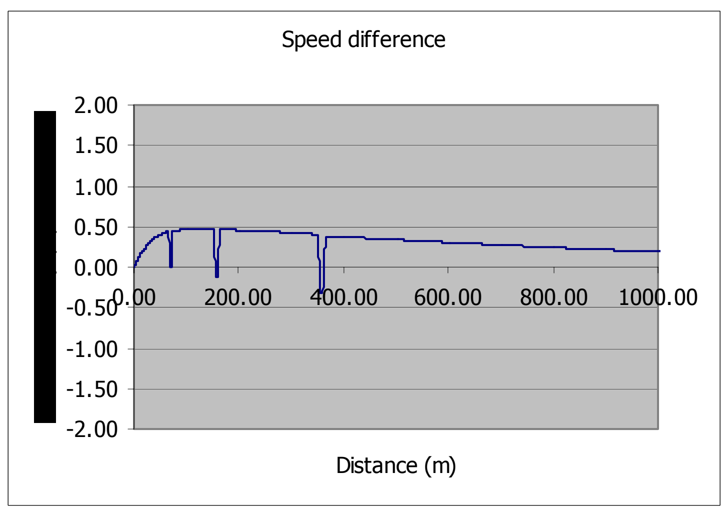
- A: Lowest MMI flywheel/clutch combo, two front tires, two rear tires, four OZ wheels - 15.5lb flywheel, Tilton 5.5" clutch
- B: Highest MMI flywheel/clutch combo, two front tires, two rear tires, four OZ wheels - 19.4lb flywheel, Quartermaster 7.25" clutch

Note that inertia of the remainder of the engine and drivetrain is not considered in the calculation. This would include crankshaft, gearbox, differential, driveshafts, hubs, brake discs etc.





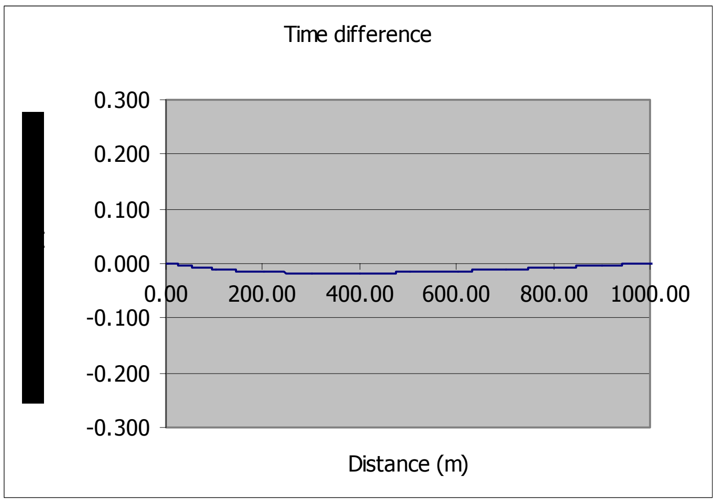


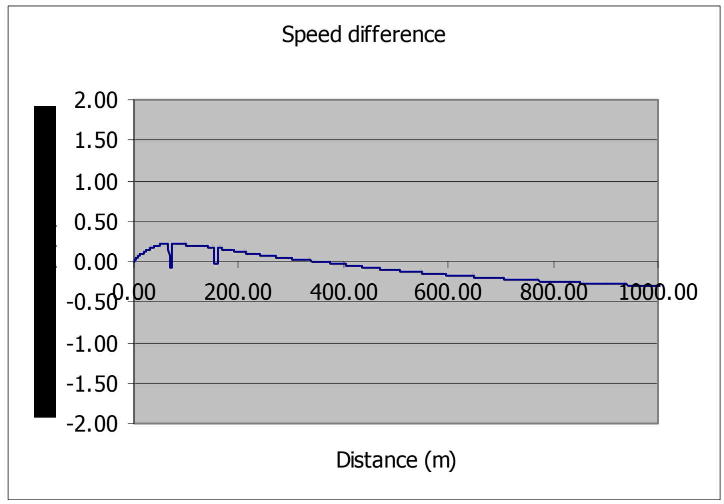


Clearly there is not a huge difference in speed or elapsed time, and the differences show themselves at low speed. Note that despite drag eroding the 0.5 mph increase in speed at the beginning of the run, the very fact that a slightly higher speed is maintained benefits the time difference until the end of the run at 1000m.

After 1000m of straight-line acceleration from 40mph, the car with the lighter flywheel and clutch is ahead by 0.08s.

In order to make up the time difference at 1000m, the engine curve must be scaled to give an additional 1.3hp at the peak of the curve. More power results eventually in higher speeds, thus making up for the better slow-speed acceleration of the car with less inertia. This is shown in the graphs below.





To make up the time difference at 500m, an additional 1.7hp would be required.

If a comparison is made between the Tilton 7.5” and 5.5” clutches on a car with a 15.5lb flywheel, the difference is 0.02s after 1000m of acceleration from 40mph.