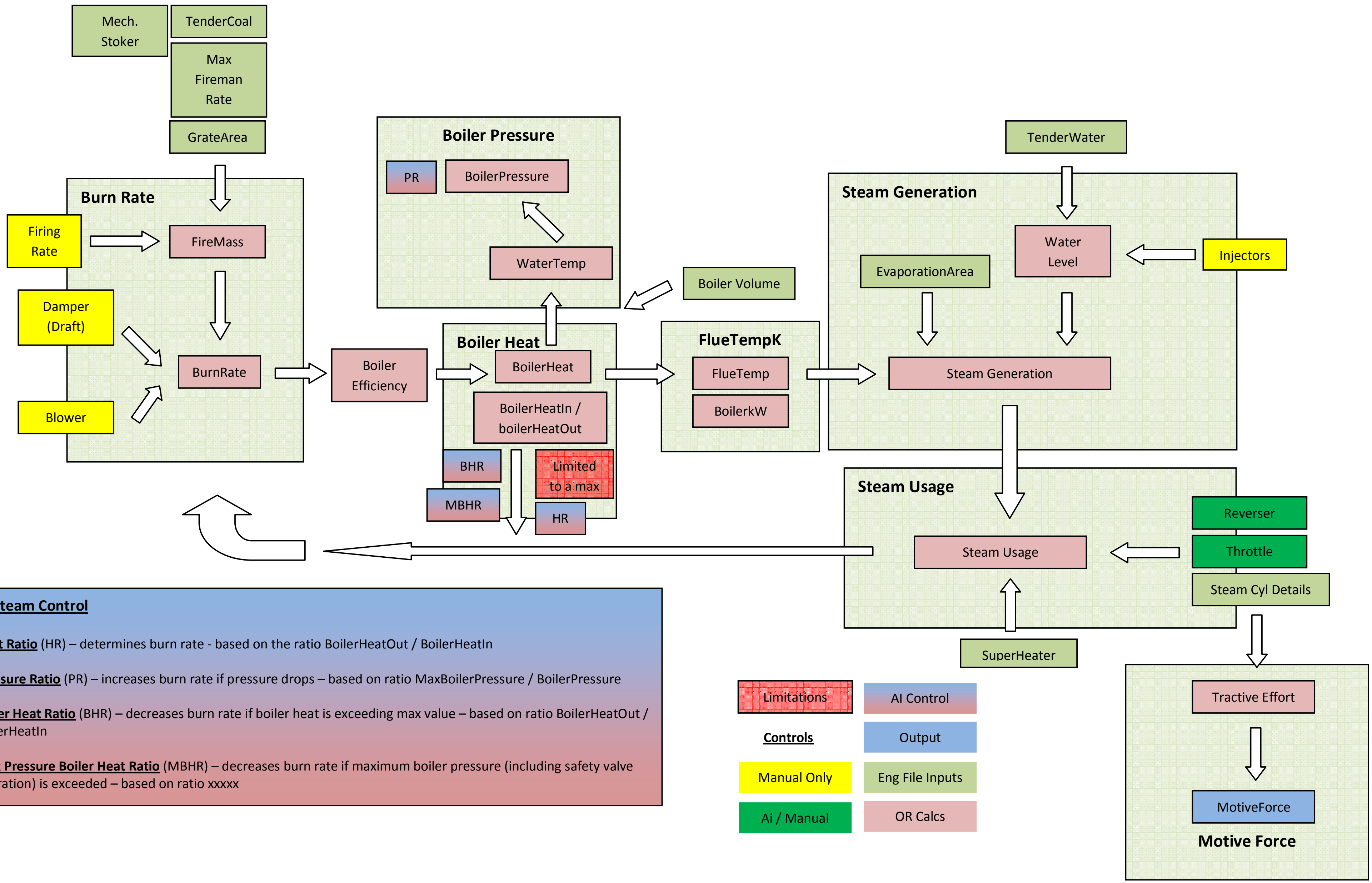
Open Rails

Steam Locomotive Steam Heat Model

Peter Newell
12/8/2013

Steam Locomotive – Heat Model - Overall



AI Steam Control

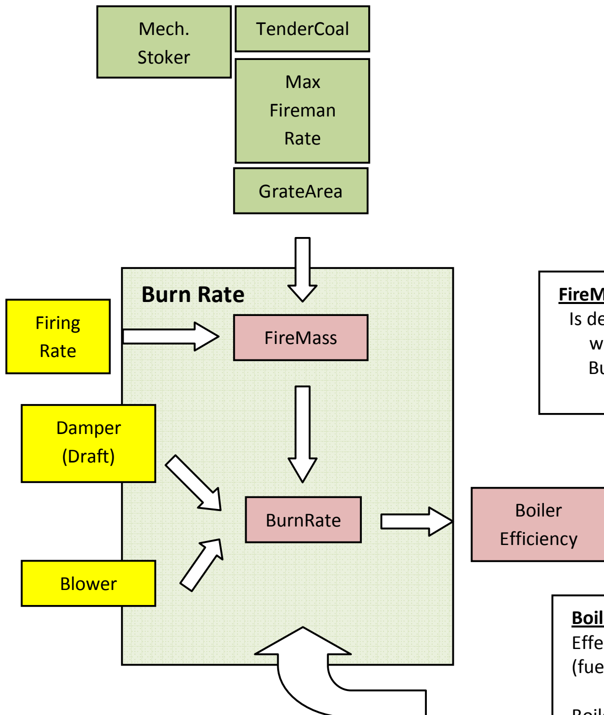
Heat Ratio (HR) – determines burn rate - based on the ratio BoilerHeatOut / BoilerHeatIn

Pressure Ratio (PR) – increases burn rate if pressure drops – based on ratio MaxBoilerPressure / BoilerPressure

Boiler Heat Ratio (BHR) – decreases burn rate if boiler heat is exceeding max value – based on ratio BoilerHeatOut / BoilerHeatIn

Max Pressure Boiler Heat Ratio (MBHR) – decreases burn rate if maximum boiler pressure (including safety valve operation) is exceeded – based on ratio xxxxx

Steam Locomotive – Heat Model – Burn Rate Module



FireMass
Is dependent upon the amount of coal burnt and the coal feed rate. The firemass typically will be maintained around the ideal fire mass, which is determined by the grate area. Burning coal beyond the ability of the fireman to feed the fire will result in decreased firemass.

BurnRate
Is determined by a table relating steam consumption to lbs of coal burnt. The GrateLimit will impact upon the ability of the fire to produce heat (and steam) energy.

Boiler Efficiency
Effectively describes the relationship between the amount of heat inputted into the boiler (fuel burnt) versus the effective heat produced by the boiler (steam generation).

Boiler efficiency depends on the design on boiler and firebox, the type of fuel, and the draughting system. In the case of coal-fired boilers, boiler efficiency declines linearly with rate of fuel feed.

BurnRate Limitation

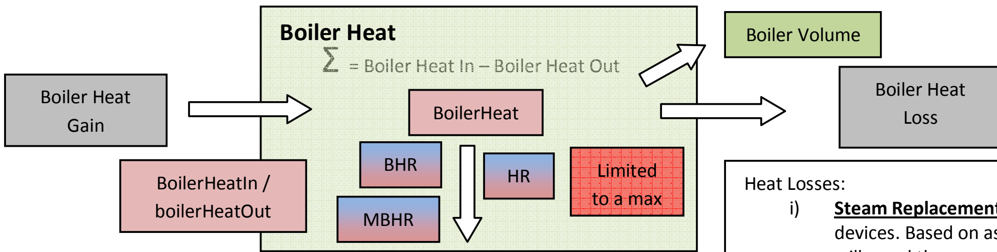
i) Can't exceed fuel firing rate indefinitely
ii) Exceeding the GrateLimit will reduce ability of fire to produce heat (modelled through the use of Boiler Efficiency)

Steam Locomotive – Heat Model – Boiler Heat Module

AI Steam Control

Boiler Heat Ratio (BHR) – decreases burn rate if boiler heat is exceeding max value – based on ratio BoilerHeatOut / BoilerHeatIn

Max Pressure Boiler Heat Ratio (MBHR) – decreases burn rate if maximum boiler pressure (including safety valve operation) is exceeded – based on ratio xxxxx



AI Steam Control

Heat Ratio (HR) – determines burn rate - based on the ratio BoilerHeatOut / BoilerHeatIn

Pressure Ratio (PR) – increases burn rate if pressure drops – based on ratio MaxBoilerPressure / BoilerPressure

Heat Gain:

Fuel Burn - Heat generated by the burning of the fuel

Heat In = Fuel Burnt = Fuel Burnt x Fuel Calorific x Boiler Efficiency / (Specific Heat Fuel x Fire Mass)

Heat Losses:

i) **Steam Replacement** - Heat required to replace steam used by the cylinders and other steam devices. Based on assuming that water mass heat remains the same, then assume heat "lost" will equal the amount of heat needed to raise temp from current boiler water temp to current boiler steam heat, for the amount of steam used. Water mass heat will change when water replacement occurs.

Heat "out" = Steam Used x (Boiler Steam Heat – Boiler Water Heat)

ii) **Water Replacement** - Heat required to heat replacement water coming into boiler from injectors. This will be the amount of water times the heat required to rise temp from injector water temp to boiler water temp

Heat "out" = Water Input x (Boiler Water Heat – Injector Water Heat)

See Injector model

Injector Types Modelled (Based on Sellers Injectors)

Live Steam Type – use live steam from the boiler for water propulsion, feedwater is feed into the injector at ambient temperature (65F) and steam is then used to "push" water into the boiler, typically water will be delivered into the boiler at a temperature of up to 269F.

- Delivery water temp – max 269F – assume heat loss differential (Boiler Heat BTU)
- Small boiler steam usage – small increase required in heating to compensate – based on steam to water rates?

Exhaust Steam Type – in this type exhaust steam is used to heat the feedwater, as well as provide the propulsion for injecting water into the boiler. This returns some heat to the boiler that otherwise would be vented, typically water will be delivered into the boiler at a temperature of up to 300F.

Advantages of exhaust injectors –

- Delivery water temp higher than above – assume 40F linear increase on above model
- Reduce steam loss from boiler as waste steam returned to the boiler – use rates to determine steam return (reduced boiler mass loss)
- Reduces cylinder backpressure (by about 10%) ? how to model

Example Locomotive States

State 1 - Steady State

Locomotive is at rest, with a full boiler, and @ operating boiler pressure - as an example, and using the steam tables, a saturated locomotive with 160psi would have the following temp. Water - 371F, Input water heat (water delivery temP) - 200F

In this state BoilerHeatIn (heat generation by coal burning) = BoilerHeatOut (heat to be replaced = 0

State 2 - Steam Usage (through cylinders), but no water input

In this state, to maintain heat balance, the heat input required would only be that necessary to generate replacement steam. Given that no water is being added to the boiler, and that the water in the boiler is @ 371F already, the only heat required to bring us back to the "steady state" condition, is that necessary to heat the water to create steam, ie it is necessary to increase heat from 344 BTU/lb to 1196 BTU/lb. Thus for example if the loco is using 10,000 lb/h of steam. This is a heat reduction that needs to be balanced by a heat "input".

Replacement Steam (Heat Input required) = 10,000 (Steam heat - water heat)

State 3 - Loco stationary, but injecting water into the boiler.

In this state, the water temp in the boiler is 371F, but we are adding water at a temp of say, 200F, thus we need to add sufficient heat to the boiler to heat the water from 200 to 371F, and return it to the steady state condition. Thus for example if the loco is injecting 5,000 lb/h of water. This is a heat reduction that needs to be balanced by a heat "input".

Water Heating (Heat Input required) = 5,000 (Water heat - input water heat)

State 4 - Loco in motion and injecting water

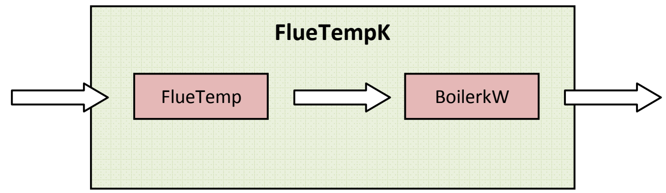
In this state, the locomotive is using steam and injecting water, and therefore it would be a combination of state 2 & 3, to maintain steady state.

BoilerHeat Limitation

A boiler is only capable of holding a certain amount of heat; this will be determined by the volume of the boiler and the boiler operating pressure. Once this boiler heat value is exceeded, the boiler will start exhaust steam through the safety valve in an effort to reduce the heat value.

Typically the locomotive boiler works on the principle of "heat transfer", ie heat put into the boiler is used by the cylinders straight away and therefore the boiler heat value should normally not be exceeded.

Steam Locomotive – Heat Model – FlueTemp Module



FlueTempK is determined by summing the change in Boiler Heat (ie BoilerHeatIn – BoilerHeatOut).

FlueTempK = ΔBoilerHeat / Boiler Evaporation Area

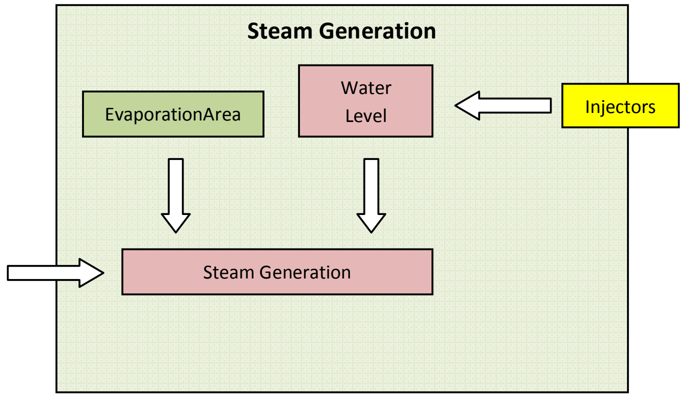
FlueTempK is currently not limited, and will continue to rise until a maximum figure; according to the change in boiler heat is reached.

BoilekW is principally determined by the FlueTemp.

BoilerkW = FlueTemp * Evaporation Area

BoilerkW is currently not limited, and will continue to rise until a maximum figure; according to the FlueTemp.

Steam Locomotive – Heat Model – Steam Generation Module



SteamGeneration (EvaporationLbpS) is principally determined by the BoilerkW, and is a conversion of kW into LbpS of steam generation.

Evaporation = BoilerkW (converted to lbps)

Steam Generation Limitation
A boiler relies on heat transfers, and is only capable of producing a finite amount of steam output.
Some of these limitations include:

i) Max Steam Generation – typically approx. 15 x Evaporation Area (this is not a hard limit – see text box to right)
ii) Max Steam Usage – can exceed generation for short periods of time – time will be dependent upon the boiler volume, and subsequent heat loss, and water mass loss (ie can the injectors keep up with the load). It is not limited; however steam generation should be limited to maximum evaporation rate.

Steam Generation

The steam generation value is an "indicative" number only, and it therefore is not a hard limit for the maximum output of the boiler. It is possible to exceed the steam generation figure under certain circumstances for short periods of time. The figure is an average value over the hour.

It appears that the following factors will limit the steam generation output –

Injector Limit - the amount of steam that can be produced will be limited by the amount of water that can be injected into the boiler. Undersized injectors would limit steam generation rate.

Discharge Limit - this appears to be related to the exhaust blast limit and the draft rate.

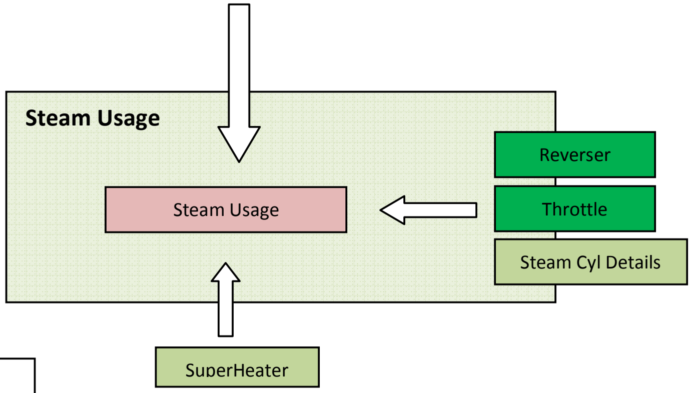
Grate Limit - This appears to be reached when the amount of coal being combusted reaches approx 140-150 lbs/SQFT Grate Area. Trying to burn any additional coal will not produce anymore heat.

Firing Rate - the rate at which a fireman can feed the fire will determine how much heat energy can be "injected" into the boiler. The use of mechanical stokers have overcome this issue, provided the grate area was large enough to support it.

Evaporation Area - will determine how efficient heat energy can be transferred into the boiler.

Fuel calorific - fuels with lower fuel calorific values will produce less heat per SqFt Grate Area, and consequently it also acts as a limit to steam generation.

Steam Locomotive – Heat Model – Steam Usage Module



Cylinder Efficiency
The efficiency of the steam cylinder operation will be different depending upon whether the locomotive is a saturated or superheated steam unit.

Saturated - When steam is injected into the cylinder, it comes into contact with the cylinder wall and some of the steam is condensed as water vapour. This means that extra steam is required to maintain sufficient pressure to drive the cylinder, and consequently causes higher steam consumption and fuel rates to be recorded.

Superheated – Superheated steam has a lot more heat energy in it then saturated steam, and consequently it is less likely to condense when it comes into contact with the cylinder wall (heats the wall up). It also has a higher volume and consequently less steam mass (lbs) are required to do the same amount of work in the cylinder. Consequently this makes the locomotive more efficient, with less steam and fuel consumption compared to a saturated locomotive.

Steam Usage – is approx. equal to the volume of the cylinder at cutoff x exhaust pressure. There is additional usage due to condensation of the cylinder. A certain amount of steam is left in the cylinder after compression, and this can be calculated by the volume space in the cylinder clearance (x2) and using a final compression pressure approx. equal to that of the initial pressure.

Saturated
Saturated locomotives will use more steam due to losses through condensation. This will vary depending upon the cutoff value; typically condensation will be greater at longer values of cutoff.

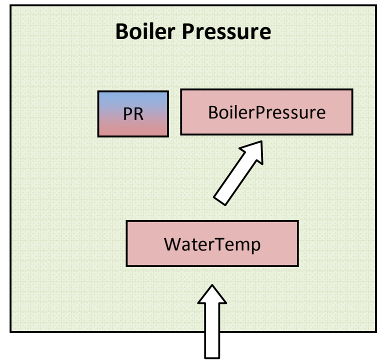
Typically condensation may increase steam consumption by up to 20% more, depending upon the level of cutoff.

Superheater
The superheater relies on the following components:

i) Calculation of superheat steam temp
ii) Determining the value of steam heat that is required to prevent cylinder condensation
iii) Calculating current steam heat temp and steam volume increase over saturated steam
iv) Reducing steam usage depending upon the steam volume increase calculated in iii)

Typically superheating will reduce steam consumption by up to 40%, depending upon the level of superheating.

Steam Locomotive – Heat Model – Boiler Pressure



Locomotive pressures

To understand the operation of a locomotive, and its capability to do work, it is useful to understand the different pressure measurements, as these represent available forces. The following pressure measurements represent the force capability available at different stages of the steam cycle.

Boiler Pressure – pressure in the boiler, and represents the maximum available pressure to be provided to the cylinders.

Steam Chest Pressure – pressure in the steam chest on the input side of the cylinders, and represents the maximum steam pressure to the cylinders. Typically this would normally be the same as the boiler pressure.

Initial Pressure – is the pressure that is actually applied to the cylinder piston and will be less than the boiler and steam chest pressures due to losses through the steam pipes and openings.

Mean Effective Pressure (MEP) – represents the "mean" pressure available to drive the piston in the cylinder. Typically this pressure is the one that is used for relevant tractive effort and horsepower calculations.

The MEP also decreases with the increase in locomotive speed; this is due to the influence of the valve gear.

Back Pressure – is the pressure that is generated by the resistance to exhausting the steam form the cylinder. Typically it is desired to keep this as low as possible.

MEP = Pressure into Cylinder – Back Pressure

Steam Locomotive – Heat Model – Motive Force Module

Tractive Effort (Motive Force)
The power needed to turn the wheels of the locomotive is known as the tractive effort.

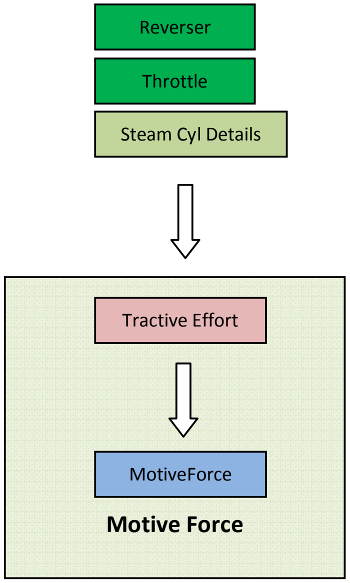
$$TE = (CylDiam^2 \times MEP \times CylStroke) / DrvWheelDia$$

To accurately calculate the TE, it is necessary to calculate the MEP, as this will vary with cylinder cutoff.

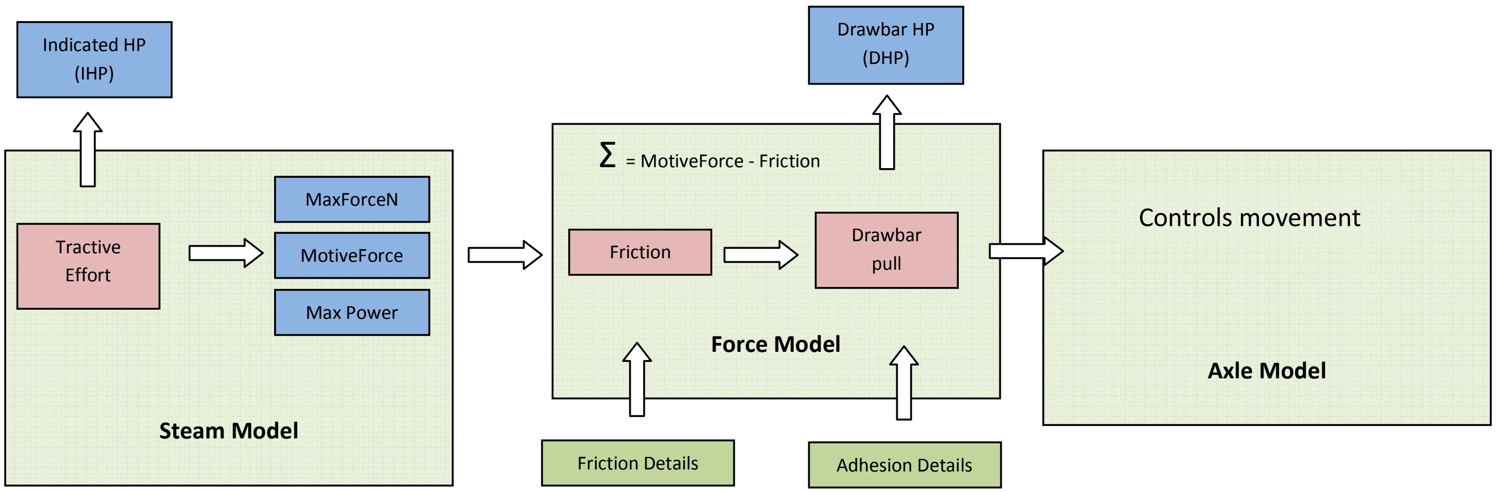
Mean Effective Pressure (MEP)
The mean effective pressure is mean value of the pressure applied within the cylinder and provides a measure of the work done in the cylinder by the steam.

Several pressure drops occur during the journey of the steam to the cylinder from the boiler, and these impact the final value of MEP:

i) Drop between boiler and cylinder steam chest – speed dependent
ii) Drop going through steam chest port into steam cylinder – speed dependent (also called "wire-drawing", and is caused by opening and closing of the valves.
iii) Cylinder condensation – causes both a pressure drop as well as increased steam usage rate.



Steam Locomotive – Steam Model – Outputs



MaxForceN - it is the maximal force allowed - the MotiveForceN is limitted to this value. (Based upon Starting TE)
MaxPowerW - is used to limit MotiveForceN (Based upon Max IHP)
MotiveForceN - it is the main pulling (or pushing) force of locomotives. It is the main output of the model used for a train movement.

MotiveForceN – is calculated based upon the MEP and the size of the steam cylinders. The MEP will tend to decrease as the locomotive speed increases. It is calculated based upon the tractive effort.

A steam locomotive has a “critical” speed where the IHP reaches a maximum value. For saturated steam this is 700ft/min and superheated it is 1000 ft/min. MotiveForceN will also be limited by this speed as well.

Thus -
MotiveForceN = TractiveEffort = (Max IHP x 375) / max speed

Required Input ENG File Parameters

Refer to the Open Rails Manual for information on specific parameters used in the model.