MOTORCYCLE FUEL INJECTION

- How it works – Step by Step
- From Carburetors to Fuel Injection
- Elimination of Myths and weird Theories
- Modifications and Improvements
- Explained in plain language for non-engineers

JENS LYCK

Chapters

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1. Introduction

The purpose of this book is to provide the ordinary motorcycle owner with a better understanding of how modern fuel injection systems work in a motorcycle.

Since we launched the BoosterPlug in 2009, I have been answering fuel injection related questions every day, and I have been in touch with thousands of motorcycle owners from all parts of the world.

The questions I have received have ranged all over the complexity scale – from very simple questions to really advanced discussions.

It all paints a picture of a very dedicated owner group with a big technical interest, but it have also shown that there is so much incomplete information floating around: False assumptions, outdated information from the first generations of electronic fuel injection, attempts to transform carburetor theory to fuel injection, wild guesswork, etc.

So during the past year I have toyed with the idea of offering a proper explanation on how modern fuel injection systems actually works;

- Partly because I can see a huge need for a book like this.
- Partly because I like the idea of giving something back to the international motorcycle community that have been an important part of my life for more than 30 years.

I have tried to keep the explanations as non-technical as possible and illustrate everything with charts to make this rather complex topic a bit more digestible, and it's my hope that you will enjoy reading the book and that it may be used as a reference in the usual technical discussions among motorcyclists.

I want this information to be available to everyone, so I decided to make this a free book. (Please see the copyright details).

As I'm the founder of the BoosterPlug company you may suspect that this is nothing but BoosterPlug advertising. I'm obviously biased towards our own solution, but you will see that the vast majority of this book is not about the BoosterPlug at all.

During the book, I have assumed that you already know the basic principle of a four stroke engine, so I will not take you through this. If you need to learn or refresh how the four stroke engine works, there's plenty of sources for this on the internet.

That's it – enjoy the book :-)

/Jens Lyck
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2. Mixing air and fuel

As you probably know, your motorcycle engine runs on a mix of air and fuel – or rather fuel evaporated to form a misty mixture that will ignite inside your engine.

The ratio between air and fuel is important because it will have a huge influence on how the engine runs:

- Power – you probably guessed or already knew this ☺
- Rideability – how easy and pleasant the bike is to control
- Engine life – the wrong mixture can destroy your engine or reduce its life dramatically
- Pollution – adding too much fuel will increase pollution.

So getting the air/fuel ratio right is very important.

In theory, the ideal ratio between air and fuel is 14,7:1 in a gasoline driven engine. This is called the stoichiometric mixture

Please note that this ratio is mass based, so we are talking 14,7 kg's of air to 1 kg of fuel.

As air is not very heavy, we obviously need a lot of air for every liter of fuel.

Air density depends on its temperature, but for this simple calculation, we can consider the density of air to be 1,2 gram per liter. Gasoline have a standard density of 755 grams per liter.

So, one liter of gasoline has the same weight as 629,17 liters of air, and if we want to produce a 14,7:1 mixture, we need 9249 liters of air for every liter of fuel. This is just to give you an idea of how much air is actually sucked into your engine for every liter of fuel that is used.

AFR is commonly used as an abbreviation for "Air/Fuel Ratio"

"Richer mixture" means a higher gasoline content in the Air/Fuel Mixture, and thereby a LOWER Air/Fuel Ratio figure.

"Leaner mixture" means a lower gasoline content in the Air/Fuel Mixture, and thereby a HIGHER Air/Fuel Ratio figure.

Lambda value is the same as Air/Fuel Ratio, but expressed differently. A Lambda value of 1,0 equals an AFR of 14,7:1, a lambda value of 0,9 equals an AFR of 0,9 x 14,7 = 13,23:1 etc.

To keep the terms consistent in this book, I will refrain from using the Lambda value expression in this book – I just wanted to show the connection between AFR and Lambda.

With an AFR of 14,7:1, all the fuel will be burned up inside the engine, and there will be no excess air molecules – if the world was an ideal place.

Unfortunately, there are a number of factors that will make it impossible for the engine to run at 14,7:1:

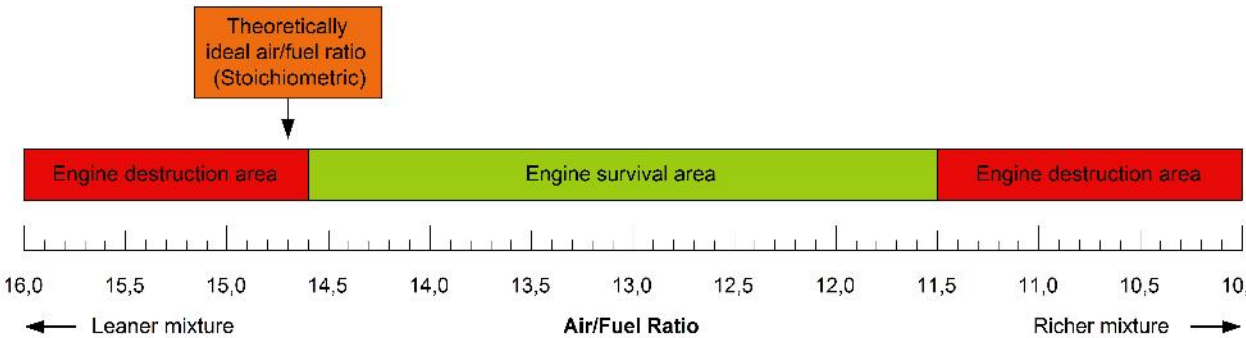
- The evaporation process where air and fuel is mixed is not 100% perfect
- The ideal combustion chamber shape would be perfect spherical, and the mixture would be ignited from the middle of the sphere. The Combustion chamber in your engine will never be shaped like this.
- Intake and exhaust channels, engine cooling and flywheel weight will have an influence too.

So, the engine needs a mixture slightly richer than the ideal 14,7:1 to run properly – More on the best AFR later.

First we will have a look at the extreme rich and extreme lean mixture to see how this will affect your engine.

Running the engine too rich or too lean will obviously lower the power and the rideability of the engine, but there's also a big risk to destroy the powerplant.

- **Risks with a very rich mixture**
  - Gasoline is a very good degreaser, and the excess fuel can wash away the oil film on the cylinder wall and make the pistons seize in the cylinder bores.
  - Large amount of unburned fuel will clog up the catalytic converter and destroy it.
- **Risks with very lean mixture**
  - Too lean mixture will cause the air/fuel mixture to explode during the engines compression stroke. This way you will not have the desired controlled combustion, but an explosion that will put a lot of extra strain on the moving parts – and destroy the engine over time.
  - The excess air in the very lean mixture will increase the combustion temperature a lot, which is very bad for your engine – especially the already thermally stressed exhaust valves will suffer.



AFR for highest power.

The first question that pops up in AFR discussions is usually which AFR will yield the highest power.

It is not possible to provide a firm answer, because it depends a lot on the engine configuration. The following factors will influence the ideal AFR.

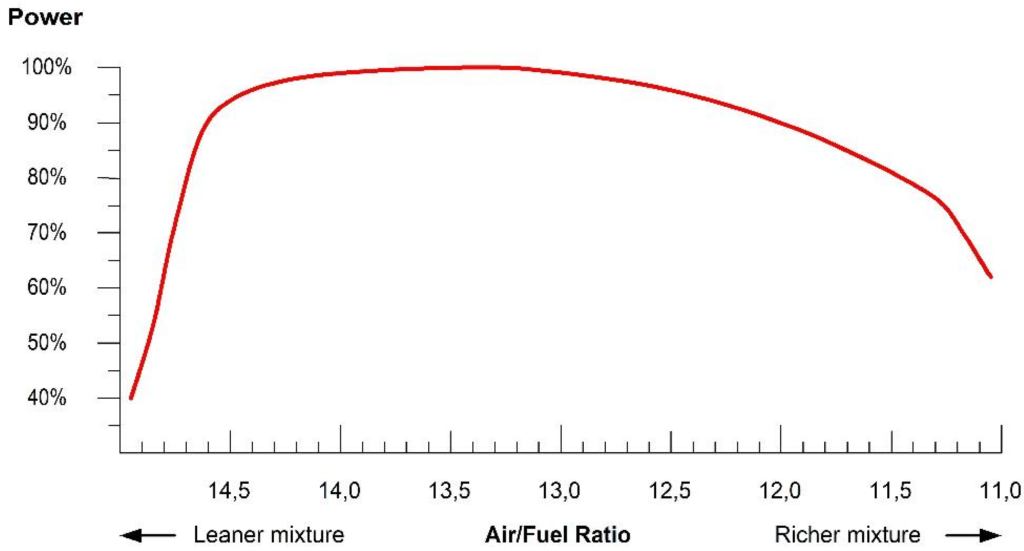
- Combustion chamber and piston head shape
- Cooling method
- Ignition system
- Flywheel weight

Modern, liquid cooled four valve engines will run a bit leaner than an air cooled, two valve engine, and most modern engines are delivering the highest output with an AFR between 13,5:1 and 12,5:1.

The engine will not lose a significant amount of power when you go a bit leaner than 13,5:1 – not until you reach the 14,7:1 mark where the power output will drop of steeply.

Going richer than 12,5:1 will lower the output at a much slower rate, and as you go richer you will feel the engine becoming more and more sluggish and lazy.

The graph below will show the typical relation between Power and AFR in a modern liquid cooled four valve engine.



AFR for best rideability.

Those of us old enough to remember when motorcycles all had carburetors, can remember how our bikes was much easier and pleasant to ride back then. No low speed surging, no tendency to stall the engine on every take off, and throttle pickup after braking into a corner was smooth and it was easy to apply the right amount of throttle.

It was not because the carburetor was a better solution – but the bikes was allowed to run much richer back then, and that made a hell of a difference to how the bike responded to your input – Rideability.

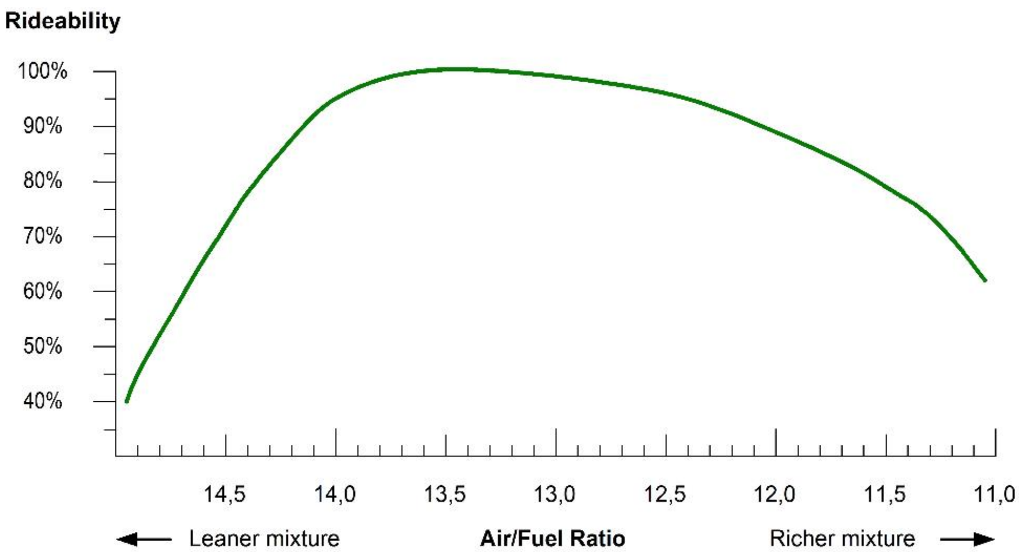
Therefore, the much leaner AFR in our modern fuel injected motorcycles is to blame for the poor Rideability mentioned above (Low speed surging, stalls, hard and unpleasant throttle action)

The modern emission standards are made for cars, which have a very big, and heavy flywheel and larger internal rotating mass compared to the lighter and nimbler motorcycle engines.

The big flywheels will make the cars accept the lean AFR fairly well, but our motorcycles suffer at lower RPM because the rotating mass is too low to allow smooth running.

As soon as the motorcycle engine reaches a certain RPM level, it will be running OK, but riding the bike in city traffic or hairpin corners is pretty horrible.

The graph below will show the relation between AFR and low speed Rideability. Again, there will be slight differences depending on engine configuration, but the tendency will be the same on all motorcycle engines: When you make the mixture leaner, Rideability suffers long before top end power starts to decrease significantly.

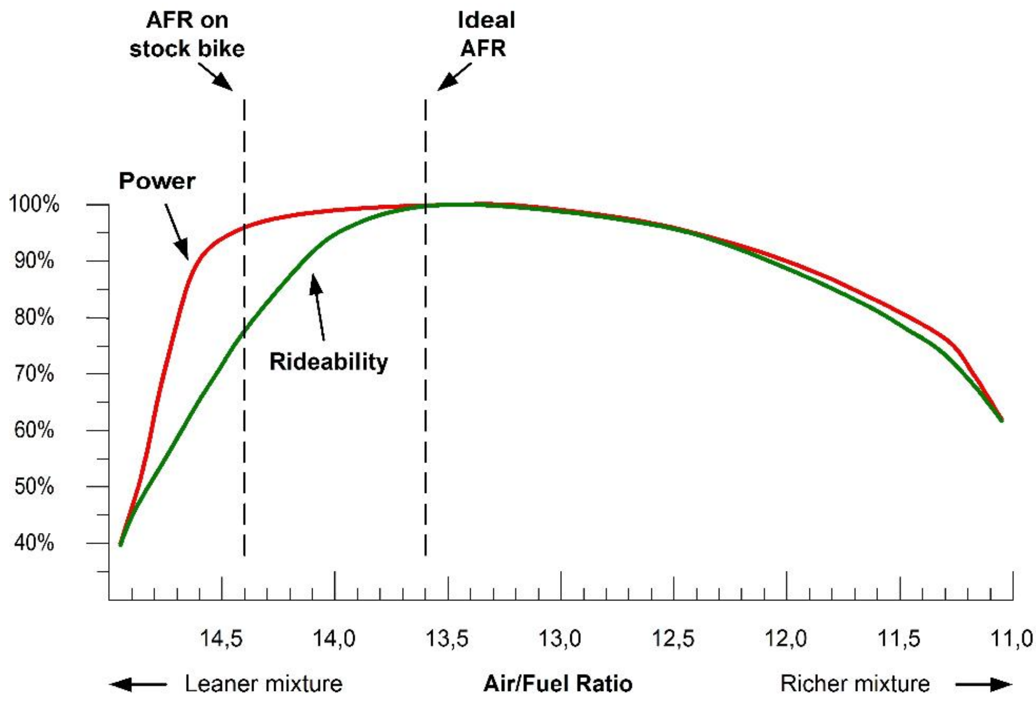


The AFR for optimum Rideability differs to a certain extent from the requirements for the highest power output.

- For mixtures richer than an AFR of 13,6:1, the Power and the Rideability curve will be fairly equal.
- But when you are going leaner than 13,6:1, the Rideability drops of much faster than the Power.

And so what ????

Modern engines are required to run with an AFR very close to 14,4:1, and if you look at the chart below it's clear that the motorcycle engine will not be lacking top end power, but low speed Rideability is poor.



If you own a car, you know that it is able to run slow without making the ride unpleasant. As mentioned earlier, this is due to the big flywheel in the car engine.

On our motorcycles, we are often forced to run a lower gear than necessary in city traffic to get the RPM's up (Which will not benefit the environment), and we face a bigger risk of finding ourselves in dangerous situations due to engine stalls and difficult throttle handling.

The motorcycle manufacturers are using all the tricks in the book to make our engines behave just reasonably well, and the following recent inventions are all a result of the research to improve Rideability – not really a search for more top end power.

- Ride by wire throttle (Computer controlled throttle valves)
- Dual ignition (Two spark plugs per cylinder, sometime even individually controlled)
- CNC milled combustion chamber shapes (as opposed to the cheaper casted cylinder head shapes)
- Lambda sensor (O2 sensor) in the exhaust header pipe
- Butterfly valves in the exhaust (Computer operated)
- Variable inlet duct length (Computer operated)

But the motorcycle engine constructors can never make things perfect because the legal AFR requirements are not made for motorcycles but for car engines with higher rotating mass, and the environmental restrictions are getting tighter over the years at more or less at the same pace as new developments are implemented.

The only way to cure the common Rideability problems is to make the engine run slightly richer, and the "sweet spot" AFR in a modern engine seems to be around 13,6:1.

And it's important to mention that you only need the richer mixture during idle, low RPM running and acceleration and engine braking. As soon as you maintain a steady speed on the open roads, there is no benefit from running the engine richer than stock. Actually this would just be a waste of fuel !

If you expected a graph that would show you which AFR that would give you 20% more top end power, I'll have to disappoint you. There are virtually no top end power gains to achieve by changing the fuel injection AFR in a modern engine, but if the AFR tweak is done correctly, it can make your bike safer and more pleasant to ride - virtually without changing overall fuel consumption.

3. Carburetors

Most of us old enough to remember motorcycles with carburetors find ourselves longing back to the simpler days where we could understand the air/fuel mixing process and fix the carburetor in the garden shed when something went wrong.

The main reason why we loved the carburetors was threefold:

- We understood the technology (or thought we did)
- We could fix the carb ourselves when a nozzle clogged up
- Throttle action was soft and easy to control, as opposed to the hard, on/off like, throttle action on the fuel injected bikes.

The carburetor was a very fine mechanical instrument, but actually never completely suitable for mixing air and fuel !

It may seem like a rough statement after 100 years with the carburetor, but there was a few things fundamentally wrong with the carburetor:

- Mechanical wear in jets, nozzles, needles, and slides could change the air/fuel ratio dramatically over time.
- No compensation for air pressure or air temperature.
- Even the best and most accurate adjusted carburetor would provide a much wider air/fuel ratio (AFR) range than the electronic fuel injection.

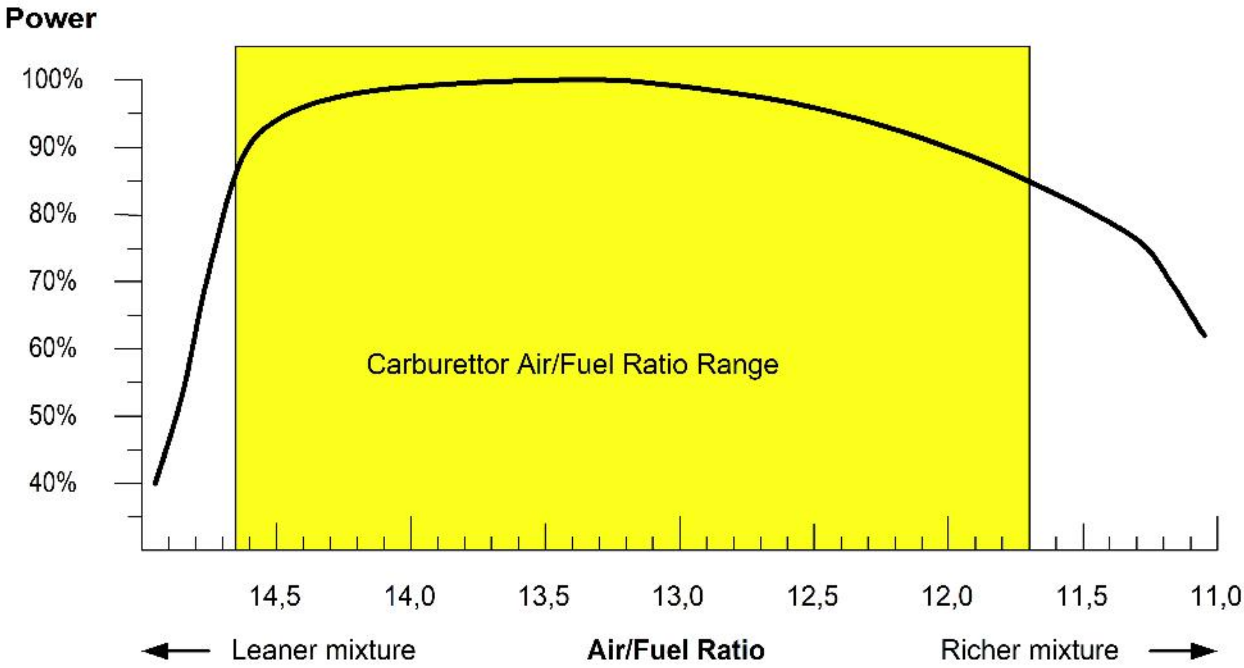
Even if you was always running the engine in the same temperature and air pressure conditions the carburetor would still be working across a wider AFR range than a properly programmed electronic fuel injection.

But as real life conditions are never stable, the carburetor bike would:

- Run richer on a hot day and leaner in cold weather.
- Run richer in the mountain pass and leaner near sea level
- Run richer on a rainy day (Low air pressure) and lean in sunshine (High air pressure)

So the only reason why the carburetor actually worked was that emission standards was not present or not very tight, so the carburetor was allowed to (and had to) use the entire air/fuel ratio range.

As you will see on the AFR vs. Power chart from the last chapter, the carburetor could provide reasonable results, and we all accepted the carburetor because we did not have better alternatives.



The entire industry had more than a hundred years of experience with the carburetor, and the manufacturers, the dealers, the mechanics and the customer was all confident with it, and if the tightening emission regulations had not killed the carburetor, we would probably still have it on our bikes.

In the early 2000's it became increasingly harder to get carburetor bikes approved, and the new emission standards introduced in 2006/2007 finally killed the carburetor on road legal motorcycles.

4. Moving from carburetors to fuel injection

The motorcycle industry was generally slow to change from carburetors to electronic fuel injection.

The carburetor suppliers had a tried and tested product, and there was an entire sub-business focusing on re-jetting, tweaking, adjusting, and repairing carburetors, and everyone was happy with the situation.

Electronic fuel injection was seen as much too complicated and fragile technology, difficult to service and repair, and impossible to adjust when the customer installed a new aftermarket exhaust and air filter. The fact that this technology was commonly used in cars seemed to make little difference…

During the early 80'ies, there was a few attempts by some of the Japanese manufacturers to implement fuel injection on new top end models, but they was never popular with the dealers and mechanics who had no clue on how to work them, so they quietly reverted to carburetors and forgot all about it.

BMW was the first manufacturer to seriously implement electronic fuel injection, and they did so with the K75 and K100 series that was launched in the mid 80'ies. BMW had in-house experience with fuel injection from the car industry and the fuel injection equipment they used in the beginning was very similar to the equipment used in their cars. By todays standards it was not ideal for a high performance engine, but BMW had a good starting point, and slowly the market accepted fuel injection on motorcycles as a possible solution.

Going fast forward 10 years to the mid 90'ies, and we see that some Italian brands are now using fuel injection on their top models. They clearly did not have the same knowledge and experience in-house as BMW, because the programming of the first fuel injections was actually quite horrible.

This was not a problem that was isolated to the Italian brands, because 5 years later when the first fuel injected Japanese motorcycles arrived, we saw the same pattern on those bikes.

By the turn of the century, it was clearly a young industry and the learning curve was steep !

But after year 2000, things moved fast and the motorcycle industry changed over to fuel injection with an incredible speed. They knew very well that the tighter emission standards that was announced for 2006/2007 would kill the carburetor, so they had to start investing time and money in research and development of the fuel injection.

In 2005, all carburetor motorcycles was older developments in their last years of production, all new models was fuel injected, and by 2007, virtually all new bikes was fuel injected.

So 2007 was the year the carburetor passed away after more than a hundred years of more or less faithful service.

5. Basic Fuel Injection Theory (Open loop operation)

The carburetor is mixing air and fuel by letting the air passing through the carburetor body suck up a certain amount of fuel on the way.

The fuel injection system will have a throttle body (usually one per cylinder) with a butterfly valve and a fuel injector.

- The butterfly valve is adjusting the air flow to the engine (and thereby engine speed)
- The fuel injector is pressing/injecting a computer-calculated amount of fuel that is mixed with the air flow.

A fuel pump and a fuel pressure regulator is used to feed the fuel injector, and the amount of fuel injected to the engine depends on the fuel pressure and how long the fuel injector is kept open. (The fuel injector is an on/off device, so there is no regulation by opening it more or less)

Fuel pressure is kept stable by the pressure regulator, so the amount of fuel to be injected is controlled by keeping the nozzle open for a shorter or longer period.

The fuel injection computer (The ECU) will then decide how long to keep the fuel injector open.

A few ECU's are capable of regulating the fuel pressure as well as adjusting the fuel injector opening duration. You can also find setups with more than one fuel injector per cylinder and other variations.

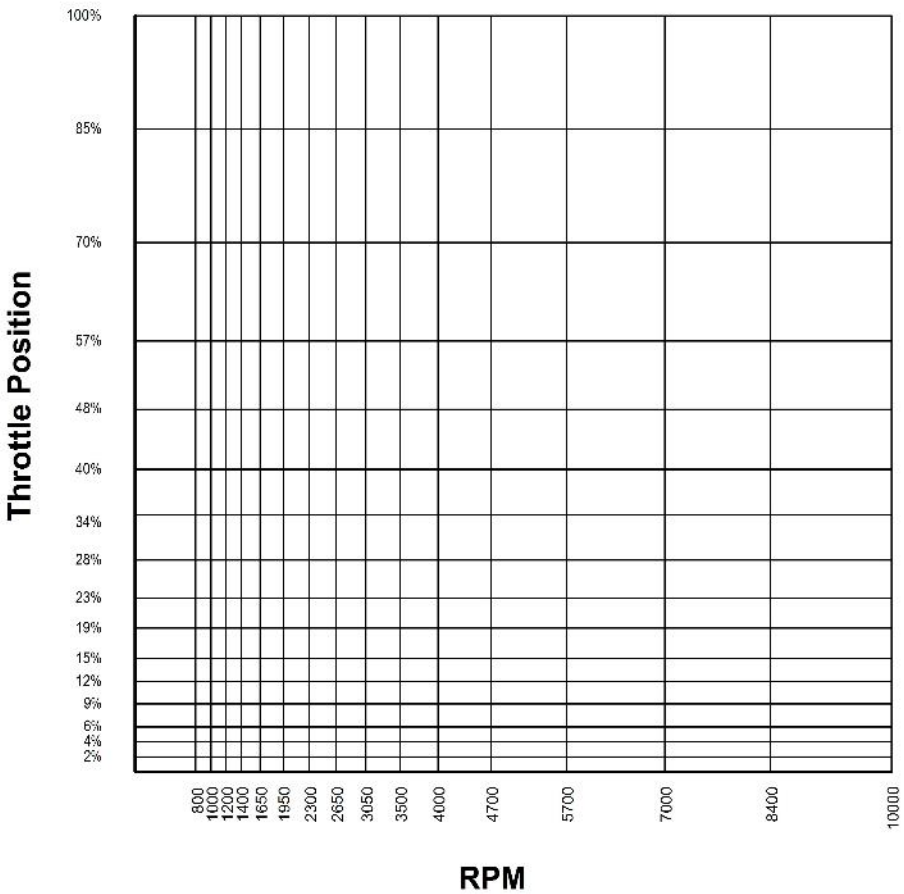
But these variations does not influence the basic fuel injection theory, so they will not be discussed further in this book.

Fuel Map

The ECU is supposed to keep the Air/Fuel Ratio (AFR) at the desired level in all situations, no matter the engine speed or the commands from the rider (How much the throttle valve is opened).

So the ECU will decide how much fuel to inject based on the predefined information stored in the fuel map.

The fuel map is like a big chessboard or a chart with typically 16 by 16 tiles. On one axis we have the engine RPM, on the other axis we have the throttle opening percentage.



The ECU will look at the tile or cell that is matching the actual RPM and throttle valve position, and each cell contains information on how long the fuel injector should be kept open.

You will see that the cells are spaced much closer to each other at low RPM and low throttle openings. This is because this area is by far the hardest to control, so when the engine is operating in the lower left hand side of the fuel map, even the slightest shift in RPM or throttle position will require a different amount of fuel to keep the AFR steady.

As mentioned earlier, the amount of fuel to be injected is adjusted by changing the fuel injector opening duration, and the figures in the chart below is an example on fuel injector opening duration across the fuel map.

Fuel injection map (Injector open duration)

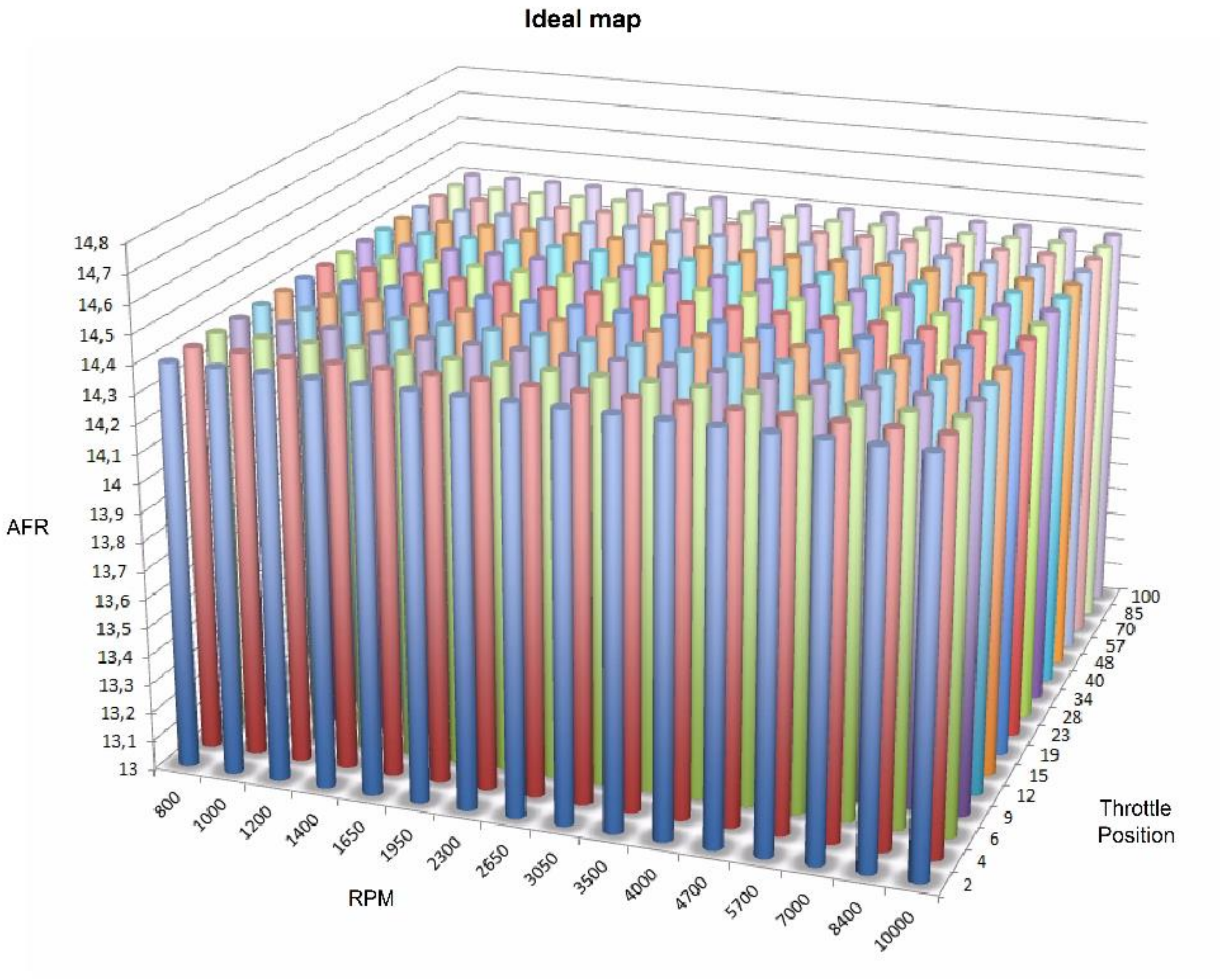
Throttle Position																
100	5232	12032	12960	12656	12512	12288	12080	11920	12048	12000	11648	11552	12416	13184	13184	13248
85	5232	11984	12912	12608	12448	12256	12032	11856	11968	11936	11616	11472	12240	12992	12992	12992
70	5232	11936	12864	12560	12384	12224	11984	11792	11888	11872	11584	11392	12064	12800	12800	12736
57	5232	11856	12736	12448	12272	12128	11888	11648	11696	11680	11488	12016	12368	12288	12224	12192
48	5232	11568	12400	12208	12096	11872	11600	11360	11232	11088	11296	10976	11552	11088	10080	9952
40	5232	11360	12176	12096	12032	11696	11440	11296	11088	11456	11264	10144	10112	9712	8688	8256
34	5232	10112	10768	10624	10560	10304	10080	9856	10528	9920	8832	8208	8112	7616	7232	6848
28	5232	8832	9312	9152	9072	8880	8688	8512	8480	8032	7328	7120	7024	6592	6192	5792
23	5232	8720	9040	8912	8848	8608	8432	8192	8080	7408	6656	5968	5936	5776	5712	5264
19	5232	8576	8608	8464	8048	7616	7472	7296	7152	6560	5920	5328	5264	5168	4848	4592
15	5232	7920	7984	7600	7392	6960	6416	6320	6080	5888	5376	4928	4752	4592	4400	4048
12	4976	6528	6656	6352	6176	5824	5808	5728	5648	5120	4720	4480	4256	4144	4000	3808
9	4512	5264	5184	5040	5184	4992	4976	4976	4784	4496	4288	4112	3952	3632	3520	3488
6	4496	4640	4592	4544	4448	4416	4384	4336	4272	4048	4000	3696	3552	3392	3088	2800
4	4512	4544	4256	3936	3808	3744	3680	3552	3328	3200	3072	3040	3024	2736	2592	2400
2	4016	3904	3392	2976	2928	2928	2912	2880	2688	2608	2512	2432	2384	2192	2080	1888
	800	**1000**	**1200**	**1400**	**1650**	**1950**	**2300**	**2650**	**3050**	**3500**	**4000**	**4700**	**5700**	**7000**	**8400**	**10000**

RPM

All these numbers are entered by the factory team, and this is the main programming of the ECU. If the development guys have done a proper job, the end result will be a stable AFR in all situations.

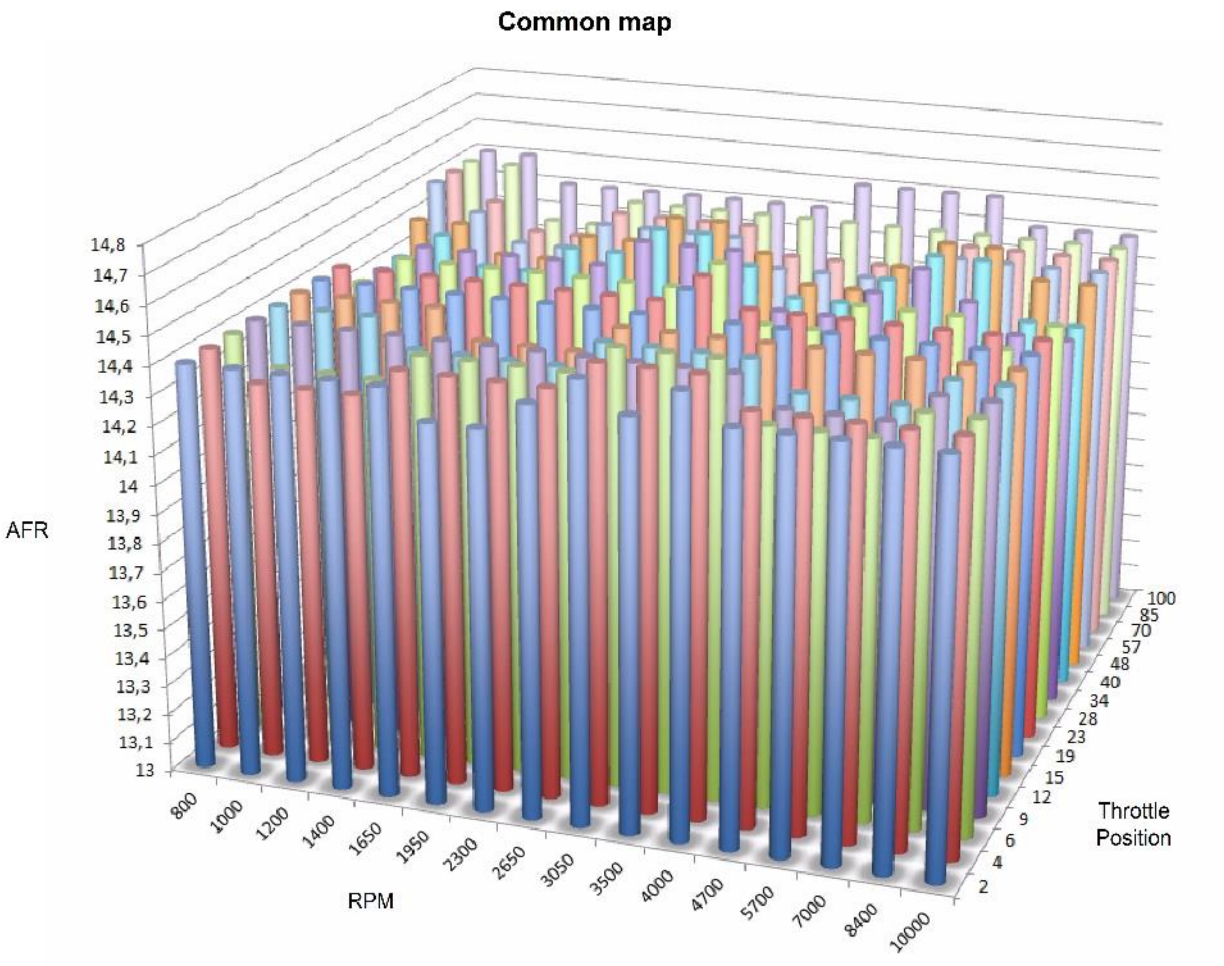
The chart below will show the result of an ideal fuel map programming. As you will see, the AFR is stable at 14,4:1 across the map.

(I'm not saying that 14,4:1 is the ideal AFR, just that the programming is consistent and therefore very good)



But the world is never ideal, so in reality you will see small AFR variations across the map - like in the chart below.

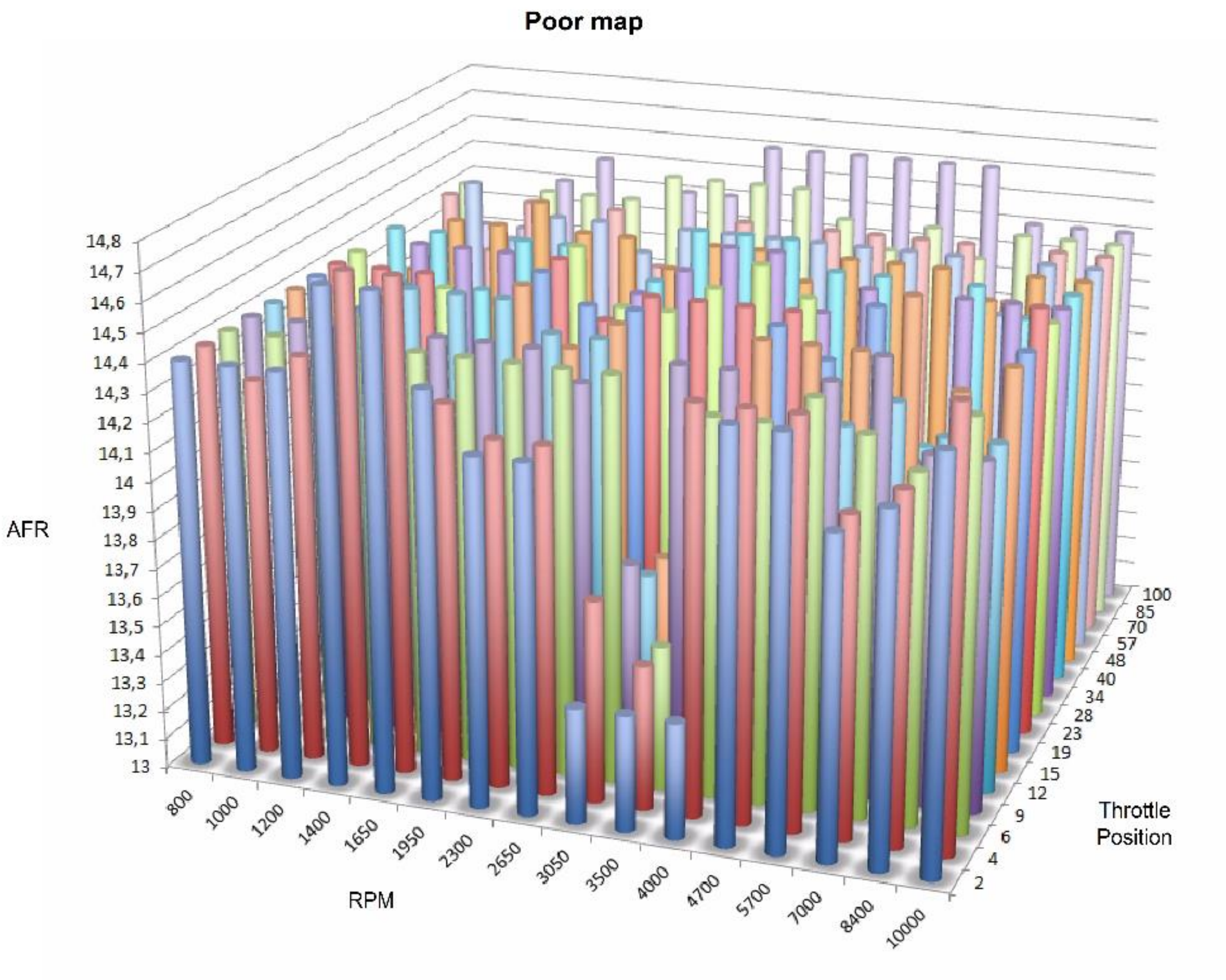
You will see that the AFR ranges from 14,3:1 to 14,5:1 across the map. This level of inaccuracy is common and nothing to worry about – this how a fuel map in a modern production bike will look like.



If the AFR variations gets bigger, you will experience different issues when you ride the bike: Flat spots, hesitation, misfire, exhaust popping, stalling, extreme fuel consumption, etc.

Fuel maps like the one in the chart below was not uncommon on the early generations of fuel injected motorcycles, and as you can see there are rather big AFR variations.

Some bikes were worse than others and it all depended on knowledge and experience of the factory's R&D team. They obviously never admitted that their bikes were less than perfect, but some of them actually had horrible fuel map programming.



The tighter emission requirements in 2006/2007 forced the factories to sharpen up and invest more time in the fuel map programming, because if the map was as poor as in the example above, they could no longer get the bike approved for road use.

Some manufacturers got the fuel mapping right earlier, but quite a few of them had a steep learning curve in 2005 and 2006 ☺

So on motorcycles from 2007 and newer the basic fuel map is pretty accurate. As mentioned in a previous chapter the 14,4:1 AFR does not make the bike perfect to ride, but the mapping itself is done with a high degree of precision.

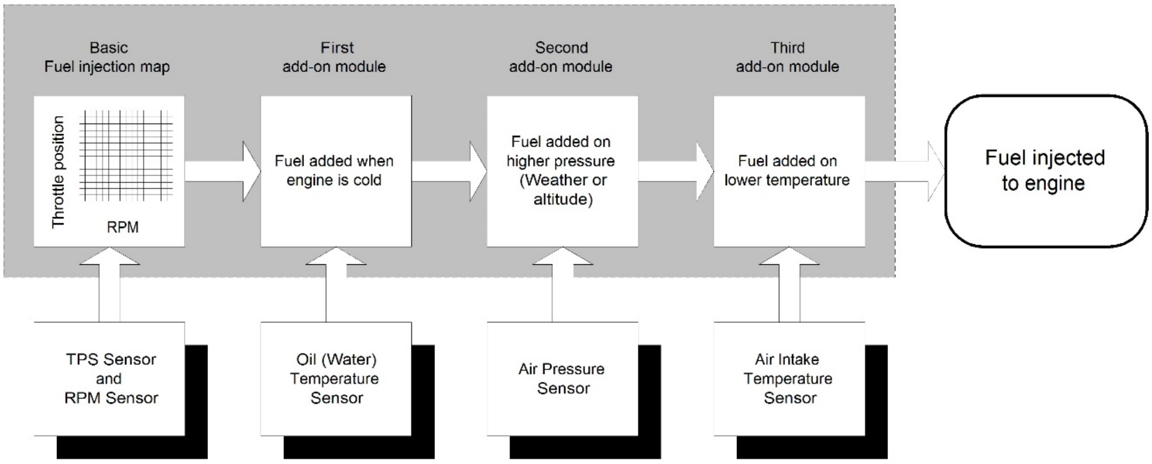
Bottom line in this chapter is that the basic fuel map already have the potential to outperform the carburetor, because you have much more precise control on the amount of fuel injection in different combinations of RPM and throttle opening. This level of control can never be obtained with a mechanical device. And even though the last generation of carburetors was developed with a 100 years of knowledge and expertise, they still found themselves outperformed by the fuel map.

But we are not done yet - By including the information from additional information sources (sensors), we can improve things further. A lot further actually!

Additional inputs.

After the ECU have been looking at the fuel map to find the basic fuel injection amount, there will be a number of adjustments to this figure before a signal is send to the fuel injectors. This is done in the add-on modules where additional information from other sensors are taken into account.

Do make a mental note on the chart below, because I will be referring to it a lot in the following chapter.



In the chart you will see the fuel injection map and the typical three add on modules. In the following I'll take you through the three modules one by one.

Please note that the map and the add on modules are all sitting inside the ECU in a mix of hardware and software – you will not be able to find these modules anywhere on the bike ☺

The first module is similar to the Choke on the carburetor – a device to provide a richer air/fuel ratio for starting the cold engine and when the engine is in the warm up phase. (All engines requires a richer AFR when they are forced to operate below their usual operating temperature – which they obviously must do during cold starts and warm up)

Back in the carburetor days you had a lever on the handlebar or directly at the carburetor to apply the richer mixture when you was starting a cold engine.

In the fuel injected motorcycle today, this is done automatically by the first add on module that is reading the engine oil temperature (and sometimes also the cooling water temperature), to tell if the engine is cold or not yet at it's usual operating temperature.

This module will gradually reduce the fuel enrichment as the engine heats up, and do absolutely nothing when the operating temperature is reached.

Early fuel injected motorcycles are often equipped with a choke lever too, but this is only to allow the rider to raise the idle speed slightly during the warm up phase.

The first fuel injected bikes did not have a stepper motor to control the idle speed, so the rider had to adjust this. Today, almost all fuel injected motorcycle engines are equipped with the small stepper motor that will automatically raise idle speed during the warm up phase.

The oil temperature sensor signal was still used to make the air/fuel ratio richer, but without the stepper motor, there was no way to adjust the idle speed automatically.

The second and third add on module is where the fuel injection is really adding value and precision to an extent the carburetor could only dream of. Now we are able to compensate for changes in the environment we are riding in, and make the bike adapt to changes in air pressure and ambient temperatures. This is one of the big advantages with fuel injection!

The second add on module will adjust the injected amount of fuel to keep the AFR steady when the air pressure changes.

Air pressure will be higher on a sunny day, and lower when the weather is poor – and higher at sea level than in the mountain passes.

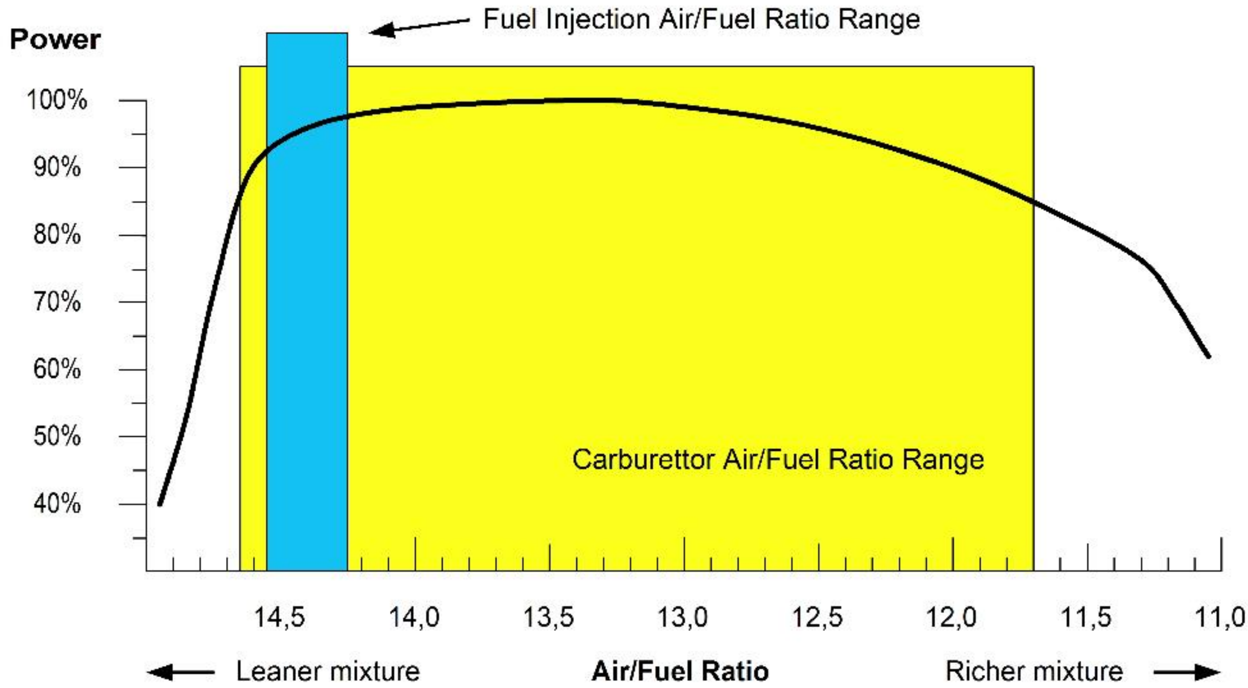
Atmospheric air contains more air molecules per liter (or gallon) in high-pressure conditions that in low-pressure conditions, and the input from the air pressure sensor will allow the add on module to compensate for the changes in air pressure. This way the air/fuel ratio can be kept steady in different air pressure conditions.

Sorry if this gets a bit technical – but the essence of this is that the air pressure compensation will make your bike perform the same at sea level or in the mountains, and if you remember how bad a carburetor bike reacted to these changes you will know that this is a major improvement.

The third add on module is keeping the AFR constant when the air temperature changes.

It's more or less the same situation as in the previous module: Cold air contains more air molecules than hot air, and the ECU is using the information from the air temperature sensor to compensate the injected fuel amount to keep the AFR steady.

This ability to provide an automatic compensation for the shifting air pressure and air temperature, gives the fuel injection an advantage that the carburetor can never compete with.



The difference in the AFR range (Accuracy) of the fuel injection and the carburetor is partly due to the use of a fuel map that gives you a better control of the AFR, but it is mainly because the fuel injection system gives you the automatic compensation for shifts in air pressure and air temperature.

With the calculations from the fuel map and the add on modules we now have a very good qualified guess on the amount of fuel to inject to the engine in all situations.

But it's important to understand that the output signal to the fuel injector is a predetermined calculation, based on various inputs. **This is called open loop operation**.

We do not have any feedback from the engine if the air/fuel mixture that is fed to the engine is actually correct.

This is already far better and more precise than what can be achieved with the carburetor and this is how most early fuel injections worked. But it is still not 100 % perfect because of the tolerances in the component specs.

Tolerances in components

All industrial components have a certain tolerance in the output. Some of them are really accurate where other will have a bigger variation in output. Here are some typical tolerance figures:

- Fuel injectors 0-1 %
- Fuel pump pressure regulator 3 %
- RPM sensor 0 %
- TPS sensor 1 %
- Air pressure sensor 3 %
- Air temperature sensor 1 %

This does not mean that all air pressure sensors are 3 % off, but the sensor will be approved in production if it is delivering an output within +/- 3% of the spec sheet figure.

Most of the components are performing close to the specs, and if you sum up all the tolerances of the involved components, you will usually see that some variations will make the AFR slightly richer, some of them slightly leaner, so the end result is fairly good on most bikes.

But if all the components on your bike was at the maximum tolerance and they was all pulling the AFR in the same direction you could have a bike that is running 8% leaner or 8% richer than the preprogrammed value.

It will be very few of the bikes that are running extremely rich or lean, but most of them will have a smaller or larger offset compared to the programmed AFR.

Without the current emissions restrictions, this would never be a problem, because the end result is so much better than what a carburetor can deliver, but as the manufacturers are forced to run the bikes very lean (very close to the border where your engine will stall or destroy itself long term), the small AFR variation is not acceptable.

So if you looked at a random selection of a hundred production bikes you would see a pattern like this:

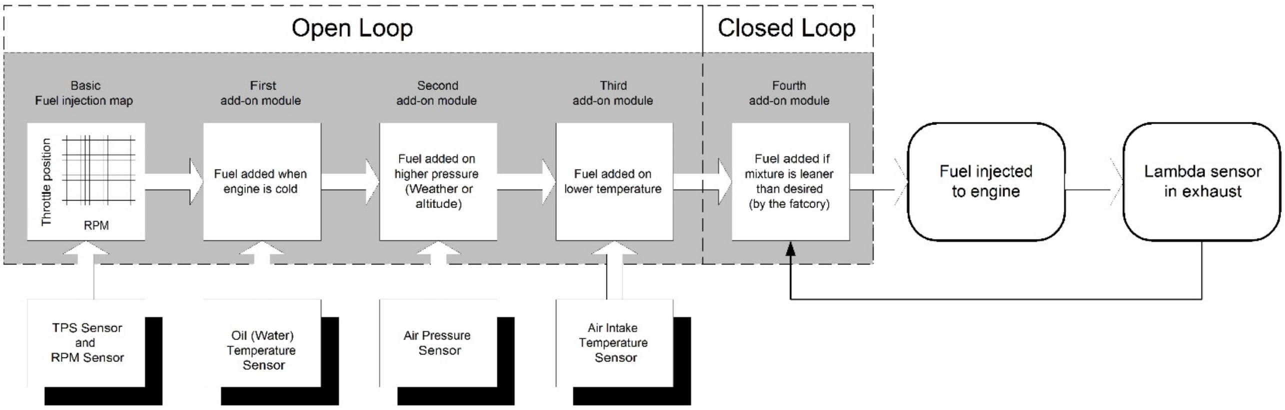
- Most of the bikes would be more or less OK, but slightly different due to the tolerances in the fuel injection components.
- A handful of them would be running very lean, overheat, stall the engine at every stop and in general be very unpleasant to ride.
- Another handful of bikes would be running way richer than the target AFR and would be much more pleasant to ride – but would not pass the environmental tests.

This is obviously not ideal, and after the introduction of the tighter environmental standards in 2006/2007, the full Open Loop fuel injection system was no longer precise enough to meet the new standards.

6. Advanced Fuel Injection Theory (Introduction to Closed Loop and the Lambda sensor)

It was necessary to add a fourth correction module that could constantly measure the result of the combustion inside the engine and use this information to make a final adjustment of the fuel injection.

This feedback process is known as Closed Loop operation, and the air molecule content in the exhaust gasses is measured by the Lambda sensor that is located in the exhaust header – See the chart below.



If the lambda sensor is seeing any oxygen molecules in the exhaust fumes, it will inform the ECU of a “Lean” condition, and if not, it will let the ECU know that the conditions are “Rich” – the lambda sensor is very close to being an on/off switch.

The Lambda sensor is a very important and rather complex device, so I will deal with it in details in a separate chapter.

First it makes sense to discuss the constant switch between open loop and closed loop operation.

Open loop – Closed loop switch.

The signal feedback process from the Lambda sensor is not without problems, because there’s a certain delay from the time you change the engines conditions until you can measure the result reliably in the exhaust.

So the ECU must sense a “Stable” condition for a few seconds before it will take the lambda sensor input into consideration.

The only way the ECU can sense if the condition is stable is by looking at the fuel map and see if the active cell stays the same or not (If RPM and throttle positions are kept at a steady level).

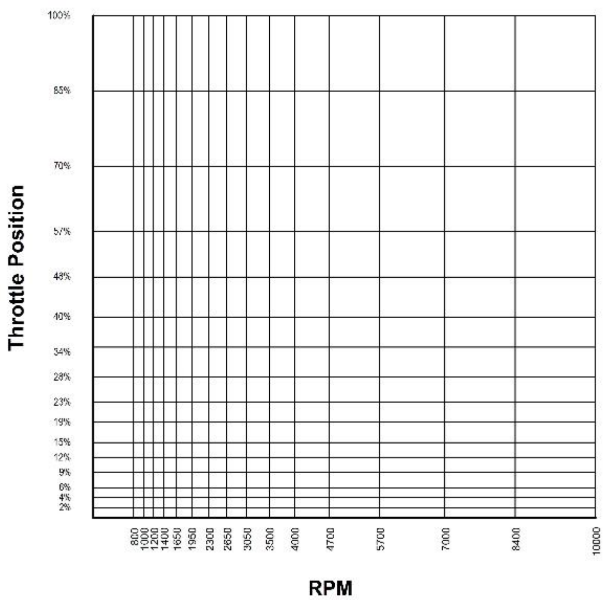
- If the active cell in the fuel map stays the same for a few seconds or more, the ECU will see the engine conditions as stable – and make a final adjustment to the air/fuel mixture according to the signal from the Lambda sensor.
    - Now the ECU is operating in **Closed loop mode**, and the Lambda sensor is effectively in charge of the air/fuel Ratio
- As soon as engine speed (RPM) moves up or down or the rider moves the throttle, another cell in the fuel map will become active. Now the ECU will see the condition as “Not stable” and ignore the Lambda sensor signal.
    - The ECU is now operating in **Open loop mode**, and the air/fuel mixture to be injected to the engine is calculated from the information stored in the fuel map and input from the temperature and pressure sensors.

This process is repeating itself constantly where the ECU will switch to closed loop operation when the conditions have been stable for a few seconds, and go back to open loop operation instantly when another cell in the fuel map becomes active.

The term “a few seconds” is used deliberately, because the different manufactures are using slightly different numbers here, and the necessary delay will also change with the overall engine configuration (Displacement and bore/stroke ratio). But it’s usually in the range between 1,2-2,6 seconds.

It is obvious that closed loop is at steady speeds and open loop is during acceleration and engine braking, but there is one more important thing to consider.

The nature of the fuel map is that the cells in the lower left hand quarter is spaced much closer than in the rest of the map because it is very hard to control the AFR in the low RPM and low throttle opening area.



As a result, you will never stay long enough in the same cell in the fuel map at low speeds because even though you think you are riding at a steady low speed, the slightest movement of throttle or RPM will take you to a new cell in the fuel map – and the lambda sensor will be ignored for another few seconds. And in reality, you will never be able to keep the conditions stable enough in this part of the map to make the ECU go closed loop.

Open Loop / Closed Loop summary:

- **Open Loop**
  - In Open Loop mode, the injected fuel amount is preprogrammed by the information in the fuel map and the input from temperature and pressure sensors.
  - **The ECU is operating in Open Loop mode in these situations:**
    - **Idle**
    - **Low RPM**
    - **Acceleration**
    - **Deceleration (Engine braking)**
- **Closed Loop**
  - In Closed Loop mode, the ECU will use the input from the lambda sensor in the exhaust to determine the correct amount of fuel to inject to the engine.
  - This way the ECU is able to adjust or regulate the AFR based on the actual result of the combustion.
  - **The ECU is operating in Closed Loop mode when you maintain a constant speed on the open roads.**
- **Open Loop / Closed Loop switch**
  - The ECU will switch from Closed Loop to Open Loop operation when a new cell in the fuel map becomes active (By shifting throttle position or engine RPM).
    - The switch from Closed Loop to Open Loop is instant.
  - The ECU will switch from Open Loop to Closed Loop mode when the engine conditions is considered stable (When throttle position and RPM is constant so the active cell in the fuel map stays the same)
    - You need to keep the active cell in the fuel map constant for a few seconds before the ECU will consider the engine situation as being “Stable”, so the switch from Open Loop back to Closed Loop takes a few seconds.

Bottom line of all this is that the addition of the Lambda sensor and Closed Loop operation makes it possible for the manufactures to control the AFR with a much higher precision (obviously only in Closed Loop mode)

Due to the tolerances in the involved components, they could never obtain the necessary control with an open loop system, so the manufacturer had to add the Closed Loop mode module in the ECU to make their bikes pass the emission requirements.

And as the manufactures are forced to run the bike very lean (very close to the limit of damaging the engine), it would mean that they would have a lot of bikes breaking down prematurely due to the bigger AFR range in a 100% Open Loop system (and some of them would be running really bad).

From a customer perspective, it is obvious that the Lambda sensor makes our bikes more complex, more expensive, and add another component that can fail.

But in reality, the Lambda sensor is a sturdy component and it does actually give us a few important advantages:

- **Fuel Economy**
  - Closed Loop operation fuel consumption will be excellent as the engine is kept at a lean, but safe AFR
    - The average user is spending about 80% of the riding time in Closed Loop mode, so the Lambda sensor is a major contributor to the fuel economy on your bike.
- **Aftermarket exhaust and filters**
  - The addition of the Lambda sensor and Closed Loop operation means that you can now install aftermarket exhausts and air filters without the risk of damaging your engine.
    - With engines fed by carburetor or an early "Open Loop only" fuel injection, you have nothing in place to compensate for the higher airflow found in most aftermarket exhausts and air filters, and you would have to re-jet the carb or re-program the ECU to avoid running the bike dangerously lean.
    - With the Closed Loop operation in place on the modern fuel injection system, the ECU will automatically adjust the AFR back to factory level in Closed Loop mode. And as high power conditions are almost exclusively Closed Loop territory, the engine will not suffer.
      - Acceleration is obviously an Open Loop thing and there will be no AFR compensation here, but as you are only accelerating for a limited time, there is no risk of damaging the engine during acceleration.
      - Idle and low speed running are also Open Loop mode, but at low RPM, the air flow in the aftermarket filters and exhaust is only a little higher than in the standard parts. And as this is a low power situation, your engine will survive without problems.
      - The aftermarket exhaust and filters means that you WILL be running the engine slightly leaner in Open Loop mode, and even though this will not harm your engine, the rideability issues mentioned in an earlier chapter, will be even more pronounced. But the closed Loop mode and the Lambda sensor can obviously not be blamed for this disadvantage :-)

All in all, the Closed loop mode and the Lambda sensor gives the bike owner more advantages than problems, and you should think carefully before tampering with the Lambda sensor or bypassing it !

7. The Lambda Sensor in details

In the previous chapter it was described how the Lambda sensor is integrated to the fuel injection system, and what influence it has on our bike.

There are so many rumors and theories on how the lambda sensor works and what it can do, so I decided to offer some more detailed information on the lambda sensor itself in a separate chapter.

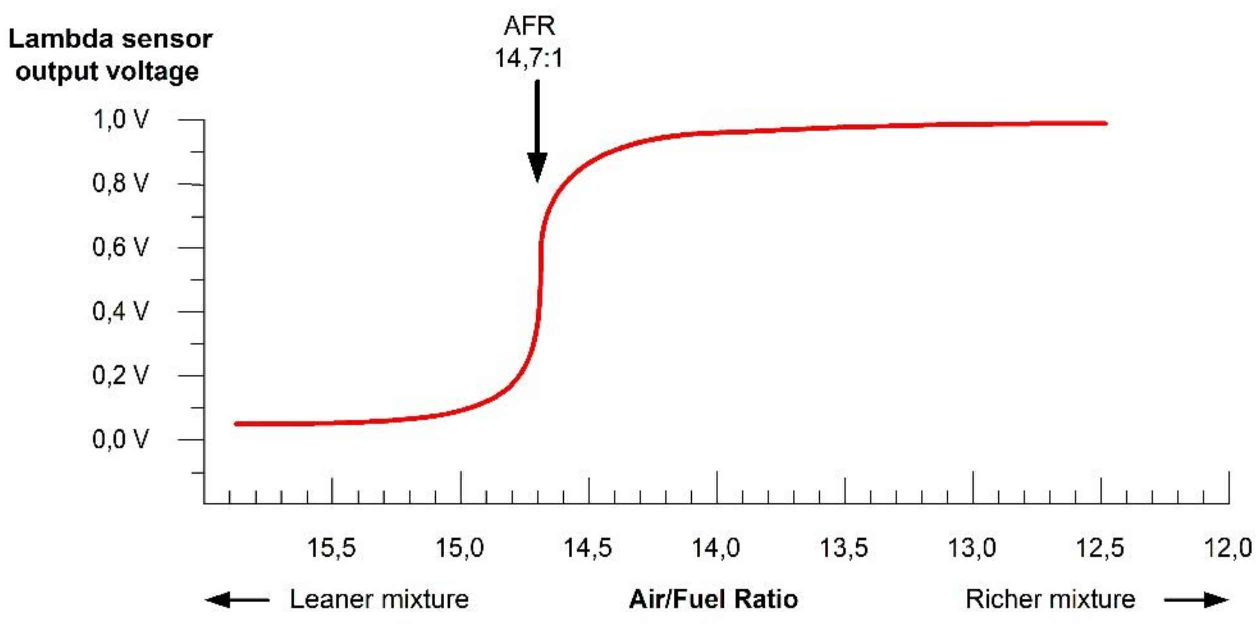
The Lambda sensor is also known as an O2 sensor, but during this Book, I will only use the Lambda sensor term.

Measuring exhaust gasses.

If you could produce a perfect combustion process, the fuel would consume all air molecules during the combustion and there would be no burnable fuel remains or any air molecules in the exhaust gasses. This would be the result if we could run the engine at the stoichiometric ideal AFR of 14,7:1.

The common narrow band output Lambda sensor that is used in all production motorcycles will search for air molecules in the exhaust and inform the ECU of a “Lean” condition if it detects air molecules in the exhaust.

The Lambda sensor is not very good at measuring the amount of air molecules in the exhaust, so it will basically switch its signal state within a very narrow AFR range when air molecules start to appear. (More or less like an on off switch)

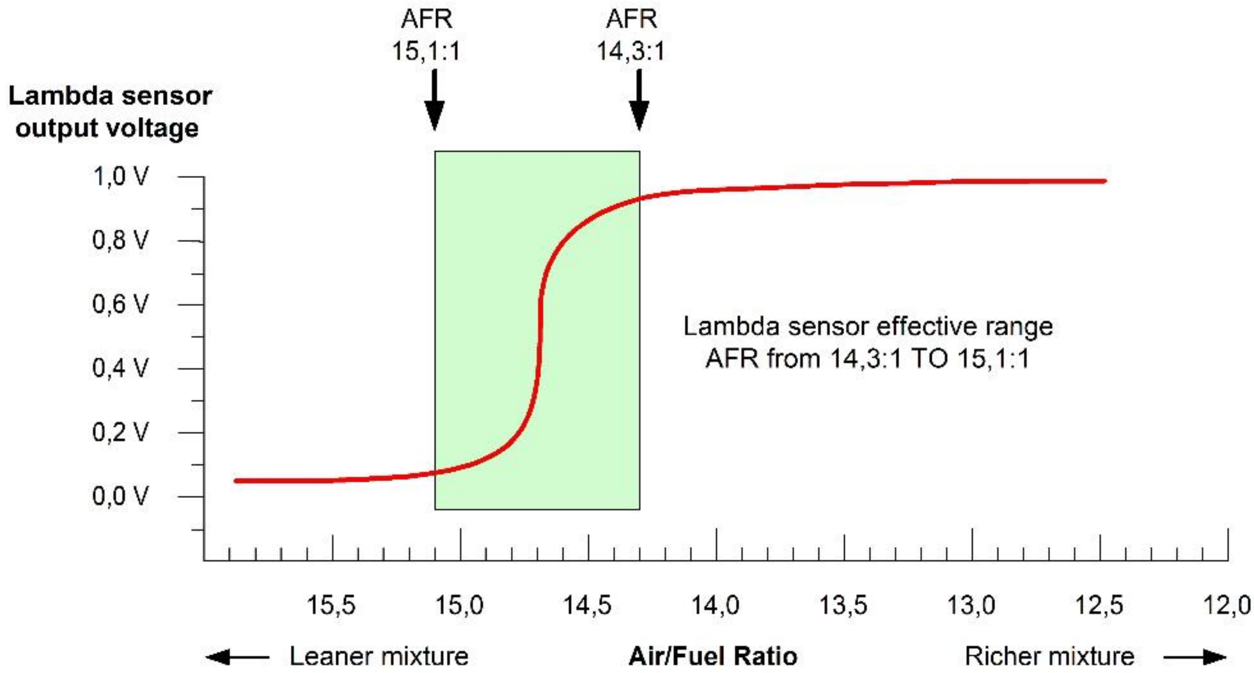


The standard Lambda sensor is known as a “Narrow band Lambda sensor” due to its very fast shift in signal state.

It is important to understand that the lambda sensor will only detect excess air molecules, but can not see unburnt fuel molecules. So the Lambda sensor will have no clue what is going on when the mixture is getting richer – it will only react when the AFR is becoming borderline lean.

The Lambda sensor contains a heating element too, which seems a little weird considering that it is installed in the hot exhaust header pipe. But one of the problems with the lambda sensor is that its output characteristics will change with the temperature of the sensor, so the heater is included to heat up the sensor head as fast as possible.

This fundamental behavior means that the narrow band lambda sensor has a well-defined operational range which is from around 14,3:1 to 15,1:1 (See the chart below)



To meet the emission requirements, the engine must be kept very close to an AFR of 14,4:1, which is close to the limit of the Lambda sensors effective range. But modern electronics and proper ECU programming makes it possible, and Closed loop operation where the Lambda sensor is keeping the AFR close to AFR 14,4:1 seems to work well on all bikes today.

But there is no way the narrow band Lambda sensor can be tweaked to adjust the closed loop AFR to a richer mixture, because it will have no clue what is going on when the AFR gets richer than aprox. 14,0:1.

The Wide Band Lambda Sensor

It only makes sense to talk about a narrow band sensor if there is also something called a wide band sensor – and there certainly is :-)

The wide band lambda sensor have a much wider operational range, and can cover any AFR you would want to run on your bike. It can be programmed to any AFR range you may desire, and is a great tool in racing and development, because it can tell you the exact AFR at any time.

Unfortunately, they are not for production bikes as they are expensive, fragile and needs frequent recalibration and they are not found on any production motorcycle.

Even if you were ready to pay the money for a wide band sensor and live with the frequent calibrations, you cannot just install a wideband sensor on your bike. The fuel injection ECU is preprogrammed to expect the input from a narrow band sensor, so it would not work.

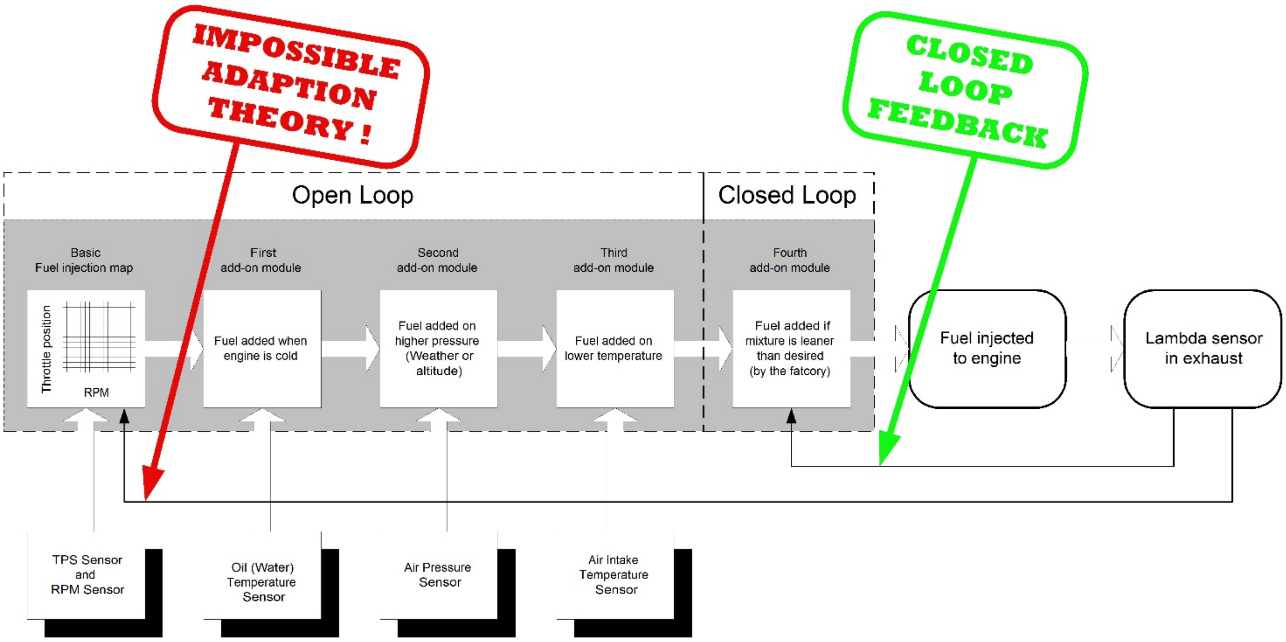
The map adaption theory.

As the Lambda sensor is giving feedback to the ECU, it is no wonder that there are discussions on what the feedback is used for.

It's a common theory that the Lambda sensor feedback can be used to improve the basic fuel map. This is known as the adaption theory.

It would be nice if this was possible, because then the Lambda sensor feedback would be able to improve the fuel map which would benefit the open loop operation.

Unfortunately there is no way the narrow band sensor can accomplish this !



There's a number of reasons why this can not work:

- The Narrow band lambda sensor have a very digital (on/off like) output behavior that far from ideal for adaption.
- The very narrow operational range of the lambda sensor makes it impossible for the sensor to inform the ECU how much to adjust the AFR.
- The time delay in the sensor feedback require you to stay for a certain time in the same cell in the fuel map – which you only do in very few cells on the map.

If you were using the same fuel injection setup on a stationary engine with a constant speed and load, I'd say that it would be possible to let the lambda sensor adjust the map (because you would always be running the engine under the same conditions).

If you tried to do the same with the motorcycle engine you would see that a few cells would be updated, but you would never stay long enough in most of the over 200 cells in the fuel map to get them all done. This would just end up in a horrible uneven map, where you would actually destroy the original mapping.

We know that similar bikes from the production line are not running equally (too) lean from the factory – all due to the sensor tolerances discussed in a previous chapter (Actually the same tolerances that made the Lambda sensor necessary in the first place….)

If the adaption theory was correct and the ECU was able to update its own fuel map with input from the Lambda sensor, all bikes of the same type would end up with the same Air/Fuel Ratio over time. But a bike that is extremely lean from the factory does not correct itself, and a lucky owner of a bike that is running a tad richer than the rest will not see this advantage disappear over time.

The Lambda sensor will provide a real time fuel correction when you are riding in closed loop conditions, but this is just a final adjustment to the fuel injection calculations (The fourth add-on module).

There is no way the narrow band lambda sensor can provide information to update the fuel map in the ECU, and this means that the Open Loop fueling will stay as programmed by the factory.

The easy way to prove that the Lambda sensor can not update the fuel map:

- If you look at the millions of motorcycles with aftermarket exhausts installed, you will see (hear) that most of them have some degree of backfire or popping in the exhaust when the rider close the throttle.
- The aftermarket exhaust will flow a bit more air than the stock exhaust, and more air means that the air/fuel ratio (AFR) changes to the lean side - which causes the backfire on deceleration.
- If the adaption theory was right, the lambda sensor would sense the change in AFR, and the ECU would update its basic fuel map - and then the problem would be solved and there would be no more popping or backfire in the exhaust.
- But we all know that these bikes does not cure themselves and the backfire stays the same over time - so there is no adaption process taking place !!!

8. Fuel Injection Modifications

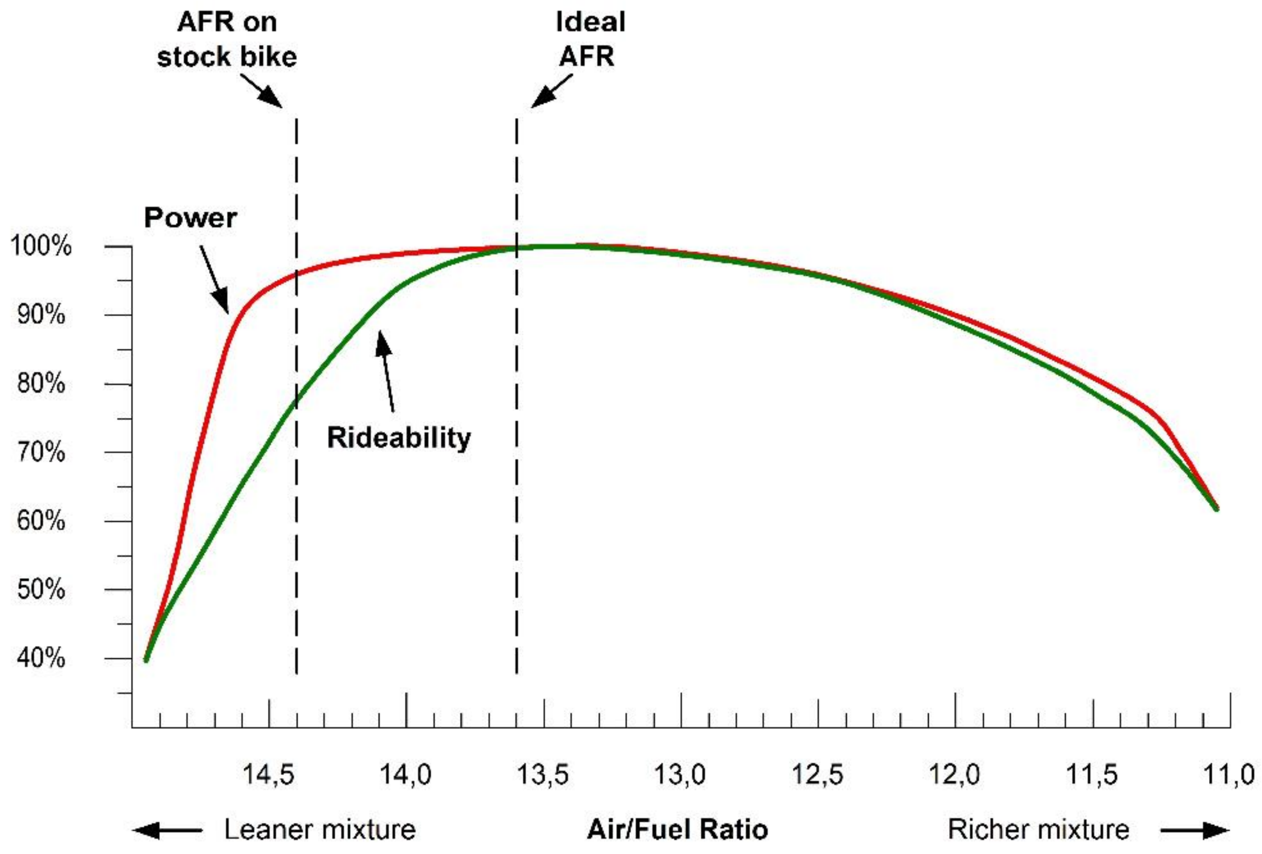
Motorcycle owners love to modify and improve their bikes with aftermarket parts, and there is a huge market for devices that will tweak the fuel injection hardware/software.

The purchase of a Fuel Injection modification device is usually based on a more or less well defined wish to "improve" the bike, but it is important to understand what kind of improvements can actually be achieved.

If we go back to the chart from the chapter about mixing air and fuel, it's clear that the modern fuel injected bike already have plenty of top end power, and the possible improvements in this area is within a few percent.

A few modern bikes have very restricted exhausts or air filters, and you can get more power from the engine by installing aftermarket parts, but this is an improvement made by increasing the air flow through the engine – not a fundamental glitch in the fuel injection ECU programming that is stopping your bike from performing at its best.

But it is also clear that the low speed rideability and throttle control is poor on all standard motorcycles, and there are significant improvements possible in this area, which will make your bike nicer and safer to ride.



So, the improvements we can expect to see when we tweak the fuel injection correctly is about rideability – not top end power !

You can find loads of products with fantasy claims and fake dyno charts promising you amazing gains in top end power. Forget about it – it is not going to happen. A proper fuel injection modification will make your bike safer, easier, and more rewarding to ride, but it will not increase top end power to any significant degree.

This goes for all modern closed loop fuel injected motorcycles (all bikes from 2006/2007 and newer, but also some earlier bikes). The picture may be slightly different on older "open loop only" fuel injected bikes.

The rise and fall of the Power Commander.

The head line above may well trouble the common opinion that the Power Commander is the only true solution in the search for the perfect bike.

In this chapter I will stay with the term "Power Commander", as this is the most common multi-adjustable Fuel Injection modification. But the chapter also covers devices like the Bazzaz, Fuel Pak, etc….

All the multi-adjustable devices require you to remove or bypass the lambda sensor to make the ECU operate in full open loop mode. This means that you no longer have the very good closed loop mode to keep the AFR safe, but you have now taken full responsibility of the AFR, and if you program the device wrong you can destroy your engine, or make it run really poor.

And as you no longer have a closed loop function, you will have to dyno and set up the Power Commander again if you install another exhaust or air filter.

It is often mentioned that the opportunity and freedom to adjust any parameter you can think of is a big advantage with the Power Commander, but this is only true if you or your mechanic is able to get the programming right. I have no reason to doubt the qualifications of your local mechanic, but his chances of outperforming the factory development team is rather slim. And the fuel mapping on a modern motorcycle is actually very good – it's just running the bike a tad lean overall.

If you have a thousand parameters to adjust, you have a thousand ways of doing things wrong and only one way to do it right - And this is actually the biggest problem with the Power Commander and similar multi adjustable devices.

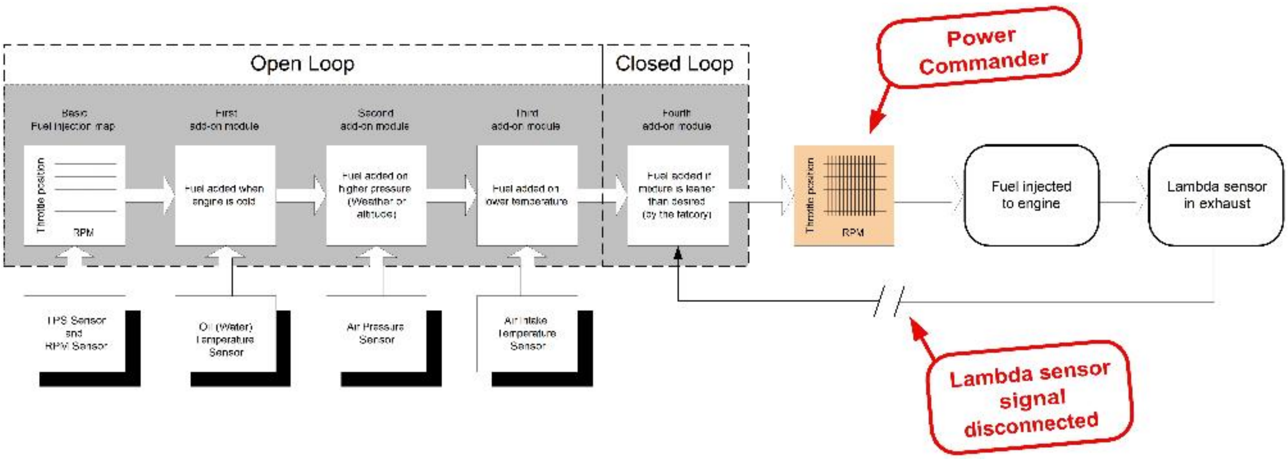
Most of the Power Commander installations we see are making the bike run way too rich, and are just wasting a lot of fuel and increasing pollution a lot.

Rideabiity are mostly still better than on the stock bike because the engine runs better on too rich mixture than on too lean mixture, but it's an expensive choice for a solution that is mostly less than perfect.

To be fair to the Power Commander, it should be mentioned that it is often the only solution to improve the early fuel injected motorcycles. Some of the early “open loop only” bikes often had a very poor fuel map resulting in big AFR variations across the map. This can not be solved by simpler solutions, but the Power Commander can be adjusted to correct the fuel map.

If you are changing the basic engine configuration (Bore, stroke, cams, valves, pressurized charging, etc., you will probably also need the Power Commander. This is way to far from the standard engine setup to be solved by simpler solutions.

In the chart below you can see how the Power Commander works.



- You will see that the multi adjustable Power Commander sits between the bikes own fuel injection ECU and the injector nozzles and will allow you to change the fuel injector signal any way you like.
- The lambda sensor is disconnected and there is no longer any kind of AFR adjustments done in closed loop mode.
- You have full control AND full responsibility of the result.

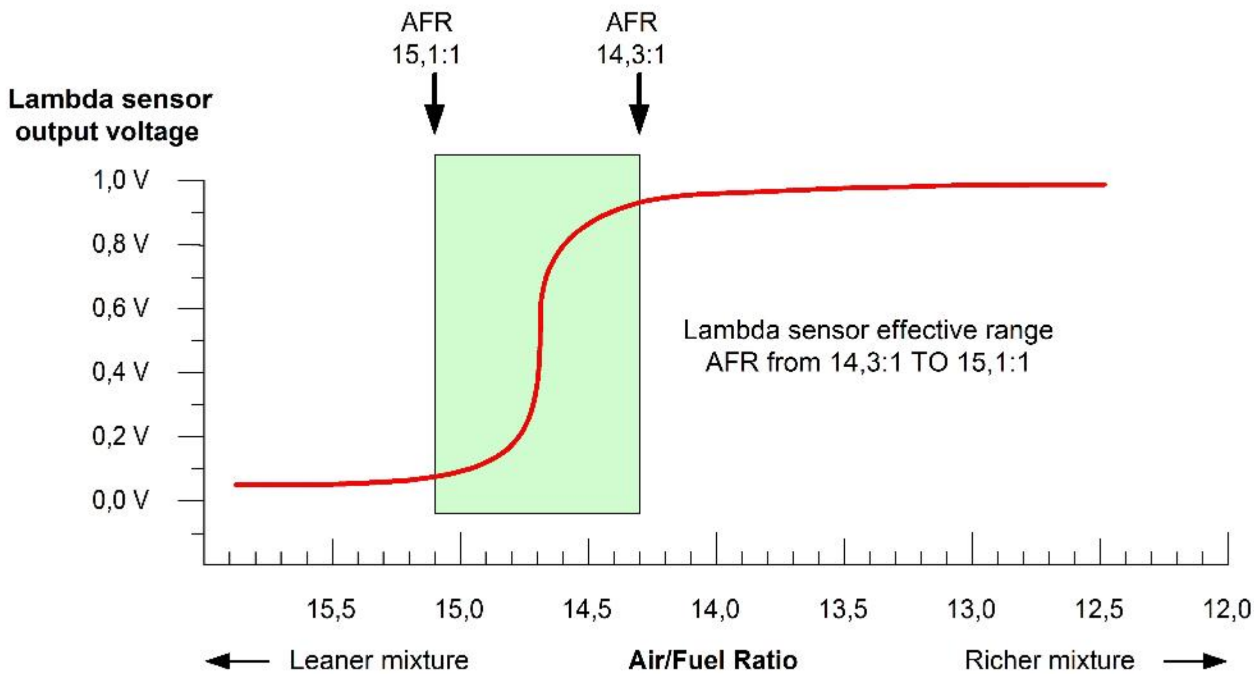
Lambda sensor tweaks

There are plenty of devices available that is tweaking lambda sensor signal. They are usually cheap and easy to install, so many people are tempted to give them a try, but it is a poor solution that should be avoided.

There are several reasons to stay away from lambda sensor tweaks:

- This is a closed loop operation tweak, and it will give your engine the richer mixture where it is needed the least.
    - So you are mostly just increasing fuel consumption and pollution a lot without significant rideability improvements.
- You are not really in control of the process because the lambda sensor signal can not be tweaked to make the engine run at the AFR we want – The device will just make the bike run as rich as the ECU software allows.
- There is no longer a closed loop feedback regulation to adjust AFR for different exhausts and filters.

The chart on the effective range of the lambda sensor clearly shows that it can never be tweaked to the AFR we want for the best rideability (Usually around 13,6:1). Simply because the lambda sensor will have no idea what is going on when the mixture gets richer than aprox. 14,1:1.



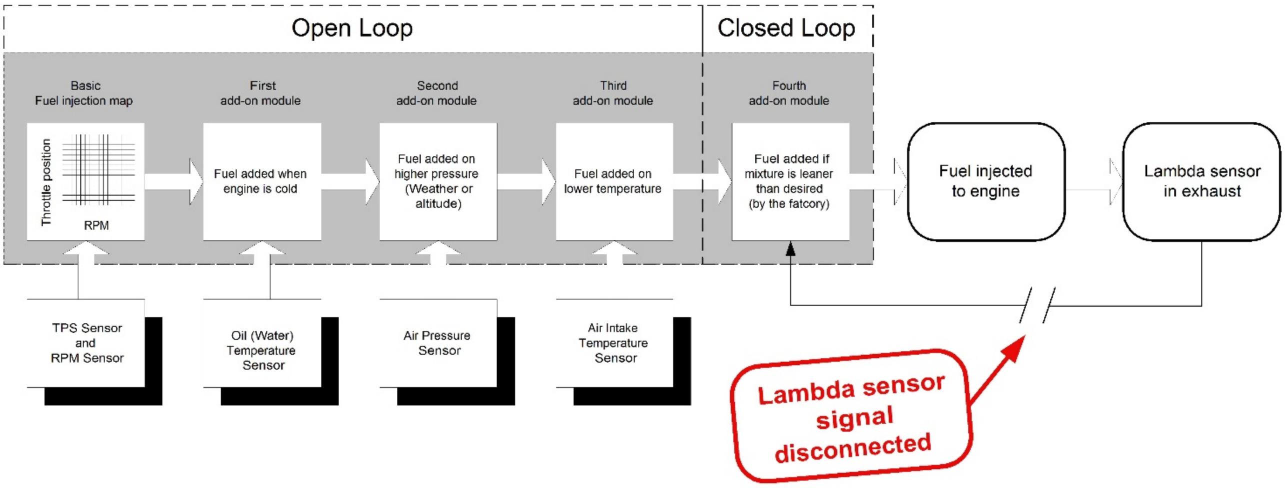
It does not matter much if you just remove the lambda sensor, or install a lambda eliminator dongle, or an adjustable device – the lambda sensor can still not be tweaked beyond it's physical abilities!

The common picture for all lambda sensor tweaks is that they will make the AFR richer by an unknown percentage in the area where you need it the least. So they will just make your bike waste a lot of fuel and increase pollution.

Here's a description of the different lambda sensor tweak methods.

Lambda sensor removal

This is the simple DIY approach lambda sensor connector where the lambda sensor connector is just unplugged.

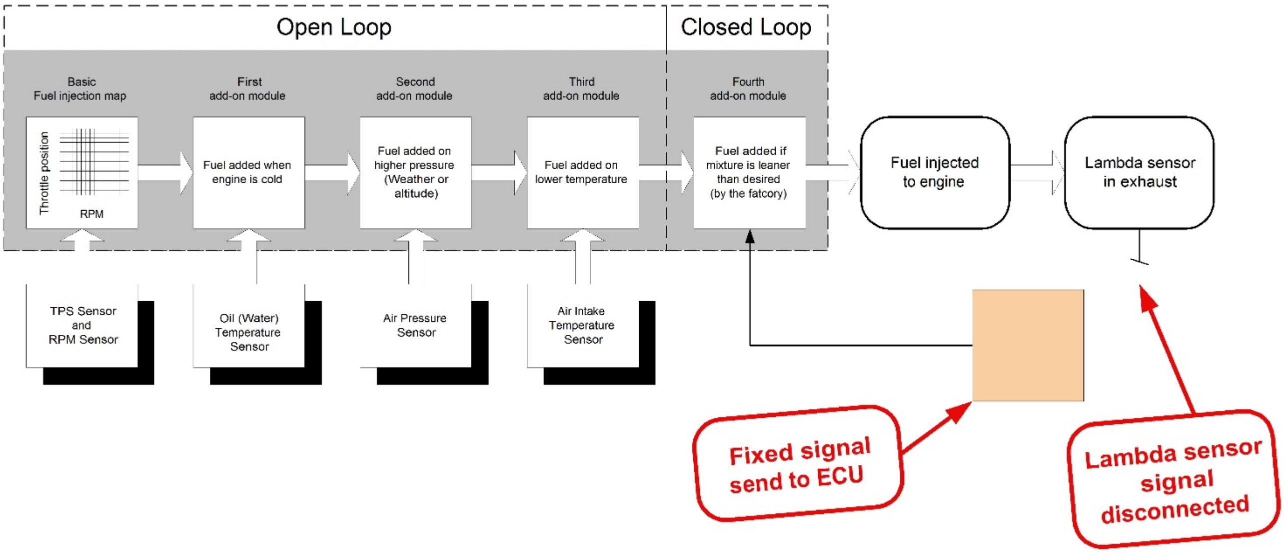


- The ECU will receive no signal from the lambda sensor = a 0 volt signal.
- So the ECU will believe the AFR is too lean and add more fuel.
- But this will not change the AFR (because there is still no signal), and the ECU will add more fuel in an attempt to correct the AFR.
- This process will continue until the mixture is as rich as the ECU software allows.

Lambda sensor eliminator dongle

This is a simple dongle (Connector with no wires) that you just plug into the cable connector that is normally attached to the lambda sensor.

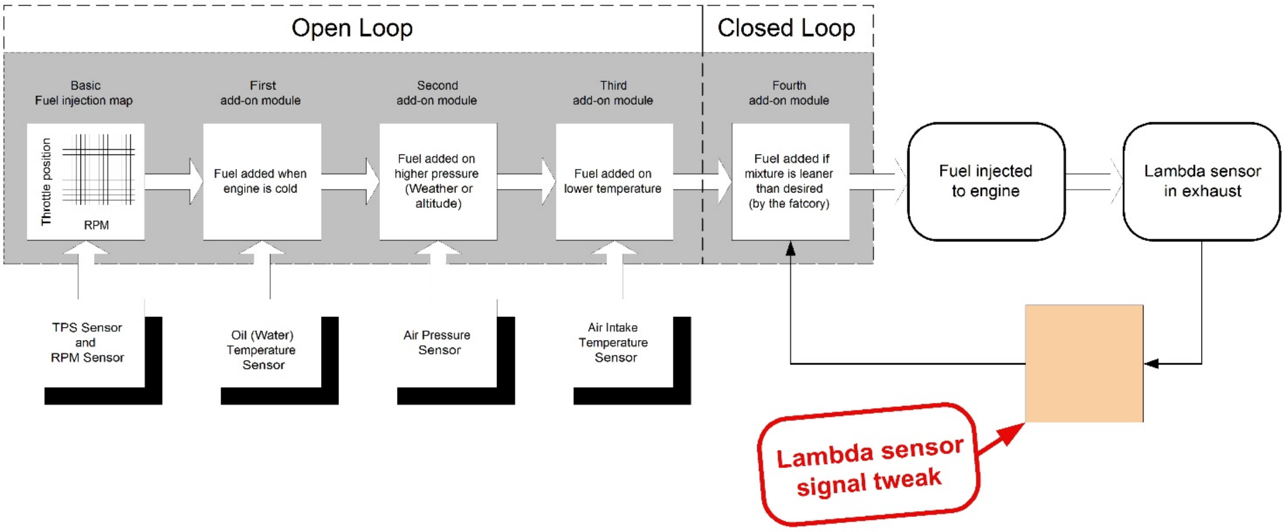
You can find plenty of these in various webshops, and they often come with fairy tale like promises of improvements – I've even seen them advertised as fuel savers :-)



- You'll see that it's a slightly different setup than just disconnection the lambda sensor, but it's not better in any way.
- Most of them are only a resistor that will let the heater circuit pull enough power so the ECU does not flash a warning in the dashboard for "faulty lambda sensor heater circuit". The actual lambda sensor signal to the ECU is still just disconnected.
- A few of them is adding a resistor to fix the lambda sensor input voltage, and this way you can adjust the sensor signal to make the ECU believe the AFR is at a certain level.
    - But you are still restricted by the lambda sensor's effective range, so there is no way you can adjust the AFR to a desired level by using the dongle.

The adjustable Lambda sensor tweaking device

The adjustable lambda sensor tweaker is not disconnecting the Lambda sensor signal, but sits between the lambda sensor and the ECU and will try to adjust the lambda sensor signal to make ECU change the AFR to a more desirable level.



- The theory is that it is possible to make the lambda sensor regulate the AFR outside it's effective range, but you would never be able to obtain a stable signal.
  - We are usually aiming for an AFR around 13,6:1 for best rideability, and if you look at the "lambda sensor effective range chart" you will see that we are now in an area where the lambda sensor signal will be very (VERY) close to 1,0 Volt.
    - A 1,0 volt signal is a low range and a low voltage signal. It is very sensitive and easy to disturb, and even a 0,05 volt variation would change the AFR a lot.
    - This part of the lambda sensor output curve is varying a lot with the sensor temperature, so even if you could adjust the AFR to the desired level in laboratory conditions, you would see a completely different result when you took the bike on the road.
    - It is not without reason that the lambda sensor have an "Effective Range", and trying to make the sensor work outside the physical limits is doomed.
  - And even if you found a magic trick to make this setup work, you would still get the fuel enrichment where you don't really need it !

You may remember my recommendation NOT to tweak or remove the lambda sensor – now you know why :-)

The BoosterPlug

Already in the introduction chapter, I mentioned that I am the inventor of the BoosterPlug, so I am obviously not unbiased. But I'm convinced that the BoosterPlug is by far the best solution for most bikes, and my claim is backed up by more than 35.000 happy customers world wide, so it's probably not too bad ☺

Feel free to decide for yourself if this is just slick high-pitched sales talk or if there may be something to it…

Tweaking the air temperature sensor signal can be a very good solution provided it's done correctly.

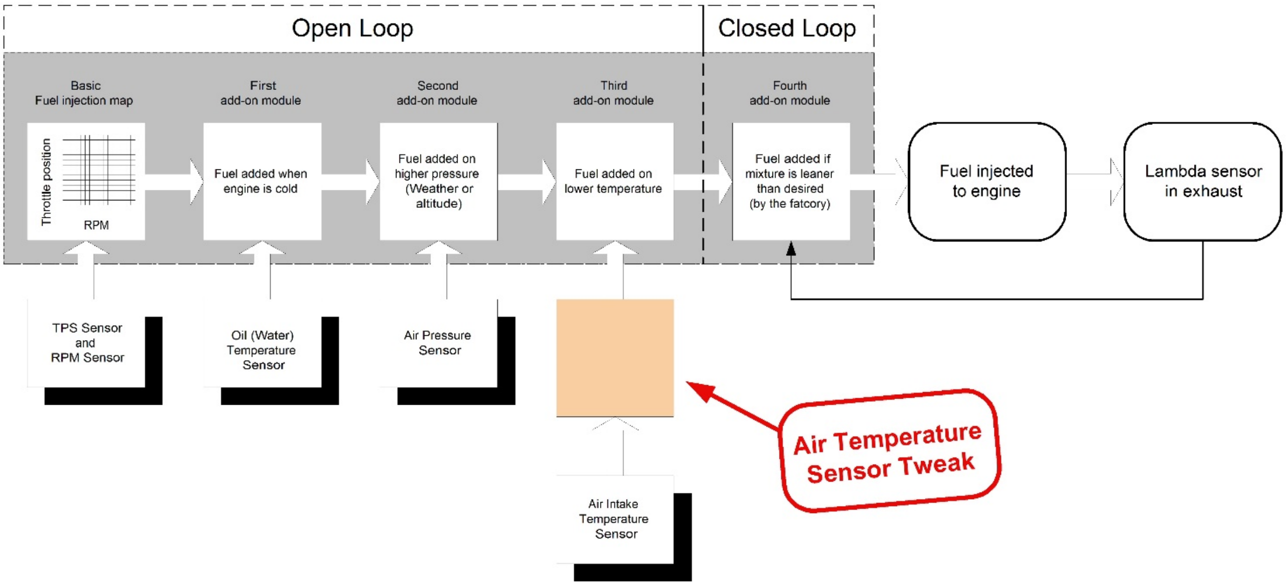
The idea is to change the air temperature sensor signal to make the ECU believe the air is a bit colder than the actual outside temperature, and the ECU will respond by making the AFR slightly richer. And as the Lambda sensor signal is not interrupted, your bike will only get the richer mixture when needed to improve rideability, as the lambda sensor will adjust the mixture back to the leaner setting on the open roads to save fuel and keep emissions low.

This simple lift of the entire open loop programming can only be successful if the basic fuel map in the ECU is reasonably accurate. If the ECU fuel mapping is resulting in very different AFR across the map, there is no easy plug and play solution.
All bikes from 2006/2007 are running under very strict emission regulations and WILL have excellent base maps – otherwise they would never have been approved for road use.
For bikes before 2006/2007 the picture is different. Some motorcycle brands got the mapping right early, where other was pretty horrible until they had to improve to get the bikes approved for road use. This is why we do not offer the BoosterPlug for all models older than 2006.

Tweaking the air temperature sensor signal correctly is not as easy as it seems, because the air temperature sensor is not a linear output device. This means that if you just add a fixed resistor to the temperature sensor signal line, you could reach a solution that could perform well in 20C, but would not work properly in 15C or 25C.

The BoosterPlug comes with it's own temperature sensor and is set up to make the original air temperature sensor and the BoosterPlug sensor work in cooperation to provide an output that is correct and stable in all ambient temperatures. It sounds simple, but it will only work if you have sufficient knowledge on engines and electronics. There's a lot of hidden engineering in making things simple and good !

In the chart below you can se how the BoosterPlug is installed between the air temperature sensor and the ECU, and that the lambda sensor signal is left undisturbed.



Here's why the BoosterPlug is the better solution:

- The BoosterPlug will only provide the slightly richer AFR when needed (Open loop mode) to improve overall rideability and make the bike easier and safer to handle.
- As soon as you ride at a constant speed on the open roads, the bike will be able to retain closed loop mode because the lambda sensor is kept active. This is keeping fuel consumption and emissions low, so the BoosterPlug will give you the best of both worlds.
- As the BoosterPlug works in cooperation with the lambda sensor, you can swap exhausts and air filters as you like without risking expensive and dangerous engine breakdowns.

9. Future predictions

The new emission restrictions for 2017 make it even harder for the manufactures to offer a decent running motorcycle to their customers.

Motorcycles are still approved under the same restrictions as cars, which is not really fair because the motorcycle have a lot less rotating mass, and is therefore not capable of running as lean as the heavier car engine.

So we will still have bikes that are not as safe as they could be and less than perfect to ride, because they will continue to stall easily and have the lumpy low speed running and snatchy throttle action.

The factories development teams are using every trick in the book to make the engines run as good as possible, but the emission limit requirements seem to tighten up faster than the development of new technologies, so our bikes does not really improve year by year.

We can obviously expect the emission restrictions will be even tighter in the future, but there is also talk about different anti-tampering feature requirements that will make it difficult to improve automotive fuel injection systems. There are not a lot of details on these future requirements yet, but we can expect the following requirements in a not too far future:

- Standardized on board diagnosis (OBD), will allow the authorities to check if your ECU is using the standard fuel map (Some modern ECU's allow the owner or the authorized dealer to load other maps to the ECU)
- A warning device that will monitor input from different sensors and flash a warning in the dashboard if a sensor is not providing a "likely" signal level.
  - Best example here is the lambda sensor: It is designed to regulate the mixture in closed loop mode, and the signal from the lambda sensor will change constantly as the AFR changes. If the ECU receives a fixed signal from the Lambda sensor because it is disconnected or not working, the monitoring system will see an "unlikely" signal and flash a warning in the dashboard.
  - This will most likely mean an end to the Power Commander and the common Lambda sensor tweaks.

Looking further ahead, it's a fair guess that we will see full time AFR monitoring requirements that will flash an alarm (or even stop the vehicle) if the required AFR level is not met. This would require better and more reliable wide band lambda sensors than we have today – otherwise we would see plenty of cars and motorcycles with false alarms from the rather fragile wide band sensor :-)

But electric cars and motorcycles may well have taken over the majority of the market by then, and no matter how much we love our gasoline powered motorcycle engines, we WILL see a different picture in a not so distant future.