Lambda Control
Fuel Adaptation and Fuel Trim

Q: What is Lambda and Lambda Control?
A: In the case of a gasoline engine, the optimal mixture of air to fuel for complete combustion is a ratio of 14.7 parts of air to 1 part fuel. This stoichiometric (the quantitative relationship between reactants and products in a chemical reaction) air to fuel ratio (AFR) is the called Lambda = 1.

A Lambda of 1 is normally considered the best trade off between emissions, fuel economy and power production.

Running LEAN is when the AFR has more air in it. This is called Lambda >1. For example a ratio of 16:1 AFR is lean. Running lean increases emissions, particularly NOx, increases heat, usually increases fuel economy, reduces power and increases the chances of knocking.

Running RICH is when your AFR has more fuel in it. The AFR is less then 14.7:1 (Lambda <1) for example 13:1 AFR is rich. Running rich increases emissions, usually decreases heat, decreases fuel economy, increases power (to a point), decreases the chance of knocking. Running rich for long periods of time can cause deposits to build up on the plugs and O2 sensors (fouling) and can clog your catalytic converter. Maximum power is usually obtained running around a 12.3:1 AFR. Going richer then that will cost a little power but you loose less power then being leaner then 12.3:1.

Q: How does the controller know what to do?
A: By monitoring the primary Oxygen sensor(s) (pre catalytic convertor), engine coolant temperature, throttle position, air mass volume, engine speed (rpm) and to a lesser extent changes in altitude, humidity, ambient temperature, fuel quality,...etc, the ECU computes the necessary air to fuel ratio for optimal combustion.

Q: What is “Fuel Adaptation” and what is “Fuel Trim”?
A: “Fuel Adaptation” is the fine tune control of fuel delivery by the ECU. To accomplish this the ECU increases or decreases fuel delivery by increasing or decreasing the time that the injectors are open. The amount of this adjustment is known as the “Fuel Trim”. The fuel trim values over a range of engine speeds are known as the “Adaptation Values”.

The ECU modifies the injection rate under two areas of engine operation. These areas are the idle or low load mid range engine operation and operation under a normal to higher load when at higher engine speeds. These altered injection rates are known as **Long Term Fuel Trim (LTFT) Additive** and **Short Term Fuel Trim (STFT) Multiplicative**. See figure 1.

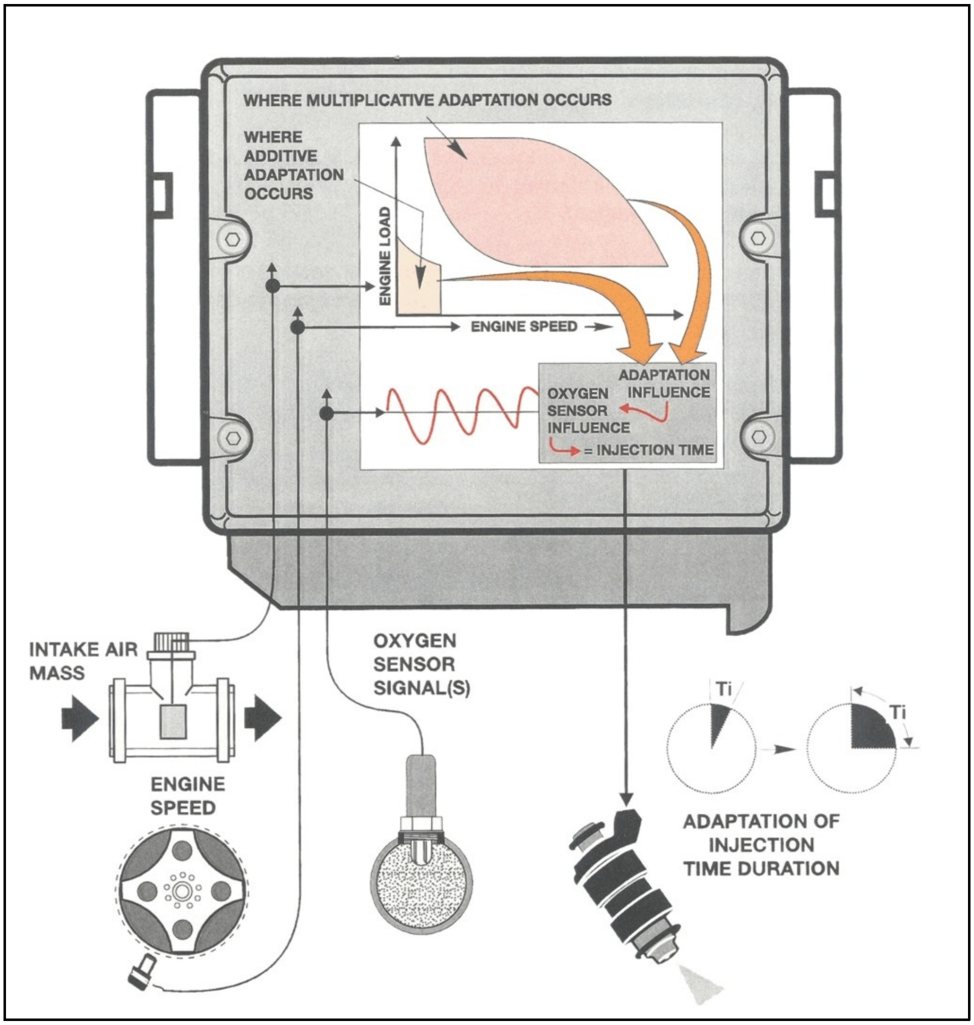

Figure 1 Courtesy BMW

Long Term Fuel Trim (LTFT)
This is the control of Injection Pulse Time Open (ti) (also called Injection Pulse Width) over the entire range of engine operation. It is primarily calculated at idle or low load mid range engine operation and is averaged over time.

In these idle/low load conditions the amount of fuel variation is small due to the relatively small amount of air input. The computer monitors the O2 sensor and **ADDS** or **SUBTRACTS** approximately 0.001msec to the injection pulse time (ti) in order to maintain a Lambda = 1 (14.7 to 1 Air to Fuel ratio). The amount of increase or decrease of the injection pulse width is known as the **LTFT Adaptation Value** (This is known as Additive Adaptation since the injector open time is added to the base injection pulse open time.). This is the value output by the ECU when reading the live data stream.

For example: If an **LTFT** of 1 is the factory spec for a new injector's injection pulse width (time open). This would corresponds to an **LTFT Adaptation Value** of 0.0.

An LTFT of 1.100 would indicate a wider injection pulse width. This corresponds to an **LTFT Adaptation Value** of 0.100 .

LTFT of 0.980 would indicate a narrower injection pulse width. This corresponds to an **LTFT Adaptation Value** of -0.020.

The LTFT is also influence by the Short Term Fuel Trim (STFT).

Short Term Fuel Trim (STFT) Multiplicative
This is the control of the Injection Pulse Time Open over the mid to upper range of engine operation.
When the engine operates at normal or higher load or at higher engine speeds, larger volumes of fuel and air are needed. In order to maintain a Lambda = 1 in these conditions, the ECU monitors the O2 sensor and calculated load (see figure 2) and compares the values against the optimal value for the fuel injection pulse width stored in the drive map. If this base fuel injection pulse width value does not yield a Lambda = 1 at the O2 sensor for the measured air mass, the computer increases or decreases the pulse width by a percentage (%) determined by the difference in Lambda from optimal. These percentages have been computed by the engineers at the factory from extensive dynamometer testing and are stored in a "weighted STFT value array[1]" in the drive maps.

$$\text{Calculated Load} = \frac{\text{Current Air Mass}}{\text{Maximum Air Mass}} \times \frac{\text{Atmospheric Pressure @ sea level}}{\text{Current Barometric Pressure}}$$

Figure. 2

When the STFT reaches the limit of its adjustment it will cause corresponding decrease or increase to the Long Term Fuel Trim. If the correction to the base value exceeds +25% or -25% for longer than 10 seconds a DTC is set for rich or lean stop for STFT.
Short Term Fuel Trim in general makes very quick and small temporary changes to the fuel

[1] The exact method of utilizing the weighted STFT array is held proprietary by BMW, but a good example is that used by GM. See http://members.iatn.net/tech/gm/obd2/obd2-6-3.html .

being delivered to the engine. **Long Term Fuel Trim** makes slower more permanent changes. Each change in the Long Term Fuel Trim is equivalent to a change of the Short Term Fuel Trim over it's entire range. The idea of this being that when the Short Term hits it's upper/lower limit, it resets back to the beginning, and moves the long term TRIM up or down by one count. The Short Term continues to change very quickly, and if it hit's it's limit again, it increments/decrements the Long Term again. This continues until the Long Term has added enough fuel to compensate for the problem or until the long term has hit it's own limit. When the later occurs the Air/Fuel ratio cannot be maintained at Lambda=1 and a “Lambda Control” DTC would normally be set and in later injection systems a “LTFT at rich/lean stop” fault.

Once a LTFT DTC is set, depending on the calibration, the ECU usually defaults to Open Loop (O2 sensor not on line) the ECU determines fuel delivery based on all sensor inputs (except oxygen sensor) and predetermined internal “drive maps”.

During Closed Loop, the input from the Oxygen sensor(s) is used by the ECU to calculate fuel delivery adjustments or Adaptations. If the Oxygen sensor(s) indicate a lean condition, the Adaptation values will be above 0. If the oxygen sensors indicate a rich condition, Adaptation values will be below 0. Adaptation values that are between +10% and -10% of the base injection pulse width are an indication that the ECU is maintaining proper fuel control.

If the ECU drops into Open Loop for what ever reason, you will notice that the long term fuel trim adaptation value will show 0.0 ms. This is because the ECU is no longer looking at the O2 sensor, and therefore can't make any adjustments to the fuel delivery. It must rely only on the fuel curve that has been programmed into the drive map. This is a good reason for having the fuel curve as close to perfect as possible.

Let's look at some conditions that will set adaptations faults and there causes.

Intake air leaks
Incorrect Fuel Pressure
Injector valve defective or coked
Engine Temperature Sensor defective
EGR valve defective
Secondary air leak
Fuel evaporation conntai.

STFT Adaptation Value positive (+) (ECU thinks mixture is lean)
Consistent high positive value can mean bad MAF (reporting measured volume too low), low exhaust back pressure, blown TWCC, misfires, large intake or exhaust leak (Large air volume).

STFT Adaptation Value negative (-) (ECU thinks mixture is rich)
Consistent high negative value can mean high exhaust back pressure, clogged TWCC, injectors stuck open.

OBD II Requirements
The OBD-II requirements for fuel system monitoring says that the fuel delivery system must be continuously monitored for the ability to provide compliance with emission standards. The fuel trim monitoring system is considered malfunctioning when it causes the emission levels to exceed 1.5 times the FTP standards. The regulations specifically require a monitor of the long-term fuel trim limits. The operating conditions at the instant of fault detection must be stored in Freeze Frame data for the automotive technician.
BMW monitors LTFT and STFT in all LEV systems.

Fuel Trim Diagnostic Monitoring
The Fuel Trim Diagnostic monitors the averages of Long Term and Short Term Fuel Trim. If these fuel trim values reach and stay at their maximum limits for a period of time, a malfunction is indicated. The fuel trim Diagnostic compares an average of Long Term Trim values and Short Term Trim values to rich and lean limits which are the calibrated fail thresholds for the test. If either value is within the fail thresholds, a pass is recorded. The closed loop system still has control authority. If both values are outside the fail thresholds, then a failure condition exists. This will cause a DTC to be stored and the rich or lean condition to be recorded. The fuel trim diagnostic also conducts an intrusive test to determine if a rich condition is being caused by excessive vapor from the EVAP canister.

BMW Fuel Trim (DME 5.2)

	Nominal Value	Range	Limit
LTFT	0 ms	**±0.675 ms**	±>25% for 10 seconds
STFT	0 %	**±15%**	±>15% for 10 seconds

BMW Fuel Trim (MS42)

	Nominal Value	Range	Limit
LTFT	0 ms	**±0.35 ms**	±>12% for 10 seconds
STFT	0 %	**±8%**	±>8% for 10 seconds

Rear O2 Sensor Fuel Trim

The rear oxygen sensor, located after the catalyst, is used for fuel trim corrections on some OBD-II vehicles. By virtue of its location, the rear sensor is generally protected from high temperatures and much of the contamination that affects the front oxygen sensors. In addition, the rear sensor sees exhaust gases that are equilibrated – they have already been converted by the catalyst so that there is very little residual oxygen. This allows the rear sensor to respond to much smaller changes in exhaust gas oxygen content. In turn, it then possible for the rear sensor voltage to remain near the 0.45 volt switchpoint. This characteristic allows the rear sensor to be used for fuel control. Under steady rpm and load conditions, the short term fuel trim bias can be adjusted so that the rear sensor voltage is maintained near the 0.45 volt switchpoint. This ensures that the catalyst is getting a stoichiometric exhaust gas mixture, despite any shift in the front sensor switchpoint. The rear fuel trim corrections are learned in KAM. Internally, this system is known as Fore Aft Oxygen Sensor Control (FAOSC). Note that FAOSC learns and reacts very slowly because the catalyst, with its large/slow oxygen storage and release characteristic, is part of the control loop. Also, this system cannot be used with a "y-pipe" exhaust where a single rear sensor would try to adjust dual front sensors.

