Technical Support Note

Title: Measuring Emissions from Diesel-Fueled Equipment
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Created by: R. Schrader
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Overview:

Diesel fueled equipment have become increasingly popular due to their robustness and low maintenance in the industrial environment. The exhaust emissions from these engines have come under likewise closer and closer scrutiny as they are more frequently being operated in closed spaces or in other circumstances which lead to an increase in human exposure. In particular both the EPA and OSHA have been promulgating more strict regulations on diesel emissions than they have in the past. Some review of previous, current, and future emission regulations trends may be in order:

Historically, Diesel engines have been largely unregulated – with specifications only on opacity (black smoke) being promulgated internationally. The exhaust emissions of 'real' gases have been ignored until lately – and only the amount of smoke the diesels generate has been a topic of concern. In the past few years, it has become recognized that diesel engines are not as clean as they have been purported, and produce high volumes of NOx as well as particulates (smoke), oxides of Sulfur, and fuel mist. Regulations are currently being promulgated domestically and internationally which require the diesel engines to control all of these emissions. In the future, diesel engines will have to be equipped with much more sophisticated emission control devices - including particle traps and NO reducing and CO and HC oxidizing catalytic converters, and the sulfur content of diesel fuel will be controlled to lower levels to reduce sulfur emissions as well. These changes will require substantially increased emission testing to support maintenance of the basic engine and verify correct operation of the post engine treatment devices.

The purpose of this Technical Note is to advise how the Bridge Exhaust Gas Analyzers may be used to perform basic exhaust gas analysis on diesel engines.

The Differences between Diesel (Compression Ignition) and Gasoline (Spark Ignition) Engines:

These two engines may look similar, and produce similar power from the same package size – but there are more differences between them than meets the eye – and not just the fuel type either. The basic way they operate is substantially different – and should be understood before applying a gas analyzer to the exhaust and attempting to understand what you are seeing.

In essence, the gasoline powered engines seek to meter air (Oxygen) to control power (that's why they have a throttle plate) – and then gasoline is metered into the combustion process to match the amount of oxygen present at the ideal stoichometric level – Lambda = 1.000 or A/F mass ratio = 14.7:1. This mixture is ignited by a spark, combustion occurs, and the oxygen in the air charge combines with the H and C in the fuel to create H_2O (water) and CO_2 (carbon dioxide). When you look at the exhaust from a gasoline fueled vehicle – you expect to see low levels of O_2 (it is supposed to be all combined with the fuel under ideal conditions) – low levels of CO (incompletely burned fuel – around 1.0% is typical, high levels of CO_2 (around 14.0%), and small amounts of unburned fuel (hydrocarbons – HC) in the range of 100 ppm or so, and likewise relatively small amounts of NO – 800 ppm or so. These gas values are for undiluted exhaust gas. That is, as the power level goes down, the throttle plate closes. The combustion mixture is maintained at close to stoichometric. There is no excess air in a normal gasoline powered engine.

Contrast this situation to that of a diesel engine, and you can see where substantial corrections must be made to the exhaust gas readings to compare the two types of engines.

Unlike the gasoline engine described above, the Diesel engine has NO air throttle plate. It is like running a gasoline powered engine at full throttle all the time – as a full charge of air is required to develop enough compression to ignite whatever fuel is in the combustion chamber. If a throttle plate were attached, the compression would go down under idle or low power conditions, and the charge would not ignite.

In order to regulate power, the fuel is metered. Thus, more fuel is injected into the full air charge if more power is desired – up to a full stoichometric mix at full power.

As can be seen from the above discussion, the Diesel engine (unlike the gasoline engine) varies in air/fuel mix from very lean (at idle) to stoichometric at full power. The only time it gets close to the constant stoichometric condition of a gasoline engine is at full power. The rest of the time it is very lean – equivalent to an air-diluted gasoline exhaust.

In the case of the Diesel engine, you would expect to see quite different gas levels in the exhaust – depending on the power setting of the engine. At idle or very low power, you will see a small amount of combustion products, and a large amount of excess air. In this case, you will see much higher O2 readings than equivalent gasoline engine exhaust (due to the excess air), and the excess air will also dilute the other gases too – resulting in an artificially small value for CO, CO2, HC and NOx. Bear in mind, though, that the exhaust gas volume from a diesel engine is much larger at low power settings than a gasoline engine. The exhaust is diluted by the excess air so that the concentrations are different – but if the excess air were accounted for – the exhaust gas readings could be compared between the two cases.

A table of the typical exhaust gas values from a gasoline and diesel engine are given below:

GAS	Gasoline	Diesel (Idle)	Diesel (Mid)	Diesel (Full)
CO (%)	1.00	0.02	0.03	0.05
HC (PPM Hexane)	200	20	25	30
CO2 (%)	13.2	2.9	7.7	11.3
O2 (%)	1.0	16.5	10.0	5.0
NO (PPM)	800	500	900	1250
Lambda	1.010	2.000	1.871	1.296
CE (%)	95.67	99.26	99.61	99.62

The gasoline engine exhaust gas levels do not change much with throttle setting and are fully concentrated. The diesel engine exhaust levels are very much a function of power, and are very diluted at low power settings, and only approach the undiluted gas levels of the gasoline engine at full power. This can be seen by the high level of O2 in the exhaust. In addition, the nature of gasoline and diesel fuels are very similar in one aspect. When they are burned, the sum of CO and CO2 in the combustion gases are close to 15% in both cases.

Using this standard of comparison, the table above can be corrected for air dilution to yield the following:

Air Dilution	**4.85%**	**80.10%**	**48.54%**	**24.27%**
Correction Factor 1/(1-Air Dil)	**0.9515%**	**0.1990**	**0.5146**	**0.7573**
GAS	**Gasoline**	**Diesel (Idle)**	**Diesel (Mid)**	**Diesel (Full)**
CO (%)	1.05	0.10	0.06	0.07
HC (PPM Hexane)	210	100	49	40
CO2 (%)	13.9	14.8	14.9	14.9
O2 (%)	0.0	0.0	0.0	0.0
NO (PPM)	841	2512	1749	1651
Lambda	0.9630	0.999	1.000	1.000
A/F Ratio	14.17	14.69	14.71	14.71
CE (%)	95.67	99.26	99.61	99.62

(Note ,by the way, that the CE values do not change – as the CE calculation is not effected by air dilution.) The other gas values do change, though – as a function of the air dilution present in diesel engines.

To Summarize:

Diesel engine exhaust can be compared to the equivalent of gasoline engine exhaust if the air dilution effects present in diesel engine exhaust can be compensated for. The way this is done is as follows:

1. Take exhaust gas readings with the analyzer fuel selection set to measure HC as Hexane (H-C6) – as with a gasoline powered engine.
2. Add the CO and CO2 values just obtained. (Note that the sum of the two concentrations is considerably below 15.0%.) This sum will vary considerably by engine power setting – as it is an indication of the degree of air dilution. The sum approaches 15% only at maximum power setting.
3. Divide the value just obtained into 15.0%. This is the gas correction value due to the natural air dilution effects of the diesel engine design.

4. Multiply the CO, HC, CO_2, and NO readings by this number. The result is the equivalent undiluted gas readings, and can be compared to the spark-ignition gasoline engine values above, or saved for reference. These readings will vary somewhat with power, but not nearly as much as the raw gas values.
5. Check your math by seeing if the air dilution you just corrected for accounts for the excess oxygen in the exhaust.
   - 5.1 Divide 20.6 (the amount of oxygen in air) by the correction factor obtained above. This is the excess oxygen in the exhaust due to air dilution.
   - 5.2 Compare the value above to the oxygen you measured in the exhaust. If they are close, you are correctly accounting for air dilution. If the value is substantially higher than the oxygen you measured, you are over-correcting for air dilution. If the value is substantially under, you are under-correcting – or the fuel is simply not burning (look at the CE value to see how close it is to 100%)

Now we will look at some typical values and do the math above:

1. Say you are testing a diesel engine at about ½ power, and get the following:

GAS	**Diesel (Mid)**
CO (%)	0.10
HC (PPM Hexane)	60
CO_2 (%)	7.5
O_2 (%)	10.5
NO (PPM)	1000
Lambda	1.871
CE (%)	99.61

2. Add CO and CO_2. (7.6%)
3. Divide this value into 15.0. (15.0 / 7.6 = 1.974)

4. Multiply the CO, CO2, HC, and NO values just obtained by this correction.

GAS	Diesel (Mid)	Correction Factor	Corrected Diesel (Mid)
CO (%)	0.10	1.974	0.20
HC (PPM Hexane)	60	1.974	122
CO2 (%)	7.5	1.974	14.8
O2 (%)	10.5	N/A	10.5
NO (PPM)	1000	1.974	1974
Lambda	1.871	N/A	N/A
CE (%)	99.61	N/A	99.61

5. Test this correction by seeing if it accounts for the O2 measured in the exhaust gas:

5.1 Divide 20.6 by the correction factor determined above and subtract this from 20.6. (20.6-(20.6/1.974) = 20.6-10.4 = 10.2

5.2 Compare this value to the O2 measured in the exhaust:

GAS	Diesel (Mid) Measured O2	Correction Factor Calculated O2
O2 (%)	10.5	10.2

As you can see – the values agree pretty closely – so in this case, the air dilution correction above is valid.

Other Testing Considerations:

Mind the Filters:

Diesel engine exhaust can be pretty dirty. Operate the gas analyzer with clean filters. Plan on changing filters (ALL of them) much more frequently than you have to with gasoline or propane engines. Modern gasoline engines (on automobiles and trucks) have catalytic converters on them – so the amount of particulate matter they produce is very small compared to 10 or 20 years ago. Diesel engines are not – and they are much dirtier in general than the gasoline engines were of the same period.

Diesel engines have gotten cleaner – but they are still 10 to 50 times dirtier than a modern gasoline engine – and propane fueled engines are pristine by comparison to them both.

A word to the wise here – change filters often and check the water trap for contamination. If you see dirt in the water trap – it is getting past the input filter.

Engine Loading During Testing:

The Higher the true engine load – the closer the exhaust gas values are to undiluted gas. Measuring exhaust gas values under low or idle conditions is pretty much meaningless for a diesel. On the other hand – these engines can produce quite a lot of power.

You need to find some comfortable point of operation – enough power to reduce dilution and produce reasonable exhaust gas levels – but no too much to be unmanageable. Care should be taken to make sure the exhaust conditioning systems are up to operating temperature during the test – but the engine (and drive systems) are not damaged due to stalled running conditions.

Sulfur Compounds in the Exhaust Gas:

The testing above will NOT account for all the noxious gases delivered from a diesel engine. You can smell other compounds in diesel exhaust – as even trace amounts of the oxides of Sulfur are very irritating. As these oxides of sulfur are not measured, but may be present and causing a noxious smell – there is not much you can do about this – except mandate that a low-sulfur diesel fuel be used.

(Gasoline and Propane simply do not have this problem due to the refined nature of these fuels.)

Lambda and A/F Ratio on a Diesel:

The natural air dilution present in diesel exhaust make the Lambda and A/F ratio calculation in the Model 9004 and 9005 pretty meaningless. You cannot rely on these values for diagnostic purposes without correcting for the air dilution inherent in the diesel engine.

Combustion Efficiency (CE) on a Diesel:

The CE calculation in the Model 9004 and 9005 is NOT effected by the air dilution present in diesel engines. Combustion Efficiency can be used as a valid diagnostic parameter for diesel engines without modification.

Bridge Analyzers, Inc.
PO Box 39325
Solon, Ohio 44139 USA

(510) 337-1605 office
(216) 274-9262 fax
support@bridgeanalyzers.com