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MEMORANDUM

To: International Accuscan Users

From: University of Denver (Dr. Donald Stedman) and ESP-RSD Engineering

cc:

Date: August 20, 2004

Re: REMOTE SENSING SMOKE VS. HARTIRIDGE SMOKE UNITS

Section 1 discusses remote sensing theory in the context of the smoke opacity measurement, contrasting it with the old Hartridge Smoke Units measurement still in use in many locals.

Section 2 presents the mathematics of the Accuscan Smoke Factor.

1. RSD Smoke vs. HSU

Assume $6m^2$/gm combined scattering and absorption coefficient for soot at 230 nm and assume approximately the same in the visible for a human observer. These numbers are actually dependent upon both the size distribution and the composition of the smoke.
Assume that an RSD opacity of 1.0 corresponds to 1% of the fuel mass emitted as soot.
Assume that Singapore vehicles operate with a fuel economy of 10L/100km.
Assume a 5cm diameter tailpipe.
Assume a fuel density of 750gm/L and formula of CH_2

Note that all the above assumptions are approximate but make for easy calculation.

When the RSD reports emission data, the % (or ppm) in the database is corrected for excess water and excess air not involved in combustion. This latter correction is important for diesel vehicles. The pollutant ratios and the pollutant emissions per kg of fuel are not affected by these corrections.

14 gm ($^{12}\mathbf{C} + 2x^{1}\mathbf{H}$) of fuel burns at stoichiometry to create 7 moles of dry exhaust thus:

$$\mathbf{CH_2 + 1.5(O_2 + 4N_2)} = H_2O + \mathbf{CO_2 + 6N_2}$$

A kg of fuel uses about 500 mole of air, each one of which occupies about 20L Thus if burned at stoichiometry and with no excess air, the 10g of soot per kg of fuel produced from a vehicle with an RSD opacity of 1 would be diluted in $10m^3$ of air for an overall emitted concentration of 1gm soot/m^3. The fact is that a typical diesel is operating with about 50% excess air so this same RSD opacity of 1 would correspond in that vehicle to an exhaust containing only 0.5 gm soot/m^3.

At a fuel economy of 10L/100km the vehicle uses 7.5 kg of fuel per 100km. From this information, one can deduce that an RSD opacity of 1 corresponds to about 75 gm of soot per 100km or 750 mg soot/km driven. This is not far from the 1 gm/km which I estimated over the phone and in any case is a HIGH emitter.

When it comes to observable opacity, it is important to mention that HSU units are an ancient British invention and are rather unreliable and empirical. Two trained observers on opposite sides of the street can easily report the same vehicle at 45 HSU (passing) and 55 HSU (failing) on the same day at the same time. For that reason alone, one would tend to enforce opacity readings, much like one enforces speeding tickets, at much higher cut points than the formal standard.

Now it is time to return to what an opacity observer might see from a passing vehicle and what the RSD instrument "sees" from the same passing vehicle. The first important thing to note is that the human observer's eye will always be drawn to observe the most opaque plume centerline. The instrument looks only where its optical beam is and that very often is NOT along the plume centerline.

At plume centerline for an RSD opacity of 1 and an imaginary vehicle with no excess air, the exhaust would be 15%CO_2, the optical path is 5cm and at the instant of that measurement the reported %.cm CO_2 would be 15x5 = 75 %.cm. This would be the CO2max for this plume which would generally dilute rapidly to lower values. The UV absorption would be given by Beer's law as:

I/I_0 = exp-(6x1x0.05) [6 m^2/gm coefficient x 1 gm/m^3 smoke level x 0.05m wide exhaust pipe] = 0.74. This is 74% transmission (26% absorption).

More realistically the diesel vehicle would have 50% excess air in the tailpipe, the smoke level would be 0.5 gm/m^3. This would result in 86% transmission (14% absorption) when viewed at the tailpipe, and if the RSD saw the tailpipe the CO2 max would be 75/2 = 37.5 %.cm.

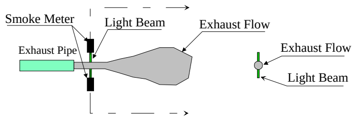
The RSD often views vehicle exhaust only after further dilution. In this case suppose, for a moment, that the peak exhaust reading from the RSD 4000 is diluted twofold more down to about 19 %.cm for the CO2max. This reading will correspond to the UV opacity meter reading a 7% absorption (93% transmission). Now this exhaust will further dilute and the CO_2 and UV opacity readings will each go down correspondingly. The ratio however will not change.

Note that what the RSD "sees" is only a snapshot of the exhaust plume and is usually already diluted compared to what a human observer would see. We can, and the system does, report an opacity reading which is extrapolated back to the tailpipe with two caveats, namely the result is corrected for water and excess air present in the exhaust. The result is correct per kg of fuel, however all diesel vehicles have excess air in their exhaust pipes which is intentionally passed through the combustion chamber. This excess air can not be observed by an RSD because it is buried in all the ambient air which the RSD also looks through. This excess air dilutes the exhaust, and it is variable depending on the load of the diesel vehicle. In this illustration I suggested 50% excess air 50% exhaust products, but this can vary a great deal depending on vehicle load. At low load, 85% excess air is possible and at high load this can go down to only about 15%. This variation alone is why HSU units are not a perfectly correlated indicator of either fuel or km based emissions, and conversely why an RSDS which correctly measures gm of emissions per kg of fuel can never perfectly correlate to an estimate in HSU units. Nevertheless it is certain that vehicles which read high on RSD opacity units will in general read high on HSU and vice-versa.

Actually, for the purposes of an emission inventory, knowledge of diesel fuel sales and average RSD opacity can be used to obtain a mass of soot emission inventory. HSU can not do that. With a high RSD opacity reading and a photograph of the vehicle and tailpipe, I imagine even locations with standards written in ancient British opacity units should have no trouble enforcing their observations in court. With the passage of time, and increased confidence, it might even be possible to change the legal standards into a more appropriate set of units such as emissions per kg of fuel.

Smoke Factor Calculations

Standard Smoke Meter
(light beam passes through entire smoke column)

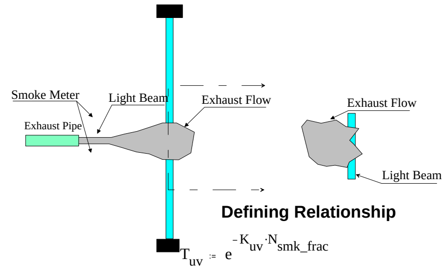


Defining Relationship

$$T_{gl} := e^{-K_{gl} \cdot N_{smk\_total}}$$

T_{gl}	Green light transmittance (1-opacity) measurement.
K_{gl}	Apparent cross-sectional size per particle at green light wavelength.
N_{smk_total}	Total number of smoke particles per unit cross-section.

Remote Sensing Smoke Measurement
(light beam passes through a portion of smoke column)



Defining Relationship

$$T_{uv} := e^{-K_{uv} \cdot N_{smk\_frac}}$$

T_{uv}	UV transmittance (1-opacity) measurement
K_{uv}	Apparent cross-sectional size per particle at UV wavelength.
N_{smk_frac}	The number of smoke particles per unit cross-sectional area; a fraction of total.

Remote Sensing Foundation

- Since the sensing beam does not necessarily pass through the entire exhaust column, “total” exhaust measurements are not possible.
- On the other hand, for a small time period (time prior to significant diffusion or stratification effects), the exhaust can be treated as a uniform mixture at any instant in time. This means the ratio measurement of one exhaust component to another exhaust component is accurate.
- Remote sensing measurements are ratios!

Other Gas Relationships

(simplified approximations)

Defining Relationships

$$T_{CO} := e^{-K_{CO} \cdot N_{CO\_frac}} \qquad N_{CO\_frac} := \frac{-\ln(T_{CO})}{K_{CO}}$$

$$T_{CO2} := e^{-K_{CO2} \cdot N_{CO2\_frac}} \qquad N_{CO2\_frac} := \frac{-\ln(T_{CO2})}{K_{CO2}}$$

$$T_{HC} := e^{-K_{HC} \cdot N_{HC\_frac}} \qquad N_{HC\_frac} := \frac{-\ln(T_{HC})}{K_{HC}}$$

Our Smoke Number

(a value proportional to number of exhaust smoke particles per unit fuel)

$$SF := \frac{-100 \cdot \ln(T_{uv})}{N_{CO2\_frac} + N_{CO\_frac} + N_{HC\_frac}}$$

where

N_{CO2_frac}	is amount of plume CO2 in %-cm
N_{CO_frac}	is amount of plume CO in %-cm
N_{HC_frac}	is amount of plume HC in %-cm

SF Summary

- Numerator is result of opacity-based measurement across an unknown portion of the exhaust column. Measurement is made at UV wavelengths (~232nm) which is the ~wavelength for peak mass density of diesel particulate
- Denominator is the sum of measured carbon-based gases across the same unknown portion of the exhaust column. Carbon-based components can only come from the fuel.
- The ratio is an accurate representation of smoke per unit fuel at the instant (0.5-second) that the data is acquired.
- Smoke can be represented as particle density or as mass density per unit fuel through proper engineering units.